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第 2 代杉木幼林生态系统水化学特征

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摘要：对第 2 代杉木幼林生态系统的降雨、穿透水、茎流、地表和地下径流等水文过程中 N、P、K、Ca、Mg、Cu、Fe、Zn 和 Mn 9 种养分元素含量进行了连续 5a 的测定，结果表明：降雨通过林冠后其化学特性发生明显变化，pH 值出现酸化现象，穿透水中 Zn 和 Org-N 为负淋溶，其余各元素浓度有所增加。树干茎流的富集作用比穿透水强，其中 Zn 为负，其它元素的浓度均比林外降雨的高。地表径流中 Zn>Org-N>NO_3-N，与降雨中含量相比较为淋失迁移型，Ca>K>Cu>Mg>P>NH_4-N>Mn>Fe 为内贮型，pH 值增大。地下径流中 Zn>Org-N>NH_4-N>K>Mn 为淋失迁移型、Ca>Mg>Cu>NO_3-N>P>Fe 为内贮型。该系统的水循环中 Ca>Mg>Fe>P 为净损失、Zn>K>Org-N>NH_4-N>Mn>NO_3-N>Cu 为净积累，与第 1 代杉木林相比，第 2 代杉木幼林水化学过滤与吸贮功能较差，系统稳定性也较弱，生态功能的恢复需要一定的时间。

关键词：第 2 代杉木幼林；养分含量；降雨；茎流；穿透水；径流

Nutrient Characteristics of Hydrological Process in Young Second-rotation Chinese Fir Plantations

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Abstract: Chinese fir or *Cunninghamia lanceolata* is a dominant native species for timber production in southern China. With the rapid expansion of planting acreage and extensive practice of successive rotations, the urgent need to sustain long-term productivity of the forested land with this species has attracted nationwide attention. The present project is concerned with the nutrient flux in the process of hydrological cycling in a forest ecosystem, which is believed to be an important aspect enabling the system to maintain its ability to be productive and stable. The project site is situated in Huitong Located Forest Ecosystem, a field location established in 1978 by the authors and their colleagues for the purpose of working out solutions to sustain the productivity of Chinese fir plantations. There are 8 small watersheds in the station, paralleling one another with the distance no wider than 100 m in between, and the present study was conducted in Watershed No. 3.

The second-rotation Chinese fir plantation under observation was established in 1989 when the first rotation crop was clear cut. The planting density was 2 490 trees/hm^2, and the average tree height at the time of the first observation was 9 m, with the mean dbh approximating 8 cm. From 1995 to 2000 such hydrological data as the rainfall, throughfall, stemflow, surface runoff and groundwater were automatically measured. Specifically, water samples were collected for chemical analysis each month after the rain. Precipitation samples were collected from the gauge fixed on the two measuring towers above the forest canopy at the top and foot of the valley. Throughfall samples were taken from three receivers installed in the valley slope and foot of the hill. Stemflow samples were collected from receivers fixed at

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the stem ground, and the samples of surface and ground runoff were collected from the watershed weirs. 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 methods used for analyzing water samples were as follows: electric potential method for pH value, naxon-agent colorimetric method for NH_4-N, phthol disulforic acid colorimetric method for NO_3-N, vaporization colorimetric method for organic N, molybdic-blue colorimetric method for P, and atomic spectrometer for K, Ca, Mg, Fe, Cu, Zn and Mn.

The data collection lasted 5 years, and the analytical results are shown as follows. For rainfall, K ranked the top in concentration among the 9 nutrient elements tested, i. e. N, P, K, Ca, Mg, Fe, Cu, Zn and Mn, being 2.016mg/L; P and Cu were the lowest in concentration, both being 0.018mg/L. For throughfall and stemflow, Cu was the lowest in concentration in both samples, but the concentrations of Ca and K ranked the highest in both the throughfall and the stemflow, respectively. The hydrochemical characteristics changed obviously after the rainfall passed through the forest canopy, and acidification was found in the throughfall and stemflow. The concentrations of Zn and Org-N in the throughfall were lower than those in the rainfall, while the concentrations of other elements were higher. The leaching coefficient of the elements in the throughfall was in the descending order of Mg, Mn, Fe, Ca, P, NH_4-N, Cu, NO_3-N, K, Org-N, and Zn. In the stemflow a stronger nutrients enrichment was identified than in the throughfall. The concentration of Zn in the stemflow was lower than that in the rainfall but other elements (N, P, K, Ca, Mg, Cu, Fe and Mn) showed higher concentrations. The order of leaching coefficient in stemflow was, descendingly, Mn, Mg, NH_4-N, P, Ca, Fe, K, NO_3-N, Cu, Org-N, and Zn.

The concentration of Ca amounted to 8.021mg/L and 6.222mg/L in the surface runoff and groundwater, respectively, which was the highest of the 9 nutrient elements tested. The concentration of Cu in the surface runoff and groundwater was the lowest with the amount being 0.033mg/L and 0.026mg/L, respectively. The pH values in the surface runoff and groundwater were higher than in the rainfall. While leaching of Zn, Org-N and NO_3-N was identified in the surface runoff, accumulation of Ca, K, Fe, Mg, P, NH_4-N, Mn and Cu were present in the ecosystem. The concentrations of Zn, Org-N, NH_4-N, K and Mn were lower in the groundwater than in the rainfall due to leaching, but the concentrations of Ca, Mg, Fe, NO_3-N, P and Cu were higher in the former than in the latter.

The input of K in the rainfall was the highest with the amount of 23.599kg/(hm^2·a), with the second and third highest being Zn and Ca, accounting for 18.191kg/(hm^2·a) and 16.178kg/(hm^2·a), respectively. P and Cu ranked the lowest in input with the amount of 0.211kg/(hm^2·a). Leaching was the main nutrient return to soil in the young second rotation Chinese fir plantation. The leaching return of Zn and Org-N was below zero, and that of Ca —50.171kg/(hm^2·a)— ranked the highest. The output of Ca equaled to 26.965kg/(hm^2·a), which was the highest in the runoff. The second and third highest output elements were K and Mg, up to 8.593kg/(hm^2·a) and 7.228kg/(hm^2·a), respectively. The net nutrient loss of Ca, Mg, Fe and P due to leaching was found in the second-rotation Chinese fir plantation; however, a rich accumulation of Zn, K Org-N, NH_4-N, Mn, NO_3-N and Cu was present.

Therefore, it might be concluded that the second-rotation Chinese fir plantation has a weaker effect of nutrient filtration, uptake and accumulation than the first-rotation plantation. Its system stability is also lower. And it will have to take a certain length of time for the ecosystem to restore its full functions.

Key words: young second-rotation Chinese fir plantation; nutrient concentration; rainfall; stemflow; throughfall; runoff

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森林生态系统中的水分和养分循环结合在一起,构成维持系统物质生产的基本过程之一,对系统的稳定性、连续性和生物生产力产生极大影响[1]。大气降雨携带养分进入森林生态系统,由于这部分养分是水溶性的,无需经过复杂的分解过程,可以被植物直接吸收,它具有加速植物生长和促进养分循环的重要作用[2],而通过地表和地下径流则将部分养分迁出系统,即为养分的地球化学过程。因此,分析森林水文学各过程中的养分含量对于研究一个系统的养分输入、输出以及评价养分循环是必不可少的[3]。

有关降雨对林冠淋溶作用的研究已有较多报道,涉及不同森林类型,如寒温带白桦、硬阔、栎树天然次生林[4],暖温带落叶松和油松林[5],亚热带杉木[1~3,6]、马尾松[2]、湿地松[7]和桤木[8]等人工林,热带半落叶季雨林和山地雨林[9],结果表明降雨淋溶与树种、降雨时刻大气和森林林冠的干净程度、降雨量的大小等有很大关系。径流水化学特征研究方面也有一些的报道,如海南岛热带森林生态系统具有较强的水化学过滤和吸贮功能[9],稳定态的第 1 代杉木林的养分处于积累的过程[1],等等。目前,还未见第 2 代杉木幼林中水文过程中养分化学特征的系统报道。本研究根据连续 5 个水文年的定位观测所取得的数据,对第 2 代杉木幼林水化学特征进行研究。

1　材料与方法

1.1　试验地概况

试验地设立在国家重点野外科学观测试验站——会同森林生态系统定位研究站内,地理位置为东经 109°45′,北纬 26°50′,气候属典型的亚热带湿润性气候,年平均温度为 16.8℃,年平均降水量在 1100～1400mm 之间,年平均相对湿度约为 80%。地貌为低山丘陵,海拔高为 270～400m,相对高度在 150m 以下。地层属于震旦纪板溪系灰绿色变质板页岩,土壤为山地黄壤。站内有 8 个试验集水区,其自然地理状况基本上相似,彼此相距不超过 100m。本试验在第 3 号集水区进行,集水区内为 1988 年营造的第 2 代杉木人工幼林。现实林分平均树高为 9m,胸径为 8cm,立木密度为 2490 株/hm^2,郁闭度为 0.6。林下代表性植被有杜茎山(*Macsa japonica*)、柃木(*Eurga spiece*)、拔葜(*Smidax china*)、狗脊(*Woodardia japonica*)等。

1.2　研究方法

1.1.1　水文过程的观测　由安装在集水区内观测铁塔(高出林冠 1.5 m)上的雨量计观测降雨量。林内穿透水由分别设置在山洼、山麓、山坡的 3 个约 18 m^2 的穿透水承接装置导入测流堰自动记录仪进行测定。树干茎流采用聚乙烯塑料管蛇形缠绕树干基部,10 株杉木为 1 组将塑料管下端接入遥测雨量计自动记录。在小集水区出口设置测流堰,分别测定地表径流和地下径流[10]。

1.1.2　水样收集　大气降雨水样在集水区内的观测铁塔上的雨量计中采集;穿透水水样在集水区内山谷、山麓和山坡部位的承接器中分别采集,然后进行混合,采取混合样;树干茎流水样在树干径流束导管口采集,地表径流和地下径流分别在地表径流和地下径流测流堰口采集水样。自 1995 年 5 月至 2000 年 11 月,每月采集降雨、穿透水、树干茎流、地表径流和地下径流的水样 1～2 次,每次每个水样的采集量为 2000 ml,盛于清洁的塑料瓶中,并及时送实验室分析。

1.1.3　化学分析　pH 值用电位法测定;铵态 N(NH_4-N)用纳氏试剂比色法测定,硝态 N(NO_3-N)用酚二磺酸比色法测定,有机氮 N(Org-N)用蒸馏比色法测定;P 用磷钼蓝比色法测定;K、Ca、Mg、Fe、Mn、Cu、Zn 用 HP3510 型原子吸收分光光度计测定。

2　结果与分析

2.1　大气降雨的养分特征及淋溶作用

大气降雨是外界各种物质进入森林生态系统的主要途径之一,它含有作为凝结核、升华核的海盐粒子,并吸附大气中所固有的各种化学成分的浮游物质[11]。从表 1 可知,大气降雨中以 K 元素含量最高,为 2.016mg/L,P 和 Cu 元素含量最低,仅 0.018mg/L,两者竟相差 112 倍。无机态 N(氨态氮 NH_4-N 和硝态氮 NO_3-N)则以 NH_4-N 为主,比 NO_3-N 约高 1 倍 。降雨中各养分元素含量排列顺序为:K＞Zn＞Ca＞Org-N＞NH_4-N＞NO_3-N＞Fe＞Mg＞Mn＞P＝Cu。降雨中除 pH 值和 Mg 的浓度季节变化较小外,其它各元素浓度的季节变化较大,尤以 K、P 明显,4 月份降雨中的钾含量最大,达 9.29mg/L,8 月份的含量最低,只有 0.34mg/L。P 在 7 月份降雨中浓度最大,比其它各月高出 7～19 倍。

穿透水中 Ca 的含量最高，P 和 Cu 的含量最低，排列顺序为 Ca＞K＞Mg＞NH_4-N＞Fe ＞Mn＞Org-N＞NO_3-N＞Zn＞P＞Cu。树干茎流中 K 的含量最高，P 与 Cu 的含量最低。排列顺序为 K＞Ca＞NH_4-N＞Mg＞Mn＞Org-N＞Zn＞Fe＞NO_3-N＞P＞Cu。受气候条件、大气尘埃物、降雨时间、降雨强度、降雨间隔期以及树木生理活动等因素的影响，使穿透水、树干茎流中元素的浓度表现出季节性变化，穿透水、树干茎流的 pH 值季节差异不明显，变化系数最小，其它各元素的季节差异因不同类型的水而有所不同。树干流中的 NO_3-N 的变动系数最小，只有 0.294，这说明树干对硝态 N 和有机物的分泌及吸收，淋溶有一个相对平衡稳定的过程。与降雨相比，穿透水、树干流中的 NH_4-N、NO_3-N、Org-N、P、K、Cu、Mn 的变动系数都分别小于降雨，而 Ca、Mg、Fe、Zn 的变动系数都大于降雨。

表 1 大气降雨、穿透水和树干茎流中养分元素浓度(mg/L)

Table 1 Nutrient elements concentration of rainfall, throughfall and stemflow

项目 Item		pH	NH_4-N	NO_3-N	Org-N	P	K	Ca	Mg	Fe	Cu	Zn	Mn
降雨 Rainfall	x	6.79	0.286	0.167	0.576	0.018	2.016	1.382	0.098	0.133	0.018	1.554	0.075
	s	0.355	0.267	0.158	0.597	0.028	3.566	1.114	0.032	0.113	0.025	1.060	0.099
	cv	0.05	0.93	0.94	1.04	1.61	1.77	0.81	0.33	0.85	1.38	0.68	1.33
穿透水 Throughfall	x	6.32	1.015	0.308	0.509	0.069	3.080	6.502	1.084	0.908	0.035	0.108	0.649
	s	1.07	0.782	0.175	0.495	0.079	2.369	6.552	0.674	1.680	0.043	0.049	0.620
	cv	0.17	0.771	0.569	0.974	1.145	0.770	1.008	0.662	1.851	1.250	0.455	0.955
树干茎流 Stemflow	x	5.12	1.880	0.366	0.587	0.088	7.400	5.780	1.190	0.520	0.035	0.562	1.067
	s	0.83	0.950	0.108	0.510	0.056	5.880	7.690	1.171	0.692	0.039	0.484	1.440
	cv	0.16	0.500	0.294	0.876	0.640	0.790	1.330	0.980	1.330	1.130	0.860	1.350

x 、s 和 cv 分别表示平均值、标准差和变动系数 x, s and cv represent mean, standard variance and variance coefficient, $cv=x/s$

降雨通过林冠后其化学特性发生改变有两个方面的原因，一方面大气降雨淋洗大气中和林冠上的尘埃、雨水淋溶叶片的分泌物，另一方面林木对降雨过程中的吸附[5,6]。由表 1 可看出大气降雨通过林冠后，酸度发生了明显变化，大气降雨的 pH 值为 6.79，穿透水为 6.32，稍低于大气降雨，树干茎流的 pH 为 5.12，出现明显酸化现象，与福建杉木林的研究结果相似[6]。

表 2 列出了穿透水、树干茎流与大气降雨的比较结果，其中的净淋溶为穿透水或树干茎流的养分浓度与大气降雨养分浓度的差值，淋容系数为穿透水或树干茎流的养分浓度除以大气降雨养分浓度[9]。表 2 的结果表明，穿透水中 Zn 和 Org-N 为负淋溶，其余各元素浓度有所增加，根据淋溶系数的大小排列穿透水的

表 2 降雨净淋溶的养分含量和淋溶系数

Table 2 Net leaching amount and leaching coefficient of throughfall and stemflow

项目	NH_4-N	NO_3-N	Org-N	P	K	Ca	Mg	Fe	Cu	Zn	Mn
穿透水净淋溶 Net leaching of throughfall (mg/L)	0.729	0.141	−0.067	0.051	1.064	5.12	0.986	0.775	0.017	−1.446	0.574
树干茎流净淋溶 Net leaching of stemflow (mg/L)	1.594	0.199	0.011	0.070	5.408	4.396	1.093	0.387	0.017	−0.992	0.992
穿透水淋溶系数 Leaching coefficient of throughfall	3.549	1.844	0.884	3.833	1.528	4.705	11.061	6.827	1.944	0.0695	8.653
树干茎流淋溶系数 Leaching coefficient of stemflow	6.573	2.192	1.019	4.889	3.682	4.181	12.153	3.910	1.944	0.362	14.227

淋溶序列为:Mg＞Mn＞Fe＞Ca＞P＞NH_4-N＞Cu＞NO_3-N＞K＞Org-N＞Zn。树干茎流中 Zn 为负淋溶,其它元素的浓度均比大气降雨的高。除 Ca、Fe 和 Cu 外,树干茎流中其它养分元素的富集作用比穿透水强。各元素的淋溶系列为:Mn＞Mg＞NH_4-N＞P＞Ca＞Fe＞K＞NO_3-N＞Cu＞Org-N＞Zn。

2.2　地表和地下径流养分特征与迁移

降雨-穿透水、茎流-径流的养分化学性状系统变化,可相对地反映系统内的水化学平衡状况和生态系统物质循环特征[9]。径流是降雨通过森林生态系统立体空间多层次再分配后的输出,其化学成分变化是复杂的。地表径流中 Ca 的含量最高,为 8.021mg/L,Cu 的含量最低,为 0.033mg/L,排列顺序为 Ca＞K＞Fe＞Mg＞NH_4-N＞Mn＞Org-N＞NO_3-N＞P＞Zn＞Cu。地下径流中 Ca 的含量最高,为 6.222mg/L,Cu 的含量最低,为 0.026mg/L,排列顺序为 Ca＞K＞Mg＞Fe＞NO_3-N＞NH_4-N＞P＞Zn＞Org-N＞Mn＞Cu。地下径流中 NO_3-N、P 和 Mg 的含量高于地表径流,其它元素在地表径流中的含量高。

以地表径流或地下径流的元素输出含量与降水的元素输入含量之比值(迁移系数)等于 1,或以输出含量与输入含量之差值等于 0 为平衡界限[9],地表径流中迁移量 Zn＞Org-N＞NO_3-N 为负值(表 4),即淋失迁移型,Ca＞K＞Fe＞Mg＞P＞NH_4-N＞Mn＞Cu 为内贮型,输入量有部分被森林生态系统吸收贮存,pH 值增加(表 3)。地下径流中 Zn＞Org-N＞NH_4-N＞K＞Mn 为淋失迁移型(表 4),Ca＞Mg＞Fe＞NO_3-N＞P＞Cu 为内贮型(表 3)。

表 3　大气降雨、地表和地下径流中养分元素浓度 (mg/L)

Table 3　Nutrient concentration of rainfall, surface runoff and underground flow

项目 Item	pH	NH_4-N	NO_3-N	Org-N	P	K	Ca	Mg	Fe	Cu	Zn	Mn
大气降雨 Rainfall	6.79	0.286	0.167	0.576	0.018	2.016	1.382	0.098	0.133	0.018	1.554	0.075
地表径流 Surface runoff	7.23	0.696	0.150	0.154	0.060	3.617	8.021	0.858	1.359	0.033	0.054	0.246
地下径流 Underground flow	7.18	0.124	0.417	0.041	0.072	1.935	6.222	1.726	0.681	0.026	0.054	0.036

表 4　地表径流与地下径流相对降水浓度的迁移量和迁移系数

Table 4　Migration amount and coefficient of surface runoff and underground flow compared with rainfall

项目	NH_4-N	NO_3-N	Org-N	P	K	Ca	Mg	Fe	Cu	Zn	Mn
地表径流迁移量 Migration of surface runoff (mg/L)	0.41	−0.017	−0.422	0.042	1.601	6.639	0.76	1.226	0.015	−1.500	0.171
地下径流迁移量 Migration of underground flow (mg/L)	−0.162	0.25	−0.535	0.054	−0.081	4.84	1.628	0.548	0.008	−1.500	−0.039
地表径流迁移系数 Migration coefficient of surface runoff	2.434	0.898	0.267	3.333	1.794	5.803	8.755	10.218	1.833	0.0347	3.280
地下径流迁移系数 Migration coefficient of underground low	0.433	2.497	0.071	4.000	0.960	4.502	17.612	5.120	1.444	0.0347	0.480

2.3　水文学过程在养分循环中的贡献

降雨是森林生态系统养分的主要输入源,林外降雨的养分输入量以 K 元素为主(表 5),输入量为 23.599kg/(hm^2·a),其次是 Zn 和 Ca,分别为 18.191kg/(hm^2·a)和 16.178kg/(hm^2·a),最小的是 P 与 Cu,为 0.211kg/(hm^2·a),各元素通过降雨输入量的大小依次为 K＞Zn＞Ca＞Org-N＞NH_4-N＞NO_3-N＞Fe＞Mg＞Mn＞Cu＞P。

在第 2 代杉木幼林生态系统中,降雨淋溶是养分从林木中归还给土壤的主要途径之一,各营养元素从

林冠中被淋溶出来的数量有所不同，养分淋溶的特点为：① Zn 和 Org-N 表现为负淋溶，表明林冠对它们吸收；② P 和 Cu 元素在降雨中含量很低，且难溶解，故其淋溶量低；③ Ca 元素淋溶量高，达 50.171 kg/(hm^2·a)，但 Ca 在植物体内是以果胶形式永久固定于细胞壁的中胶层，不易移动[12]，这表明粘附在幼杉针叶表面的尘埃物被降雨淋洗，比叶细胞中元素的淋溶作用更为重要；④ 林冠养分淋溶量的大小，依次为：Ca＞Mg＞K＞Fe＞NH_4-N＞Mn＞NO_3-N＞P＞Cu＞Org-N＞Zn。

表 5 第 2 代杉木幼林生态系统水文过程的养分贡献(kg/(hm^2·a))

Table 5 Nutrient contribution of hydrological process in second-rotation Chinese fir stands

项目 Item	NH_4-N	NO_3-N	Org-N	P	K	Ca	Mg	Fe	Cu	Zn	Mn
降雨养分输入 Input of rainfall	3.348	1.955	6.743	0.211	23.599	16.178	1.147	1.557	0.211	18.191	0.877
淋溶归还 Leaching return	7.044	1.191	−1.544	0.494	7.996	50.171	9.922	7.698	0.146	−17.072	5.762
径流养分输出 Output of runoff	0.636	1.736	0.196	0.306	8.593	26.965	7.228	3.040	0.112	0.231	0.193
系统养分平衡 System nutrient balance	2.712	0.219	6.547	−0.095	15.006	−10.788	−6.081	−1.483	0.099	17.960	0.684

第 2 代杉木林生态系统中，径流的养分输出量以 Ca 最高，输出量达 26.965kg/(hm^2·a)，其次是 K 和 Mg，分别为 8.593kg/(hm^2·a)和 7.228kg/(hm^2·a)，最小的是 Cu，为 0.231kg/(hm^2·a)，各元素通过径流输出量的大小依次为 Ca＞K＞Ma＞Fe＞NO_3-N＞NH_4-N＞P＞Zn＞Org-N＞Mn＞Cu。系统输入和输出之差说明系统的养分平衡状况，系统中 Ca＞Mg＞Fe＞P 为净损失，Zn＞K＞Org-N＞NH_4-N＞Mn＞NO_3-N＞Cu 为净积累，与稳定态的第 1 代杉木林[1]和热带半落叶季雨林、山地雨林[9]相比，第 2 代杉木幼林水化学过滤与吸贮功能差，系统稳定较弱，生态功能的恢复需要一定的时间。

3 结论

(1)大气降雨中以 K 元素含量最高，为 2.016mg/L，P 和 Cu 元素含量最低，仅 0.018mg/L，两者竟相差 112 倍。穿透水中 Ca 的含量最高，P 和 Cu 的含量最低。树干茎流中 K 的含量最高，P 与 Cu 的含量最低。降雨通过林冠后，其化学特性发生明显变化，出现酸化现象，穿透水中 Zn 和 Org-N 为负淋溶，其余各元素浓度有所增加，根据淋溶系数的大小排列穿透水的淋溶序列为：Mg＞Mn＞Fe＞Ca＞P＞NH_4-N＞Cu＞NO_3-N＞K＞Org-N＞Zn。树干茎流的富集作用比穿透水强，Zn 为负淋溶，其它元素的浓度均比大气降雨的高，各元素的淋溶系列为：Mn＞Mg＞NH_4-N＞P＞Ca＞Fe＞K＞NO_3-N＞Cu＞Org-N＞Zn。

(2)地表和地下径流中 Ca 含量最高，分别为 8.021mg/L 和 6.222mg/L，Cu 含量最低，分别为 0.033mg/L 和 0.026mg/L。地下径流中 NO_3-N、P 和 Mg 的含量高于地表径流，其它元素则地表径流高。地表径流中 Zn＞Org-N＞NO_3-N 为淋失迁移型，Ca＞K＞Fe＞Mg＞P＞NH_4-N＞Mn＞Cu 为内贮型，pH 值增大。地下径流中 Zn＞Org-N＞NH_4-N＞K＞Mn 为淋失迁移型，Ca＞Mg＞Fe＞NO_3-N＞P＞Cu 为内贮型。

(3)大气降雨的养分输入量以 K 元素为主，输入量为 23.599kg/(hm^2·a)，其次是 Zn 和 Ca，分别为 18.191kg/(hm^2·a)和 16.178kg/(hm^2·a)，最小的是 P 与 Cu，为 0.211kg/(hm^2·a)。第 2 代杉木幼林生态系统中，凋落物量极少时，林木归还给土壤养分的主要途径是降雨淋溶，Zn 和 Org-N 表现为负淋溶，P 和 Cu 元素淋溶量低，Ca 元素淋溶量高，达 50.171kg/(hm^2·a)。径流的养分输出量以 Ca 最高，为 26.965kg/(hm^2·a)，其次是 K 和 Mg，分别为 8.593kg/(hm^2·a)和 7.228kg/(hm^2·a)，最小的是 Cu，为 0.231kg/(hm^2·a)。系统中 Ca＞Mg＞Fe＞P 为净损失，Zn＞K＞Org-N＞NH_4-N＞Mn＞NO_3-N＞Cu 为净积累。第 2 代杉木幼林水化学过滤与吸贮功能差、系统稳定较弱，生态功能恢复需要一定时间。

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