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RESEARCH ARTICLE

Jing YIN, Fan HE, Guoyu QIU, Kangning HE, Jinghui TIAN, Weiqiang ZHANG, Yujiu XIONG, Shaohua ZHAO, Jianxin LIU

Characteristics of leaf areas of plantations in semiarid hills and gully loess regions

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Abstract The objectives of our study were to explore the relationship of leaf area and stand density and to find a convenient way to measure stand leaf areas. During the 2004 growing season, from May to October, we used direct and indirect methods to measure the seasonal variation of the leaf areas of tree and shrub species. The trees were from *Robinia pseudoacacia* stands of four densities (3333 plants/hm^2, 1666 plants/hm^2, 1111 plants/hm^2, and 833 plants/hm^2) and *Platycladus orientalis* stands of three densities (3333 plants/hm^2, 1666 plants/hm^2, and 1111 plants/hm^2). The shrub species were *Caragana korshinskii*, *Hippophae rhamnoides*, and *Amorpha fruticosa*. Based on our survey data, empirical formulas for calculating leaf area were obtained by correlating leaf fresh weight, diameter of base branches, and leaf areas. Our results show the following: 1) in September, the leaf area and leaf area index (LAI) of trees (*R. pseudoacacia* and *P. orientalis*) reached their maximum values, with LAI peak values of 10.5 and 3.2, respectively. In August, the leaf area and LAI of shrubs (*C. korshinskii, H. rhamnoides*, and *A. fruticosa*) reached their maximum values, with LAI peak values of 1.195, 1.123, and 1.882, respectively. 2) There is a statistically significant power relation between leaf area and leaf fresh weight for *R. pseudoacacia*. There are significant linear relationships between leaf area and leaf fresh weight for *P. orientalis*, *C. korshinskii*, *H. rhamnoides*, and *A. fruticosa*. Moreover, there is also a significant power relation between leaf area and diameter of base branches for *C. korshinskii*. There are significant linear relations between leaf area and diameter of base branches of *H. rhamnoides* and *A. fruticosa*. 3) In the hills and gully regions of the Loess Plateau, the LAIs of *R. pseudoacacia* stand at different densities converged after the planted stands entered their fast growth stage. Their LAI do not seem to be affected by its initial and current density. The same is true for *P. orientalis* stands. However, the leaf area of individual trees is negatively and linearly related with stand density. We conclude that, in the hills and gully regions of the Loess Plateau , the bearing capacity of *R. pseudoacacia* and *P. orientalis* stands we studied have reached their maximum limitation, owing to restricted access to soil water. Therefore, in consideration of improving the quality of single trees, a stand density not exceeding 833 and 1111 plants/hm^2 is recommended for *R. pseudoacacia* and *P. orientalis*, respectively. In consideration of improving the quality of the entire stands, the density can be reduced even a little more.

Keywords leaf area, leaf area index (LAI), *Robinia pseudoacacia*, *Platycladus orientalis*, hills and gully regions of Loess Plateau

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Jing YIN
Department Water Resources, China Institute of Water Resource and Hydropower Research, Beijing 100044, China

Fan HE (✉)
Department of Sediment Research, China Institute of Water Resource and Hydropower Research, Beijing 100044, China
E-mail: hefan_98@sina.com

Guoyu QIU, Yujiu XIONG, Shaohua ZHAO
College of Resources Science and Technology, Beijing Normal University, Beijing 100875, China

Kangning HE, Jinghui TIAN, Weiqiang ZHANG, Jianxin LIU
College of Soil and Water Conservation, Beijing Forestry University, Beijing 100083, China

1 Introduction

Shrubs are the preferential choices in arid regions in vegetation recovery and soil and water conservation, reducing the effect of wind and stabilizing sand (Pei and Zhou, 1993). *Caragana korshinskii,Hippophae rhamnoides*, and *Amorpha fruticosa* are ordinary, artificially introduced shrubs that have high economic value and are widely distributed in loess and hill regions. *Robinia pseudoacacia* and *Platycladus orientalis* are two largely artificially introduced tree species in this area and have played an important role in improving the environment, preventing water loss and soil erosion, and adjusting water resources of the Yellow River catchment areas (Li et al., 1986; Wang and Liu, 1994). The phenomenon of a decline in existing *R. pseudoacacia* and *P. orientalis* plantations during their growing season has become a focus in the domain of shelterbelt prosecution (Wang et al., 2002). Previous studies have indicated that forest density is the key factor affecting stand structure, tree growth, and the utilization ratio of woodlands and stand productivity (Qin et al., 1999; Yu et al., 1999). It appears that an unsuitable forest density was one of the main reasons for the reduction in the number of trees in these plantations.

As nutritive plant organs, leaves are the main parts where photosynthesis takes place and play an important role in adjusting energy flows, the cycle of organic matter, especially the hydrology cycle. Leaves also form an important study field of forest ecosystem productivity, the amount of transpiration, photosynthetic efficiency, and canopy interception. Therefore, leaf area is a key in structural and functional studies of forest ecosystems (Wang, 1995; Lu, 1996). Given that the area and distribution of leaves directly affect the capture and utilization of sunshine received by forests (Zhu et al., 2001), leaf area is a necessary factor of physiology and biochemistry, genetics and breeding, and crop cultivation research (Yu et al., 2007). In the aspects of gas exchange, photosynthetic production, water utilization, and changes in forest ecological systems, leaf area index (LAI) is an absolutely necessary parameter (Nackaerts et al., 2000; Zhu et al., 2001). LAI studies can provide theoretical references for suitable cultivation of high-yield forests and be a standard of stand quality evaluation (Wang et al., 2005). Comprehensive research in LAI has been carried out in China and elsewhere. By applying corresponding periodic Landsat TM data, the Forest Research Institute of China has analyzed the relationship of several plants and stand indices (Wu et al., 1997). Based on the comparison of the seasonal dynamics of stand indices and unobstructed canopy characteristics of three representative forest communities of the warm temperate zone (i.e., *Quercus liaotungensis, Larix principis-rupprechtii*, and *Pinus tabulaeformis* stands), Chen and Sang (2007) have discovered the characteristic differences of these various forest communities. Beijing Forestry University adopted a method of combining optical measurements with remote sensing techniques to study changes in LAI regularity of *P. tabulaeformis* and *P. orientalis* plantations at the Ming Toms near Beijing (Wang et al., 2006). Georgian University scientists have studied the relationship of LAI of *Pinus taeda* stands at different densities and effective radiation used as photosynthesis (i.e., the greater the stand density, the more effective the radiation being intercepted) (Will et al., 2005).

Our objective was to explore the relationship of leaf area and stand density, to establish empirical formulas for shrub leaf area measurements, and to provide theoretical principles for the arrangement of trees and shrubs (Pei and Zhou, 1993). We measured seasonal variation in leaf areas of tree and shrub species in *R. pseudoacacia* stands with four densities (3333 plants/hm^2, 1666 plants/hm^2, 1111 plants/hm^2, and 833 plants/hm^2); *P. orientalis* stands with three densities (3333 plants/hm^2, 1666 plants/hm^2, and 1111 plants/hm^2); and *C. korshinskii, H. rhamnoides*, and *A. fruticosa* stands during the 2004 growing season (i.e., from May to October).

2 Site description

Our research area (37°36'58"N, 110°02'55"E) was located at the west side of the Tuqiao watershed and the Luliang mountains of Fangshan County, Shanxi Province. Its mean elevation is 1200 m in the hills and valley regions of the Loess Plateau. Most of the surface is covered by new Cenozoic quaternary Malan loess. As a typical loamy loess soil, the soil texture is uniform, and its pH value is 8.0 to 8.4.

Controlled by a warm continental monsoon climate, the regional climate is cold and dry in the winter and spring while cool and dry in the autumn. Its average temperature is 7.3°C, and average accumulated temperature is 2223.5°C. The mean annual precipitation is 416 mm, and more than 70% of it occurs during the period from June to September, whereas the largest evaporation occurs during the period from April to June. These facts indicate typically severe spring drought characteristics in Northern China.

Our study site was located at the Forestry Runoff Test Site of Beijing Forestry University at an elevation of 1250 m. Given the purpose of our experiment, *C. korshinskii, H. rhamnoides*, and *A. fruticosa* shrubs; broad-leaved species *R. pseudoacacia* and *P. orientalis*; and the conifer species *P. orientalis* were selected as the most complete and representative types in the test area and the most common species in local plantations. Detailed information on their condition is shown in Table 1.

3 Methods

The choice of a correct method is important in leaf area measurement. The number of measurement methods can be classified into two kinds: direct and indirect. Direct methods contain sample tree cutting and leaf litter collection. Indirect methods predict the LAI by instruments that measure the rays through the leaves (Eriksson et al., 2005). Although direct measurements are accurate, they also require much work and material resources and especially may damage trees. These days, indirect measurements are very popular; for example, the use of LAI-2000 (Leblanc and Chen, 2001; Nagler et al., 2004; Eriksson et al., 2005), but their results are often lower than

Table 1 Basic information of each forest stand test site

species	year of planting	density /(plants×hm^{-2})	plant /m× row /m	average height /m	average diameter/cm	forest coverage	biomass /(kg·hm^{-2})	aspect	slope
R. pseudoacacia	1986	3333	1.5×2	7.99	7.87	1	41089	N180°	20°
		1666	1.5×4	8.61	9.14	1	78583	N180°	20°
		1111	1.5×6	8.98	10.47	0.8	74625	N200°	20°
		833	1.5×8	9.82	11.62	0.7	69058	N190°	18°
P. orientalis	1993	3333	1.5×2	5.43	5.93	0.8	34070	N200°	15°
		1666	1.5×4	5.77	6.55	0.7	43632	N200°	16°
		1111	1.5×6	6.08	6.81	0.6	41058	N200°	14°

their actual values (Sonnentag et al., 2007). Therefore, our study adopted a method of combining direct and indirect measurements to obtain results easily and rapidly.

3.1 Selection of sample trees and sample branches

On the basis of our investigation of tree diameter, height, and crown area and our calculation of average values from four selected *R. pseudoacacia* and three *P. orientalis* stands, where two sample trees were selected in each stand, with height, diameter, and crown area approximately equal to the average values of their stands. Then, in different directions from the middle of the canopy, two sample branches were selected on each sample tree. The sample trees should have straight trunks without a fork or compromised canopy. Sample branches on the same sample tree should have similar length and diameter and be without insect pest incursion.

The same method used in the investigation of the *R. pseudoacacia* and *P. orientalis* stands was used to calculate the average value of plant height, crown area, and root diameter of *C. korshinskii, H. rhamnoides*, and *A. fruticosa* shrubs. We also selected two sample trees, and from which, we selected two sample branches.

3.2 Leaf moisture content of trees and shrubs

The moisture content of leaves is always fluctuating with the growing season and not only with its own physiological leaf characteristics but also with soil moisture and temperature. To establish an accurate regression equation about leaf areas and the fresh weight of the trees and shrubs, we used a drying method to measure the moisture content of leaves in May, July, August, and October during which the leaf moisture content varied appreciably. Detailed results are shown in Table 2.

From Table 2, it can be seen that the moisture content of leaves of *P. orientalis*, *R. pseudoacacia, C. korshinskii* Kom, *H. rhamnoides*, and *A. fruticosa* changed by 6%, 20%, 15%, 13%, and 9% respectively. Approximately, in the entire growing season, we used a regression equation established in August for *P. orientalis* and *A. fruticosa*, while we establish regression equations in May, July, August, and October separately for *R. pseudoacacia, C. korshinskii* Kom, and *H. hymnodies*.

Table 2 Monthly variation of leaf moisture content of trees and shrubs (unit: %)

species	May	Jul.	Aug.	Oct.
C. korshinskii	55.42	59.38	62.47	47.46
H. rhamnoides	54.78	58.36	65.70	52.43
A. fruticosa	56.47	61.15	59.50	52.83
R. pseudoacacia	51.03	71.74	65.60	59.98
P. orientalis	52.26	58.24	57.65	55.46

3.3 Calculation of leaf area of sample branches

A leaf area instrument method was adopted to calculate the leaf area of *R. pseudoacacia* and the three shrub species. The detailed method is as follows: on the basis of a large number of random samples collected in each stand in May, August, and October, we calculated the fresh weights of leaves and their areas by a high-class balance and LI-3000A leaf area instrument and then established empirical equations of leaf fresh weights and their areas with the SPSS 10.0 software. Therefore, the leaf areas of sample branches in May, August, and October should be obtained only for using the fresh weights of sample leaves in the established regression equation of the corresponding month. The empirical equations of May and August are suitable for June and July, and the equation of August is suitable for September.

In our study, we assumed that the leaf areas of two branches are the same when the length and stem diameter of the two branches are very similar. The detailed method of obtaining the fresh weight of leaves is as follows: select a branch of another plant whose length and diameter are similar to the sample branch, then pick up all its leaves, and weigh their fresh weights. This value can be substituted for the actual fresh leaf weights of the sample branch.

Given the special case of *P. orientalis* leaves, an image method (Bao et al., 2002; Yang and Chen, 2002; Bai and Yang, 2004; Cheng and Lu, 2003) was used to calculate the leaf areas. Because both sides of its leaves engage in photosynthesis and transpiration, the actual leaf areas was calculated by multiplying the value obtained by the image method by 2. For *P. orientalis* and *A. fruticosa*, the regression equations of July were used to calculate the leaf areas of the sample branches for each month during the entire growing season.

3.4 Calculation leaf area of sample trees

For the trees and shrubs, we assumed that the ratio of leaf areas of the entire sample tree to that of the sample branches during the entire growing season is a fixed value. We only needed to calculate the leaf area of the sample trees in each stand according to the method described in section 3.3 from May to September. During the last month of the growing season, October, we picked up all the leaves of the sample trees and their sample branches and measured their fresh weights separately. On the basis of calculating the ratio of leaf areas of the entire sample tree to that of the sample branches in October, the entire leaf area of sample trees in May, June, July, August, and September could be obtained by multiplying the leaf area of their sample branches of each month with the ratio calculated in October.

3.5 Stand LAI calculation

The formula for calculating the stand LAI is as follows:

$$\mathrm{LAI} = \mathrm{LA} \times d \tag{1}$$

where LAI represents the LAI of the stand, LA represents the leaf area of the sample trees (m^2), and d represents the plant density (plants/m^2).

4 Results and discussion

4.1 Relationship of tree leaf areas and their weights

By fitting the leaf areas and their weights with the SPSS 10.0 software, we obtained highly significant power functions for *R. pseudoacacia* and a linear function for *P. orientalis*. Detailed results are shown in Table 3.

4.2 Relationship of shrub leaf areas and their weights, and stem diameter

By fitting the shrub leaf areas, their weights, and stem diameters with the SPSS 10.0 software, we obtained statistically significant linear regression equations of leaf areas and their weights for the three shrubs, a power function of leaf areas and their stem diameter for *C. korshinskii*, and linear functions for *H. rhamnoides* and *A. fruticosa*. Detailed results are shown in Table 4.

4.3 Analysis to leaf areas and LAI of shrubs

The variation of leaf area and LAI of the three shrubs from May to October are shown in Figs. 1 and 2.

From Figs. 1 and 2, we see that the shrubs showed single-peaked curves of leaf areas and LAI changes from May to October and reached their maximum value in August. The leaf areas and LAI of *A. fruticosa* was higher than those of the other two shrubs. In June and July, the

Table 3 Results of regression analysis of leaf fresh weight and leaf area of *R. pseudoacacia* and *P. orientalis*

species	month	equation	R^2	F	P	df
R. pseudoacacia	May to Jul.	$Y = 89.5131X^{0.9872}$	0.998^{**}	29548.9	0.00	1
	Aug. to Sept.	$Y = 80.8764X^{1.013}$	0.998^{**}	12849.3	0.00	1
	Oct.	$Y = 73.9759X^{0.9855}$	0.996^{**}	5167.5	0.00	1
P. orientalis	May to Oct.	$Y = 16.6159X + 0.7747$	0.981^{**}	2317.2	0.00	1

Note: ** The regression coefficients are highly significant. X is the fresh weight of leaves; Y is their corresponding leaf areas.

Table 4 Regression equations of leaf areas of shrubs as a function of fresh weight or branch diameter

species	month	leaf fresh weight and leaf area					branch diameter and leaf area				
		equation	R^2	F	p	df	equation	R^2	F	p	df
C. korshinskii	May to Jul.	$Y = 51.272X - 0.593$	0.998	26519.8	0.00	1	$Y = 1490X^{2.0585}$	0.959	948.4	0.00	1
	Aug. to Sept.	$Y = 51.125X + 1.4884$	0.999	19009.8	0.00	1					
	Oct.	$Y = 48.692X - 0.4515$	0.999	27615.3	0.00	1					
H. rhamnoides	May to Jul.	$Y = 49.143X - 0.2234$	0.999	15226.8	0.00	1	$Y = 1490.55 - 3404.2X + 4182.47X^2$	0.960	708.5	0.00	2
	Aug. to Sept.	$Y = 40.122X + 3.3811$	0.999	45583.0	0.00	1					
	Oct.	$Y = 39.573X - 1.2589$	0.999	28254.0	0.00	1					
A. fruticosa	May to Oct.	$Y = 91.076X + 5.3917$	0.999	19697.6	0.00	1	$Y = -2390.9 + 5139.04X$	0.803	151.2	0.00	1

Note: X is the fresh weight of leaf or branch diameter; Y is the corresponding leaf area.

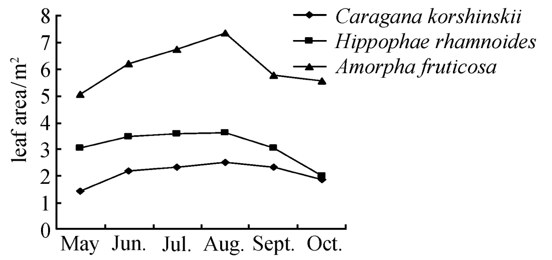

Fig. 1 Monthly variation of shrubs leaf area

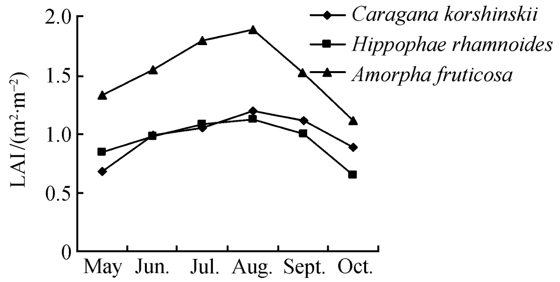

Fig. 2 Monthly variation of LAI of shrubs

values of *C. korshinskii* and *H. rhamnoides* were very similar.

4.4 Leaf areas and LAI of trees

4.4.1 Leaf areas of single trees from different densities

Leaf areas of single trees from different densities between May and October are shown in Figs. 3 and 4.

From Figs. 3 and 4, we see that, for *R. pseudoacacia* and *P. orientalis* stands, their individual leaf areas decreased with an increase in stand density and reached their maximum values in September.

4.4.2 Leaf areas of stands with different densities

The results of stands and leaf areas with different densities are calculated by Eq. (1) and are shown in Table 5.

To compare differences in LAI of stands with different densities, a paired-sample t test was used. Detailed results are shown in Figs. 6 and 7.

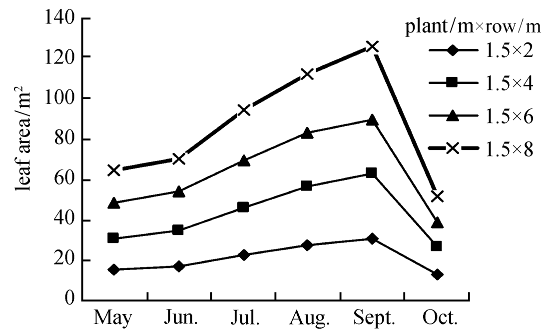

Fig. 3 Monthly variation of individual leaf areas of *R. pseudoacacia*

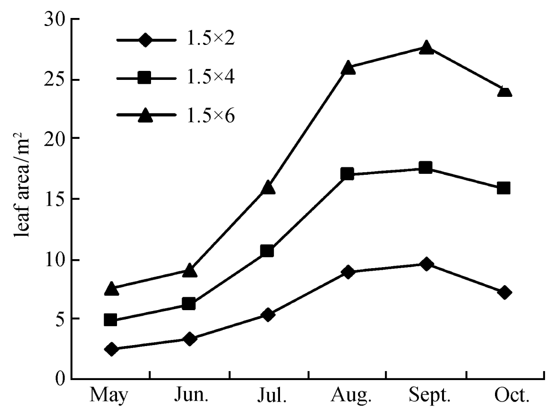

Fig. 4 Monthly variation of individual leaf areas of *P. orientalis*

Table 5 LAI of *R. pseudoacacia* and *P. orientalis* forest with different densities (plant /m×row /m)

month	*R. pseudoacacia*				*P. orientalis*		
	1.5×2	1.5×4	1.5×6	1.5×8	1.5×2	1.5×4	1.5×6
May	5.2	5.1	5.4	5.4	0.9	0.8	0.8
Jun.	5.8	5.9	6.1	5.9	1.1	1.0	1.0
Jul.	7.6	7.7	7.8	7.9	1.8	1.8	1.8
Aug.	9.3	9.5	9.2	9.4	3.0	2.8	2.9
Sept.	10.3	10.5	10.0	10.5	3.2	2.9	3.1
Oct.	4.4	4.4	4.3	4.3	2.4	2.6	2.7
average	7.1	7.2	7.1	7.2	2.1	2.0	2.1

Table 6 Results of paired-sample t test for LAI of *R. pseudoacacia* forests with different densities

plant /m×row /m	plant /m×row /m							
	1.5×2		1.5×4		1.5×6		1.5×8	
	t	Sig. (2-tailed)	*t*	Sig. (2-tailed)	*t*	Sig. (2-tailed)	*t*	Sig. (2-tailed)
1.5×4	−1.746	0.141	—	—	—	—	—	—
1.5×6	−0.349	0.741	0.397	0.704	—	—	—	—
1.5×8	−2.706	0.093	−1.387	0.224	−1.397	0.221	—	—

Table 7 Results of paired-sample t test for LAI of *Platycladus orientalis* forests with different densities

plant /m×row /m	1.5×2		1.5×4		1.5×6	
	t	Sig. (2-tailed)	*t*	Sig. (2-tailed)	*t*	Sig.(2-tailed)
1.5×4	1.185	0.289	—	—	—	—
1.5×6	0.255	0.809	0.200	0.102	—	—

From Tables 6 and 7, it should be pointed out that for *R. pseudoacacia* and *P. orientalis* stands, there were no significant differences in LAI between different stands.

For the LAI of different stands at the same time: $LAI_1 = LA_1 \times d_1$ and $LAI_2 = LA_2 \times d_2$ .Based on the results of Tables 6 and 7, we can conclude that $LAI_1 \approx LAI_2$, that is, $LA_1 \times d_1 \approx LA_2 \times d_2$, $\frac{LA_1}{LA_2} \approx \frac{d_2}{d_1}$. We can see that the ratio of leaf areas of different stands is approximately equal to the inverse ratio of their stand densities. When stand moisture and nutrients are insufficient in certain environments or when the environmental capacity of stands is saturated, the LAIs of *R. pseudoacacia* and *P. orientalis* stands do not change, no matter how stand densities change.

5 Conclusions

In September, the leaf area and LAI of trees (*R. pseudoacacia* and *P. orientalis*) reached their maximum value, and the peak values of their LAI were 10.5 and 3.2, respectively. In August, the leaf area and LAI of shrubs (*C. korshinskii*, *H. rhamnoides*, and *A. fruticosa*) reached their maximum value, with LAI peak values of 1.195, 1.123, and 1.882, respectively.

There was a statistically significant power relationship between leaf area and leaf fresh weight for *R. pseudoacacia* and significant linear relationships between leaf area and leaf fresh weight for *P. orientalis, C. korshinskii, H. rhamnoides*, and *A. fruticosa*. Moreover, there were significant power relationships between leaf area and diameter of base branches for *C. korshinskii*. There were also significant linear relationships between leaf area and diameter of base branches for *H. rhamnoides* and *A. fruticosa*.

In the hills and gully regions of the Loess Plateau, after the planted vegetation entered its fast growth stage, the LAIs of *R. pseudoacacia* stands with different densities converged and showed that LAI was not affected by initial and current density. The same is true for *P. orientalis* stands. However, the leaf area of single trees has a negative linear relation with stand density.

We conclude that, in the hills and gully regions of the Loess Plateau, the bearing capacity of *R. pseudoacacia* and *P. orientalis* stands reached their maximal limitation, owing to a restricted amount of soil water. Therefore, in consideration of improving the quality of single trees, stand densities, not exceeding 833 and 1111 plants/hm^2, are recommended for *R. pseudoacacia* and *P. orientalis*, respectively. In consideration of improving the quality of the entire stands, density could be reduced even a little more.

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