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RESEARCH ARTICLE

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Appropriate density of water and soil conservation of *Pinus tabulaeformis* and *Robinia pseudoacacia* forests in loess area, North China

Abstract In this paper, based on a long-term monitoring of water cycle in the water and soil conservation forest stands of *Pinus tabulaeformis* and *Robinia pseudoacacia*, the soil moisture deficit is calculated. Following the principles of runoff-collecting forestry and applying the forest structure investigation results, the authors developed a formula to calculate appropriate density for forests on the basis of different diameters at breast height (DBH). Using this method to manage forests, the natural water requirement of forests can be met and soil drought can be avoided. In addition, with long-term monitoring of soil moisture in stands, the authors also give an appropriate managing density specifically for the water and soil conservation forests of *P. tabulaeformis* and *R. pseudoacacia* in the loess area which is according to soil moisture content, or with the lowest soil moisture content and invalid moisture frequency as the indexes.

Keywords appropriate density, water and soil conservation forests, soil moisture, loess area

1 Introduction

In the arid and semi-arid areas of the Loess Plateau, precipitation is the only water source which sustains plant growth. Soil moisture is the main limiting factor restricting the growth of trees and the benefits of soil and water conservation (Bian et al., 1994; Bian et al., 1996; Zhang et al., 2003; Wang et al., 2004). Under these limited precipitation condition, the most important issues in building the soil and water conservation forest in the Loess Plateau are how to improve the survival rate of afforestation and how to effectively manage the existing soil and water conservation forest in order to maximize and maintain forest's defending function (Xu et al., 2003). To solve these problems, we must determine a rational forest density on the basis of water balance calculation (Yu et al., 1996; Zhang et al., 2002).

Forest tree density is the basic factor of the forest structure. In the nurturing process of the soil and water conservation forest, we frequently use the concept of initial planting density and management density (Sun et al., 2006). Reasonable density should be the management density, which could meet certain needs in the whole growth process and does not cause deficiency in the soil moisture.

The precipitation resource in an area is limited. After arriving in the forest, the precipitation first meets the canopy interception needs, the vegetation interception needs, and the litter storing needs, and then forms the effective precipitation. Finally, the effective precipitation forms the runoff after meeting the needs of infiltration.

For woodland soil, soil infiltration among the precipitation can be only used for plant growth. In severe soil erosion areas of the Loess Plateau, there is a long-term soil moisture deficit. Therefore, we must calculate the amount of soil water deficit via the water balance analysis, which is the key issue in determining the reasonable density of forest stand.

2 Study area

The study area is located in the Hongqi forest farm in Ji County of Shanxi Province (38°05′58′′N, 110°45′55′′E) which belongs to the gully area of West Shanxi Province, China. The elevation is between 950 m and 1370 m, annual precipitation is 575.9 mm, annual free water

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surface evaporation is 1732.9 mm, and the annual mean temperature is 10°C. Soil texture is an even loess soil. Forest coverage rate is 39.8%. Predominant tree species of the study area are *Pinus tabulaeformis* and *Robinia pseudoacacia*, and the predominant shrubs are *Hippophae rhamnoides* and *Ostryopsis davidiana* (Table 1).

3 Materials and methods

3.1 Materials

From 1988 to 1992, we used the automatic rain gauge (B-432-Z) for measuring precipitation. The groove (5 m × 0.2 m) was used to measure the rainfall in the forest in order to calculate canopy interception. The runoff plots (5 m × 20 m) were set to observe slope runoff. The soil water infiltration was determined by artificial rainfall (Zhang et al., 2002). The soil water dynamics of 0–100 cm soil layer dividing five horizons were measured by oven dry method once a week. Tensile gauge was used for measuring soil water potentials. Positioning flux method was used for calculating forest stand evapotranspiration (Yu et al., 1995). The relationship between the canopy projection area and DBH was determined by sample plot investigation.

3.2 Methods

In order to determine the reasonable density of the soil and water conservation forest, we first calculated the amount of forest water deficit by the forest water balance analysis and then calculated the reasonable density using the principle of the runoff forestry.

4 Results and analysis

4.1 Evapotranspiration in the water and soil conservation forests

Amount of evapotranspiration is equal to forest transpiration and soil evaporation volume. Except for the climatic factors and soil water-yield capacity, the amount of evapotranspiration is mainly controlled by forest growth. For a stand in an area, if the species and soil water-supply capacity were the same, the stand density is the main factor determining evapotranspiration amount. Therefore, the precise determination of the shelter forest system evapotranspiration is to derive the basis of the reasonable density of the soil and water conservation forest. The growing evapotranspiration of each land use types by position flux measurement is shown in Table 2.

As shown in Table 2, the evapotranspiration of the *P. tabulaeformis* forest land was the largest, followed by *R. pseudoacacia* forest land. The evapotranspiration of *H. rhamnoides* and *O. davidiana* forest lands were almost the same. The evapotranspiration of the grass land was less than that of the shrub forest land but more than that of the uncovered land. The evaporation of uncovered land was minimal.

4.2 Water deficit of forest land

When rainfall reached the forest land, part of them were intercepted by the canopy and branches, which is the first redistribution of rainfall. The intercepted rainfall eventually turns to atmospheric evaporation. Then rainfall through the canopy of forest arrived at the litter layer, and second redistribution was finished. Litter-storing water also eventually returned to atmospheric evaporation. Then rainfall arrived at the soil surface. Water conserved in low areas will all enter the soil except for surface runoff. This was the redistributing effects of soil on rainfall. Under the principle of water balance, a certain period of time units of the soil water balance equation is:

$$P - I_{LG} - I_{LK} - R - ET = \pm \Delta W \qquad (1)$$

where P is interval rainfall (mm), I_{LG} is interception (mm), I_{LK} is litter water storage capacity (mm), R is surface runoff (mm), ET is evapotranspiration of stand (mm), ΔW is soil moisture content variation (mm).

In the study area, the litter decomposition rate is faster. Since there is less water conservation in litter layer, the I_{LK} was ignored. So the forest land water balance equation can be written as follows:

$$\Delta W = P - I_{LG} - R - ET \qquad (2)$$

Table 1 Basic status of the study area

species	slope/°	aspect/°	position	age/year	density/ tree·hm^{-2}	height/m	diameters at chest height/cm	litter thickness/cm	fresh grass weight/g·m^{-2}
P. tabulaeformis	22	N300	Down	14	3200	7.6	6.0	1.0	397
R. pseudoacacia	26.5	N340	Middle	13	4900	2.6	3.0	1.1	130
O. davidiana	28	N335	Middle	7	420000	0.8	0.6	1.5	41
H. rhamnoides	24.5	N4	Middle	8	25000	1.1	2.2	1.0	521
Grassland	27.0	N315	Middle	—	—	—	—	—	762
Uncovered land	23	N315	Middle	—	—	—	—	—	—

Table 2 Amounts of evapotranspiration in water and soil conservation forests (unit: mm)

project	1988	1989	1990	1991	1992	average
Precipitation	338.4	377.8	441.7	385.6	396.0	387.90
R. pseudoacacia	381.4	328.3	369.9	369.9	379.7	365.84
P. tabulaeformis	400.9	338.1	420.7	384.0	364.8	381.70
H. rhamnoides	307.2	319.3	330.8	283.6	302.2	308.62
O. davidiana	302.7	320.4	325.5	312.5	283.7	308.96
Grassland	230.5	269.3	268.2	260.7	207.4	247.22
Uncovered land	188.5	229.2	233.5	192.6	171.6	203.08

Water deficiency in typical growing season (March to November) was calculated according to Eq. (2) (Table 3).

Table 3 Moisture deficit calculations of plants

year	species of the forests	*P*/mm	*ET*/mm	*R*/mm	I_{LG}/mm	ΔW/mm
1988	*R. pseudoacacia*	338.4	365.6	8.16	52.5	−87.9
	P. tabulaeformis		384.6	6.17	65.1	−117.4
	H. rhamnoides		290.7	4.16	55.7	−12.1
	O. davidiana		287.8	4.30	54.9	−8.6
1990	*R. pseudoacacia*	441.7	354.0	8.88	67.2	11.6
	P. tabulaeformis		402.8	7.43	82.3	−50.9
	H. rhamnoides		317.5	8.57	70.5	45.1
	O. davidiana		309.8	7.41	69.8	54.7
1992	*R. pseudoacacia*	396.0	351.5	9.86	60.7	−26.1
	P. tabulaeformis		349.2	6.88	74.8	−34.8
	H. rhamnoides		289.7	6.16	64.0	36.1
	O. davidiana		271.6	5.79	63.2	55.4

As shown in Table 3, soil moisture is in serious shortage because of less precipitation in 1988. In the *P. tabulaeformis* forest land, soil water deficiency is as high as 117.4 mm. In the *Robinia pseudoacacia* forest land, water deficiency is 87.9 mm. In the *H. rhamnoides* and *O. davidiana* forest lands, soil moisture shortage is between 12.1 mm and 8.6 mm. When precipitation was relatively high in 1990, the *P. tabulaeformis* forest land still had water shortage of 50.9 mm whereas the *Robinia pseudoacacia* forest land and shrub land both had soil moisture surplus.

When rainfall is less than 400 mm, the timber forest becomes moisture deficient; and when the rainfall is below 400 mm, the shrub land incurs moisture deficiency. In the growing season, where the rainfall is less than 400 mm in a semi-arid region, the water supply capacity of the timber-forest lands will be unable to meet the growth needs of trees. It is necessary, therefore, to take appropriate measures to maintain water to ensure the growth of trees like adjusting the density of the stand or lowering forest land evapotranspiration to ensure the soil moisture supply. Obviously, in the arid, semi-arid Loess Plateau region, it is necessary to take appropriate afforestation measures. The so-called moderate afforestation refers to the water balance on principle and theory based on the premise that trees' normal physiological activities requirement is ensured to determine stand density. The forest should be allocated, in key parts, in a watershed to make a sustained, stable and effective forest protection, and to ensure that soil and water conservation function is being continually improved.

4.3 Soil moisture in the *R. pseudoacacia* forests of different densities

The effects of soil moisture is the main index in the effectiveness evaluation of plants, particularly in soil moisture levels and the use of water stress on plant growth, as well as the key in plant or crop water use and the cultivation of artificial vegetation in semi-arid areas (Yang et al., 2006). When field moisture capacity is below 60%, the soil moisture is known as hard-water. At this time, most of the growth activities will be affected, and the energy consumption of soil moisture for root development will greatly increase. It is not easy to use soil water for plants.

Table 4 presented the average soil water content, lowest moisture content, and frequency of hard-water in the *R. pseudoacacia* forest in different densities during the growing season. On No. 1 and 2, where density were 2600 and 4762 tree/hm^2, the annual average water contents were 13.16% and 12.57%, respectively. The former was higher by 0.59%. The lowest moisture contents were 9.56% and 7.82% respectively. The former was higher by 1.74%. The frequencies of hard-water were 55% and 61%, the former was lower by 6%. Obviously, with the density increases, both the average moisture content and the lowest moisture content are reduced while the frequency of hard-water is increased. Therefore, from the perspective of soil moisture, soil and water conservation forest density must be appropriately controlled to a certain extent. This result is consistent with the study results from Li et al. (2003) conducted in the similar area.

The Nos. 1 and 5 densities were above 3000 tree/hm^2, with the average soil moisture at only 12.57% and 12.19%, the extreme lowest water content of 7.82% and 6.83%, and the hard-water frequencies of 61% and 64%. Soil moisture in the long-term will block the water below and the growth of trees will adversely affected. So, the *R. pseudoacacia* forest should have a density less than 3000 tree/hm^2.

Comparing the density of No. 6 with No. 4, we can conclude that although the density difference was 800 tree/hm^2, their biomasses were same. The average moisture and extreme lowest moisture content was close. The demands for higher biomass are in the density of 1300–2100 tree/hm^2, and for soil and water conservation, the greatest density of the *R. pseudoacacia* forest should be less than 3000 tree/hm^2.

Generally, No. 7 plot had the minimum density. The average moisture content, lowest moisture content,

Table 4 Soil moisture in the *R. pseudoacacia* forests of different densities

no.	exposure	diameters at breast height/cm	forest density/tree·hm^{-2}	biomass/t·hm^{-2}	average soil water content/%	lowest moisture content/%	hard-water probability/%
1	SW40°	5.82	2600	42.90	13.16	9.56	55
2	SW40°	5.62	4762	71.43	12.57	7.82	61
3	NE5°	5.50	2300	33.85	15.19	10.70	24
4	NE15°	9.46	2100	115.50	13.64	8.45	48
5	W	8.5	3001	114.00	12.19	6.83	64
6	NE15°	11.9	1300	115.24	14.61	9.56	36
7	NE15°	11.2	700	73.15	15.91	11.06	29

hard-water probability of No. 7 were better than those of other plots. For the *R. pseudoacacia* with DBH of 11 cm, when the forest density is within 700 tree/hm^2, hard-water probability can be controlled in less than 30%. For the young *R. pseudoacacia* forest with DBH of 5 cm, when density was below 2300 tree/hm^2, hard-water probability can be controlled below 25%. Soil water as a water resource can be recovered. In a normal flow year or a low flow year, water shortage can be recovered to a certain extent in a high flow year. In this scenario, the hard-water probability was less than 30% of the result; the density of *R. pseudoacacia* forest should be controlled below 700 tree/hm^2 and the young *R. pseudoacacia* forest should be controlled within 2300 tree/hm^2.

Comparing No. 3 plot with No. 4, we can see that their densities were close at 2100 and 2300 tree/hm^2, respectively. The biomass varied greatly, with 33.85 and 115.5 t/ hm^2 and the average water contents were 15.19% and 13.64% respectively. In the extreme lowest water content of 10.70% and 8.45%, the former was higher by 2.25%; while in the hard-water frequency of 24% and 48%, the former was lower by 24%. This shows that the higher the biomass, the lower the average moisture, and the smaller the extreme minimum value, the greater the hard-water probability. With the increase of biomass, the hard-water probability also increased. In the Loess Plateau, soil and water conservation forest should be carried out in a rational time to ensure soil moisture. At the same time, to create a higher biomass stand in the Loess Plateau, it is essential to choose channels and other water conditions. This is the only way to ensure that the function of soil and water conservation forest continues to perform. In the loess slope with poor water-supply and water-retaining capacity, forests with higher biomass should not be set. Instead, forestland, shrubs and grassland should be used.

4.4 Decision of reasonable density

The definition of reasonable density is that the water supply ability of the soil can satisfy the tree growth demand, that the soil does not lack of humidity and there is no soil water shortage. In the area of the Loess Plateau, although rainfall is certain, it is impossible to increase it by some measures. Therefore, we should change the spatial and time distribution of rainfall to increase water resource of partial districts. This is the basic principle of runoff forestry.

In the year that has plentiful precipitation, the water content of forestland can basically satisfy the tree growth demand. The soil water content during a dry season (also in a dry year) was the most serious factor affecting tree growth, therefore, when we decided upon the reasonable density, we had to analyze the soil water deficit of the driest stage. It can be concluded that in the growth season (dry year), among these native trees, the soil water shortage of *P. tabulaeformis* forest was 117.4 mm and the soil water shortage of *R. pseudoacacia* forest was 87.9 mm. The lack of water in forestland can only be supplied by developing a water gathering slope, thus, the reasonable water gathering area was the premise for reasonable density determination.

The water content supplied by the water gathering area must suit the water shortage in the tree humidity nourishment area. Moreover, it should also satisfy the following relationship:

$$QS = aGP \tag{3}$$

where Q is the water shortage of forestland (mm); S is the humidity nourishment area of a single tree (m^2); a is the average runoff coefficient (%); G is the water gathering area required (the water gathering area that demands the addition of water excludes the nourishment area) (m^2); and P is the precipitation that fits a certain frequency (mm).

The humidity nourishment area can be roughly treated as the projection area of the tree canopy. According to the investigation conducted, the relationship between the humidity nourishment area and the DBH of *P. tabulaeformis* and *R. pseudoacacia* forests was as follows:

$$S_R = 0.9063D - 2.0280 \quad R^2=0.858 \tag{4}$$

$$S_P = 0.2772D + 0.3705 \quad R^2=0.980 \tag{5}$$

where D is the DBH in cm; S_R is the humidity nourishment area of *R. pseudoacacia* (m^2); S_P is the humidity nourishment area of *P. tabulaeformis* (m^2).

By analyzing the rainfall data for many years in Ji County, it can be concluded that the precipitation was 320 mm with a frequency of 95%, and the average runoff coefficient was 10% (rainy season). In years with less water, the water shortage of *P. tabulaeformis* and *R. pseudoacacia* forests were 117 mm and 87.9 mm, respectively, and the relationship between the demanding water gathering area and the DBH was:

$$Q_R \times (0.9063D_R - 2.0280) = 0.1 \times 320 \times G_R \quad (6)$$

We can get the relationship between the water gathering area and the DBH of *R. pseudoacacia* by the formula:

$$G_R = 2.485D_R - 5.5707 \quad (7)$$

The total nourishment area of single *R. pseudoacacia* (HLS_R) was:

$$HLS_R = S_R + G_R = 3.3958D_R - 7.5987 \quad (8)$$

The formula for reasonable density (tree/hm^2) of *R. pseudoacacia* forest:

$$N = 10000/(3.3958D_R - 7.5987) \quad (9)$$

In the same way, the relationship between the demanding water providing area and the DBH of *P. tabulaeformis* forest was:

$$Q_P \times (0.2772D_P + 0.3705) = 0.1 \times 320 \times G_P \quad (10)$$

$$117 \times (0.2772D_P + 0.3815) = 0.1 \times 320 \times G_P \quad (11)$$

The relationship between the demanding water gathering area and the DBH of *P. tabulaeformis* forest was:

$$G_P = 1.10135D_P + 1.3547 \quad (12)$$

The total nourishment area (HLS_P) of single *P. tabulaeformis* was:

$$HLS_P = S_P + G_P = 1.2907D_P + 1.7252 \quad (13)$$

The formula for the reasonable density (tree/hm^2) of *P. tabulaeformis* forest:

$$N = 10000/(1.2907D_P + 1.7252) \quad (14)$$

Using the formula for the reasonable density of *P. tabulaeformis* and *R. pseudoacacia* forest, we calculated the reasonable density of *P. tabulaeformis* and *R. pseudoacacia* forest with different DBH (Table 5).

As shown in Table 5, the reasonable densities (including *P. tabulaeformis* and *R. pseudoacacia* forests) were based on the analysis of water balance and the precipitation and runoff generation coefficient in a year with less water. Planting or management of the soil and water conservation forest according to Table 5 can ensure enough water gathering on the slope. At the same time, together with the runoff forestry measure, the runoff (created on the water gathering slope) can be kept in the soil and it becomes available water. The soil water content can satisfy the wood growth demand. Therefore, when the forest developed its protecting function, the soil will not be drier. Reasonable densities can improve the soil and the water conservation forest's function.

5 Conclusions

It can be concluded, from the water shortage of soil and water conservation forests through the analysis of water balance in a less-water year, that the soil water of soil and water conservation forests were lacking. The water shortage of *P. tabulaeformis* forest was up to 117.4 mm, and *R. pseudoacacia* forest 87.9 mm. When precipitation was less than 400 mm, the soil water of *P. tabulaeformis* and *R. pseudoacacia* forests will be found lacking. When the rainfall was less than 350 mm, the soil water of *H. rhamnoides* L. subsp. *sinensis* Rousi and *O. davidiana* Decen shrub will be found lacking.

Based on the water shortage of soil and water conservation forests, and according to the relationship between the DBH and the shadow area of wood hat and the surface runoff generation condition, we presented a formula for calculating the reasonable densities of *P. tabulaeformis* and *R. pseudoacacia* forests, and calculated the reasonable densities of *P. tabulaeformis* and *R. pseudoacacia* forests with different DBH. The research expressed that *P. tabulaeformis* and *R. pseudoacacia*

Table 5 Reasonable densities in *P. tabulaeformis* and *R. pseudoacacia* forests with different DBH

DBH/cm	reasonable densities/tree·hm^{-2}		DBH/cm	reasonable densities/tree·hm^{-2}	
	R. pseudoacacia	*P. tabulaeformis*		*R. pseudoacacia*	*P. tabulaeformis*
3	3863	1787	12	302	581
4	1671	1452	13	274	540
5	1066	1223	14	250	505
6	783	1056	15	231	474
7	618	929	16	214	447
8	511	830	17	199	423
9	435	750	18	187	401
10	379	683	19	176	381
11	336	628	20	166	363

forest densities ranged from partial to obviously large in this region, both above their reasonable densities which means an urgency for specified logging.

The soil water of *P. tabulaeformis* and *Robinia pseudoacacia* forests cannot satisfy the required tree growth in the region. The soil water condition of shrub was obviously better than that of arbour wood land. Therefore, when planting soil and water conservation forests during dry or less dry season in the loess area, growing of shrubs is strongly promoted. .

According to the soil water usefulness analysis of *R. pseudoacacia* forest, the average soil water content will become less when the forest density increases. When the extreme and the lowest water content becomes even lower, the frequency of the adverse effects of water will increase. Based on the usefulness of water soil, for the *R. pseudoacacia* forest's density, mature forests should be below 700 tree/hm^2 and immature forests should be below 2300 tree/hm^2 and the extreme density should be less than 3000 tree/hm^2.

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