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杉木人工林生态系统水文学过程的养分特性

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摘要:根据 5a 定位观测的数据,对湖南会同 24~28a 生的杉木人工林生态系统各水文学过程中的养分特性进行了研究。结果表明:林冠降水是杉木人工林生态系统养分输入的重要来源,其中 Ca 的养分含量最高,P 的含量最低。林内穿透水各养分元素的含量明显高于林冠降水中养分的含量。除 Ca 外,树干茎流中其它养分元素的含量为林冠降水的 6 倍以上。可见,林内穿透水和树干茎流是杉木林生态系统内养分循环的重要组成部分,有利于提高系统的养分利用率。地表径流中除硝态氮外,各元素的含量与穿透水的含量接近,其中 P、Na 和 K 三种元素的含量较低,但未超过林冠降水中养分元素含量。地下径流中 N 和 K 的含量较低,而 Ca 的含量与林冠降水相比没有差异。因而地表径流和地下径流不可避免的造成生态系统的养分损失,但 24~28a 生杉木林生态系统的调控能力较强,地表径流和地下径流量较小,生态系统的养分损失也相对较小,养分为净积累。不同季节之间水文学过程中养分元素含量存在一定程度的差异。降水形态、雷电和地形等要素影响养分元素含量。硝态氮在冰雹中未检出,而在雨水中的含量是雪水的 2 倍。铵态氮、K 和 Mg 等元素在雨水中的含量最高。P 和 Ca 以雪水的含量最高,与雨水和冰雹相比不存在数量级差异。雷电明显增加降水中养分的含量,特别是林冠上层的低空放电使降水中 N 的含量增加 3~5 倍。由于山谷和山麓的立地条件较好,其穿透水中养分含量比山坡的高,山谷与山麓的大致相等。在采集水样进行养分分析时,应考虑降水时间、降水形态和地形等因子的影响。

关键词:杉木人工林;水文学过程;养分含量;降水形态;地形

Nutrient characteristics in hydrological processes of Chinese fir plantation ecosystem

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Abstract: Based on the data collected over 5 years from January of 1990 to December of 1994 at Huitong Located Research Station of Forest Ecology, the nutrient characteristics of hydrological processes in a Chinese fir plantation ecosystem of 24 ~ 28 years old were investigated. The results showed that precipitation was a main source of nutrient input in Chinese fir plantation. The concentration of Ca was the highest and that of P was the lowest in precipitation. The nutrients concentrations in throughfall were conspicuously higher than those in precipitation. Except for Ca, the concentrations of other nutrient

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elements in stemflow were 6 times higher than those in precipitation. The nutrient transfer in throughfall and stemfall was a critical function of the intrasystem nutrient cycling that could improve nutrient use efficiency. The nutrient concentrations in surface runoff were roughly the same as those in throughfall except for NO_3-N. Compared with other nutrient elements, the concentrations of P, Na and K were lower in surface runoff but did not exceed those in precipitation. In ground runoff, the concentrations of N and K were lower and no difference was found in Ca between ground runoff and precipitation. The differences of total nutrient concentration in hydrological processes over months and years were significant or even extremely significant. Although the surface runoff and ground runoff inevitably resulted in nutrient losses, a net nutrient accumulation in 24～28 year old China fir plantation indicated that the plantation at the stable stage could control nutrient loss.

There were three factors, i.e. form of precipitation, lightning and location, that affected nutrient concentration and water quality variation. NO_3-N concentration in rainfall was almost 2 times as much as that in snow. The concentrations of NH_4-N, K and Mg were higher in rainfall than in snow and hailstone. Although the concentrations of P and Ca were higher in snow, no difference was found between the rainfall and hailstone. Lightning remarkably increased nutrient concentrations in precipitation. In particular, when lightning occurred in the lower atmosphere over the watershed, the concentration of N was increased by 3～5 times. Because of better site conditions in the valley and foot of the hill, nutrient concentrations in throughfall were higher than those in the slope, and the nutrient concentrations in the valley and foot of the hill were approximately the same. The factors such as rain time, precipitation form and topography should be considered when the samples are collected for chemical analysis.

Key words: Chinese fir plantation; hydrological process; nutrient concentration; precipitation form; topography

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1 Introduction

Water represents the greatest flow of any material substance through an ecosystem and is always an essential factor in any stage of tree growth[1]. Precipitation, as the main source of water required by the growth of stand trees, plays an important role in carrying various substances into a forest ecosystem[2,3]. Dusts and particles in the air therefore enter the forest ecosystem along with precipitation as input of chemical substances[4]. Although the contents of those substances imported at each individual precipitation event are low, their long-term accumulation becomes an important component of biogeochemical cycle. Accurately analyzing the nutrient contents in various hydrologic processes is therefore very important for studying the nutrient input and output of a forest ecosystem and making evaluation of nutrient cycling. In recent years, analysis of water quality in forest hydrologic processes is becoming more and more concerned. However, information and related documents on this subject are not extensively reported. With the aim to provide foresters and researchers in forest hydrology with some information, the results of characteristics analyses of nutrients in hydrologic processes obtained from our experimental watersheds of Chinese fir plantation ecosystem are presented as follows.

2 Site description

The research was conducted at Huitong Located Research Station of Forest Ecology, one of the National Key Field Station for Scientific Observation and Experiment (E109°45′, N26°50′). It belongs to the subtropical monsoon climatic zone with the annual mean air temperature of 16.8℃, annual relative humidity of 80% and total annual rainfall of 1100～1400 mm. The topography is characterized by the lower hill with the altitude from 270 to 400 m above sea level. Forestland soil is typical mountainous yellow soil derived from metamorphic slate and shale rocks. The pH-value of the soil is 4.5 and organic matter content is equivalent to 18.1 g/kg. The bulk density of the soil ranges from 1.11 to 1.25 g/cm^3. There are 8 parallel experimental small watersheds with similar topography and habitant environment. The area of each small watershed is about 2×10^4 m^2. The experimental stand of Chinese fir plantation during the study period was 24～28 years old. The stand density was 2276 trees per hectare, with the average height and diameter at breast height of 12.8 m and 14.1 cm, respectively.

3 Materials and methods

All water samples to be collected for our study were taken from the runoff plot of the experimental watershed of Chinese fir plantation ecosystem. Precipitation samples were collected from precipitation gauge fixed on two measuring towers, which were set up over the forest canopy at the top and foot of the valley in Watershed. Throughfall samples were taken from three 18～20 m^2 receivers installed in the valley, slope and foot of the hill. Stemflow samples were collected from receivers fixed at the stem ground, and the samples of surface and ground runoff were collected from the watershed weirs. According to weather condition and forest processes at each individual precipitation event, water samples were graded and collected in clean plastic bottles. The volume of each water sample was around 2000 ml. In order to prevent algae from growing, 5 drops of methane trichloride (CH_4Cl_3) were added into each sample before sampling. The chemical analysis was undertaken by the Research Laboratory of Forest Ecology at our institution.

The pH value was determined by electric potential method. The analysis for NH_4-N, NO_3-N and organic N was performed using naxon-agent colorimetric method, phthol disulforic acid colorimetric method and vaporization colorimetric method, respectively. The concentration of P was determined by molybdic-blue colorimetric method and the concentration of Na was measured by flame photometer method. The analysis for K, Ca and Mg was performed using atomic absorption spectrometer equipment.

4 Results

4.1 Nutrient concentration in hydrological processes of Chinese fir plantation

In precipitation, some amounts of the nutrients imported are intercepted and absorbed by the leaves in the canopy, whereas those nutrients un-intercepted or leached from the canopy come into the forest floor with throughfall and stemflow[5, 6]. Those nutrients then enter soil or are exported from the system along with surface and ground runoff. Among these processes, variation of nutrient concentration is rather complex and is affected by tree species, nutrient regime in the canopy, weather condition and precipitation. In order to prevent deviation, accurate determination of nutrient concentration in these processes should be validated by the data of chemical analyses of a great number of precipitation events. The weighted mean nutrient concentrations in various hydrological processes, calculated from a number of hydrochemical analyses made in 5 year-study, were presented in Table 1.

(1) Nutrient concentration in precipitation The main sources of nutrients in precipitation above the canopy are dusts and particles floating in the air, and substances produced through chemical reactions caused by lightning. Among nutrients in precipitation, the concentration of Ca was 1.31 mg/kg and ranked the highest, and P had the lowest concentration in precipitation. Moreover, NH_4-N was the primary form of nitrogen and its concentration was 2.9 times as high as that of NO_3-N.

(2) Nutrient concentration in throughfall The nutrient substances in throughfall are those that are not intercepted or imputed into the system along with precipitation, and other substances of dusts, particles and organic substances leached from the canopy[6]. Apart from the emulsion and secretion of

plants, all the nutrients attaching to leaf-surfaces are external. Meanwhile, nutrients in leaf cells are displaced by hydrogen cation in precipitation. Because of interception and leaching, the nutrient contents in throughfall were higher than those in precipitation above the canopy. The concentrations of Na, Mg, K, Ca, inorganic nitrogen and P were 4.8, 3.9, 3.6, 1.7, 2.2 and 2 times as much as those in precipitation, respectively.

Table 1 The average nutrient concentrations in forest hydrologic processes over 5 years from January 1990 to November 1994 (mg/kg)

Item	Times of hydrochemical analysis	pH	NO_3-N	NH_4-N	Org-N	P	Na	K	Ca	Mg
Precipitation	39	6.0	0.119	0.342		0.049	0.80	0.90	1.31	0.30
Throughfall	202	5.9	0.199	0.714	0.670	0.098	3.82	3.22	2.17	1.17
Stemflow	33	4.3	0.734	1.745	1.496	0.323	5.13	4.96	2.44	2.28
Surface runoff	126	6.1	0.411	0.894	0.754	0.076	3.36	3.92	3.29	1.85
Ground runoff	129	6.5	0.086	0.286	0	0.060	8.36	0.70	1.33	1.51

(3) Nutrient concentration in stemflow Stemflow is the water that flows down the surface of the boles after the bark is saturated with water. Among all the forest hydrological processes, stemflow contained the highest nutrient contents. To be more specific, the nutrient contents in stemflow were 5 times over those measured in precipitation except for Ca and K.

(4) Nutrient concentration in runoff Surface runoff refers to the water running across the soil surface after throughfall passes through the litter layer. The nutrients concentrations in surface runoff were roughly the same as those in throughfall except for NO_3-N which was much higher in surface runoff. Ground runoff is the water exported after the infiltrated water reaches the ground water level. Except for the concentrations of P, Na and Mg in ground water that were higher than those in precipitation, the concentrations of N and K in ground water were lower and no difference was observed for the concentration of Ca.

Hydrological processes are closely related to the nutrient cycling in forest ecosystem. The nutrient input and output processes are completed via the rainfall and runoff[7]. In Chinese fir plantation rainfall was an important nutrient source (Table 1). However, the surface runoff and ground runoff inevitably resulted in nutrient losses in Chinese fir plantation. Fortunately, although the surface runoff contained higher nutrient concentration than rainfall, the amount of surface runoff was only 0.9 percent of rainfall. A net nutrient accumulation in 24～28 year old China fir plantation indicated that Chinese fir plantation at the stable stage could control nutrient loss[3, 8, 9].

Besides litterfall, throughfall and stemfall add available nutrients directly to the soil without the intervention of any process of decomposition on the forest floor[5]. In 24 ～ 28 year old Chinese fir plantation, the nutrient concentration in throughfall and stemfall was higher than rainfall. Subsequently, the nutrient transfer in throughfall and stemfall was a critical function of the intrasystem nutrient cycling that could improve nutrient use efficiency.

4.2 Seasonal change in nutrients concentrations in hydrological processes

Due to the changes in climate and other natural conditions, nutrient concentrations in hydrological processes varied from month to month. For example, nutrient concentration of each element in surface runoff differed as shown in Figure 1. The concentration of NH_4-N and NO_3-N in surface runoff was the highest in September and May respectively. The month of the highest concentration of P in surface was November and that of the lowest is February and May. The pH value and concentration of other nutrients showed different change patterns. In December, element K was the highest concentration in surface runoff and Mg is lower. However, in November K is lower while Mg is the highest.

Using the analyzed data obtained during the 5-year period, we conducted a significance test on total nutrient contents of all water samples collected in all the months and years (Table 2 and Table 3). The results showed that the differences of total nutrient concentration in forest hydrological processes over years and months were significant or even extremely significant. The statistics was adequate enough to illustrate a case that a great number of samples must be collected from different years and months in order to accurately measure and analyze the nutrient concentration in hydrological processes of a forest ecosystem. The chemical analyses of the water samples should be made separately. It is inappropriate to deduce the nutrient concentrations for an entire year from results of a few analyses. Otherwise, great deviation would be brought up.

4.3 Factors influencing nutrient concentration in hydrological processes

The hydrological processe in forest ecosystem is a natural phenomenon, in which the nutrient concentrations are constantly changing[10]. One analytic result may not be the same as that of previous time. Since hydrological processes are random, they follow probability rules. According to the results of hydrochemical analyses made over 5 years, it was found that nutrient concentrations in hydrological

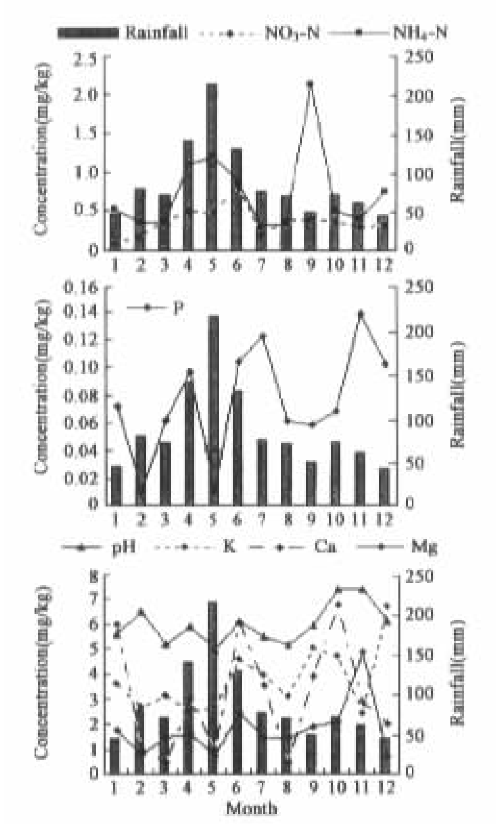

Fig. 1 Monthly change in pH value and nutrients concentration in surface runoff with rainfall

Table 2 Yearly variance analysis of nutrient concentration over 5 years from January 1990 to December 1994

Item	Variance source	Degree of Variance	Total of variance	Mean square deviation	Ratio of mean square deviations	*Fa*
Over-crown precipitation	Between groups	4	79.469	19.867		
	Within groups	38	149.625	3.938	$F=5.05^{**}$	$F_{0.01}=3.86$
	Total	42	229.04			
Throughfall	Between groups	4	154.315	38.579		
	Within groups	60	608.724	10.145	$F=3.80^{**}$	$F_{0.01}=3.65$
	Total	64	763.039			
Stemflow	Between groups	3	242.191	80.730		
	Within groups	27	667.537	24.724	$F=3.27^{*}$	$F_{0.05}=2.96$
	Total	30	909.728			
Surface runoff	Between groups	4	201.620	50.405		
	Within groups	30	447.215	14.907	$F=3.38^{*}$	$F_{0.05}=2.69$
	Total	34	648.835			
Ground runoff	Between groups	4	207.518	51.880		
	Within groups	77	148.247	1.925	$F=26.95^{**}$	$F_{0.01}=3.56$
	Total	81	355.765			

Note: the asterisk * represents that variance is significant. The double asterisk * * represents that variance is extremely significant.

processes not only depended on the property of precipitation, but also were influenced by many other factors, such as lightning, wind direction and speed, air pollution and other climatic phenomena. Based on our observation, three factors, i. e. form of precipitation, lightning and location, that affect nutrient concentration and water quality variation were discussed here.

Table 3 Monthly variance analysis of nutrient concentration over 5 years from January 1990 to December 1994

Item	Variance source	Degree of freedom	Total of variance	Mean square deviation	Ratio of mean square deviations	*Fa*
Throughfall	Between groups	10	211.724	21.172		
	Within groups	44	296.696	6.743	$F=3.14^{**}$	$F_{0.01}=2.75$
	Total	54	508.420			
Surface runoff	Between groups	10	491.441	49.114		
	Within groups	44	519.404	11.805	$F=4.16^{**}$	$F_{0.01}=2.75$
	Total	54	1010.845			

(1) Form of precipitation The results in table 4 showed that the nutrient concentrations changed with precipitation forms. NO_3-N content could not been tested out in hailstone. But NO_3-N concentration in rainfall was almost 2 times as high as that in snow. The concentrations of NH_4-N, K and Mg were higher in rainfall than in snow and hailstone. Although the concentrations of P and Ca were higher in snow, no difference was observed between the rainfall and hailstone.

(2) Lightning Other climatic factors may alter nutrient concentration, but lightning is an important factor influencing the nutrient concentration. As shown in table 5, lightning remarkably increased nutrient contents in precipitation. Especially when lightning occurred in the lower atmosphere over the watershed, the content of N was increased by 3～5 times.

Table 4 Nutrient concentrations in different forms of precipitation in 1991 (mg/kg)

Form of precipitation	pH	NO_3-N	NH_4-N	P	K	Ca	Mg
Rainfall	6.4	0.229	0.770	0.029	1.089	1.625	0.318
Hailstone	5.0	—	0.663	0.041	0.694	1.407	0.180
Snow	6.3	0.129	0.225	0.048	0.388	1.767	0.268

Table 5 The relationship between lightning and nutrient concentration in over crown precipitation in May and June 1994 (mg/kg)

Lightning condition	N	P	K	Ca	Mg
Lightning in the lower atmosphere	0.907	0.067	1.07	2.07	0.57
	0.533	0	0.23	0.30	0.68
Lightning in the higher atmosphere	0.282	0.034	1.00	0	0.60
	0.213	0.031	0.35	0.50	0
	0.229	0.028	1.70	0.20	0.64
No lightning	0.183	0.041	0	0.40	0

(3) Topography Owing to the fact that the nutrient concentrations in precipitation absorbed by and released from the forest canopies are not always the same, nutrient concentrations in throughfall at different locations of a forest ecosystem are not alike. In table 6, the results of hydrochemical analyses showed that nutrient concentrations in throughfall were higher than those in the slope, and the nutrient concentrations in the valley and foot of the hill were approximately the same because of better site conditions in the valley and foot of the hill.

The result of variance analysis and significance test presented in table 7 and 8 could further validate this case. In other words, differences of nutrient concentrati-ons in throughfall between the valley and foot of the hill were not significant while differences of nutrient concentrations in throughfall on slope of the hill were significant, compared with those in the valley and foot of the hill. This was indicative of the fact that nutrient concentration varied with different stand positions. Therefore, water samples should be collected from different positions and the samples should be as representative as possible to ensure the accuracy of water quality analysis.

Table 6 Mean concentration of nutrients in throughfall at different locations from 1991 to 1994 (mg/kg)

Location	pH	NO_3-N	NH_4-N	P	K	Ca	Mg
Slope of the hill	6.1	0.21	0.64	0.10	2.89	1.87	1.17
Foot of the hill	5.8	0.22	0.71	0.14	4.24	2.01	1.41
Valley	6.0	0.21	0.72	0.14	3.72	2.25	1.61

Table 7 Variance analysis of water quality in through fall in different locations

Variance source	Degree of freedom	Total of variance	Mean square deviation	Ratio of mean square deviation	*Fa*
Between groups	2	101.00	50.50		
Within groups	87	979.81	11.26	$F=4.48^*$	$F_{0.05}=3.11$
Total	89	1080.81			

5 Conclusion and discussion

Table 8 Quest for variations of mean value of nutrient concentration in throughfall at different locations

Mean value of nutrient concentration	Substrates on slope of the hill	Substrates at foot of the hill
Mean value for foot of the hill =8.777	2.47*	0.55
Mean value for the valley =8.228	1.92	
Mean value for the slope of the hill =6.306		

Hydrological processes are closely related to nutrient cycling in a forest ecosystem. The nutrient input and output processes are completed via the rainfall and runoff. In Chinese fir plantation rainfall was an important nutrient source. The concentration of Ca was the highest and that of P was the lowest in over-crown precipitation. The nutrient concentrations in throughfall were conspicuously higher than those in precipitation. Except for Ca, the concentrations of other nutrient elements in stemflow were 5 times higher than those in precipitation. The nutrient transfer in throughfall and stemfall was a critical function of the intrasystem nutrient cycling that could improve nutrient use efficiency. The nutrient concentrations in surface runoff were roughly the same as those in throughfall except for NO_3-N. Compared with other nutrient elements, P, Na and K were lower than those in precipitation. In ground runoff, N and K were lower than that in precipitation and no difference was observed for Ca concentration between ground runoff and precipitation. Although the surface runoff and ground runoff inevitably resulted in nutrient losses, a net nutrient accumulation in 24～28 year old Chinese fir plantation indicated that the plantation at the stable stage could control nutrient loss.

The differences of total nutrient concentration in hydrological processes over months and years were significant or even extremely significant. In order to accurately measure and analyze the nutrient concentration in hydrological processes of a forest ecosystem, a great number of samples must be collected for different months and years. The chemical analyses of water samples should be made separately. It is inappropriate to deduce the nutrient concentrations for an entire year from results of a few analyses.

On the basis of our observation, three factors i.e. form of precipitation, lightning and location, affected nutrient concentration and water quality variation. NO_3-N concentration in rainfall was almost twice as much as that in snow. The concentrations of NH_4-N, K and Mg were higher in rainfall than in snow and hailstone. Although the concentrations of P and Ca were higher in snow, no difference was found between the rainfall and hailstone. Lightning remarkably increased nutrient concentrations in precipitation. Especially when lightning occurred in the lower atmosphere over the watershed, the concentration of N was increased by 3～5 times. Because of better site conditions in the valley and foot of the hill, nutrient concentrations in throughfall were higher than those in the slope, and the nutrient concentrations in the valley and foot of the hill were approximately the same. The factors such as rain time, precipitation form and topography should be considered when the samples are collected for chemical analysis.

References:

[1] Waring R H and Schlesinger W H. *Forest Ecosystem: Concept and Management*. Orlando: Academic Press, 1985. 94.

[2] Ma X H. Effects of rainfall on the nutrient cycling in man-made forests of *Cunninghamia lanceolata* and *Pinus massoniana*. *Acta Ecologica Sinica*, 1989, **9**(1): 15～20.

[3] Pan W C, Tian D L, Chen X Y, *et al*. Hydrological process and nutrient dynamics of a subtropical Chinese fir plantation ecosystem. *Journal of Central South Forestry College*, 1989(sup): 1～9.

[4] Barnes, V B, Zak D R, Denton S R. *Forest Ecology* 4th Edition. New York: John Wiley & Sons, Inc., 1998.

[5] Eaton J S, Likens G E, Bormann F H. Throughfall and stemflow chemistry in a northern hardwood forest. *Journal of Ecology*, 1973, **61**(2): 495～508.

[6] Huang J H, Li H T, Han X G, *et al*. Nutrient characteristics of stemflow and throughfall in two coniferous forest ecosystem. *Acta Phytoecologica Sinica*, 2000, **24**(2): 248～251.

[7] Zhou M, Wang Q H, Liu C G, *et al*. Character analysis of import nutrient imported form rainfall in virgin forest of *Larix gmelini*. *Journal of Inner Mongolia Agricultural University*, 2000, **20**(1): 48～51.

[8] Sheng W T. A study on soil erosion and nutrient loss in Chinese fir plantation. *Forest Research*, 2000, **13**(6): 589～597.

[9] Zhou G Y, Chen B F, Zeng Q B, *et al*. Water balance and geochemical cycling of main nutrients in the tropical mountain rainforest, Hainan Island. *Acta Ecologica Sinica*, 1996, **16**(1): 28～32.

[10] Chen B F, Zhou G Y, Zeng Q B, *et al*. Hydro-ecological effect of tropical mountain rainforest ecosystem-potential energy of storm decreased by canopy and nutrients of storm stored in the system. *Acta Ecologica Sinica*, 1997, **17**(6): 635～639.

参考文献:

[2] **马雪华. 在杉木林和马尾松林中雨水的养分淋溶作用. 生态学报**, 1989, **9**(1): 15～20.

[3] **潘维俦, 田大伦, 谌小勇, 等. 亚热带杉木人工林生态系统中的水文学过程和养分动态. 中南林学院学报**, 1989(sup): 1～9.

[6] **黄建辉, 李海涛, 韩兴国, 等. 暖温带两种针叶林生态系统中茎流和穿透雨的养分特征研究. 植物生态学报**, 2000, **24**(2): 248～251.

[7] **周 梅, 王庆海, 刘春革, 等. 兴安落叶松原始林区降水输入养分特征分析. 内蒙古农业大学学报**, 2000, **20**(1): 48～51.

[8] **盛炜彤. 杉木人工林水土流失及养分损耗研究. 林业科学研究**, 2000, **13**(6): 589～597.

[9] **周光益, 陈步峰, 曾庆波, 等. 海南岛热带山地雨林短期水量平衡及主要养分的地球化学循环研究. 生态学报**, 1996, **16**(1): 28～32.

[10] **陈步峰, 周光益, 曾庆波, 等. 热带山地雨林生态系统的水分生态效应-冠层对暴雨势能的消减、暴雨养分贮存. 生态学报**, 1997, **17**(6): 635～639.