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RESEARCH ARTICLE

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Density structure and growth dynamics of a *Larix principis-rupprechtii* stand for water conservation in the Wutai Mountain Region of Shanxi Province, North China

Abstract To discover the site adaptability and density suitability of *Larix principis-rupprechtii* as a water conservation forest in Wutai Mountain, Shanxi Province, the growth process and diameter distribution characteristics of 10-year-old artificial *L. principis-rupprechtii* forests with density structures of 2600 trees/hm^2 and 3500 trees/hm^2 were studied using trunk analysis of a sample tree. The results showed that: 1) The tree height increment of the two kinds of forests were the same, and it was almost not affected by density. However, the growth process of the diameter and timber volume showed a great distinction. The growth status and density structure of the low density forest were superior to the high density forest. 2) The skewness (S_k) of diameter distribution had great distinction. The S_k (0.01) of the low density forest approached a normal distribution, which showed that the density structure was reasonable, while the S_k (0.45) of the high density forest was partial to a normal distribution, which showed that the density structure was on the high side. The kurtosis (K) of the two forests (one was -0.64, the other was -0.74) had little distinction and the density factor had limited function to forest polarization. 3) The increment of diameter at breast height, timber volume and trunk stock of the low density forest increased yearly without the effect of density. However, the increment of high density forests had declined from the sixth year, which was restricted by high density. 4) The reasonable density of the 10-year-old *L. principis-rupprechtii* artificial forest was about 2600 trees/hm^2, which is also the reasonable planting density if the utilization of double cutting is not considered.

Keywords *Larix principis-rupprechtii*, forest for water source conservation, forest increment, diameter distribution, forest density

1 Introduction

The Wutai Mountain, also called the "fastigium of north China", not only is famous as a Buddhism bethel and scenic spot for tourists, but is also one of the important watershed spots of Shanxi Province, including the Haihe drainage area. Because of frequent unreasonable human activity, natural forests have been destroyed and replaced by secondary forests and plantations; water resource conservation and similar protection functions were thus reduced significantly (Ma and Guo, 1999; Cheng et al., 2003; Wang, 2003; Zhou et al., 2003). To improve the forest ecological function as soon as possible, water and soil conservation projects, including protecting natural forests, restoring reclaimed land to the forest, and ecological restoration (Xu et al., 2003; Liu et al., 2004; Li, 2006) were implemented successively, and the measures included plantation, closing hillsides to facilitate afforestation, tending and regeneration, and tending thinning-improvement of secondary forests (Zhai, 2003; He, 2004). Large plantation areas of the *Larix principis-rupprechtii*, one of the main trees for forestation, had important ecological effects on water and soil conservation, but many forests apparently had recessionary growth and depressed ecological effects due to irrational planting technology and extensive management. The high density of seedlings in the initial planting over the forestland carrying capacity was also a key factor (Wang et al., 2002; Li et al., 2003). Therefore, a reasonable

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adjustment and controlling density structure have turned into pivotal technology to ensure forest growth stabilization and major improvements (Li, 2003). So far, studies on *L. principis-rupprechtii* have mostly focused on cultivating fast-growing and high-yielding plantations, and few have touched on water conservation forests and other ecologically beneficial forests (Chai et al., 1999; Chen, 2003; Ji and Chen, 2003), especially on rational planting density and forest density. Therefore, to discover the adaptability on site and suitability on density of *L. principis-rupprechtii*, the diameter distribution and growth process (10-year-old) for water conservation were studied, which will offer references and theory a resource for density management of water conservation forests of *Larix principis-rupprechtii* in the Wutai Mountain Region.

2 Study area

The study area is located at the Nanliang channel drainage area, with an elevation of 1400–2200 m at the Menxianshi forestry center (113°10′–113°50′E, 38°40′–39°15′N) of the Forest Management Bureau of Wutai Mountain, Shanxi Province. The annual mean precipitation is 560–650 mm and occurs mostly from July to September. The dryness coefficient is 1.42, while relative humidity is 50%–60%. The annual mean air temperature is 6.8°C, and the accumulative temperature above 10°C is up to 3000–3600°C; the frost-free period is 120–130 days. The main soil is mountainous brown soil and eluviating cinnamon soil, organism content is 7%–15%, and pH value is 6.5–7.0. Vegetation species take on a distinct changing trend and have transitional characteristics between forest and grassland. The predominant arbor trees principally include *Larix principis-rupprechtii*, *Betula platyphylla*, and *Populus davidiana*, and most of them are natural secondary forests. *Lespedeza bicolor*, *Abelia biflora*, and *Spiraea tuilobata* are the main shrubs. The herbages were mainly *Carex lanceolata* and *Artemisia gmelini* (Chen and Zhang, 1996; Ma, 2000).

The site of the forest under study is located at the water conservation forest area in Wutai Mountain. The elevation is 1650–1850 m, the slope is about 20° trending north to west (shady slope and semi-shady slope), the gradient is 20–25°, and soil thickness is 40–50 cm. Forests were plantations of 10-year-old *L. principis-rupprechtii*. Density involved two types: the lower density forest (A): 2600 trees/hm^2 (the individual plant and row spacing of afforestation is 2.0 m × 2.0 m), and the higher density forest (B): 3500 trees/hm^2 (the individual plant and row spacing of afforestation is 1.5 m × 2.0 m). Mean tree diameter at breast height of the lower density forests is 7.2 cm, mean tree height is 5.6 cm, mean crown diameter is 2.1 m, and mean height below branch is 3.1 m. Mean tree diameter at breast height of the higher density forests is 6.1 cm, mean tree height is 5.7 cm, mean crown diameter is 1.7 m, and mean height below branch is 3.9 m.

3 Methods

3.1 Tree growth process

Plot and trunk analysis of the sample trees were used to evaluate the tree growth process (Wei, 2001). Three sample plots of 400 m^2, located at the middle of the slope, were respectively selected in representative forest plots with lower density forests and higher density forests. Every tree in the sample plots was surveyed, and measured indices included tree height, tree diameter at breast height, crown diameter and height below branch. According to the average value of these indices, the sample trees were selected. After cutting down the samples, total growth increment, mean annual increment and current annual increment of tree height (H), tree diameter at breast height (D), single timber volume (V) and stumpage accumulation per hectare of the sample trees were measured using trunk analysis, and in every density forest, mean value of three sample trees were selected (Figs. 1–8). Using quadratic equations, total growth processes of tree height, tree diameter at breast height, single timber volume, and stumpage accumulation were drafted; after extracting those variables, the models of annual growth process, i.e., the accelerating ratio of annual growth, were educed (Table 1). Sequentially, the rules of growth trend of the two density forests were analyzed.

3.2 Tree diameter distribution

Based on every tree surveyed in the sample plots, applying the theory of statistics and physics, taking the

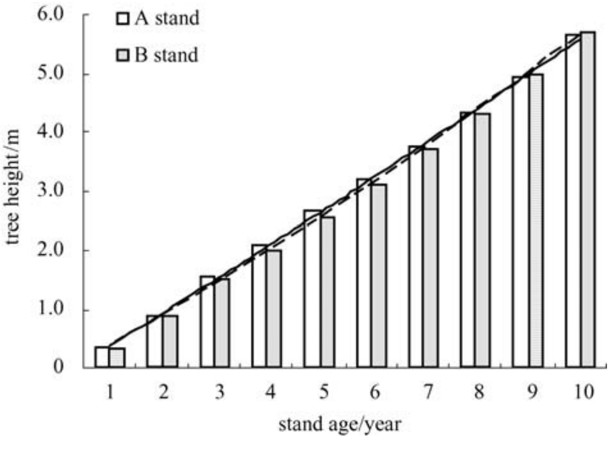

Fig. 1 Total tree height (H) increment of stand with lower density (A stand) and higher density (B stand)

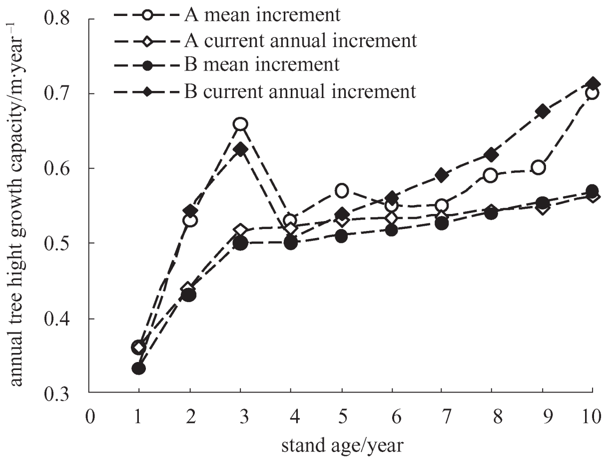

Fig. 2 Annual tree height (*H*) increment of stand with lower density (A stand) and higher density (B stand)

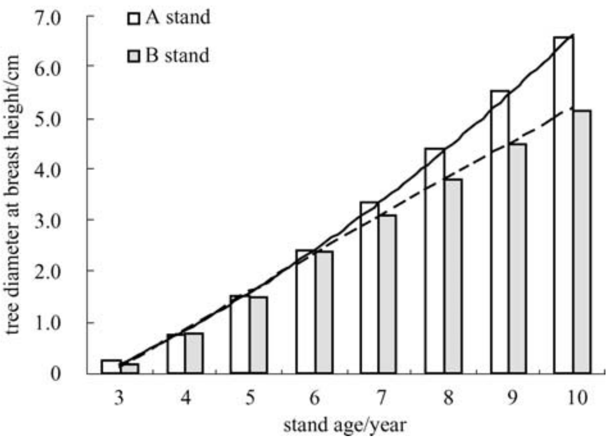

Fig. 3 Total diameter at breast height (*D*) increment of stand with lower density (A stand) and higher density (B stand)

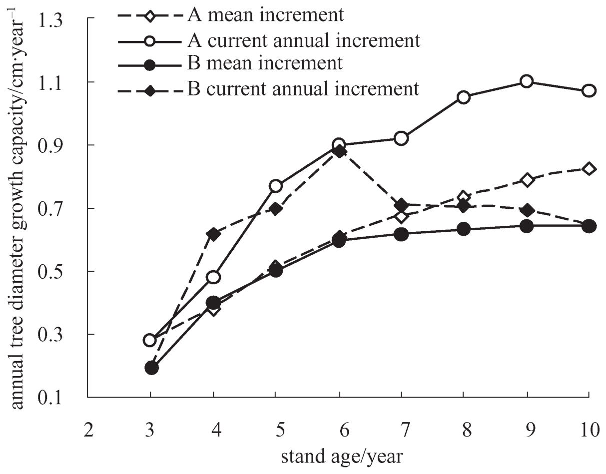

Fig. 4 Annual diameter at breast height (*D*) increment of stand with lower density (A stand) and higher density (B stand)

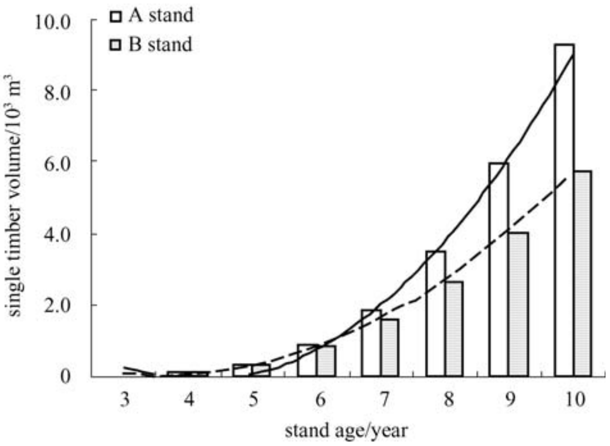

Fig. 5 Total tree volume (*V*) increment of stand with lower density (A stand) and higher density (B stand)

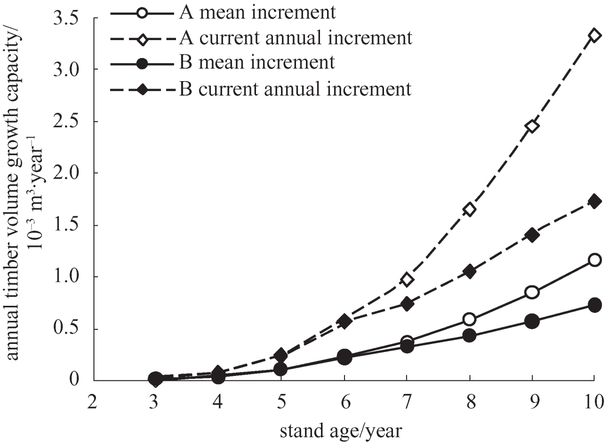

Fig. 6 Annual tree volume (*V*) increment of stand with lower density (A stand) and higher density (B stand)

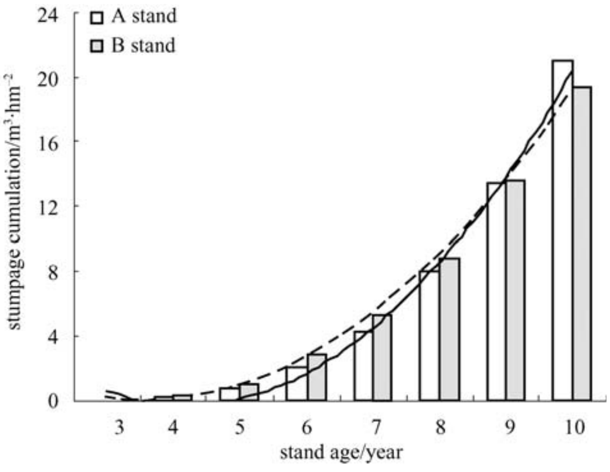

Fig. 7 Total trees volume storage (*S*) increment of stand with lower density (A stand) and higher density (B stand)

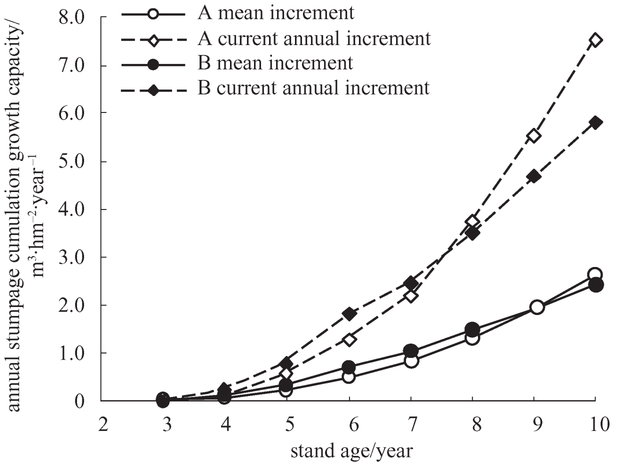

Fig. 8 Annual trees volume storage (S) increment of stand with lower density (A stand) and higher density (B stand)

tree diameter at breast height as a stochastic variable, using SPSS software for statistical analyses of sample trees, the coefficients of skewness and kurtosis of the tree diameter distribution were educed, and the histogram of the number of trees according to the distribution of diameter class was drawn (Fig. 9). Tree diameter distribution characteristics and the reasonable extent of density structure of the two forests were then analyzed.

4 Results and analysis

4.1 Annual growth dynamic of the two forests

4.1.1 Growth process of tree height

The tree height growth process and growth yield of the two density forests are shown in Figs. 1 and 2. From the tree height total increment (Fig. 1), the tree height growth process was conical (Table 1), and the increase rate of annual growth yield of low and high stand density was 0.007 m/year and 0.018 m/year, respectively. Tree height growth rate and annual growth yield of the two forests increased every year. In the same stand age, the difference of average tree height for the two forests were not obvious; in the 10-year-old forest, the tree height of lower and higher density was 5.6 m and 5.7 m, respectively. The result of variance analysis was $F = 0.311 < F_{0.05} = 3.919$, $P = 0.578 > 0.05$, which indicated that there was no obvious tree height differences between the two forests.

According to the annual increment (Fig. 4), the growth process of the two forests was almost similar. The mean increment increased every year, and it was almost the same in the same stand age. The mean increment was about 0.5 m/year at the 10-year-old stand age. The first growth maximum of the current annual increment appeared in the third year, at 0.6 m/year. The current annual increment dropped at the 4-year-old stand, and then it increased every year. There was almost no discrepancy in current annual increment; in the tenth year, it was 0.7 m/year. In addition, the current annual tree height increment of the two density stands was always higher than that of the mean increment.

4.1.2 Growth process of forest diameter at breast height

The growth process and growth yield of forest diameter at breast height of the two density stands are shown in Figs. 3 and 4. There were obvious differences between the two stands. From the total diameter at breast height increment (Fig. 3), it can be concluded that the diameter at breast height growth process was conical (Table 1). The rate of increase of the annual increment of diameter at breast height in the lower stand density was positive, which indicated that the growth rate of diameter at breast height increased every year at an annual increment of 0.089 cm/year. However, that of the higher stand density is negative, which showed that the growth rate of diameter at breast height decreased year after year at an annual increment of 0.009 cm/year. At the same stand age, the mean diameter at breast height of lower density

Table 1 Regression equations of growth course in two density forests

density	growth indexes	regression models		correlation coefficient (R^2)
		total growth capacity (growth processes)	annual growth capacity (annual growth process)	
Lower density forest (A)	Tree height/m	$H_A = 0.003a^2 + 0.541a - 0.166$	$dH_A/da = 0.007a + 0.541$	0.9995
	Tree diameter at breast height/cm	$D_A = 0.045a^2 + 0.518a - 0.366$	$dD_A/da = 0.089a + 0.518$	0.9992
	Single timber volume/10^{-3} $m^3 \cdot tree^{-1}$	$V_A = 0.273a^2 - 1.206a + 1.210$	$dV_A/da = 0.546a - 1.206$	0.9949
	Stumpage cumulation/$m^3 \cdot hm^{-2}$	$S_A = 0.617a^2 - 2.726a + 2.734$	$dS_A/da = 1.234a - 2.726$	0.9949
Higher density forest (B)	Tree height/m	$H_B = 0.009a^2 + 0.483a - 0.115$	$dH_B/da = 0.019a + 0.483$	0.9995
	Tree diameter at breast height/cm	$D_B = -0.005a^2 + 0.763a - 0.646$	$dD_B/da = -0.009a + 0.763$	0.9988
	Single timber volume/10^{-3} $m^3 \cdot tree^{-1}$	$V_B = 0.140a^2 - 0.451a + 0.371$	$dV_B/da = 0.280a - 0.451$	0.9994
	Stumpage cumulation/$m^3 \cdot hm^{-2}$	$S_B = 0.469a^2 - 1.512a + 1.243$	$dS_B/da = 0.938a - 1.512$	0.9994

Note: a is stand age.

was larger than that of higher density, and the difference increased along with the stand age. For example, at the 10-year-old stand age, the diameter at breast height of higher density and lower density was 6.6 cm and 5.1 cm, respectively. The result of variance analysis was $F = 36.895 > F_{0.01} = 6.743$, $P = 4.95 \times 10^{-9} < 0.01$, which indicated that the difference of mean diameter at breast height of the two forests were prominent.

From the evaluation of changes to annual increments of forest diameter at breast height (Fig. 4), there were no differences between the two kinds of stand density before six years old, and it increased along with stand age. The current annual increment was about 0.9 m/year at the 6-year-old stand. There were obvious differences between the two forest densities in terms of diameter at breast height growth process after six years. The forest increment of the lower density increased yearly, and the current annual increment of diameter at breast height was about 1.1 cm/year at the 10-year-old stand — larger than that of the mean increment. However, the forest increment of higher density obviously diminished. The current annual increment decreased every year and was only 0.6 cm/year at the 10-year-old stand — the same as the mean increment. The above analysis showed that the potential diameter at breast height growth of higher density forests was restricted, and the increment was obviously less than that of lower density forests.

4.1.3 Timber volume growing process of single tree

There were distinct differences in timber volume increment and growth process of single trees in two density stands (Figs. 5 and 6). From the total timber volume increment (Fig. 5), we can see that the timber volume growth process was conical (Table 1). The annual increment rate of tree timber volume in the two stands was positive, which showed that the tree timber volume growth rate (annual increment) of the stands increased year after year. However, the rate of increase of lower density (0.55×10^{-3} m^3/year) was obviously larger than that of higher density (0.28×10^{-3} m^3/year). At the 10-year-old stand, the tree timber volume of lower density (about 9.3×10^{-3} m^3) was obviously larger than that of higher density (about 5.8×10^{-3} m^3).

There were no differences between the tree volume annual increments of the two density stands before six-years. At the 6-year-old stand, they were all close to 0.6×10^{-3} m^3/year. But the tree volume annual increment of the lower stand density was larger than that of the higher stand density. At the 10-year-old stand, the tree volume annual increment of the former was about 3.33×10^{-3} m^3/year, twice as large as that of the latter (1.73×10^{-3} m^3/year). This indicated that potential growth of higher stand density timber volume was restricted, and its tree volume annual increment was less than that of lower stand density.

4.1.4 Increase process of tree volume storage

The total and annual volume storage increment of the two density stands is expressed in Figs. 7 and 8. There were obvious differences between the two stands. From the tree volume storage total increment (Fig. 7), we can see that its growth process was defined by conic (Table 1). The rate of increase of total increment of tree volume storage in two density stands was positive; it showed the tree volume storage growth rate (annual increment) of the two density stands increased year after year. However, the rate of lower density (1.234 m^3/year) was obviously larger than that of higher density (0.938 m^3/year).

In addition, the total tree volume storage increment of higher stand density was larger than that of lower stand density (Fig. 7) before six years. At the 6-year-old stand, the former was about 2.9 m^3/hm^2, while the latter was 2.0 m^3/hm^2. After six years, the tree volume storage total increment of the higher density stand was obviously less than that of the lower density stand; at the 10-year-old stand age, the former was 19.3 m^3/hm^2, while the latter was 21.0 m^3/hm^2. The tree volume storage annual increment of the two density stands (Fig. 8) showed the same changing course as total increment. It indicated that the individual tree volume storage of higher stand density was obviously restricted, which induced an obvious decline in colonial productivity.

4.2 Distribution characteristics of trees diameter

There were obvious differences in the distribution characteristics curve of tree diameter of the two density stands (Fig. 9). Compared with normal distribution, the distribution curve peak of the higher stand density tree diameter was obviously deviated to the left, and its deviation degree was obviously larger than that of the lower stand density (Fig. 9). Selecting the tree diameter at breast height as an independent variable, two diameter distribution characteristic parameters were gained according to statistical analysis: skewness (S_k) and kurtosis (K). The S_k and K of lower density stands was 0.01 and −0.74, respectively (Fig. 9), while that for higher density stands was 0.45 and −0.64, respectively (Fig. 9). S_k (normal distribution) was more approaching to 0, which predicated that the tree diameter distribution and density structure was more reasonable (Sun, 1990; Shen, 2001). The larger the K, the greater the number of trees centralizing mean diameter, and the more trim the forests growing (the less the differentiation degree). Therefore, the tree diameter structure and density structure of lower density forests were superior to those of high density forests.

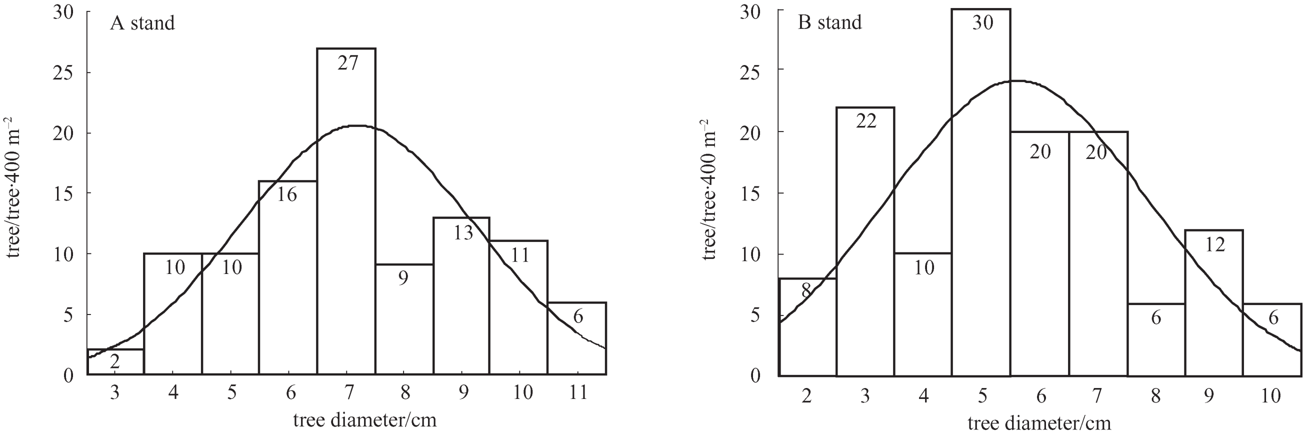

Fig. 9 Trees diameter distribution characteristics of stand with lower density (A stand) and higher density (B stand)

5 Conclusions and discussion

5.1 Forest density and tree height growth

Tree height growth was influenced by many factors, with the condition of forest site apparently the most evident. The better the site conditions became, the greater the tree height growth, which was mostly influenced by forest density at the definite density extent (Sun, 1990; Shen, 2001). Therefore, tree height growth was selected as the index of site quality evaluation and site classification. The results showed that the densities of the two forests had distinct differences, but tree height growth had no distinct differences. The effect of forest density on tree height growth was not obvious. Previous results (China Silva Editing Committee, 1981) showed that on better site conditions, the forest of *L. principis-rupprechtii* grew normally. Tree height growth was slow at the initial stage and increased from the fifth to the tenth year with an annual average 0.4–0.7 m/year. Compared with our results, the mean annual tree height growth was 0.5–0.6 m/year, tree height growth was normal, growth potential was perfectly exerted and not influenced by density. Therefore, *L. principis-rupprechtii* was an excellent tree for water conservation forests or other ecological forests at study area.

5.2 Forest density and tree diameter distribution

Tree diameter distribution was an important theoretical basis for verifying feasible state of forest density and rationally adjusting forest density (Sun, 1990; Shen, 2001). When forest density was appropriate and forests grew normally, tree diameter distribution approximated a normal distribution, and the skew coefficient (S_k) was between -0.3 and 0.3 (Huang and Zhang, 1989; Zhang et al., 1999). When forest density was on the high side, tree diameter distribution kurtosis deviated to the left, ($S_k > 0$), and the larger the value of S_k was, the higher the forest density was. The results showed that S_k (0.01) of the lower density forests approached a normal distribution and the density structure was reasonable. S_k (0.45) of the higher density forests was partial to normal distribution, and the density structure was on the high side. Artificial forests lack factors of forest polarization and environmental conditions of natural sparse genetics; if forest density was on the high side, individual forest and community were restricted distinctly (Wang and Wang, 1996; Yang, 1996; Li et al., 2003). In this paper, it was shown that tree diameter increment at breast height, single timber volume increment and stumpage accumulation increment of the higher density forests were distinctly less than those of the lower density forests. Contrasted with the former results (China Silva Editing Committee, 1981), when the forest of *L. principis-rupprechtii* grew normally, tree diameter growth at breast height was slower in the initial stages and increased from the tenth to the fifteenth year, and the increment rose year after year. Tree diameter increment at breast height of the lower density forests was basically normal and strongly restricted by forest density. However, tree diameter increment at breast height of the higher density forests declined ahead of schedule and was restricted by six-year-old forest density, which resulted in a distinct decline of single timber volume increment and reduced forest community productivity (i.e. stumpage cumulation increment).

5.3 Feasible forest density of *L. principis-rupprechtii*

Forest density is one of the keys for artificial forest cultivation and management. Rational forest density is the basis of a reasonable forest structure and exerts greater effect; it is not a constant, but is a variational quantitative range along with tree species, forest age and field environment (Sun, 1990; Shen, 2001). The above discussion show that at the study area, reasonable forest density of the 10-year-old *L. principis-rupprechtii* forest was about 2600 trees/hm^2. Neglecting the intermediate fall before the tenth year, the 2600 trees/hm^2 (initial tree and row spacing may be about 2.0 m × 2.0 m or 1.5 m × 2.5 m) approached the lowest value of planting density of *L. principis-rupprechtii* in the *Chinese Forestation Technology Regulations* (2400–5000 trees/hm^2) (Sun, 1990; Shen, 2001) and can be regarded as the density of initial planting. When forest density was 3500 trees/hm^2, the range of reasonable density is overstepped, restraining forest growth and exerting ecological effects on the sixth year. Therefore, the higher density forests must be thinned in time after six years, controlling density below 2600 trees/hm^2. However, *L. principis-rupprechtii* belongs to long-life tree species. The reasonable density of water conservation stands of *L. principis-rupprechtii* at other growth phases, for example at 20 or 30 years, at the study site has not been determined in previous results and need further study.

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