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Research Article

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Impact of Initial Planting Density on Soil Water Resource use Limit by Plants

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Abstract

Soil Water Resource Use Limit by Plants (SWRULP) is one of the most important indexes to express whether or not plant overuses soil water resources. However, it is still unclear how the impact of initial planting density on SWRULP. In this study, we investigated the changes of plant growth with time and soil water content with soil depth and time in caragana shrubland at different planting density and the change of soil water content with soil suction in the semiarid Loess hilly region since 2002. The results shows that Caragana forests at higher initial planting density grew and covered land fast. At the same time, the depth of root to absorb soil water increased and soil water content in the root zone soil reduced. When soil water resources in the maximum infiltration depth (MID) reduced to SWRULP, Caragana growth reduced or stoped with tree age. The soil water resource in the MID in the Caragana shrubland at the highest initial planting density first reach the SWRULP and the time soil water resource in the shrubland at lower density reach the limit delayed. When the soil water resources in the MID approach to the limit, it is the start time to reduce Caragana density on soil water carrying capacity for vegetation to prevent further soil desiccation and soil degradation.

Keywords

Water-limited regions; Initial planting density; Caragana growth; Soil water; Soil water resources use limit by plants

Introduction

Because the origin vegetation is changed into sparse vegetation or farmland, soil and water loss in Loess Plateau of China is serious and became one of the most serious regions in the world after human activity lasted for thousands of years [1-4]. In order to conserve water and soil and improve ecological environment, since 1950, a large-scale afforestation has been carried out on the Loess Plateau, and great progress has been made [5].

Rainfall is the main way to recharge soil moisture in perennial forest and grass in the most of the Loess Plateau because groundwater table is deep and water resources are scarcity and irrigation is limited. Soil drought is easy to appear in perennial forest and grass. Dried soil layer is the soil layer in which the soil water content is equal to or lowers than the distinguishing standard, wilt point [6]. With vegetation restoration, soil and water loss reduced but the dried soil layer (DSL) appeared and then the location DSL appeared becomes deep. The soil water environment in root zone soil is getting worse because plant consumes large amounts of water which destroy the relationship between soil water and plant growth and at the same time, the recharged soil water is limited in perennial forest and grass.

Long term cumulative desiccation of soil forms severe desiccation of soil and DSL occurs in deeper soil layer. The soil desiccation causes soil water mobility reduces and the soil water exchange depth weakens, which cut off soil moisture contact between the soil layers higher than the MID and that in the soil layer lower than the MID [7]. The soil desiccation deteriorates soil water environment, slow down plant growth and speed up plant communities' recession. The declined forest and grassland is difficult to be renewed [8].

Severe desiccation of soil causes soil degradation and vegetation decline, which influences the stability of forest vegetation ecosystem and national ecologic security system. Controlling soil drought is important for vegetation restoration and reconstruction of ecological environment.

In order to control soil degradation and vegetation decline, we have to regulate the relationship between soil water and plant growth at appropriate time by cutting some trees because there is a poor self-regulation of plant to regulate the relationship between soil water and plant growth in those artificial forests. Before regulating the relationship, there are two most important issues we have to solve. The first one is the start time to regulate the relationship between soil water and plant growth. The foundation to determine the start time is SWRULP short for soil water resource use limit by plants expressed by indicator plant or purpose tree or grass species in a plant community. Soil water resource are soil water storage in a given soil depth. The SWRULP is the limit of plants in using soil water resource. It can be defined as the soil water storage in the MID when all of the soil layers in the MID became DSL, which means that the soil water content at all of the soil layers within the MID equals wilting point [9,10]. The second is the quantity of cut or thinned trees when soil water resource is equal to the SWRULP and the relationship between soil water and plant growth need to be adjusted, based on SWCCV short for Soil Water Carrying Capacity for Vegetation. SWCCV is the capacity of soil water resources to support vegetation. It can be defined as the maximum amount of plant population soil water resources of a unit area can sustain plant and make it grow healthy during a fairly long period of time and in a given place, when the consumption of water absorbed by plant from the soil equals the water supply in the root zone. SWCCV is denoted by the population number of plant indicator, such as caragana in caragana community (absolute index) or the density of them (relative index). Plant indicator is the constructive species for natural vegetation, with goal tree or grass for artificial vegetation [10,11].

There are some studies on soil water resource use limit by plants [5,9], the start stage to regulate the relationship between soil water and plant growth [6] and SWCCV [5,10-12]. But there are a few reports on the influence of planting density on SWRULP. The purpose of the study is to make long-term observations of the interaction between soil water and plant growth in the Caragana forest at different initial

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planting densities, and then to estimate the influence of initial planting density on SWRULP and then to determine the start time when soil water resource in the MID reaches the soil water resource use limit by plant in Caragana forest.

Materials and Methods

Study site

The study was carried out at the Shanghuang Eco-experimental Station (latitude 35˚59´ - 36˚03´N, longitude 106˚ 26´-106˚ 30´E) in the semi-arid region of the Loess Plateau, Guyuan city, Ningxia Hui Autonomous Region, China (Figure 1). The station is located in a hilly loess region with slope gradients of 0˚ to 10˚, and the elevation ranges from 1,534 to 1,824 m. The region has a temperate semiarid climate, with annual precipitation of 415.6 mm (1983-2002). The coefficient of variation of precipitation among the years from 1983 to 2001 was 23.8% and rainfall amounts ranged from 260 to 635 mm, with a median rainfall amount of 434 mm. The rainfall from June to September accounts for more than 70 percent of the total annual precipitation. The main soil type is Huangmian soil, vegetation types is Forest-steppe transition to typical steppe. Caragana (*Caragana korshinkii* Korm) is a perennial sandy grassland and desert deciduous shrub species, indigenous to and distributed throughout the northwest of China and Mongolia [13]. Herbaceous plants growing under the shrubs included *Stipa bungeana*, *Heteropappus attaicus*, *Artemisia giraldii*, *Lespedeza davurica*, and *Thymus mongolicus.*

The experimental plots were established in wasteland in 2002, including the abandoned land and Caragana woodland with different initial plant densities. The five similar 100 m^2 (5 × 20 m) plots with almost the same conditions, including slope gradient (about 8˚), slope direction (East by South), slope position (in the middle of Heici mountain) and soil (Huangmian loess soil) and vegetation type. The sowing amount of Caragana seeds is 2.0, 1.5, 1.0 and 0.5 kg/100 m^2. The corresponding initial plant density is 6700, 6500, 5100, 2500 stem per 100 m^2, respectively in 2002. The caragana density changes with time. The caragana density in 2011 is 4800, 4600, 2900, 2500 stem per 100 m^2, respectively [10].

Measurements

Rainfall data and other meteorological data obtained from the Shanghuang Eco-experiment monitoring station, which was about Northwestern 50 m from the study site.

Plant measurements

Plant density was investigated using the line-intercept method in 2002 and 2011-2012. Two parallel sample lines were parallel and 1 meter apart from the two side line of plot, and then a square meter sample plots were set every other meter were set along the sample line, and then the caragana quantitative was measured.

In each plot, 40 stems were selected to determine the mean stem height or length and base diameter of the selected shrubs and measuring location at the 3 cm above the land surface was labeled by red lacquer. Measurements of plant growth and soil water content were made at every 15 days interval of height and basic diameter during the growing period. The measurements of soil water were carried out in the growing season from germination (mid-April) to defoliation (October) in a year for the previous five years from 2002 to 2006 and the past three years from 2011 to 2013, and lasted for 8 years.

Soil water measurements

Two 4 m long, aluminum access tubes were inserted into the soil at the center of each experimental plot with a 2 m contour distance between them in 2002. Aluminum access tubes were changed to 8m long Polyvinyl chloride polymer since 2011 because the soil depth plant use soil water increased. A neutron probe, CNC503A (DR) (Beijing Nuclear Instrument Company, Beijing), was used for monitoring the soil water content. The neutron probe was calibrated for the soil in the study area using standard methods [14]. The neutron probe detected slow neutrons, which are in linear proportion to the soil water content [15]. Measurements were made every 15 days to a depth of 4 m and then change to 8m after 2011 in increments of 20 cm starting at the 5 cm depth, The soil water content obtained for each measuring depth was taken to be representative for the soil layer that included the measuring point ± 10 cm depth, apart from that for the 5 cm depth, which was taken to represent the upper 10 cm of soil. Neutron counts were made for 16 seconds. In addition, we measured the soil water content before and after a rainfall event. The measurements of soil water were carried out from mid-April to October or November in a year for the previous five years from 2002 to 2006, from January to December for the past three years from 2011 to 2013, and lasted for 8 years.

The data were analyzed by Excel 2010, and also mapped with excel software. Soil water resources were calculate by the formula

$$Dw = \sum_{0}^{n} VSWC_i \times \frac{H_i}{10}$$

Where Dw is soil water resource (mm), VSWC is volumetric soil water content at different measured soil layer (%), H is soil thickness (cm), H=20 cm, apart from surface soil layer in which H_1=10 cm, I represents the number of soil layer, ***n*** stands for the total number of soil layer, n=20. Because the measuring point 5 cm stands for the upper 10 cm of soil, the H_1 equals 10 cm.

Statistical analysis

The significance of the planting density effects on all the measured parameters were analyzed using ANOVA with SPSS 13.0 software. Regression analysis was used to determine the relationships between planting density and other various attributes using the least square method. Data were transformed when necessary to obtain a linear relationship [5].

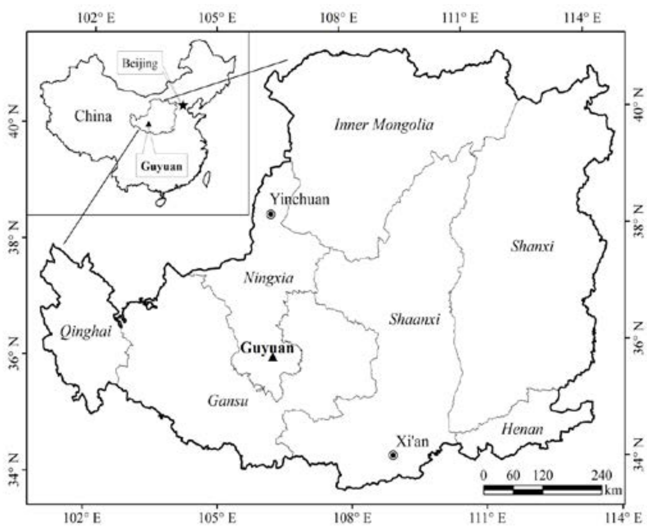

Figure 1: The location of the study site on the loess plateau of China.

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Results

The change of Caragana growth with time

The change of Caragana growth with time sees Figure 2. It can be seen from Figure 2 that with Caragana germination and growth, Caragana height increases from germination and 0 cm when sprouts have just come up about two week later, and then to the mean height of 13.8 cm with a smaller standard error of 0.776 at the end of the first year in 2002, to 25.7 cm with the standard error of 2.0 at the end of the second year in 2003, to 28.8 cm with the standard error of 2.698 at the end of the third year in 2004, to 39.2 cm with the standard error of 3.97 at the end of the fourth year in 2005, and to 41.8 with the standard error of 4.3 cm at the end of the fifth year in 2005, height growth slowdown at the five year, showing that at the same initial planting density plot, the increments in Caragana height growth reduced after the three year because of the environmental resistance caused by soil water deficit increase with increasing initial planting density and time. At the five year the environmental resistance seriously influences plant height growth. The height growth almost stopped, especially at the highest initial planting density plot (2.0 plot) in 2006.

The dynamics of soil water resource with time

The soil water resource generally showed a decreasing trend with age with the exception of a short-lived rise after the precipitation in the artificial Caragana plantation. Soil water content in soil profile is big and the soil water resource in 0 to 290 cm soil layer is 371.5 mm with the standard error of 16 mm at sowing Caragana woodland with different amount of sowing seed in wasteland. Plant imbibed soil water along with its growth and development, soil water content decreases in Caragana woodland. Because the year 2003 is the wet year with the precipitation of 623.3 mm, seen Table 1, soil water resource increased to 402 mm with the standard error of 24 mm after the rain event, and then soil water content and soil water resource in 0 to 290 cm soil layer reduced slowly, seen Figure 3. When the soil water content in a soil layer is equal to wilting point, the soil layer is called dried soil layer (DSL). The DSL may occur and the soil layer depth DSL occurs increases with Caragana growth. Caragana had been grew vigorously in the short period after planting because the soil water content is high, and then soil water storage amount reduced yearly and seasonal change of precipitation in Caragana woodland of semiarid hilly Loess hilly region (Table 1). It can be seen from Table 1 that as time went on, high density planting Caragana intensified the soil water consumption which influences plant growth. In order to meet the caragana water requirement, with the growth of Caragana, plant extends its root to deep soil and absorb water from considerable deep soil and depletes a lot of soil water, which make soil water content gradually reduced. DSL appeared and deepened [6], (Figure 3). By the fifth year after sowing, soil water resource in the MID of 290 cm in the Caragana land in the 1.5 kg plot is below the SWRULP [16], showing that soil water severely influence Caragana growth, which is the why caragana growth almost stop and it is the right time to regulate the relationship between soil water and plant growth comes because there are no water supply but rain.

Impact of plant density on the soil water resource use limit by plant

In semi-arid loess hilly area, Caragana forest at higher initial planting density grows and covers the ground fast because caragana plant individual is small, and there are no inconspicuous intraspecific competition among caraganas and the soil water resources is quite high when sowing caragana [5], but the influence of density on soil water resource increases with increasing individual size and planting density.

The impacts of planting density on SWRULP in 2006 (Figure 4). It can be seen from Figures 3 and 4 that the soil water resource showed a decreasing trend with the increasing planting density. The time soil water resource reached to SWRULP in Caragana shrublang with a high density earlier than that in a low density. In the fifth year, the soil water resource in high density plots (2.0 and 1.5 plot) fell to the SWRULP but the time the soil water resource achieves to the SWRUL in the 1.5 kg experiment plot lags 15 day behind that in the 2.0 kg plot. The time soil water resource in low density plots (1.0 plot and 0.5 plot) approached to but not reach that limit in the end of 2006. In the 0 to 290 cm soil layer, the amount of soil water resource in 2.0 kg plot was merely 221.59 mm on June 1, 2006 and lower than the SWRULP of 223.3 mm [9,10]. The amount of soil water resource in 1.5 kg plot was merely 222.5 mm and also lower than the limit on June 15, 2006. Due to the lack of timely density adjustment of caragana in the experiment plots in time after the amount of soil water resource reaches the SWRULP, the soil water resource decreased continuously, and reduced to 204.74 cm and 205.47 cm in the two plots on August 1, 2006, respectively. Soil water seriously influences plant height growth and led to some leaf's color change to yellow and early dropped in 2006.

The soil desiccation was increasingly serious with time, which seriously influence the plant growth. The amount of soil water resource in 0.5 kg plot and 1.0 kg plot, at this moment, were merely 12.88 mm and 27.69 mm higher than the SWRULP, respectively. It was expected that the soil water resources in both plots reach the SWRULP in the near future.

Planting density, soil water resource and SWRULP

The relationship between planting density, soil water resource and SWRUL in the 2011 to 2013 year seen Figure 5. It can be seen from Figure 5 that because of the lack of caragana density adjustment in time, the amount of soil water resource in all of the experiment plots is lower than the soil water resource use limit by plant apart from check plot (wasteland) on May 1, 2011, suggesting that the time soil water resource reaches the SWRULP in 1.0 plot and in 0.5 plot is between 6^{th} and 10^{th} year. The soil water resource in the MID decreased continuously, and reduced to the minimum value of 174.1 in 2.0 plot, 178.5 in 1.5 plot, 185.1 mm in 1.0 and 183.5 mm in 0.5 plot, respectively, but the soil water resource in the MID of the control plot is 222.8 mm on August 14, 2011, approached to the SWRULP. In order to meet the need of water, caragana have to extend root to deeper soil layer and get water. And then soil water resource in the MID went up gradually and then exceeded the SWRULP on October 1, 2011 because of rainfall.

On April 30, 2012, soil water resource in the MID of 2.0 experiment plots first is lower than the SWRULP and then soil water resource of 222.1 mm in 1.5 experiment plots is less than the SWRULP 15 days later. Soil water resource in 1.0 experiment plots and that in 0.5 experiment plots is 220.7 mm and 214.6 mm, respectively, below the SWRULP on May 3, and then went up the SWRULP on Sep.1, 2012. Soil water resource in the MID in all of the experiment plots went up the SWRULP on July 15, 2012.

Soil water resource in the MID of 1.0 experiment plots and that in the MID of 0.5 experiment plots is below the SWRULP on April 15, 2013 and then went up the SWRULP because of rainfall.

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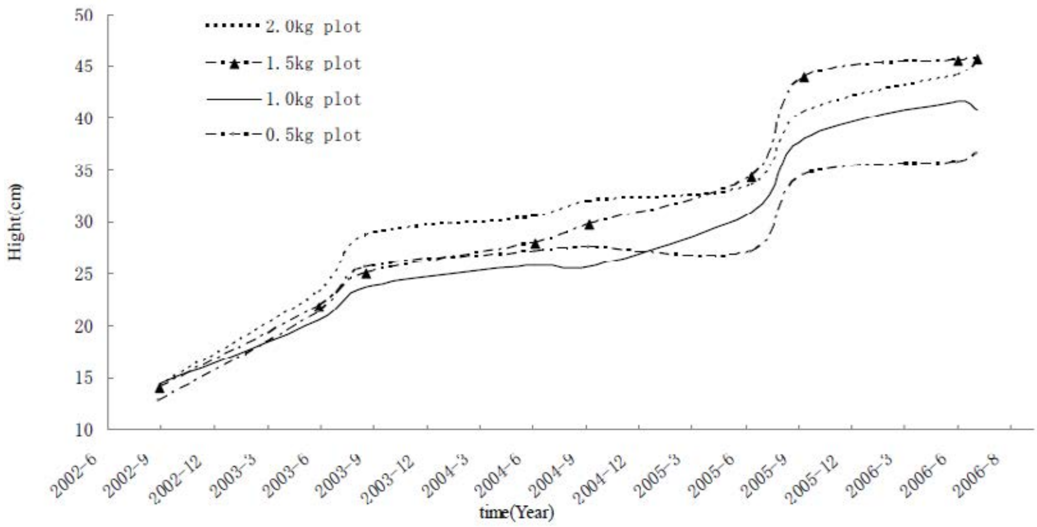

Figure 2: The change of Caragana height growth with time (2002-2006).

Table 1: Seasonal and yearly change of precipitation in Caragana shrubland.

Average precipitation from 1983 to 2001	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
	3.71	5.55	10.7	23.1	39.38	62.55	89.47	101.5	48.33	29.8	6.21
2002	2.3	4.5	15.2	16.9	49	118.6	34.8	77.1	29.6	32.6	0
2003	3.4	1.9	10.5	19.1	83.9	44.9	67.5	253.1	75.3	53.3	10.4
2004	1	1.3	7.2	0	40.4	70.1	74.7	88.5	22.8	16.9	1.2
2005	0	8.6	5.8	19.2	62.8	37.5	101.7	68	47.2	28.2	0
2006	5.1	6.8	3.9	3.2	51	42.9	36.1	78.7	62.6	7	5.7

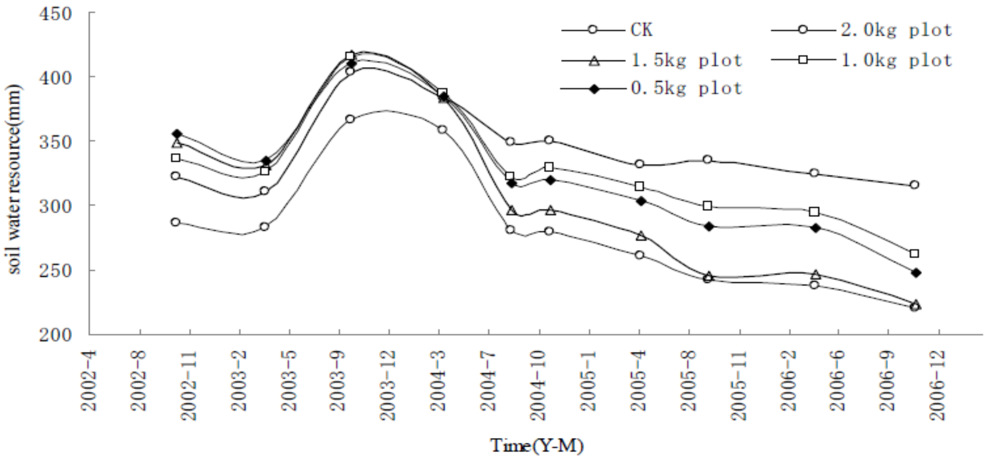

Figure 3: The Change of soil water resource with planting density in Caragana Woodland.

The soil water carrying capacity for 16-years-old Caragana planted by sowing in the fish scale pit, and for 17-years-old Caragana and for 18-years-old Caragana were 7200 shrub per ha in 2002, 8700 shrub per ha in 2003 and 16 00 shrub per ha in 2004, respectively. Caragana in 2002 need to be controlled, that is to say, 1500 shrub per ha need to be cut. In fact, the year 2003 was a rainy year (Table 1), and the rainfall reached 623.3 mm, and the soil moisture and soil water resource in 0 to 290 cm soil layer was surplus at the end of 2003 in Caragana forest land with the maximum density of 8700 shrub per ha. Affected by the soil water resources in the end of the 2002, soil drought became serious in spring, 2003, and the Caragana grew bad and appeared early deciduous on Aug. 5, 2003 before the rainy season comes in Caragana forest with the maximum density of 87 00 shrub per ha, and the interception by canopies is vanished, which is not good at conserve soil and water because raindrop is big and easy to forms runoff and dash soil. But the Caragana forest with the plant density of 7100 shrub per ha grows slightly better and the canopies is exist, so we should cut some Caragana trees to reduce soil

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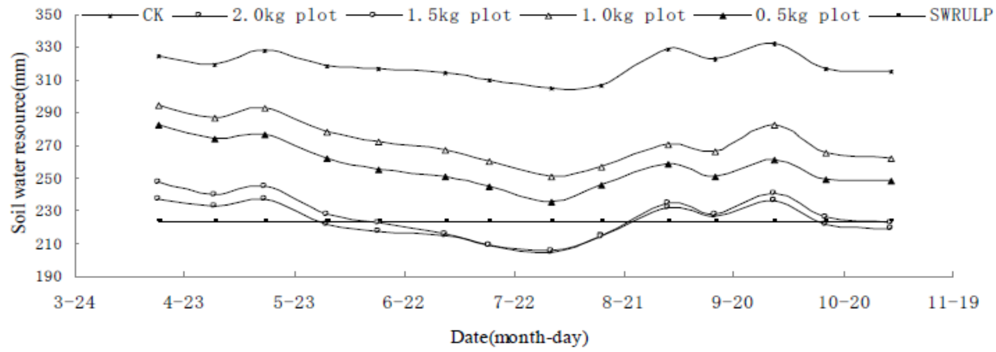

Figure 4: The impact of planting density on SWRULP in 2006.

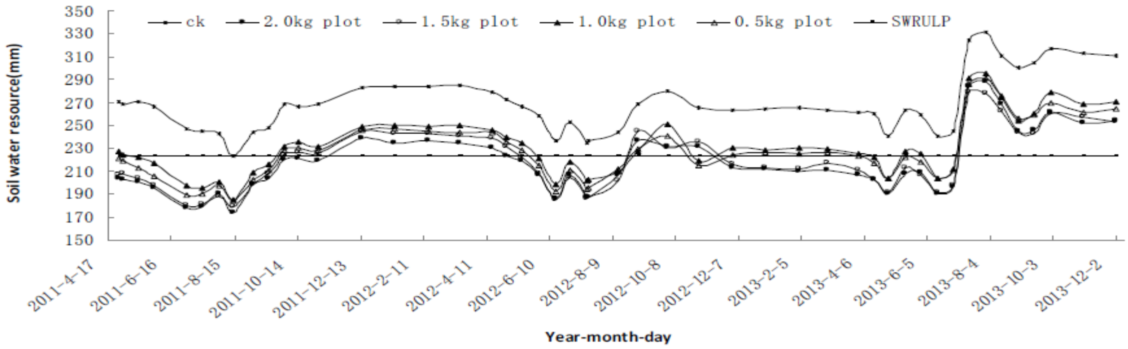

Figure 5: The relationship between planting density, soil water resource and SWRULP.

water consumption even the soil moisture in Caragana plots at the plant densities of 87 00 shrub per ha was surplus at the end of 2003.

Although the year 2004 is drought, the soil water carrying capacity for 17-year-old Caragana was 1600 shrub per ha [10], we should not adjust the Caragana density because of rainfall in the wet year 2003 and soil moisture is in good condition in the Spring of the following year (2004) and the soil water resources in Caragana land at the maximum density and Caragana grew well was greater than the soil water resource use limit by plants. Because the value of soil water carrying capacity for 10-, 11- and 12-years-old Caragana by sowwing broadcast in 2002 were 4800 stems per 100 m^2 in 2011, 4200 stems per 100 m^2 in 2012 and 4200 stems per 100 m^2 in 2013 [10], we should not adjust the relationship between soil water and Caragana growth.

Discussion

After rain infiltrated into soil and be stored in the vadose zone, it become soil water resources, the rainwater can be consumed by plants [17]. Soil water resources mainly used by plant and then are turned into useful material such as food, fruit,wood and fibers, so the soil water resources must be used; otherwise it will be wasted because the population in China is the biggest country in the world but the resources per person is in shortage [10,17,18].

At the primary stage of afforestation higher density of plantation will restore the vegetation cover in a shorter time, which accelerate the formation of soil and water conservation benefit [19], so we often select higher artificial planting density when afforesting, such as on the Loess plateau, China because the soil water content is high in the wasteland and new afforestation land. Although soil water resource is renewable resources, we cannot use soil water in an unlimited way. Otherwise, it will lead to severe drought of soil, form permanent dried soil layer, leading to soil degradation and vegetation recession. If the soil water in dried soil layer formed in the dry year can be recovered in wet years by recharge from rainfall, there will not existed the permanent dried soil layer [6,20]. Soil water in permanent dried soil layer will never recover even in the wet year [6,21]. SWRULP is the soil water storage in the maximum infiltration depth when all of the soil layers in the MID become DSL, which means that the soil water content within the MID equals wilting point [9,10]. When the soil water resource in the MID is equal to SWRULP, the soil water in the forest land seriously restrict the plant growth or led to plant death if it meet drought year. It is the right time to adjust the soil water-plant growth relationship because the self-regulation of the relationship between soil water and plant growth for artificial forests is poor and easy to form serious desiccation of soil, soil degradation and vegetation recession, which is bad for sustainable use of soil water resource and for sustainable management of forest resource in water limited regions. Therefore, we cannot use soil water resource in unlimited way and should regard the SWRULP as the cordon plants use soil water. Effective measures should be taken to control plant use soil water when the soil water resource is reach to or lower than the cordon because too early or too late to regulate this relationship easy to lead the waste of soil water resource [9-10].

There are two kinds of method to regulate the relationship between soil degradation and vegetation recession or soil water and plant growth, one is to supply water according to the plant water demand, such as irrigation or rainmaking, and the second is to reduce water consumption based on local water supply conditions and soil water carrying capacity for vegetation, the ability of soil water resources to carry vegetation. The rational methods to regulate plant-

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water relationship in water limited regions is to reduce soil water consumption by reducing plant density and biomass according to soil water resource, rainfall and soil water carrying capacity for vegetation using cutting or thinning method, and to use soil water resources rationally, and to ensure the stability of forest ecosystems and to achieve sustainable use of water resources and sustainable management of forest vegetation. When the soil water resource in the MID in the artificial forest land is equal to SWRULP, effective measures should be taken timely and cut moderate amount of trees and reduce plant density on SWCCV to control plant water consumption in case the extreme phenomena such as Caragana decline or death or soil desertification happened in forestland and grassland because when soil water resources in the MID equals SWRULP, severe desiccation of soil happens, the soil water resources seriously influence the plant, even led to Caragana decline or death when drought weather happens.

Conclusion

Soil water resources reduce with the Caragana growth and development apart from the moment in which soil water resources increase after precipitation. In contrast, whether in the wet years or dry years, soil water resources in abandoned land are all more than SWRULP.

In high density Caragana shrubland, the cover degree of Caragana increases quickly and accelerates the formation of soil and water conservation benefit. At the same time, soil water resources will reduce quickly, and then lower than SWRULP in the fifth year. The time soil water resource in the MID of Caragana shrubland with the initial planting density of 6700 plant per 100 m^2 reach the limit first appeared on June 1, 2006 and 15 days earlier than the time the soil water resource in the Caragana shrubland with initial planting density of 6500 plant per 100 m^2 approaches to the limit in 2006. The time the soil water resource reach the limit in 0.5 and 1.0 plot have happened in the period from 6^{th} to 10^{th} (2007-2010) year after sowing. The accurate time need to be determined in the near future.

When the soil water resource in the MID in Caragana shrubland is close to or smaller than SWRULP, effective measures should be taken to reduce plant density by cutting some Caragana tree on SWCCV in woodland. Only well understood SWRULP and got the time soil water resource reaches SWRULP in the management of soil water resources can we make change from passive management of soil water resources to active use of soil water resources and realize the sustainable use of soil water resources and ensure the healthy and security of national ecology system.

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