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RESEARCH ARTICLE

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Nutrient cycle of planted forest of *Pinus tabulaeformis* in the Miyun Reservoir Watershed, Beijing

Abstract We studied the nutrient cycle of a planted forest of *Pinus tabulaeformis* in the Miyun Reservoir Watershed, Beijing. Results show that the total biomass of *P. tabulaeformis* stands at age 29 in the experimental area is 92627 kg/hm^2, and the total nutrient store is 695.17 kg/hm^2 including nitrogen (N), phosphorus (P), kalium (K), calium (Ca) and magnesium (Mg). The sequence of their contents in different organs was given as follows: needle > branch > trunk > root. The annual amount of 85.37 kg/hm^2 of five nutrient elements were assimilated by *P. tabulaeformis*, about 0.34% of the total store in soil, and 3.30% of available nutrient store in soil depth from 0 to 30 cm. The nutrient annual retention is 35.92 kg/hm^2, annual returning 49.46 kg/hm^2, the rain input 26.04 kg/hm^2 to the five nutrient elements. The parameter absorption coefficient, utilization coefficient, cycle coefficient and turnover period were cited to describe the nutrient elements cycle characteristic of the planted forest ecosystem of *P. tabulaeformis*. The absorption coefficient is the ratio of plant nutrient element content to soil nutrient element content, and its sequence of five nutrient elements was given as follows: N > P > K > Ca > Mg. Utilization coefficient is the ratio of the nutrient element annual uptake amount to the nutrient element storage in standing crops, and its sequence of five nutrient elements was: Mg > K > P > N > Ca. The big utilization coefficient means more nutrients stored in the plant. The cycle coefficient is the ratio of the nutrient element annual return amount to the nutrient element annual uptake amount, its sequence: Ca > N > P > K > Mg. Turnover period is the ratio of the nutrient storage in the crops to the annual returning, its sequence: Mg > K > P > N > Ca.

Keywords Miyun Reservoir, planted forest of *P. tabulaeformis*, nutrient elements, nutrient cycle

1 Introduction

The temperate coniferous forest of Chinese pine (*Pinus tabulaeformis*) is one of the most widely distributed plant communities in China. The northern boundary of its distribution is the mountainous areas in northern China, Daqing Mountain, Wula Mountain in the Inner Mongolia Autonomous Region and the west Helan Mountains. Towards the east is Wudan, north of Chifeng. The southwest boundary is at the Qinba Mountains, 1000–1600 m elevation, in Sichuan, Shanxi and Hubei provinces, while in the south the Chinese pine forests are replaced by Masson pine (*P. massoniana*) forests. Chinese pines are distributed in the Qinling Mountains at elevations between 1400–2000 m and in the low hills, east to the Huaihe River Basin. Chinese pines are found on all the mountains and hills in the warm temperate deciduous broad-leaved forest region, except for the Qianshan Mountains at the southeast of the Liaodong Peninsula and the Shandong Peninsula which are covered with Akamatsu (*P. densiflora*) forests. The China pine therefore can be considered the most representative of northern China's coniferous forest types (Wu, 1980).

A large number of Chinese pine water conservation plantations are located in the Miyun Reservoir Watershed, which accounts for the largest area of plantations and is the second most common species after the Mongolian oak. There are 42598 hm^2 Chinese pine forests in the watershed, which takes up 18.1% of the total water conservation forest area, 17.4% of the total volume with 10.95 m^3/hm^2

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(Yu et al., 2001). Chinese pine is very adaptable, stress resistant, has absorption ability and a root system, with good soil and water conservation and soil improvement traits and is important for water conservation in northern China. Due to their broad regional distribution and diverse types, the nutrient content and nutrient cycle characteristics of these pines show distinct spatial differences and variety; in particular, the spatial variation of the characteristics of the nutrient cycle appear representative (Zhang and Shangguan, 2006). In addition to its excellent performance, spatial differentiation is also manifested at some local levels due to habitat and other external factors (Yan et al., 1993). The study of nutrient cycling of Chinese pines reveals not only the material circulation mechanism of the ecosystem, but it is also important for guiding forest production, for the regulation and improvement of the environment for tree growth, for the improvement in the nutrient utilization and to maximize productivity (Liu, 2001a; Wang, 2002).We studied the major nutrient biology cycle of the Chinese pine water conservation areas in the Miyun Reservoir Watershed Beijing and discuss its rules of circulation, with the aim to provide a theoretical basis for the management of the water conservation plantations.

2 Survey and methods

2.1 Study area survey

The study area is located upstream of the Miyun Reservoir in Miyun County, Beijing between 116°31′–117°31′E and 40°13′–40°48′N. The climate type is a warm temperate, semi-humid, monsoon climate, with an average annual temperature of 10.5°C. The coldest temperature ever recorded was −18°C and the highest 38°C. The frost-free period is 176 d, the average precipitation over a large number of years is 669 mm and is mainly concentrated from June to August. It is also the hottest period of the year. The zonal vegetation is that of a deciduous broad-leaved forest of a warm temperate zone; its present vegetation is dominated mainly by shrubs. Chinese pine (*P. tabulaeformis*) and black locust (*Robinia pseudoacacia*) plantations account for the most of the artificial vegetation. The soils are cinnamon and fluvo-aquatic soils.

2.2 Method

In our sample plot layout we selected five sample plots in the Chinese pine plantations in Miyun County, each of which covers $20\times30\ m^2$. Then we made single tree measurements and calculated the average standard tree to obtain its biomass. Simultaneously, we collected litter. Table 1 shows the site conditions of the sample plots and stand characteristics.

Analytical method We measured the concentration of five kinds of major nutritional elements in Chinese pine organs, as well as soil and the meteoric water during the major rainfall period, from June to September. Concrete measurements are as follows.

Collection of plant samples We selected one average standard tree in each sample plot for analysis to obtain biomass information of Chinese pine and from each organ sample. We removed the green from the samples at 105°C for a short time, drying at 60–70°C, grinding and bottling, then reserved the material after labeling.

Plant sample analysis Total N was measured by the sulfate-perchloric acid digestion-indophenol blue method; total P by the nitrate-perchloric acid digestion-molybdenum-antimony anti-spectrophotometric method; K by nitrate-perchloric acid digestion-flame photometry and Ca and Mg by nitrate-perchloric acid digestion-atomic absorption spectrophotometry (AAS) (Dong et al., 1996).

Soil sample collection Soil samples were obtained according to the ‘S’ type layout, at five sampling sites to determine the soil profile; at two levels, i.e., at 0–15 cm and 15–30 cm depth. We took 1000 g samples at each site back to the laboratory for soil chemical determination. The bulk soil density was tested by a cutting ring method, and repeated 4–5 times at each test site.

Soil samples analysis method The determination of the total N was performed by a semimicro-Kjeldahl method; the ammonium N by potassium chloride extraction-indophenol blue colorimetry. The total P was determined by a hydrofluoric-perchloric acid digestion-molybdenum-antimony anti-colorimetry method and available P by sodium bicarbonate extraction-molybdenum-antimony anti-colorimetry method. We determined total K by hydrofluoric-perchloric acid digestion-flame photometry and available K by ammonium acetate excavation-flame photometry. Total Ca and Mg were found by sodium

Table 1 Basic situation of *P. tabulaeformis* plantation plots

no.	density /(tree·hm^{-2})	age/year	canopy density	aspect	slope/°	slope position	slope types	soil thickness/cm	diameter /cm	tree height /m	litter thickness/cm
01	1850	32	0.83	NE	30	middle	straight	40	11.83	7.2	12
02	2025	32	0.86	NE	25	middle	straight	40	11.51	7.9	10
03	1125	25	0.68	N	25	middle	convex	25	12.59	6.4	8
04	1175	30	0.68	NW	27	mid-upper	convex	22	12.46	6.3	9
05	2355	26	0.90	NW	26	middle-lower	convex	35	10.07	5.8	10

carbonate alkali fusion-HCl extraction-atomic absorption spectrophotometry and the exchangeable Ca and Mg by ammonium acetate exchange (AAS) (Liu et al., 1996).

Meteoric water sample acquisition We collected meteoric water samples at the experiment station of the water conservation forest in Beizhuang Town, Miyun County and then measured the concentration of each nutrient immediately after each precipitation (Liu et al., 2001b).

Meteoric water sample analysis Total N was measured by alkaline potassium persulfate digestion-UV spectrophotometry, total P by the ammonium molybdate spectrophotometric method, K by flame spectrometry and Ca and Mg by AAS (Xie et al., 1998).

3 Results and discussion

3.1 Determination of Chinese pine biomass

The average biomass of the various tree organs in the five sample plots was used as the biomass of the organs of Chinese pine trees in the research area and calculated the biomass distribution ratio between different organs. The biomass determination in each sample plot is shown in Table 2. The average biomass of the Chinese pine is 92627 kg/hm^2.

In the stand biomass distribution, the average weight of the five sample plots were 49946 kg/hm^2 (trunk), 17659 kg/hm^2 (branch), 12762 kg/hm^2 (leaf), 12260 kg/hm^2 (root). We then obtained the distribution ratios between trunk, branch, leaf and root (54∶19∶14∶13).

For the leaf biomass, the ratio between the annual leaves and the perennial leaves is 24.18∶73.82 and concluded that, in the Chinese pine trees, the leaf biomass distribution of the needles at different leaf ages were 3086 kg/hm^2 (annual leaves) and 9676 kg/hm^2 (perennial leaves). Given the Chinese pine leaf biomass distribution and the distribution ratios of its organ biomass, we can obtain the average annual growth of Chinese pine trees. The average annual growth of the leaves of Chinese pine trees is 3086 kg/hm^2, that of trunks 1722 kg/hm^2, branches 609 kg/hm^2 and roots 423 kg/hm^2. Hence, the annual growth of a Chinese pine tree is 5840 kg/hm^2.

3.2 Determination of nutrient element concentration in different organs of Chinese pine

Nutrient concentrations in different organs of Chinese pine are shown in Table 3. In different Chinese pine organs, the concentration of the five elements N, P, K, Ca and Mg followed certain rules. The level of concentration of the five elements in the various organs is leaf > branch > trunk; small roots > big root > canopy; the nutrient in the hair root (< 2 mm) is smaller or close to that of leaves. For the concentration of N, P, K and Mg in needles, we found that the highest concentration is in 1-year-old needles; however, the concentration in 2-year-old needles was larger than that of 3-year-old needles, both of which show the same level of decrease. Three-year-old needles have the

Table 2 Biomass distribution in different organs of *P. tabulaeformis* trees

sample plot no.	standard strain dry weight/kg				stand density /(tree·hm^{-2})	biomass dry weight at different organ/(kg·hm^{-2})				sum
	trunk	branch	leaf	root		trunk	branch	leaf	root	
01	29.54	11.27	8.63	4.66	1850	54649	20850	15966	8621	100086
02	30.40	7.56	6.42	6.58	2025	61560	15309	13001	13325	103195
03	37.88	18.37	10.34	13.33	1125	42615	20666	11633	14996	89910
04	27.34	11.21	4.42	7.26	1175	32125	13172	5194	8531	59022
05	24.96	7.77	7.65	6.72	2355	58781	18298	18016	15826	110921
average	30.02	11.24	7.49	7.71	1706	49946	17659	12762	12260	92627

Table 3 Nutrient concentration of different organs of *P. tabulaeformis* trees (unit: %)

item	organ		N	P	K	Ca	Mg
aerial part	leaf	1-year-old	0.95	0.131	0.62	0.42	0.197
		2-year-old	0.89	0.113	0.55	0.70	0.162
		3-year-old	0.86	0.099	0.42	0.63	0.119
	branch		0.49	0.056	0.34	0.18	0.083
	trunk		0.07	0.010	0.11	0.06	0.022
underground part	< 2mm		0.44	0.075	0.80	0.41	0.147
	2–10mm		0.38	0.068	0.32	0.26	0.030
	> 10mm		0.30	0.034	0.26	0.08	0.021
	main root		0.15	0.010	0.19	0.07	0.017

highest Ca concentration, while 1-year-old needles have the lowest concentration and 2-year-old needles are in the middle.

In the discussion of different nutrient elements, we determined that the concentration of N remains the highest among the five nutrients in the aerial part of the needle. The concentration of Ca is almost the same as that of K, as is the case with the concentration of P and Mg.

The order of the concentration of the five elements in 1-year-old needles is N > K > Ca > Mg > P; however, the order of the 2- and 3-year-old needles is N > Ca > K > Mg > P, which is the same order as that of the branches. The order of concentration in the trunk is K > N > Ca > Mg > P, which differs greatly from that of needles and branches. N concentrations rank first in both needles and in branches. Elsewhere, the concentration in the trunk decreases while the order of concentration of Mg and P in the different organs changes little.

3.3 Bio-cycle characteristics of nutrient element in Chinese pine trees

Given the concentration of nutrient element and biomass in various Chinese pine organs, we calculated the amount of storage of the nutrient elements in different organs (Table 4). The total amount of storage of the five nutrient elements in Chinese pine was 695.17 kg/hm^2. For different organs, the storage volume of nutrient elements and their share are as follows: leaves 291.94 kg/hm^2 (41.99%), branches 206.33 kg/hm^2 (29.68%), trunk 110.09 kg/hm^2 (15.84%) and roots 86.81 kg/hm^2 (12.49%). The sequence in the amount of storage of nutrient elements in the different organs is leaf > branch > trunk > root.

Of the amount of storage of nutrient elements, N has the highest amount with 270.61 kg/hm^2, which is 38.93% of the total volume; the 2nd is Ca with 184.32 kg/hm^2 (26.52%); the 3rd is K with 157.24 kg/hm^2 (22.62%); the 4th is Mg with 48.77 kg/hm^2 (7.01%) and the least one is P with 34.22 kg/hm^2 (4.92%). The order of the five nutrient elements is N > Ca > K > Mg > P (Shen et al., 1985) which is a little different from the results: Ca > N > Mg > K > P > Fe > Al by Chen et al. (1987).

Given the annual average growth of various organs in Chinese pine trees and their content of nutrient elements, we can obtain the annual average uptake of nutrient elements (Table 5). Of the annual average uptake, the uptake of needles is the largest of the current year growth and that of the other organs is average. In the five nutrient elements the uptake of needles is maximum, i.e., 83.73% of the total uptake, that of branches 8.33%, trunk 4.44% and roots 3.50%. N has its maximum absorption at 40.70% of total element uptake in the five nutrient elements, P at 5.52%, K at 25.89% Ca at 19.63% and Mg at 8.27%. The uptake order is N > K > Ca > Mg > P, which agrees with the storage of the various elements in Chinese pine trees.

Nutrients in Chinese pine trees return to the soil mainly as litter and rainfall leaching and decayed roots are other forms of return. The amount of nutrients returning to the soil as litter can be accurately determined; however, because of insufficient means, the root dead matter was difficult to measure accurately; as well, the dry deposition in rainfall leaching is not easy either. Moreover, forest ecosystems take up elements from the atmosphere (Bernard et al., 1993), which is even more difficult to determine.

Given the results of our determination, every year the amount of litter which Chinese pine trees transfer to the

Table 4 Nutrient contained in different organs of *P. tabulaeformis* trees (unit: kg·hm^{-2})

element	leaf	branch	trunk	root	sum
N	115.06	86.98	34.31	34.26	270.61
P	14.57	9.91	5.14	4.60	34.22
K	67.46	32.74	28.52	28.52	157.24
Ca	74.51	62.09	31.10	16.63	184.33
Mg	20.34	14.61	11.02	2.80	48.77
sum	291.94	206.33	110.09	86.81	695.17

Table 5 Nutrient uptake in the different organs of *P. tabulaeformis* trees (unit: kg·hm^{-2}·a^{-1})

element	leaf	branch	trunk	root	sum
N	29.38	3.00	1.18	1.18	34.74
P	4.04	0.34	0.18	0.16	4.72
K	19.01	1.13	0.98	0.98	22.10
Ca	12.97	2.14	1.07	0.57	16.75
Mg	6.08	0.50	0.38	0.10	7.06
sum	71.48	7.11	3.79	2.99	85.37

soil is 2318 kg/hm^2, dominated by needle litter (up to 95%). Therefore, when computing the concentration of the nutrient elements in the litter, we calculated the nutrients in the total litter from that in decayed leaves. The total amount of nutrient elements in the litter is 49.45 kg/hm^2, represented as follows: N, P, K, Ca and Mg, accounting for 9.99, 2.30, 9.79, 14.62 and 2.75 kg/hm^2, respectively. The order of elements in the return is N > Ca > K > Mg > P, which agrees with the storage case in the Chinese pine trees.

Nutrient element storage in various organs of Chinese pine trees and the amounts of their return in the litter, are presented in Table 6. The Chinese pine is an evergreen coniferous tree, whose needles are perennial. All exfoliated needles are older than one year; one-year-old needles hardly exfoliate. The amount of litter is smaller than the amount of needles. Nutrient retention is composed partly of current year needles. Although those needles are doomed eventually to exfoliate, nutrient retention does not play a part. From our results, we conclude that N is the element with the largest storage in needles, because of the higher N concentration in needles. As for the total nutrient elements, the retention in needles remained the highest, and then branches, trunk and roots. Nutrient element retention is less than the amount returned.

Biological cycle characteristics of nutrient elements in Chinese pine trees are shown in Table 7 (Lin et al., 1998). From the absorption coefficients, of the five elements N has the maximum value, P takes second place and Mg has the least. Actually, the absorption coefficient reflects the status between soil nutrients and plant absorption. If the absorption coefficient is large, the plant takes up more nutrients and the larger the nutrient element concentration in the soil horizon, and vice versa. The order of the absorption coefficient of different elements from large to small is N > P > K > Ca > Mg. The physical meaning of the utilization coefficient characterizes the annual nutrient storage status in the ecosystem. The larger the utilization coefficient, the larger the nutrient storage in the plant. Nutrient storage depends on the total amount of nutrient elements in the ecosystem. If total storage amount in the system is large, then the utilization coefficient is large and the greater the nutrient element storage in plants. The utilization coefficients among N, P, K and Mg vary little. Ca has the smallest utilization coefficient. The physical meaning of the cycle coefficient represents the degree of return of nutrient elements to the ecosystem. The larger the cycle coefficient, the faster the nutrient elements circulate in the ecosystem. Turnover period represents the time during which some elements finish their cycle in the ecosystem. The time for turnover of the various nutrient elements in Chinese pine trees is more than 10 years. The order of turnover period of the various nutrient elements is Mg > K > P > N > Ca.

The storage of elements in the soil layer (30 cm) in Chinese pine forests are presented in Table 8. Storage of the five nutrient elements in the soil horizon is 203420 kg/hm^2, where that of Mg is the largest, Ca is second and the amount of stored K is third. The relative sum of stored Mg, Ca and K is 96.78% of total element storage. Available storage of the five nutrient elements in the soil horizon is 21042 kg/hm^2. Nutrient storage of these five predominant elements in the soil is much larger than the nutrient elements storage in the Chinese pine trees, which is 695.17 kg/hm^2, 0.34% of total nutrient storage and 3.30% of available

Table 6 Nutrient cycle in *P. tabulaeformis* trees (unit: $kg \cdot hm^{-2} \cdot a^{-1}$)

element	retention					litter return	uptake
	leaf	branch	trunk	root	subtotal		
N	9.39	3.00	1.18	1.18	14.75	19.99	34.74
P	1.74	0.34	0.18	0.16	2.42	2.30	4.72
K	9.21	1.13	0.98	0.98	12.30	9.79	22.09
Ca	–1.65	2.14	1.07	0.57	2.13	14.62	16.75
Mg	3.32	0.50	0.38	0.10	4.30	2.76	7.06
sum	22.02	7.11	3.79	2.99	35.91	49.46	85.37

Table 7 Characteristic parameter of nutrient cycle in *P. tabulaeformis* forest

item	element				
	N	P	K	Ca	Mg
absorption coefficient[a]	0.008406	0.001955	0.000402	0.000240	0.000098
utilization coefficient[b]	0.1284	0.1378	0.1406	0.0909	0.1447
cycle coefficient[c]	0.5753	0.4878	0.4431	0.8723	0.3905
turnover period[d] /year	13.54	14.88	16.06	12.61	17.70

Note: a: absorption coefficient = annual uptake/storage in surface soil (0–30 cm); b: utilization coefficient = annual uptake/storage in standing crop; c: cycle coefficient = annual return/annual uptake; d: turnover period = storage in standing crop/annual return.

Table 8 Nutrient storage in the soil reservoir of a *P. tabulaeformis* forest

item	element	soil layer				sum storage /(kg·hm^{-2})
		0–15 cm		15–30 cm		
		concentration/%	storage/(kg·hm^{-2})	concentration/%	storage/(kg·hm^{-2})	
available nutrient storage	N	0.0025	50.25	0.0021	45.93	96.18
	P	0.0009	18.09	0.0001	2.19	20.28
	K	0.0208	418.08	0.0154	336.80	754.88
	Ca	0.4651	9348.51	0.3968	8678.02	18026.53
	Mg	0.0536	1077.36	0.0488	1067.26	2144.62
sum			10912.29		10130.18	21042.47
total nutrient storage in soil	N	0.0982	2062.20	0.0947	2071.09	4133.29
	P	0.0568	1192.80	0.0557	1218.16	2410.96
	K	1.3572	28501.20	1.2103	26469.26	54970.46
	Ca	1.6885	35458.50	1.5708	34353.40	69811.90
	Mg	1.7362	36460.20	1.6293	35632.79	72092.99
sum			103674.90		99744.70	203419.60

nutrient storage in the soil layer. The order of available nutrient storage of the five elements is Ca > Mg > K > N > P.

The available nutrient storage of the five elements in the soil horizon accounts for most of the nutrient storage in the entire forest ecosystem, i.e. the soil horizon contains much more nutrients than the Chinese pine forest ecosystem, the latter only takes up a small portion.

4 Conclusions

The biomass of a 29-year-old Chinese pine forest in the research area was 92623 kg/hm^2. The distribution of biomass in the different organs respectively is as follows: leaves 12762 kg/hm^2, trunk 49946 kg/hm^2, branches 17659 kg/hm^2, roots 12260 kg/hm^2.

The total amount of nutrient elements stored in a Chinese pine tree is 695.17 kg/hm^2. The storage in needles is 291.94 kg/hm^2, branches 206.33 kg/hm^2, trunk 110.09 kg/hm^2 and roots 86.81 kg/hm^2. The order of nutrient storage by volume in the various organs is needles > branches > trunk > roots.

The uptake of nutrient elements of Chinese pine trees is 85.37 kg/hm^2 per year, of which the total amount of nutrient element returned as litter is 49.45 kg/hm^2 and the volume retained is 35.92 kg/hm^2.

Given the characteristics of the nutrient element cycle of Chinese pine trees in this water conservation plantation, the sequence of the absorption coefficient of the five elements is N > P > K > Ca > Mg. The utilization coefficients of N, P, K and Mg are close, but differ from the minimum utilization coefficient of Ca. The sequence of the cycle coefficient is Ca > N > P > K > Mg, where Mg has the longest cycle and N the shortest. The turnover period of all elements is more than 10 years.

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