Article

High-quality and Sustainable management of forest in water-limited region

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Abstract: The goods and services produced by forest vegetation ecosystem are the driving force for the rapid, high-quality and sustainable development of human society. In history, with the increase of population and economic development, there is an increasing demand for the quantity and variety of forest vegetation ecosystem products and services in a country or a region. To meet the demands, most of the original forest has become farmland, plantation and grass and crops land. As a result, the plant water relationship changed from equilibrium to non-equilibrium, which easily led to soil drought, soil degradation and vegetation decline in dry years or waste of soil water in rainy years in most of water-limited regions. In order to solve the question and realize the sustainable utilization of soil water resources and the high-quality sustainable development of forest, it is necessary to apply the limit theory of plant utilization of soil water resources and the vegetation carrying capacity theory in the critical period of plant-water relationship regulation to adjust the relationship between plant growth and soil moisture to obtain the maximum yield and benefit and realize high-quality and sustainable development.

Keywords: goods and services;water-limited area;plant water relationship; Soil water resource use limit by plants; Soil Water Carrying Capacity for Vegetation; critical period of plant-water relationship regulation; high-quality Sustainable development

1. Introduction

The goods or the products that people need, such as food, fibre and fuel wood, Medicinal materials and services, such as improving environment and soil and water conservation produced by forest and vegetation ecology system is the power by which Human society can be promoted fast in high quality and sustainable way. According to The estimation by UN Food and Agriculture Organization that the global population is about 8.0 billion in 11, 2020 and the population will reach 10 billion in 2050 in 20 years. With the increase of population and economic development, there is an increasing demand for the quantity and variety of forest vegetation ecosystem products and services in a country or a region. In order to meet this demand, most of the original forest has been turned into farmland, plantation forest, grass field and crop land, and the relationship of plant resources has changed, which is prone to soil degradation and vegetation degradation or resources waste.

Terrestrial plant growth and soil water environment has been interacted. According to the water supply of plant growth, the water environment of plant growth was divided into water sufficient area where soil water can meet the need of plant growth and soil water insufficient area or water-limited area where water cannot meet the need of plant growth.

Terrestrial Plants usually absorb water by their roots, and other kinds of water resources must be translated into soil water resources and then absorbed by plants in water-limited regions. The soil water is the most important factor influencing plant growth in water-limited regions because underground water is deep and soil water mainly from precipitation without irrigation in some of the water-limited regions, such as Chinese loess plateau.

Most of the goods and services that people in the world enjoy are produced by non-natural forests. To meet people's needs, most of original forest was changed into non-native vegetation such as farm land, fruit or grassland, which changed the relationship between plant growth and soil moisture, leading to waste in wet years or overuse of soil water resources in dry years, this is not desirable for the sustainable use of soil water resources and the high quality and sustainable development of forest vegetation. For example, in China Loess plateau, since 1960, along with the increase of the population, people’s demand for forest vegetation ecosystem products and services,

Along with plant growth, soil drought occurred, resulting in soil degradation and vegetation decline in most areas of the region (Yang &Yu, 1992; Li, 2001; Guo and Shao,2003,2013; Chen et al,2008; Guo 2020,2021a and b) because the soil water supply mainly from precipitation (Guo and Shao,2013; Guo 2020,2021a and b) and cannot meet the water needs of plants in dry year or wastes because the soil water supply from precipitation surpasses the water needs of plants in a rainy year. As a consequence, vegetation decline and eventually desertification in the artificial perennial grassland and woodland areas of the Loess Plateau (Li, 2001; Guo and Shao, 2002,2013; Chen et al, 2008) or soil water resources wastes. This, in turn, affects soil quality, non-native vegetation growth and its ecological benefits. To keep healthy growth of non-native vegetation and get its maximum produce and ecological benefits and carry out high-quality sustainable development of forest, water-plant relationship must be regulated by sparse plant density in order to increase soil moisture supply, reduce evapotranspiration and maintain soil moisture balance and the stability of artificial vegetation ecosystem to a certain extent, to prevent soil drying and soil degradation or soil water waste to get its maximum produce and ecological benefits and carry out high-quality sustainable development of forest. The rationale for regulation water-plant relation is that theory of Soil water resource use limit by plants and the theory of Soil Water Carrying Capacity for Vegetation. The purpose of the paper is to introduce the theories of Soil water resource use limit by plants and the theory of Soil Water Carrying Capacity for Vegetation and the method for obtaining the maximum produce and ecological benefits of forest.

2. Results

2.1 Soil water resources

To understand the theory of Soil water resource use limit by plants and the theory of Soil Water Vegetation Carrying Capacity, first we have to master the soil water resources because soil water resource is the basis of understanding the theory of soil water resource use limit by plants and the theory of Soil Water Vegetation Carrying Capacity.

The concept of Soil Water Resources first put forward by Budagovski in 1985 (Budagovski, 1985) after Lvovich proposed the concept of overall soil moistening in 1980 (Lvovich, 1980). Soil water resources is the sum of water in the soil body, which are renewable water resources and components of water resources. There are generalized soil water resources and narrow sense soil water resources. Generalized soil water resources can be defined as the water stored in the soil from the surface soil to the water table, commonly used in geology or architecture, and narrow soil water resources is the water stored in the root zone, commonly used in forestry, grassland and agriculture. In addition, there is a dynamic soil water resources, which is the antecedent soil water resources plus the soil water supply from precipitation in the growing season for deciduous plants, or over a year for evergreen plants. Soil Water Resources change with rainfall, soil evaporation, plant transpiration and soil water moving in the soil in most of the water-limited regions because underwater is deep and without irrigation (Guo, 2011).

2.2 Root vertical distribution

Root is an important organ for terrestrial organisms to immobilize and absorb soil moisture even though stoma in a leaf and a stem can suck a little water when air humidity is high, such as raining. Root vertical distribution is an important index to estimate soil water deficit criteria because plant absorbs soil water in the root zone. Soil water resources are good indicator to express the effect of soil moisture on plant growth because plant roots are vertically distributed and suck soil water in certain soil body and sometime the root depth is more than tree height. The plant growth and root vertically distribution of locust (Robinia pseudoacacia L.) forest in the semiarid loss hilly region, Guyuan, China, see Fig.1.

2.3 Soil water resource use limit by plants (SWRULP)

With the growth of plants, the Soil water resource in the maximum infiltration depth of soil water resources decreases. When the Soil water resources in maximum infiltration depth of soil water resources is reduced to a certain limit, soil water resources resource use limit by plants. The plant water relationship, especially plant water relationship in the critical period of plant water relationship regulation, should be considered to be adjusted because the plant water relationship in the critical period of plant water relationship regulation determines the maximum yield and service of forest vegetation.

To understand soil water resources resource use limit by plants, we have to put forward a suitable index to express plant water deficit. Soil water resource is the water storage in a given soil depth. Plant roots cannot absorb soil water without limit, and the utilization of soil water by plants is limited. There are some soil water deficit indices, such as crop water index (Palmer 1968), soil water deficit index, evapotranspiration deficit index, plant moisture deficit index (Shi et al. 2015). Because most of the drought indices are based on meteorological variables (Mckee et al. 1993) or on a moisture balance equation, they do not indicates water deficit accumulation or soil water storage (soil water resource) in root zone (Martínez-Fernández et al. 2015), they cannot act as a suitable index for distinguishing severe drying of soil in the water-limited regions because soil drought is a nature phenomenon, a water deficit accumulation or a decrease in soil water storage in the root zone soil plant root distribute.

The limit is the soil water resources use limit by plant (SWRULP) (Guo, 2010). The SWRULP can be defined as the soil water resources in the MID when the soil water content within the MID equals the wilting coefficient of an indicator plant（Guo，2010, 2014, 2020,2021）. Because the soil water content changes with soil water suction at different soil depth, and the variation of soil water content with soil water suction accords with the Garden equation, so Garden equation was used to fit the relationship between soil water content and soil water absorption and then estimate the wilting coefficient at different soil depth because the moisture content of the soil with water absorption rate of 15ba was set as the wilting coefficient (Guo and Shao,2009,2013).

2.4 Soil water characteristics curve

To estimate soil water suction at different soil depth, we have to take undisturbed soil sample. The sampling pits (soil profile) was dug in the experimental site for investigating soil profile and sampling purposes, whose dimensions were 1m2 × 4 m depth. The undisturbed soil samples were collected for 3 times at different soil depth with cutting rings (a 5 cm in high, 5 cm in inner diameter and 100 cm3 in cubage). Soil water contents at different soil suctions were measured by centrifuge method, generally using a HITACHI centrifuge, or Pressure Chamber method.

Because Gardner empirical formula can better describe the relationship between soil water content w and soil water suction S, the wilting coefficient can be estimated by the Gardner empirical formula $w=a \cdot S^b$ (Guo and Shao, 2009).

Genarally, the wilting coefficient is assumed to be the soil water content when the soil water suction is 1.5 mPa because soil water potential at wilting ranged from -1.0×105 to -2.0×105 mPa, with an average of approximately -1.5×10^5 mPa (15 bar) (Richards and Weaver,1943). So, we have to test the result with an average of approximately -1.5×105 mPa (15 bar). For example, the change of soil water content with soil water suction at different soil depth in caragana (*Caragana korshenskii*) shrubland of semiarid loess hilly region, see Fig. 2, and wilting coefficient varies with soil depth, see table 1. The wilting coefficient varies with soil depth, see the Fig. 1 and Tab. 1.

Table 1 The changes of wilting coefficient varies with soil depth in caragana shrubland of semiarid loess hilly region of Loess Plateau, Guyuan,China.

Soil depth (cm)	Saturated water content (%)	Field capacity (%)	Wilting coefficient (%)	Available water content (%)
0-5	50.64	25.31	10.32	15.00
20-25	53.19	21.94	9.79	12.15
40-45	54.16	21.36	8.88	12.48
80-85	52.38	18.95	8.13	10.82
120-125	54.09	19.55	8.08	11.47
160-165	52.47	20.35	7.67	12.68
200-205	54.60	23.45	8.74	14.71
240-245	56.38	24.99	9.54	15.45
280-285	54.88	24.79	9.22	15.57
320-325	53.88	25.49	9.75	15.74
360-365	55.63	26.67	10.45	16.21
400-405	56.12	26.65	10.07	16.58

2.5 Infiltration and maximum Infiltration depth

Fig.1 The locust (robinia pseudoacacia) root distribution in the semiarid loess hilly region (Guyuan,China)

Infiltration is the process of water entering the soil in a certain time. A neutron probe (CNC503A (DR), Beijing Nuclear Instrument Co., China) was used to monitor the changes of field volumetric soil water content (VSWC) with soil depth before a rain and after the rain event because of its high precision (Wang et al., 2003; Evett, 2012;Guo 2020).If we estimate the changes of soil water content with soil depth at starting time and ending time of infiltration process in the soil profile, there is a starting vertical distribution curve of soil water before an infiltration process and an ending vertical

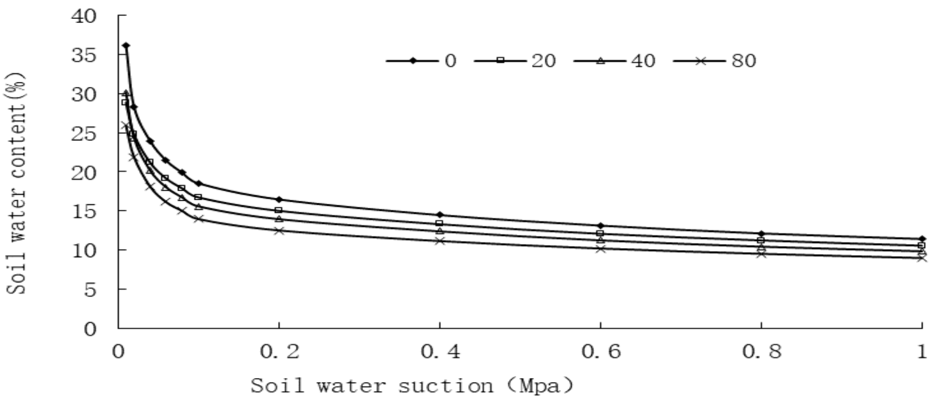

Fig. 2. The changes of soil water content with soil water suction at different soil depth in caragana shrubland of semiarid loess hilly region, Guyuan,China. The numbers of 0, 20, 40, 80 expresses soil depth of 0cm, 20cm, 40cm and 80 cm respectively.

distribution curve of soil water after the infiltration process. Two curves method was found by Guo in 2004, and used to estimate the depth of infiltration of Caragana shrubland by Guo and Shao in 2009 and Guo in 2014, and named by Guo in 2020.

The two vertical distribution curve of soil water before and after the infiltration process can be used to determine infiltration depth and soil water supply. The infiltration depth for one rain event was equal to the distance from the surface to the crossover point between the two soil water distribution curves with soil depth before a rain event and after the rain event, and MID could be estimated by a series of two-curve methods（Guo，2020）.

2.6 Regulation of plant water relationship

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After a seed germinates or buds, and as the plant grows, plant blooms, bears, matures, and eventually leaves fall off and enter a dormant period, plant finished a growth cycle in a growth season or a year. The plant-water relationship in a growth cycle can be divided into different stages: the period of sufficient soil moisture, in which the soil water resources within the maximum infiltration depth (MID) is more than the soil water resource use limit by plants (SWRULP) and the soil moisture is sufficient for plant growth and plant grow in healthy way; and the period of insufficient soil moisture in which the soil water resources within the maximum infiltration depth (MID) is smaller than the soil water resource use limit by plants, which influence the plant growth, cause vegetation decline and did not ensures sustainable use of soil water resources and high-quality sustainable development of grassland and forest.

Drought affects plant growth at all stages of the plant growth cycle, especially at the critical period of plant water relationship regulation because at this stage, water decide the maximum yield and benefits of forest vegetation. The plant water relationship changes with soil water supply and soil water condition. The plant water relationship is good relation when the soil water resources in the MID is more than SWRULP and the plant grow well. When the soil water resources in the MID is less than SWRULP, drought affects plant growth severe. The plant water relationship in the soil can be improved by reducing stand density, the degree of closed canopy, leaf area index and productivity by cutting or thinning trees based on the soil water vegetation carrying capacity (SWVCC) when the soil water resources within the maximum infiltration depth (MID) equal the soil water resource use limit by plants (SWRULP) in most of water limited region because plant have a weak self-regulation.

According to the three years study of red plum apricot forest in the 2018 to 2020, the volumetric water content in the 0 to 290cm soil profile is more than the wilting point, and the soil water resources in the MID is more than the soil water resources use limit by plant. The 23- to 25-years-old red plum apricot tree grow well and red plum apricot mature, see Fig.3. Because Low Temperature and frost in Spring affect the number of flowering and young fruit in the Spring, and heart-eating

Fig.3 Flowers and fruits of red plum apricot in the semiarid loess hilly region, Guyuan, China

harm affect the number of fruit quality in March before soil drought in water limited regions, when plant density is equal to the soil water carrying capacity of vegetation, sometimes the number of leaves and flowers or young fruit is less than the number of leaves and flowers or young fruit when planting density is equal to carrying capacity, so we have to control impact of low temperature and frost on the amount leaf and flowers and heart-eating (*Carposina sasakii Matsumura*) harm on apricot fruit using low-toxicity and high-efficiency cypermethrin and then keep the amount leaf and flowers is equal to or more than the suitable amount flowers or young fruit when plant density equals soil water carrying capacity for vegetation in the critical period of plant-water relationship regulation.

As for corn or wheat and other crop, we can increase sowing amount to ensure the plant density is equal to or more than soil water carrying capacity for vegetation in the critical period of plant-water relationship regulation. When the plant density is equal to the soil water carrying capacity for vegetation, the amount of leave and flowers or young fruit is the appropriate amounts of leaves and flowers because the water-plant relationship of the fruit trees generally can be regulated by pruning branches and leaves. Therefore, it is necessary to estimate the right amount of fruit based on the leave and fruit relation before regulating.

2.7 Soil Water Vegetation Carrying Capacity

Carrying capacity is the best indicator to express the plant resources relation. The idea of carrying capacity come from the doctrine of Malthus（Steiguer, 1995）. The term carrying capacity was first used by range managers（Price ,1999）and U.S. Department of Agriculture researchers（Young, 1998）. After Raymond Pearl and Lowell J. Reed proposed logistic equations in 1920, Odum (1953) connected the term with the constant K in logistic equations（Price 1999； Young 1998; Guo, 2019,2021).

In the early summer of 2000, Guo studied the ability of soil water resources to carry vegetation in order to solve the problems of soil degradation and vegetation decay, which determine the reasonable limits of vegetation restoration. Guo put forward the concept of soil water vegetation carrying capacity，which first appeared in a paper submitted by the author to the 7th Soil Physics Symposium on soil physics and ecological environment construction held by the Soil Physics Committee of Soil Society of China in Yang Ling, Shaanxi, China in December 2000 (Guo at el.2002) and then defined soil water carrying capacity for vegetation as the ability of soil water resources to carry vegetation (Guo & Shao, 2003; Wang et al, 2008).

The SWVCC is the capacity of soil water resources to support vegetation, which is the maximum amount of density expressed by indicator plants in a plant population or plant community that soil water resources of a unit area can sustain and allow to grow healthily in a given period and place (Guo and Shao 2004; Xia and Shao, 2008; Guo, 2011, 2013, 2014, 2021a and 2021b; Jia et al, 2020).

The SWVCC in a plant community is expressed by indicator plant because vegetation is made up of different plants and there are different communities in a nation or a district or watershed and change with plant species, time scale and location (Guo, 2014). An indicator plant is the constructive species for natural vegetation or main tree species for afforestation for non-native vegetation. The SWVCC can be estimated by classical carrying capacity equation and plant density - soil water model. According to the classical soil water carrying capacity equation, SWVCC is equal to available soil water resources divided by individual plant water requirement (Cohen, 1995; Guo, 2014,2021a,2021b). Because plant water requirement changes with weather condition, plant growth stage and soil water condition and there is not a unified definition of plant water requirement, these factors influence the application of classical soil water carrying capacity equation. According to plant density and soil water model, soil water supply reduces with plant density, at the same time, the relationship between soil water consumption and soil density was a quadratic parabola. Simultaneous solution of soil water supply - plant density relation and soil water consumption e density equation, the positive solution of the equations is the soil water carrying capacity of vegetation in the critical period of plant-water relationship regulation (Guo, 2014,2021b)，see fig 4.

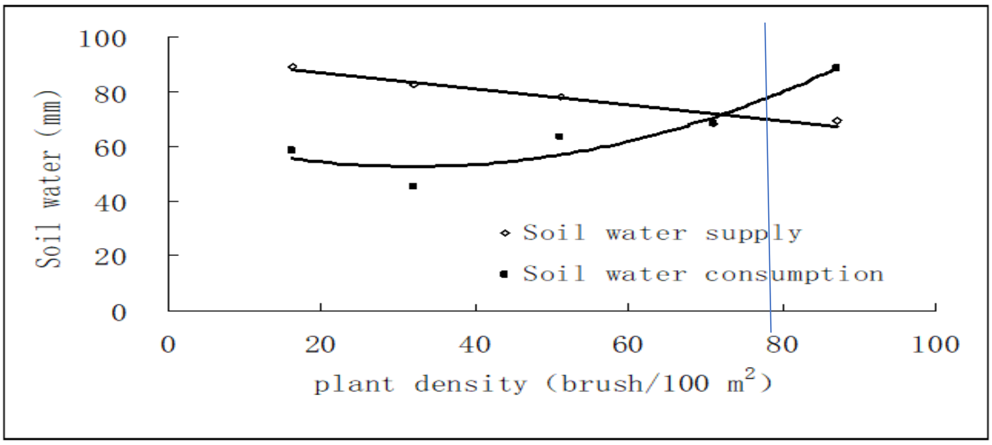

Fig.4 The relationship between plant density or soil water carrying capacity and soil water supply or consumption in the critical period of plant-water relationship regulation in 16-years-old caragana shrubland, Guyuan, China.

2.8 Critical period of plant-water relationship regulation

Although we can estimate soil water vegetation carrying capacity at different time scale in theory, but soil water carrying capacity of vegetation at different time scale have different meaning. The most important time scale for estimating soil water carrying capacity of vegetation is critical period of plant-water relationship regulation (Guo 2014,2021a,2021b).

The starting time of the critical period of plant-water relationship regulation is the time at which the soil water resources within the MID is equal to the SWRULP. The ending time of the critical period of plant-water relationship regulation is the last day on which we can regulate the plant-water relationship based on soil water carrying capacity for vegetation and get maximum yield and benefits. After the critical regulation period, soil degradation and vegetation degradation cannot be controlled by reducing plant density or branches and leave.

2.9 Sustainable use of soil water resources in non-native vegetation

Drought-tolerant plants generally have the ability of self-regulation. First, we estimate the soil water resources use limit by plants and the soil water shortage day is the time on which soil water resources is smaller than the soil water resources use limit by plants. If the drought lasts less than critical period of plant-water relationship regulation, that is the soil water shortage day is smaller than critical period of plant-water relationship regulation, the water-plant relationship does not need to be regulated. Otherwise, if present plant density is more than SWVCC in critical period of plant-water relationship regulation，in order to get the maximum yield and benefit of forest vegetation in water limited region, we have to estimate the soil water resources use limit by plants and soil water vegetation carrying capacity after estimating maximum infiltration depth and soil water supply and soil water consumption at different plant density and regulate the water-plant relationship based on SWVCC in the critical period of plant-water relationship regulation (Guo 2021a, 2021b).For economic forest, we have to regulate the reproduction and vegetative growth relationship according to the suitable leaf amount when present plant density is equal to SWVCC and the relationship between quality fruit and leaf relation(Guo 2021).

3. Conclusions

After the original forest has been turned into farmland, plantation forest, grass field and crop land, and the relationship of plant resources has been changed, which is prone to soil degradation and vegetation degradation or resources waste. In order to change this situation, We must better understand and use the plant water interaction in water-limited regions. Soil water resources is an important part of water resources in water-limited regions. When soil water resources in maximum infiltration depth of forest, grass or crops land reduce to soil water resources use limit by plants, plant water relationship enter the critical period of plant-water relationship regulation, we should consider regulate the plant water interaction. If the present plant density is more than SWVCC in the critical period of plant-water relationship regulation, showing that soil water severely influences plant growth, maximum yield and benefit. At this time, the plant-water relationship should be regulated on SWVCC in the critical period of plant-water relationship regulation. In order to realize the sustainable use of soil water resources, high-quality production of fruit crops and high-quality and sustainable management of grassland and forest, it is necessary to master the dynamic changes of soil water and plant growth and regulating the relationship between plants and water by using soil water resources use limit by plants and SWVCC in critical period of plant-water relationship regulation of water-limited regions to ensure sustainable use of soil water resources and get the maximum yield and benefit for high-quality sustainable development of grassland and forest and high-quality production of fruit crops.

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