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EFFECTS OF DIFFERENT JUVENILE MIXED PLANTATIONS ON GROWTH AND PHOTOSYNTHETIC PHYSIOLOGY OF *PINUS YUNNANENSIS* FRANCH.

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Abstract

The growth characteristics, photosynthetic gas exchange features, physiological and biochemical resistance, and soil nutrition contents of different juvenile mixed plantations were analyzed. Moreover, the synergic effect mechanism of the different species was elucidated to improve the stand quality of *Pinus yunnanensis* Franch. plantations and guide the screening of *P. yunnanensis* mixed plantations. The mixed plantations were *P. yunnanensis–Alnus nepalensis–Quercus acutissima, P. yunnanensis–A. nepalensis–Cyclobalanopsis glaucoides*, and *P. yunnanensis–Q. acutissima–C. glaucoides*. Individual juvenile plantations of pure *P. yunnanensis*, *A. nepalensis*, *Q. acutissima*, and *C. glaucoides* were used as control groups. Results showed that pure *P. yunnanensis* juvenile plantation consumed more soil organic matter, total nitrogen (TN), total phosphorus (TP), and total potassium (TK) than the other plantations. This plantation also showed poorer growth characteristics, poorer photosynthetic capability, lower water utilization efficiency (WUE), and biochemical resistance in infertile soil, as shown by the nutrition and water competition. Increasing soil organic matters, TN, TP, and TK of the different mixed plantations evidently enhanced height, ground diameter growth rate, net photosynthetic rate (Pn), transpiration rate (Tr), WUE, carboxylation efficiency (CE), soluble sugar (SS) content, and superoxide dismutase (SOD) activity. Moreover, different mixed forests slightly influenced the characteristics of photosynthetic gas exchange and physiological and biochemical resistance of *A. nepalensis*. All stand types facilitated growth of tree height and basal diameter of *Q. acutissima* sapling. Although *Q. acutissima* inhibited physiological and biochemical resistance of leaves to a certain extent, they increased WUE significantly. Different stand types slightly influenced growth features, Pn, Tr, and WUE of *C. glaucoides* sapling. Moreover, they inhibited the osmotic adjustment system and SOD activity of *C. glaucoides* to a certain extent, indicating that *C. glaucoides* was not a well-associated broad-leaf species of *P. yunnanensis* juvenile mixed plantations. Therefore, *P. yunnanensis–A. nepalensis–Q. acutissima* is an optimal mixed plantation, which is beneficial for increasing growth rate, Pn, and WUE, as well as for recovering soil fertility.

Keywords: *Pinus yunnanensis* Franch., Mixed plantation, Pure plantation, Photosynthetic characteristics, Water use efficiency, Soil nutrient.

Introduction

Pinus yunnanensis Franch. is a special tree species in southwest China. An extensive adult *P. yunnanensis* forest can be found in the Yunnan-Guizhou Plateau, covering approximately 5 million hm^2 of land and accounting for 52% of total forest area in the Yunnan Province. This forest possesses approximately 0.3 billion m^3 of timber reserves, accounting for 32% of forest reserves in the Yunnan Province (Zhao *et al.*, 2012; Yuan *et al.*, 2013). Therefore, *P. yunnanensis* plays an important role not only in the regional economic development and ecological environment construction in Yunnan but also in maintaining regional ecological balance and in the restoration and reconstruction of the ecosystem. However, most *P. yunnanensis* plantations in the Yunnan Province are low-quality and low-efficiency pure and aged stands as manifested by single tree species, poor stand stability, frequent pest outbreaks, low stand productivity, and annual increasing proportion of ill individuals (e.g., short and lodgepole pines). These characteristics restrict the ecological and economic benefits of *P. yunnanensis* (Li *et al.*, 2009; Wang *et al.*, 2010; Han *et al.*, 2011; Duan *et al.*, 2013; Xu *et al.*, 2015). Stand recession has not been resolved despite long-term extensive studies on this tree species. The serious drought since 2009 increased the damaged area in the *P. yunnanensis* forest to 2.86 million hm^2, resulting in large-scale forest death in the main planting region (Zheng *et al.*, 2013). Therefore, improving the quality and productivity of *P. yunnanensis* plantation and realizing coordinated and sustainable development of its ecological functions have become important issues for the Yunnan Forestry that requires urgent solution.

Numerous *P. yunnanensis* mixed plantations have been planted at the central region of Yunnan Province in recent years to solve the serious ecological problems in pure *P. yunnanensis* plantation. Various excellent broad-leaved commercial tree species, such as *Alnus nepalensis* (the nitrogen fixation pioneer of *Betulaceae*), *Quercus acutissima* (excellent broad-leaved pioneer commercial tree species of *Fagaceae*), and *Cyclobalanopsis glaucoides* (dominant tree species in subtropical evergreen broad-leaved forest) have been planted. Studies using these *P. yunnanensis* mixed plantations are expected to improve stand structure, soil nutrients, stand quality, and ecological and economic benefits. Moreover, these mixed plantations are projected to realize high-quality stable afforestation of *P. yunnanensis* (Yin *et al.*, 2011; Chen *et al.*, 2012). Successful mixed forest can promote tree growth, increase biodiversity, improve physicochemical properties of soil, reduce surface runoff and soil loss, and perfect ecological environment of forests, thereby improving the stability and productivity of stands

(Jiang *et al*., 2001; Qin *et al*., 2006; Wang *et al*., 2006; Wang & Wang, 2008; Yang *et al*., 2009; Li *et al*., 2010). Nevertheless, the uniqueness of revegetation and afforestation at the central region of Yunnan Province, synergistic effect of plant growth characteristics, photosynthesis, and soil nutrient in the different *P. yunnanensis* mixed plantations should be discussed. Moreover, photosynthetic physiological characteristics between mixed and pure stands, as well as mixed effect mechanism of associated species and *P. yunnanensis* (e.g., water consumption), should be compared.

Therefore, tree growth characteristics, characteristics of photosynthetic gas exchange, physiological and biochemical resistances, and soil nutrient contents of different stand types were compared and analyzed. Four pure juvenile plantations [evergreen coniferous *P. yunnanensis* plantation (P), deciduous broad-leaved *A. nepalensis* (A) and *Q. acutissima* (Q), and evergreen broad-leaved *C. glaucoides* (C)] and three mixed plantations [*P. yunnanensis–A. nepalensis–Q. acutissima* (PAQ), *P. yunnanensis–A. nepalensis–C. glaucoides* (PCA), and *P. yunnanensis–Q. acutissima–C. glaucoides* (PCQ)] were investigated. Synergy mechanism of the various tree species in the different mixed plantations was elucidated, and the optimum mixed plantation was determined. Stand quality and productivity of *P. yunnanensis* plantation were enhanced, and theoretical scientific support for mixed forest plantation was formulated.

Materials and Methods

Study area: The study area is situated in the Kunming Xishan Forest Farm. The total business area of the Xishan Forest Farm is 4,980 hm^2, including 4,037 hm^2 land area (81.07%). The percentages of forest cover for the forest farm and forest land are 67.12% and 66.44%, respectively, and the total standing timber reserves is 182,400 m^3. The study area has year-long mild weather and annual average temperature of 15°C. The local annual precipitation is 1,035 mm. The study area has long sunshine duration, short frost season, and typical monsoon climatic features of subtropical plateau mountains (Wang *et al*., 2014; Chen *et al*., 2015). The study area is approximately 2,000 m above sea level. Local temperature varies between −6.2°C and 31.6°C, with an annual average temperature of 14.8°C. Annual average precipitation and annual maximum precipitation are 900 and 1,172.1 mm, respectively. The annual frost-free season lasts for 240 days, and the annual sunshine hours reach 2,291.2 h. Soils in the study area are red earth.

Research methods: Three types of mixed stands (PCA, PCQ, and PAQ) were constructed (Table 1). Plantations of P, A, Q, and C were used as control groups. These seven plantations were constructed in independent blocks. Test seedlings were cultivated in the Kunming Xishan Forest Farm and ensured to satisfy the I-level standard before the seedlings were planted on the mountains. Afforestation started in September 2012. The planting spacing was set to 1.5 m×2 m, and mixed stands by single tree were adopted in the mixed plantations (Fig. 1). Two rows of isolation belts were built between two blocks using *Ligustrum quihoui* to avoid border effect.

Investigation of growth indices: All juvenile trees in the study area were individually measured from September 2013 to June 2014. Tree height and basal diameter (i.e. tree diameter at base height) were measured using a steel tape and electronic vernier caliper, respectively. Measurement results were used to calculate mean tree height and mean ground diameter. Growth rates of tree height and ground diameter of all target tree species were statistically analyzed.

Gas exchange measurement: Nine standard samples based on individual measurements were chosen from each tree species in the seven stand types. Thus, a total of 13×9=117 standard samples were collected. On sunny days during the mid-to-late May 2014, the parameters of photosynthetic gas exchange, namely, net photosynthetic rate (Pn), transpiration rate (Tr), and intercellular CO_2 concentration (Ci) were tested with the 3^{rd}–5^{th} healthy mature leaves in front of the southward branch of the mid-to-up part of the testing samples using a portable CO_2/H_2O analysis system (Li-Cor 6400; Li-Cor Inc., Lincoln, NE, USA). The parameters were measured in situ from 9:00 A.M.–11:00 A.M. Transient water use efficiency (WUE) was calculated as Pn/Tr, and transient carboxylation efficiency (CE) was calculated as Pn/Ci (Zheng *et al*., 2011).

Table 1. Tree species of the different stand types in the study site.

Types	*Pinus yunnanensis* Franch./ tree	*Alnus nepalensis*/ tree	*Quercus acutissima*/ tree	*Cyclobalanopsis glaucoides*/ tree	Total/ tree
PCA	676	675	/	675	2026
PCQ	630	/	631	630	1891
PAQ	726	726	728	/	2180
Pure *Pinus yunnanensis* Franch. plantation (P)	456	/	/	/	456
Pure *Alnus nepalensis* plantation (A)	/	212	/	/	212
Pure *Quercus acutissima* plantation (Q)	/	/	207	/	207
Pure *Cyclobalanopsis glaucoides* plantation (C)	/	/	/	342	342

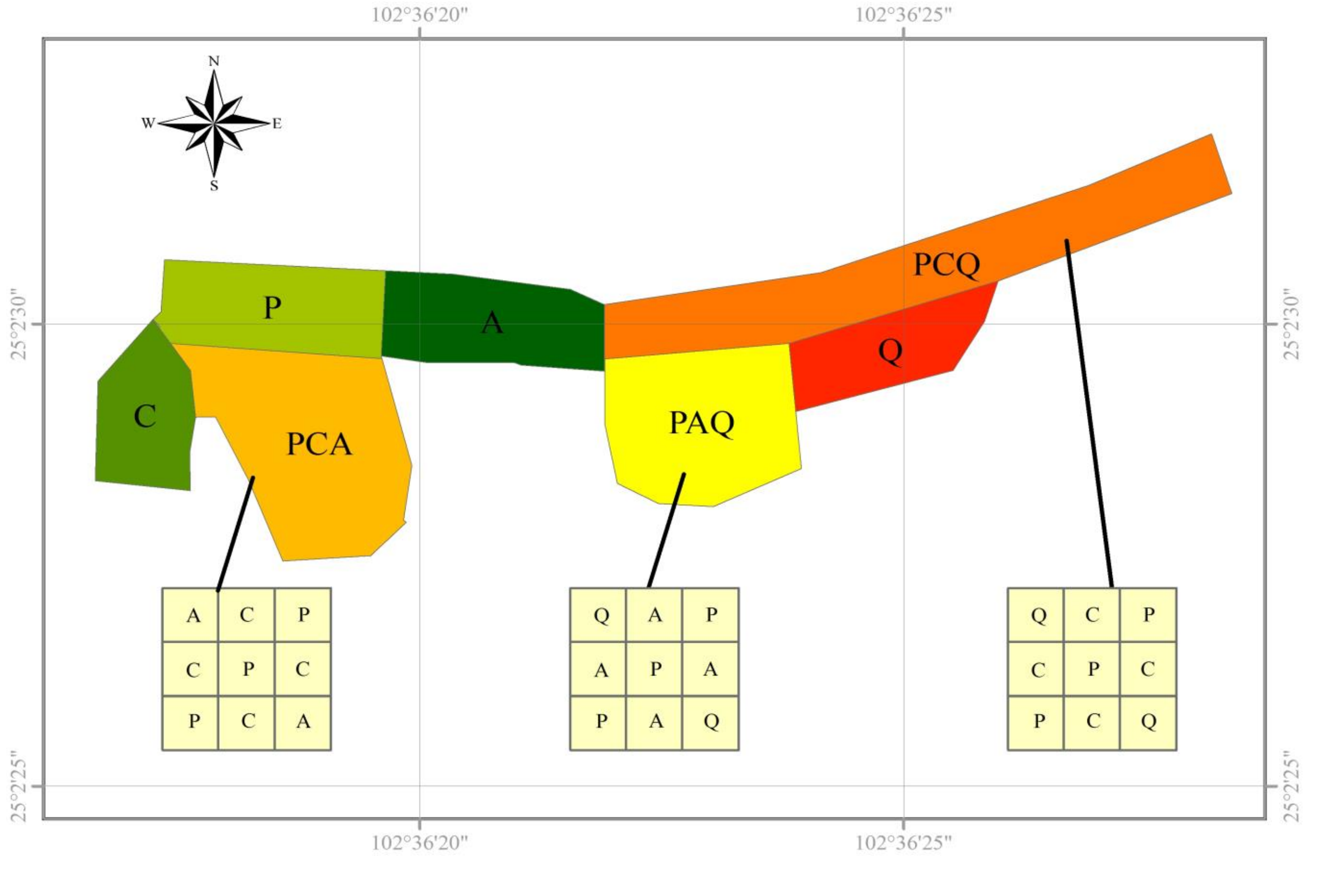

Fig. 1. Study area and block design
(P: *Pinus yunnanensis* Franch.; A: *Alnus nepalensis*; C: *Cyclobalanopsis glaucoides*; Q: *Quercus acutissima*)

Biochemical index test: Three leaves were collected from each sample and put into a curling immediately after the gas exchange measurement. The curling was carried back to the laboratory and kept in an ultra-low-temperature freezer. Soluble sugar (SS) content was tested by sulfuric acid-anthrone colorimetry. Malondialdehyde (MDA) content was tested by thiobarbituric acid chromatometry, and superoxide dismutase (SOD) activity was measured with NBT llumination method (Gao, 2006). Each index was measured thrice.

Soil nutrient test: Two representative fixed sample plots (10 m×10 m) were set in every stand type from September 2013 to June 2014. Mixed soil samples (0–20 cm) were collected from five points (determined diagonally) in sample plots to test eight conventional soil indices, namely, pH, organic matter, total nitrogen (TN), total phosphorus (TP), total potassium (TK), hydrolyzable nitrogen, available phosphorus, and available potassium.

Statistical analysis: Statistical analysis was performed using Excel 2003 and SPSS 13.0 software. Duncan's test in multiple comparison analysis was employed to analyze the significant difference, and different lowercases represent significant difference at $p<0.05$ level.

Results

Growth characteristics of juvenile plantations with different stand types: Significant differences were found in the growth rates of tree height and ground diameter among the different plantations (Table 2). Growth rate of tree height of *P. yunnanensis* was higher in PAQ than in P, but growth rate of tree height was slightly lower in PCA and PCQ than in P. Growth rate of ground diameter of *P. yunnanensis* was much higher in PCA than in P, and the ground diameter growth rate in PAQ was slightly higher. Growth rates of tree height and ground diameter of *A. nepalensis* were quite low than those in A. Mixed plantations promoted the growth of tree height and ground diameter of *Q. acutissima*. Growth rate of ground diameter of *Q. acutissima* was significantly higher in PAQ than in Q. Growth rates of tree height and ground diameter of *C. glaucoides* were slightly higher in PCQ than in C, but those in PCA were significantly lower. Hence, PAQ remarkably promoted the growth of tree height and ground diameter of *P. yunnanensis* and *Q. acutissima*. *A. nepalensis* grew quicker in A than in the other stand types. PCQ slightly improved the growth of *C. glaucoides*.

For the tree species in the three mixed plantations, the growth rates of tree height and ground diameter of *A. nepalensis* were far higher in PAQ than those of the other tree species, whereas *P. yunnanensis*, *Q. acutissima*, and *C. glaucoides* in PCA and PCQ showed similar growth rates. Hence, *A. nepalensis* grew quicker than *P. yunnanensis*, *Q. acutissima*, and *C. glaucoides* during the juvenile stage, and PAQ contributed more balanced growth promotion of the different species compared with PCA and PCQ.

Table 2. Growth characteristics of juvenile plantations with different stand types.

Types	Species	2013		2014		Growth rates	
		Tree height/ m	Ground diameter/ cm	Tree height/ m	Ground diameter/ cm	Tree height/ %	Ground diameter/ %
P	*Pinus yunnanensis* Franch.	0.82 ± 0.21	2.43 ± 0.54	1.12 ± 0.27	2.94 ± 0.77	36.59cd	20.99e
A	*Alnus nepalensis*	0.51 ± 0.32	0.87 ± 0.42	1.14 ± 0.72	2.67 ± 0.80	123.53a	206.90a
Q	*Quercus acutissima*	0.43 ± 0.22	0.38 ± 0.30	0.53 ± 0.36	0.48 ± 0.41	23.26d	26.32de
C	*Cyclobalanopsis glaucoides*	0.48 ± 0.23	0.83 ± 0.45	0.62 ± 0.31	1.17 ± 0.61	29.17cd	40.96d
PAQ	*Pinus yunnanensis* Franch.	0.83 ± 0.23	2.65 ± 0.74	1.19 ± 0.29	3.48 ± 0.81	43.37c	31.32de
	Alnus nepalensis	0.49 ± 0.31	0.78 ± 0.51	0.79 ± 0.54	1.88 ± 1.21	61.22b	141.03b
	Quercus acutissima	0.45 ± 0.19	0.43 ± 0.31	0.56 ± 0.21	0.76 ± 0.44	24.44d	76.74c
PCA	*Pinus yunnanensis* Franch.	0.71 ± 0.29	2.33 ± 0.61	0.90 ± 0.29	3.23 ± 0.82	26.76cd	38.63d
	Alnus nepalensis	0.43 ± 0.25	1.06 ± 0.53	0.53 ± 0.35	1.66 ± 0.97	23.26d	56.60cd
	Cyclobalanopsis glaucoides	0.40 ± 0.18	0.88 ± 0.46	0.46 ± 0.26	1.08 ± 0.57	15.00e	22.73e
PCQ	*Pinus yunnanensis* Franch.	0.83 ± 0.24	2.48 ± 0.63	1.00 ± 0.34	2.99 ± 0.84	20.48d	20.56e
	Quercus acutissima	0.36 ± 0.19	0.57 ± 0.34	0.47 ± 0.28	0.77 ± 0.50	30.56cd	35.09d
	Cyclobalanopsis glaucoides	0.62 ± 0.26	0.86 ± 0.44	0.82 ± 0.35	1.25 ± 0.56	32.26cd	45.35d

Different small letters in the same column indicate the significant difference among different stand types at 0.05 level ($p<0.05$)
The same as below

Table 3. Characteristics of the photosynthetic gas exchange of juvenile plantations with different stand types.

Types	Species	Pn/ (μmol m^{-2} s^{-1})	Tr/ (mmol m^{-2} s^{-1})	WUE/ (μmol $mmol^{-1}$)	CE/ (mol m^{-2} s^{-1})
P	*Pinus yunnanensis* Franch.	6.90 ± 0.55cd	2.62 ± 0.14c	2.71 ± 0.27c	0.034 ± 0.004c
A	*Alnus nepalensis*	9.99 ± 0.52c	3.29 ± 0.13c	3.05 ± 0.14bc	0.074 ± 0.006b
Q	*Quercus acutissima*	6.21 ± 0.72cd	2.65 ± 0.21c	2.31 ± 0.15c	0.023 ± 0.003c
C	*Cyclobalanopsis glaucoides*	6.22 ± 0.71cd	2.80 ± 0.23c	2.22 ± 0.19c	0.039 ± 0.006c
PAQ	*Pinus yunnanensis* Franch.	31.43 ± 6.29a	9.84 ± 1.07a	3.42 ± 0.20bc	0.210 ± 0.041a
	Alnus nepalensis	10.56 ± 0.41c	3.03 ± 0.19c	3.54 ± 0.14bc	0.080 ± 0.007b
	Quercus acutissima	5.34 ± 0.69cd	1.56 ± 0.32cd	4.25 ± 0.52b	0.019 ± 0.002cd
PCA	*Pinus yunnanensis* Franch.	30.68 ± 4.08a	8.18 ± 0.69ab	3.69 ± 0.38bc	0.181 ± 0.029a
	Alnus nepalensis	10.52 ± 0.64c	2.85 ± 0.10c	3.68 ± 0.18bc	0.091 ± 0.017b
	Cyclobalanopsis glaucoides	5.18 ± 1.55cd	1.43 ± 0.19cd	3.12 ± 0.55bc	0.028 ± 0.008c
PCQ	*Pinus yunnanensis* Franch.	17.95 ± 3.67b	6.30 ± 1.03b	5.64 ± 0.94a	0.104 ± 0.022b
	Quercus acutissima	6.13 ± 1.02cd	1.29 ± 0.23cd	5.04 ± 0.36ab	0.030 ± 0.006c
	Cyclobalanopsis glaucoides	2.26 ± 0.25d	1.18 ± 0.21cd	2.40 ± 0.43c	0.009 ± 0.001cd

Characteristics of photosynthetic gas exchange of juvenile plantations with different stand types: Juvenile plantations with different stand types showed significant differences in Pn, Tr, WUE, and CE (Table 3). Pn, Tr, and CE of *P. yunnanensis* in PAQ, PCA, and PCQ were significantly higher than those in P, that is, PAQ>PCA>PCQ. WUE of *P. yunnanensis* was far higher in PCQ than in P, whereas PAQ and PCA had slightly higher WUEs. No significant difference was found in the Pn, Tr, WUE, and CE of *A. nepalensis* among PAQ, PCA, and A. *Q. acutissima* in PAQ and PCQ were similar to those in Q, but with much higher WUE. Pn, Tr, and CE of *C. glaucoides* were slightly lower in PCA and PCQ than in C, but WUE was slightly higher. Hence, PAQ and PCA significantly increased Pn, Tr, and CE of *P. yunnanensis*, and PCQ more remarkably increased WUE of *P. yunnanensis*. Far higher WUE of *Q. acutissima* was achieved in PAQ and PCQ. Mixed plantations had little impacts on the characteristics of the photosynthetic gas exchange of *A. nepalensis* and *C. glaucoides*.

Thus, Pn, Tr, and CE of *P. yunnanensis* in all three mixed plantations were higher than those of other species, but WUE was similar with those of other species. Therefore, mixed plantations significantly improved Pn and Tr of juvenile *P. yunnanensis* but could slightly increase its WUE.

Physiological and biochemical resistance of juvenile plantations with different stand types: Juvenile plantations with different stand types presented significant differences in SS content, MDA content, and SOD activity (Table 4). SS of *P. yunnanensis* in PAQ and PCA were 48.65%–71.64% higher compared with that in P, but SS in PCQ was only 6.31% higher. MDA of *P. yunnanensis* was little lower in PAQ, PCA, and PCQ than in P. SOD activity of *P. yunnanensis* was 28.38% higher in PCA than in P, but only 12.16%–17.57% higher in PAQ and PCQ. SS and SOD activity of *A. nepalensis* were slightly higher in PAQ and PCA than in A, whereas MDA was slightly lower. SS and SOD activity of *Q. acutissima* were lower in PAQ and PCQ than in Q. SOD activity of *Q. acutissima* in PAQ was 37.09% lower than in Q. PAQ and PCQ, especially PAQ (51.97% higher) achieved higher MDA content of *Q. acutissima* than Q. Compared with C, PCA and PCQ showed lower SS contents and SOD activities of *C. glaucoides*, but higher MDA contents. PCQ presented 28.82% lower SOD activity and 44.74% higher MDA content. Therefore, PAQ and PCA significantly increased SS content of *P. yunnanensis*, whereas PCA showed a significant increase in SOD activity of *P. yunnanensis*. SS, MDA, and SOD activities of *A. nepalensis* in A and mixed plantations were similar. Mixed plantations increased MDA of *Q. acutissima* and *C. glaucoides*, but reduced their SOD activity and slightly influenced SS.

Table 4. Physiological and biochemical resistances of juvenile plantations with different stand types.

Types	Species	SS/(U g^{-1})	MDA/(mmol g^{-1})	SOD/(U g^{-1})
P	*Pinus yunnanensis* Franch.	27.75 ± 1.60d	15.85 ± 0.92b	231.25 ± 13.35b
A	*Alnus nepalensis*	77.38 ± 4.47ab	6.18 ± 0.36cd	275.00 ± 15.88ab
Q	*Quercus acutissima*	54.38 ± 3.14b	11.66 ± 0.67c	193.75 ± 11.19c
C	*Cyclobalanopsis glaucoides*	41.75 ± 2.41bc	13.97 ± 0.81bc	184.38 ± 10.64c
PAQ	*Pinus yunnanensis* Franch.	47.63 ± 2.75bc	13.89 ± 0.80bc	271.88 ± 15.70ab
	Alnus nepalensis	88.38 ± 5.10a	3.43 ± 0.20d	300.00 ± 17.32a
	Quercus acutissima	49.63 ± 2.87bc	17.72 ± 1.02ab	121.88 ± 7.04d
PCA	*Pinus yunnanensis* Franch.	41.25 ± 2.38bc	13.68 ± 0.79bc	296.88 ± 17.14a
	Alnus nepalensis	89.75 ± 5.18a	3.10 ± 0.18d	306.25 ± 17.68a
	Cyclobalanopsis glaucoides	38.25 ± 2.21c	15.75 ± 0.91b	159.38 ± 9.20c
PCQ	*Pinus yunnanensis* Franch.	29.50 ± 1.70d	14.55 ± 0.84bc	259.38 ± 14.98ab
	Quercus acutissima	45.38 ± 2.62bc	14.40 ± 0.83bc	168.75 ± 9.74c
	Cyclobalanopsis glaucoides	39.25 ± 2.27c	20.22 ± 1.17a	131.25 ± 7.58d

Table 5. Soil nutrient contents of juvenile plantations with different stand types.

Year	Types	pH	Organic matters/ (g kg^{-1})	TN/ (%)	TP/ (%)	TK/ (%)	Hydrolyzable nitrogen/ (mg kg^{-1})	Available phosphorus/ (mg kg^{-1})	Available potassium/ (mg kg^{-1})
2013	P	5.56	11.68	0.06	0.05	1.58	70.00	1.61	37.10
	A	5.99	9.21	0.06	0.03	1.26	42.70	2.45	33.06
	Q	5.74	13.25	0.09	0.04	3.61	82.30	4.34	142.03
	C	5.59	23.57	0.08	0.05	1.12	111.82	5.71	62.32
	PAQ	5.71	14.49	0.08	0.05	0.92	76.90	9.01	53.52
	PCA	5.76	8.31	0.06	0.03	0.72	55.08	3.71	32.64
	PCQ	5.73	23.56	0.11	0.05	1.24	129.92	8.22	63.61
2014	P	5.58	10.42	0.05	0.04	1.45	58.98	1.57	36.34
	A	6.01	10.34	0.06	0.03	1.26	42.70	2.45	33.06
	Q	5.65	15.21	0.10	0.04	3.42	71.28	3.88	82.27
	C	5.41	27.61	0.09	0.05	1.07	35.14	4.41	54.27
	PAQ	5.76	15.27	0.08	0.05	0.98	73.67	8.13	50.13
	PCA	5.86	8.67	0.07	0.03	0.81	52.14	3.43	28.43
	PCQ	5.75	26.24	0.11	0.05	1.25	89.73	7.86	59.88
Rate of change/%	P	0.36b	-10.79c	-16.67c	-20.00b	-8.23d	-15.74b	-2.48ab	-2.05ab
	A	0.33b	12.27a	0.00b	0.00a	0.00bc	0.00a	0.00a	0.00a
	Q	-1.57c	14.79a	11.11a	0.00a	-5.26d	-13.39b	-10.60b	-42.08c
	C	-3.22c	17.14a	12.50a	0.00a	-4.46d	-68.57d	-22.77c	-12.92b
	PAQ	0.88b	5.38b	0.00b	0.00a	6.52b	-4.20ab	-9.77b	-6.33ab
	PCA	1.74a	4.33b	16.67a	0.00a	12.50a	-5.34ab	-7.55b	-12.90b
	PCQ	0.35b	11.38a	0.00b	0.00a	0.81bc	-30.93bc	-4.38ab	-5.86ab

SS, MDA, and SOD activities of the four species in the three mixed plantations were compared. In PAQ and PCA, SS contents and SOD activities of *A. nepalensis* were 78.08%–134.64% and 3.16%–146.14% higher than other species, respectively, whereas its MDA contents were 75.31%–80.64% lower. SOD activity of *P. yunnanensis* was 53.71%–123.07% higher than those of *Q. acutissima* and *C. glaucoides*. Hence, *A. nepalensis* achieved higher physiological and biochemical resistance than the other three species in the mixed plantations.

Changes in the soil nutrient of juvenile plantations with different stand types: The study area has low levels of soil nutrients according to the grading standard of soil nutrients. Juvenile plantations with different stand types presented significant differences in the rates of change of soil nutrients (Table 5). Soil organic matters, TNs, TPs, and TKs of P decreased sharply from September 2013 to June 2014, which was the 3rd growth cycle of *P. yunnanensis*, *A. nepalensis*, *Q. acutissima*, and *C. glaucoides*. Soil organic matters of A increased significantly, but TN, TP, TK, hydrolyzable nitrogen, available phosphorus, and available potassium remained same. Soil organic matter and TN of Q considerably increased, TP was unchanged, and pH, TK, and available potassium remarkably declined. Soil organic matter and TN of *C. glaucoides* increased dramatically, TP remained same, and pH, TK, hydrolyzable nitrogen, and available phosphorus decreased significantly. Soil organic matter and TP of PAQ remained the same, but pH, TN, and TK of PCA increased greatly, and TP was unchanged. Soil organic matter of PCQ increased dramatically, TN and TP were same, and hydrolyzable nitrogen evidently declined.

The absorption, return, and transport law of soil nutrients in the different stand types was relatively complex. Generally, soil organics, TN, TP, and TK of P decreased gradually, while those of A, Q, C, PAQ, PCA, and PCQ remained at stable levels and increased gradually. Hydrolyzable nitrogen, available phosphorus, and available potassium of all stand types, except for A, declined to different extents and presented distinct variation laws.

Discussion

Effects of different stand types on the growth characteristics of juvenile plantations: Previous studies have confirmed that the average mingling degree of natural *P. yunnanensis* forests at the central region of Yunnan Province was only 0.034. Most stands were pure *P. yunnanensis* forests, associated with few arbor species. Although stands have relatively uniform size, fierce competition exists among the different diameter levels of *P. yunnanensis* forests. Reasonable mixed plantations are desired to improve space structure and quality of stands (Yuan *et al.*, 2013). *P. yunnanensis* mixed forests are superior to pure *P. yunnanensis* forest in term of species composition, vegetation diversity, stand ecological environment, and stand water retaining capacity (Dong *et al.*, 2007; Wang & Duan, 2010). In this study, under different mixed planting patterns, growth rate of tree height of *P. yunnanensis* was higher in PAQ than in P, but growth rate of tree height in PCA and PCQ was slightly lower than in P. Ground diameter growth rate of *P. yunnanensis* was significantly higher in PCA than in P, and the growth rate of ground diameter in PAQ was slightly higher. Growth rates of tree height and ground diameter and photosynthesis of *Q. acutissima* were lower than those of *P. yunnanensis* and *A. nepalensis* in all seven studied stands, but its WUE in mixed plantations remained at high level. Juvenile *Q. acutissima* stores more dry matters in the root, thus the biomass of its underground part accounts for a big proportion, and assimilated nutrients are mainly for root system growth (Xu *et al.*, 2010). *A. nepalensis* grew more quickly than *P. yunnanensis*, *Q. acutissima*, and *C. glaucoides* during the juvenile stage, and PAQ contributed more balanced growth promotion of different species compared with PCA and PCQ.

Effects of different stand types on photosynthetic physiological responses of juvenile plantations: Qin & Shangguan, (2010) analyzed variations in N and P contents, chlorophyll content, parameter of photosynthetic gas exchange, and chlorophyll fluorescence parameters of leaves of 1-year-old pure *Ulmus pumila* plantation, pure *Robinia pseudoacacia* plantation, and their mixed plantation. They found that the *U. pumila–R. pseudoacacia* mixed plantation achieved higher Pn, Tr, stomatal conductance, and PSII electron transfer quantum efficiency than the pure plantations. In the *U. pumila–R. pseudoacacia* mixed plantation, nitrogen fixation effect of *R. pseudoacacia* increased nitrogen content in the soil, which could increase N absorption and utilization of *U. pumila*. Therefore, *U. pumila–R. pseudoacacia* mixed plantation could significantly increase nutrient content and photosynthetic capacity of plant leaves. The current study showed, fierce competition of soil nutrients and water was found in P, and this process was manifested by poor growth features, photosynthesis, water utilization, and biochemical resistance. PAQ could remarkably increase growth rates of tree height and ground diameter of *P. yunnanensis*, Pn, Tr, CE, and SS content of leaves. Compared with P, PCA achieved far higher growth rate of ground diameter, Pn, Tr, CE, SS content, and SOD activity of *P. yunnanensis*. This phenomenon is primarily due to the fact that *A. nepalensis* or other associated broad-leaf species not only has significant rhizobium nitrogen fixation (Sharma *et al.*, 1998; Zuo *et al.*, 2009; Chen *et al.*, 2010) or allelopathic effect (Wang *et al.*, 2012) for *P. yunnanensis* but can also increase soil nutrient content and proportions in mixed plantations and facilitate *P. yunnanensis* to absorb and use soil N and other nutrients. Hence, the mixed plantation of *P. yunnanensis* and *A. nepalensis* could significantly enhance growth and photosynthetic physiological characteristics of juvenile *P. yunnanensis*. However, this mixed plantation could slightly affect the characteristics of photosynthetic gas exchange, as well as physiological and biochemical resistance, of juvenile *A. nepalensis*. This phenomenon may have been caused by the following conditions. *A. nepalensis* seedlings have big size and grow quickly, possessing great advantages in space competition with *P. yunnanensis* seedlings. *A. nepalensis* has few root nodules and weaker nitrogen fixation during the seedling stage, slightly promoting nutrient absorption of *P. yunnanensis* seedlings. Moreover, the growth and photosynthesis of *P. yunnanensis* on infertile soils will be inhibited significantly, because this species has high demands for abundant N. By contrast, the nitrogen fixing root nodules of *A. nepalensis* can make full use of N_2 in air on infertile soils to quickly improve soil quality (He *et al.*, 2007; Li *et al.*, 2008). Consequently, this process can increase N content of *P. yunnanensis*, facilitate *P. yunnanensis* growth, and accelerate biocycle of soil nutrients, especially N in mixed plantations. Among the three mixed stand types, *P. yunnanensis* had significantly higher Pn, Tr, and CE than the other tree species in PAQ, PCA, and PCQ. Hence, different mixed planting patterns significantly enhanced photosynthetic efficiency and transpiration intensity of *P. yunnanensis* saplings.

Effects of different stand types on the changes in soil nutrient of juvenile plantations: Considering small canopy density and adequate sunlight in stands, *C. glaucoides* is not a well-associated broad-leaf species for mixed plantation of *P. yunnanensis* during early stages. Given the soil infertility in *P. yunnanensis* forest, PAQ is an optimal mixed plantation, which is good for increasing growth rate, Pn, and WUE, as well as for recovering soil fertility. Gao *et al.*, (2014) explored the accumulation, distribution, and circulation characteristics of the main nutrient elements in 10-year-old pure *Azadirachta Indica* plantation, pure *Acacia mangium* plantation, and their mixed plantation in the dry hot valley in Yunnan. The results demonstrated that mixed plantation of *A. Indica* and *A. mangium* was conducive to maintain and improve soil fertility and increase soil nutrient supply capacity. Therefore, mixed plantation of nitrogen-fixing and non-nitrogen-fixing species can facilitate synergistic effect of photosynthesis, nutrients, and moisture of plants. Relations of photosynthetic features and nutrient absorption and utilization among *P. yunnanensis*, *A. nepalensis*, *Q. acutissima,* and *C. glaucoides* are relatively complex in the *P. yunnanensis* plantation with natural infertile soil. The interactive regulation and internal variation mechanism of these characteristics in mixed plantations need further studies. Yang *et al.* (2011) tested the nutrient mass fraction in the soil, leaves, and root system of pure *P. yunnanensis* forest, pure *A. nepalensis* forest, and *P. yunnanensis–A. nepalensis* mixed forest. The results showed that, compared with pure forests, the *P. yunnanensis–A. nepalensis* mixed forest had higher mass fraction of nutrients (e.g., N, P, and K, which are special effective nutrients) in the soil, root systems of both species, and *P. yunnanensis* leaves. In the current study, the soil nutrients of seven stand types, namely, P, A, Q, C, PAQ, PCA, and PCQ were investigated. P consumed more soil organic matter, TN, and TP, while PAQ, PCA, and PCQ increased soil organic matter, TN, TP, and TK. Moreover, A maintained high TN, TP, and TK contents, especially hydrolyzable nitrogen, available phosphorus, and available potassium, indicating outstanding nitrogen fixation and soil fertilization.

Conclusions

1. Significant differences were found in the growth rates of tree height and ground diameter of juvenile plantations under different mixed planting patterns. Growth rate of tree height of *P. yunnanensis* was slightly higher in PAQ than in P, while growth rate of ground diameter of *P. yunnanensis* was markedly higher in PCA than in P. Mixed plantations promoted the growth of tree height and ground diameter of *Q. acutissima*. Growth rates of tree height and ground diameter of *A. nepalensis* in PAQ were significantly higher than those of other tree species, which was mainly due to the faster growth of *A. nepalensis* than *P. yunnanensis*, *Q. acutissima*, and *C. glaucoides* during the juvenile stage. PAQ contributed more balanced growth promotion of the different species compared with PCA and PCQ.
2. Pure *P. yunnanensis* juvenile plantation (P) consumed more soil organic matter, TN, TP, and TK. Thus, this species showed poorer growth characteristics, photosynthetic capability, water utilization, and biochemical resistance in infertile soil, as manifested by nutrition and water competition. Mixed plantations with different stand types could significantly promote growth and photosynthetic physiological characteristics of young *P. yunnanensis* by increasing soil organic matter and TK content, as well as by maintaining high TN and TP contents. Specifically, PAQ increased growth rates of tree height and ground diameter of *P. yunnanensis*, and the Pn, Tr, Ce, and SS content of its leaves. PCA increased the growth rate of ground diameter, Pn, Tr, CE, SS content, and SOD activity. PCQ significantly improved the WUE of *P. yunnanensis*.
3. Based on the high-level soil organic matter, TN, TP, and TK, especially hydrolyzable nitrogen, available phosphorus, and available potassium, A had high Pn, Tr, WUE, CE, SS content, and SOD activity, but lower MDA content. These characteristics resulted in high growth rate of the tree height and ground diameter of *A. nepalensis*. However, juvenile plantations with different stand types slightly influenced the characteristics of the photosynthetic gas exchange and physiological and biochemical resistance of *A. nepalensis*.
4. Juvenile plantations with different stand types slightly influenced growth features, Pn, Tr, and WUE of young *C. glaucoides*. Moreover, they inhibited the osmotic adjustment system and SOD activity of *C. glaucoides* to a certain extent, indicating that *C. glaucoides* is not a well- associated broad-leaf species of *P. yunnanensis* juvenile mixed plantations.

These results suggest that PAQ is an optimal plantation considering the infertile soil in *P. yunnanensis* forest land. This mixed plantation is good for increasing growth rate, Pn, and WUE, as well as for recovering soil fertility.

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