

陈涛, 齐实, 孙保平. 川东山地马尾松林枯落物和土壤层持水能力特性[J]. 应用与环境生物学报, 2022, 28 (3): 742-750

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川东山地马尾松林枯落物和土壤层持水能力特性

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摘 要 为研究不同坡度川东山地马尾松林枯落物层和土壤层持水特性,选取马尾松-小叶青冈-香樟针阔混交林、马尾松-杉木针叶混交林、马尾松针叶纯林,按20°-30°、30°-40°和40°-50° 3个坡度范围测定林下枯落物和土壤的持水能力,探讨3个坡度水源涵养能力最佳的林分类型. 结果表明:(1)同一坡度不同林分枯落物总蓄积量差异显著($P < 0.05$),在20°-30°坡针叶纯林总蓄积量最大,为8.33 t/hm²; 30°-40°和40°-50°坡分别是针叶混交林和针阔混交林最大,其值分别为12.79和17.77 t/hm². 同一坡度不同林分枯落物有效持水量均为针阔混交林最大,其值分别为10.38、18.37和21.59 t/hm². (2)土壤有效持水量在20°-30°和30°-40°坡分别是针叶纯林和针叶混交林最大,其值为82.54和50.02 mm,40°-50°坡为针阔混交林最大,其值为60.28 mm. (3)同一坡度不同林分土壤渗透系数和累积入渗量大小排序均为针叶混交林>针阔混交林>针叶纯林. (4)综合有效持水量表现为20°-30°坡针叶纯林最高,其值为82.61 mm; 30°-40°坡针叶混交林最高,其值为50.04 mm; 40°-50°坡针阔混交林最高,其值为60.50 mm. 土壤层持水占综合有效持水量的90%以上,是该地区马尾松林地水源涵养能力的主体. (图6 表5 参37)

关键词 林分类型; 枯落物持水量; 土壤持水量; 土壤渗透系数; 坡度

Water-holding capacity of litter and soil layers of *Pinus massoniana* forest in the mountainous areas of eastern Sichuan, China

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Abstract To study the water-holding characteristics of litter layer and soil layer of *Pinus massoniana* forest with different slopes in eastern Sichuan, the water-holding capacity of litter and soil under three slope ranges of 20°-30°, 30°-40°, and 40°-50° were measured in *P. massoniana*-*Cyclobalanopsis glauca*-*Cinnamomum camphora* mixed forest, *P. massoniana*-Chinese fir coniferous mixed forest, and *Pinus massoniana* coniferous pure forest, and the stand types with the best water conservation capacity were discussed. The results showed that: (1) The total litter volume of different stands on the same slope was significantly different ($P < 0.05$), and that of pure coniferous forest was the largest on the slope of 20°-30°, which was 8.33 t/hm²; the maximum values of 30°-40° and 40°-50° slopes were 12.79 and 17.77 t/hm² in coniferous mixed forest and coniferous and broad-leaved mixed forest, respectively. The effective water holding capacity of litter in coniferous and broad-leaved mixed forest was the highest, which was 10.38, 18.37, and 21.59 t/hm², respectively. (2) The soil effective water holding capacity of pure coniferous forest and mixed coniferous forest was the largest on 20°-30° and 40°-50° slopes, with the value of 82.54 and 50.02 mm, respectively, and that of mixed coniferous and broad-leaved forest was the largest on 40°-50° slopes, with the value of 60.28 mm. (3) The order of soil permeability coefficient and cumulative infiltration of different stands on the same slope was coniferous mixed forest > coniferous and broad-leaved mixed forest > coniferous pure forest. (4) The amounts of the comprehensive effective water holding capacity of the pure coniferous forest was the largest on 20°-30° slopes, coniferous mixed forest was the largest on 30°-40° slopes, and coniferous and broad-leaved mixed forest was the largest on 40°-50° slopes, which were 82.61, 50.04, and 60.50 mm, respectively. The water holding capacity of soil layer accounted for more than 90% of the total effective water holding capacity, which was the dominant of water-holding capacity of *P. masson* pine forest in this area.

Keywords stand type; litter holding water; soil water storage; soil permeability coefficient; slope

收稿日期 Received: 2020-12-03 接受日期 Accepted: 2021-02-19

国家重点研发计划项目(2017YFC0505602)资助 Supported by the National Key R&D Program of China (2017YFC0505602)

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森林的枯落物和土壤层是调节森林生态系统水文效应的重要活动层,同时枯落物层作为森林水文调节的重要层次,对森林涵养水分发挥着重要的作用.枯落物直接覆盖在地表,能够保护土壤、减少水土流失、防止水分蒸发、拦蓄地表径流、增强土壤层调蓄水分的能力^[1-2].而土壤功能与土壤孔隙结构密切相关,土壤层作为森林生态水文系统的重要组成部分,在调节水源、保持水土等功能中发挥着重要的价值^[3].且土壤是森林涵养水源的主体,土壤的持水能力和入渗特性是森林水源涵养能力的重要体现^[4-5].近年来有关森林枯落物和土壤层水文方面的研究较多.大多数学者研究表明,枯落物持水能力初期最强,随历时增加不断降低,直至饱和,且枯落物持水量与浸泡时间呈较好的对数函数关系,而土壤层作为森林水源涵养能力的主体,其持水能力随坡度增加而减小^[6-7].也有部分研究中,由于土地利用类型的差异,得出土壤持水能力随坡度增加而增加的相反结论^[8-9].同时,重力的作用会导致土壤中的水分会沿坡向下运动,最终聚集在平缓的地方^[10].朱志俊等研究^[11]发现降雨过程中坡度对地被物的持水量有一定的影响,坡度的增加会造成地被物最大持水量的减少,这与地被物层对降水的分配有关.此外,由于研究区域气候及植被等因素的差异,使得目前有关于森林水源涵养研究方法多种多样^[12-15].而坡面水文往往受到内在因素和外在因素的影响,目前的研究多数集中于森林冠层截留,枯落物种类,分解层次,土壤理化性质等内在因素,而对于有些外在因素,如坡度等却很少研究.

马尾松(*Pinus massoniana* Lamb)是四川省主要造林树种和荒山绿化先锋树种,其分布范围广,多种植在陡坡上,且人工林面积占马尾松林地总面积的50%以上.而由于长期实行纯林经营,受自然和人为不利因素影响,森林质量差,生长缓慢,水土保持能力和保护效益较低,使得目前森林整体生态系统服务功能降低,生态系统不稳定,严重威胁长江上游低山丘陵区生态安全^[16].因此,本研究通过分析3个不同坡度马尾松林分类型(针阔混交林、针叶混交林、针叶纯林)枯落物和土壤层蓄水能力,探讨不同坡度下林地蓄水能力最佳的树种配置模式.研究结果将为该地区马尾松林陡坡地造林更好地发挥调节水源、保持水土的生态系统服务功能提供参考依据.

1 研究区概况

研究区处于四川省华蓥市(106°50'2.04"E, 30°25'20.7"N),位于会阴山中段西缘、曲江东岸,与四川盆地东部灵谷区平

行,海拔206.7-1 774.1 m,华蓥市东西两部分的地形地貌有着明显差异.西部低丘广布,地势偏低,多为丘陵,低丘为主,散布着一些平台、台地、土壤肥沃.土壤类型主要有山地黄壤、黄沙壤、紫色土.华蓥市气候类型属于热带湿润性季风气候,四季分明,夏长雨多,年降雨量1 200 mm,热量充足,年均气温15-23 °C.主要植被类型为灌木和人工植被、亚热带常绿阔叶混交林、针叶阔叶混交林、常绿针叶混交林、针叶混交林、竹混交林和常绿落叶阔叶混交林.以针叶林为主,其次是竹林和阔叶林,以马尾松、杉木[*Cunninghamia lanceolata* (Lamb.) Hook]、柏木(*Cupressus funebris* Endl)、湿地松(*Pinus elliottii* Engelman)、柳杉(*Cryptomeria fortunei* Hooibrenk ex Otto et Dietr)等树种组成的针叶林占华蓥市森林面积的96.9%,成为华蓥市典型的地带性植被.

2 材料与方法

2.1 样地调查及样品采集

2020年8月至9月,选取研究区内以马尾松为优势树种的3个林分类型:针阔混交林{马尾松,小叶青冈[*Cyclobalanopsis myrsinifolia* (Blume) Oersted],香樟(*Cinnamomum camphora*, CD)}、针叶混交林(马尾松,杉木, CM)、针叶纯林(马尾松, CP)为研究对象,按3个坡度范围[缓坡(20°-30°)、陡坡(30°-40°)和极陡(40°-50°)],每个坡度范围和林分选择3个不同坡度的典型坡面,选取林龄相近且人为干扰较少的人工林,每种林分类型内随机均匀设置5个1 m × 1 m的小样方,分两层(未分解层和半分解层)采集枯落物样品,并装入塑封袋带回实验室;同时采用便携式渗透计测定每种林分内土壤渗透系数,每种林分随机均匀选取5个点进行测定,取其平均值代表该种林分土壤渗透系数值.此外,每林分内随机均匀选择3个土壤采集样点,除去土壤表层覆盖的枯枝落叶层,用环刀沿土壤剖面按照0-20 cm、20-40 cm、40-60 cm共3层采集,每层取3个重复,将收集完成的土壤装入自封袋中并送回试验室备用,测定土壤孔隙度、含水量等物理指标.环刀的容积为100 cm³,高 $h=5.000$ cm,直径 $d=5.046$ cm.样地基本情况见表1.

2.2 指标测定及方法

2.2.1 枯落物持水能力测定 将野外采集的凋落物装入网袋称重,获取烘干前的鲜重,然后将样品放入烘箱中,调至85 °C连续烘干至恒重,称量为干重.用浸泡法测定枯枝落叶的持水能力:将枯落物烘干样品放至网袋中,然后浸入装满水的桶

表1 样地基本情况
Table 1 Basic situation of the sample plot

坡度 Slope	林分类型 Stand type	经纬度 Geographic coordinates (a°)		坡向 Aspect	海拔 Altitude (h/m)	林龄 Age (t/a)	土层厚度 Soil thickness (δ/cm)
		东经 Longitude	北纬 Latitude				
缓坡 Gentle slope	CD	106.78082	30.39583	ES	485	55	65
	CM	106.83931	30.44119	WN	431	55	65
	CP	106.78092	30.3958	EN	577	52	65
陡坡 Steep slope	CD	106.78093	30.39581	EN	594	55	55
	CM	106.84131	30.44569	WS	609	55	66
	CP	106.78071	30.39572	WS	575	52	60
极陡 Extremely steep	CD	106.78081	30.39582	WS	598	55	50
	CM	106.84132	30.44078	WN	554	55	55
	CP	106.78097	30.39589	WN	531	52	65

土壤类型均为山地黄壤. CD: 针阔混交林; CM: 针叶混交林; CP: 针叶纯林.
The soil types are all mountain yellow soil. CD: Coniferous and broad-leaved mixed forest; CM: Coniferous mixed forest; CP: Coniferous pure forest.

中,保证桶内水量可以完全没过样品,分别在15 min, 45 min, 1 h, 2 h, 4 h, 7h, 10 h, 15 h, 20 h, 24 h时取出网带控水至不再滴水后称重,作为吸水后的重量并记录. 枯落物最大持水量、有效拦蓄量计算公式^[4]如下:

$$M_m = M_1 - M_0 \quad (1)$$

$$R_m = \frac{M_m}{M_0} \times 100\% \quad (2)$$

$$m_1 = m_2 - M_0 \quad (3)$$

$$R_0 = \frac{m_1}{M_0} \times 100\% \quad (4)$$

$$W_m = (R_m - R_0) \times M \quad (5)$$

$$W = (0.85R_m - R_0) \times M \quad (6)$$

式中: M_m 为枯落物最大持水量(g); M_0 为自然枯落物质量(g); M_1 为浸泡后枯落物质量(g); R_m 为最大持水率(%); m_2 为样品鲜重(g); m_1 为样品自然含水量(g); R_0 为自然含水率(%); W_m 为最大拦蓄量(t/hm²); M 为枯落物蓄积量(t/hm²); W 为有效拦蓄量(t/hm²); 0.85为有效拦蓄系数.

2.2.2 土壤渗透系数测定 土壤渗透系数测定采用的是便携式渗透计(Mini-Disk Infiltrometer),测定步骤如下.

测定方法:将水注入便携式渗透计的上下两个腔室,上部气泡室控制虹吸过程,下室水作为渗滤水,渗透速率由上部气泡室虹吸程度控制,下腔的形状像一个标有毫升刻度的量筒.渗透计的底部由不锈钢多孔盘组成,其作用是防止水分渗漏.小直径的底盘可以保证安放在相对平整的土壤表面.渗透计置于土壤表面后,水分就会渗透到土壤中,渗透速度受到土壤水力性质的影响.记录段特定时间间隔内的渗水体积(对沙壤土来说一般是30秒).将数据记录在电子表格中并作图(渗透计随机所带光盘),得出渗透系数(k).计算公式:

$$k = \frac{C_1}{A}$$

其中, C_1 是累积入渗量与时间平方根曲线斜率的比值;参数 A 与土壤类型有关.

$$A = \frac{11.65(n^{0.1} - 1)\exp[2.92(n - 1.9)ah_0]}{(ar_0)^{0.91}}$$

式中: n 和 a 是土壤参数, r_0 是底座半径, h_0 为底座表面处的吸力,根据土壤类型 n 、 a 和 h_0 取值分别为0.124、2.28和1.8.便携式渗透计以-0.5到-6 cm的虹吸力将水渗入土壤,底座半径2.25 cm.

2.2.3 土壤持水能力测定 使用环刀法可以测定土壤的容

重、孔隙度等土壤物理状况,根据土壤持水量公式,可以计算出土壤的持水性能,单位面积土壤层持水量公式^[17]为:

$$H = \sum_{i=1}^n P_i \times \delta_i \times A_i \quad (7)$$

式中: H 为单位面积土壤层持水量(mm); δ 即土壤层的厚度(mm); P 为土壤孔隙度(%); i 为不同林分和坡度样地.

2.3 数据处理

数据整理在EXCEL 2010中完成,用SPASS 20.0对数据进行单因素方差分析(one-way ANOVA)及多重比较LSD (least-significant difference)分析,采用Origin 2017作图.

3 结果与分析

3.1 林地枯落物特征

同一坡度下不同林分半分解层枯落物蓄积量差异显著,而未分解层差异不显著(表2).在缓坡处枯落物半分解层针叶纯林显著大于针阔混交林,而在极陡坡和陡坡处针叶纯林显著小于针阔混交林和针叶混交林.缓坡,陡坡和极陡坡枯落物总厚度变化范围分别为6-10、7.6-10.75、7-12.6 cm;总蓄积量变化范围分别为4.45-8.33、6.88-15.75、4.95-17.77 t/hm²,且不同林分和坡度差异显著($P < 0.05$),其中相同林分不同坡度针阔混交林和针叶混交林总蓄积量表现为缓坡显著小于陡坡和极陡,而针叶纯林表现为缓坡显著大于陡坡和极陡;同一坡度不同林分缓坡处针叶纯林总蓄积量显著大于针阔混交林和针叶混交林,而在极陡坡和陡坡针叶纯林总蓄积量显著小于针叶混交林和针阔混交林.整体而言,陡坡地马尾松混交林枯落物总蓄积量高于马尾松纯林,且半分解层是影响不同坡度和林地枯落物蓄积量差异的主要因素.

3.2 林地枯落物持水特征

由图1可知,持水量与浸水时间呈现一定的正相关关系,持水量随着浸水时间逐渐增加,且半分解层与未分解层变化趋势基本一致.持水量增加最快的时间基本在2 h以内,在10 h后持水量基本达到饱和.同一坡度不同林分之间未分解层持水量大小依次为针阔混交林>针叶混交林>针叶纯林;半分解层持水量大小无明显规律.根据拟合得到,不同林分枯落物持水量与时间呈现较好的对数函数关系: $Q = k \ln t + b$. 式中: Q 为枯落物持水量(g/kg), t 为枯落物浸水时间(h), k 为系数, b 为常数项.

表2 3个坡度不同林分枯落物蓄积量

Table 2 Litter accumulation of different forests with different slopes

坡度 Slope	林分 Stand type	厚度 Thickness (δ /cm)	蓄积量 Stock (M/t hm ⁻²)			蓄积量比例 Stock ratio (P/%)	
			半分解层 Semi-decomposed layer	未分解层 Undecomposed layer	总蓄积量 Total accumulation	半分解层 Semi-decomposed layer	未分解层 Undecomposed layer
缓坡 Gentle slope	CD	8.60 ± 1.67Aa	2.50 ± 1.76Aa	3.93 ± 1.37Aa	6.43 ± 3.13Aa	38.94 ± 0.15Aa	61.06 ± 0.61Aa
	CM	6.00 ± 2.17ABa	1.94 ± 0.90ABa	2.51 ± 0.24Aa	4.45 ± 1.11Aa	43.54 ± 0.90Aa	56.46 ± 0.56Aa
	CP	10.00 ± 4.46Ab	4.08 ± 1.12Ba	4.25 ± 0.36Aa	8.33 ± 1.24Ba	49.00 ± 0.08Aa	51.00 ± 0.51Aa
陡坡 Steep slope	CD	10.20 ± 3.78Ab	6.69 ± 1.42Ab	6.10 ± 1.56Aa	12.79 ± 2.67Ab	52.31 ± 0.07Aa	47.69 ± 0.48Aa
	CM	10.75 ± 1.83ABb	7.99 ± 1.48ABb	7.76 ± 2.22Aa	15.75 ± 3.50Ab	50.72 ± 0.05Aa	49.28 ± 0.49Aa
	CP	7.60 ± 0.47Bb	2.63 ± 1.16Bb	4.24 ± 5.44Aa	6.88 ± 3.28Bb	38.27 ± 0.12Aa	61.73 ± 0.62Aa
极陡 Extremely steep	CD	12.60 ± 2.01Aab	8.52 ± 2.69Aab	9.26 ± 1.14Aa	17.77 ± 3.00Ab	47.93 ± 0.24Aa	52.07 ± 0.52Aa
	CM	7.00 ± 3.59ABab	3.84 ± 0.59ABab	3.60 ± 1.14Aa	7.44 ± 0.71Ab	51.63 ± 0.21Aa	48.37 ± 0.48Aa
	CP	10.20 ± 3.43Bab	2.13 ± 1.12Bab	2.82 ± 1.62Aa	4.95 ± 0.50Bb	43.03 ± 0.12Aa	56.97 ± 0.57Aa

表中数据为平均值±标准偏差($N = 5$),不同大写字母均表示同一坡度不同林分间差异性显著,不同小写字母均表示同一林分不同坡度间差异性显著($P < 0.05$). CD: 针阔混交林; CM: 针叶混交林; CP: 针叶纯林.

Different capital letters all indicate significant differences between different forest stands on the same slope ($P < 0.05$), different lowercase letters all indicate significant differences between different slopes of the same forest ($P < 0.05$). CD: Coniferous and broad-leaved mixed forest; CM: Coniferous mixed forest; CP: Coniferous pure forest.

3个坡度不同林分枯落物吸水速率与浸水时间呈较好的负相关关系,前1 h内枯落物吸水速率最大,直至4 h时吸水速率趋于平缓,10 h时处于动态平衡状态.不同林分枯落物半分解层和未分解层吸水速率大小均表现为针阔混交林>针叶混交林>针叶纯林.吸水速率与浸水时间呈现较好的幂函数关系(表3): $V = k \times t^n$.式中: V 代表枯落物吸水速率($\text{g kg}^{-1} \text{h}^{-1}$), t 为枯落物浸水时间(h), k 为系数, n 为常数项.

3.3 林地枯落物持水量

由表4可知,3个坡度枯落物不同分解层自然含水量差异显著($P < 0.05$),大小排序缓坡为针阔混交林>针叶混交林,而陡坡和极陡坡均为针叶混交林>针阔混交林>针叶纯林.不同林分枯落物最大持水量表现为极陡和陡坡半分解层和未分解层均为针阔混交林显著大于针叶混交林和针叶纯林.3个坡度枯落物最大拦蓄量和有效拦蓄量均表现

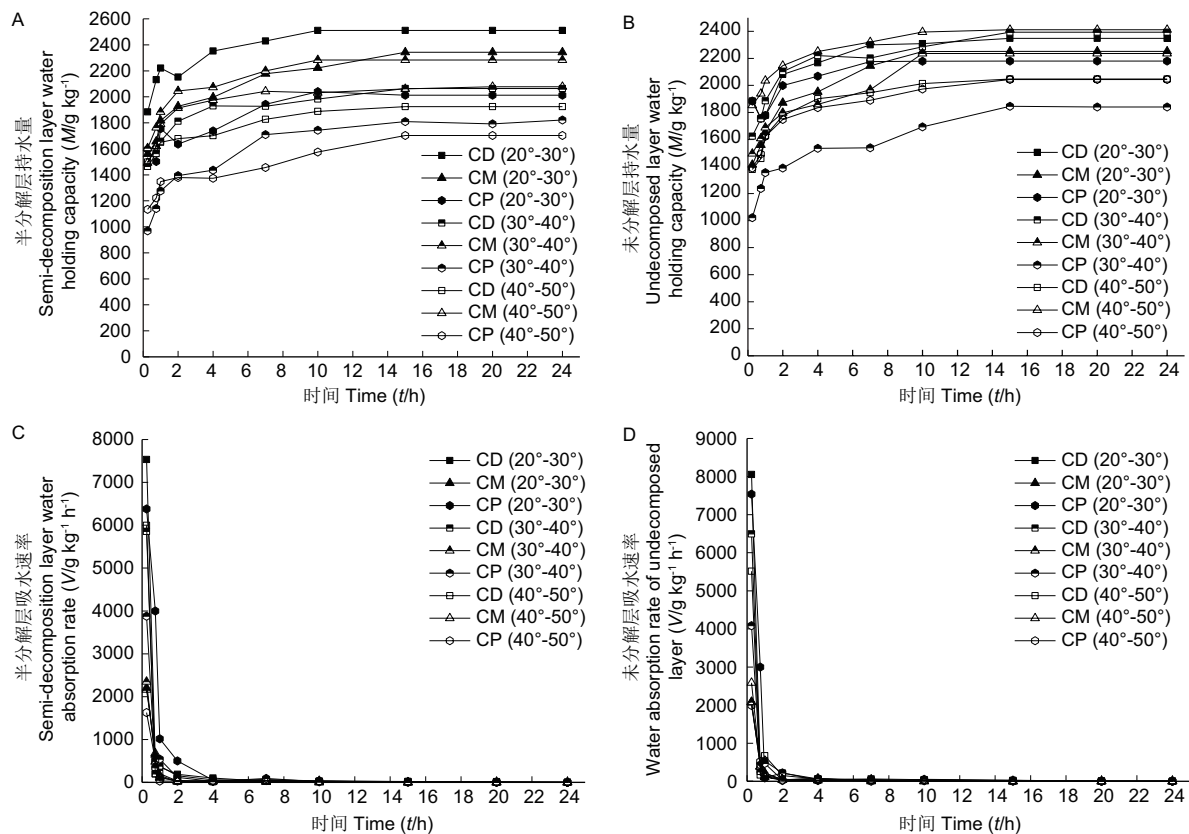


图1 不同林分和坡度枯落物半分解层与未分解层持水量(A、B)与吸水速率(C、D). CD: 针阔混交林; CM: 针叶混交林; CP: 针叶纯林.
Fig. 1 Water holding capacity (A, B) and water absorption rate (C, D) of semi-decomposed layer and undecomposed layer of litter in different forest stands and slopes. CD: Coniferous and broad-leaved mixed forest; CM: Coniferous mixed forest; CP: Coniferous pure forest.

表3 枯落物持水量、吸水速率与浸水时间的关系
Table 3 Relationship between water holding capacity, moisture absorption rate, and soaking time of litter

林分 Stand type	枯落物层 Litter layer	坡度 Slope	持水量与浸水时间 Water holding capacity and immersion time	R^2	吸水速率与浸水时间 Water absorption rate and immersion time	R^2
缓坡 Gentle slope	半分解层 Semi-decomposed layer	CD	$M = 129.91\ln t + 1625.6$	0.9122	$V = 369.12t^{-1.778}$	0.9316
		CM	$M = 163.75\ln t + 1497.1$	0.9756	$V = 208.56t^{-1.592}$	0.8857
		CP	$M = 115.91\ln t + 1438.9$	0.804	$V = 1103.8t^{-1.728}$	0.9266
CD		$M = 139.91\ln t + 1457.5$	0.9669	$V = 382.8t^{-1.619}$	0.9125	
CM		$M = 29.966\ln t + 413.6$	0.9232	$V = 33.94t^{-1.174}$	0.787	
CP		$M = 197.03\ln t + 1004.7$	0.9724	$V = 368.97t^{-1.6}$	0.8903	
极陡 Extremely steep		CD	$M = 99.157\ln t + 1375.3$	0.9674	$V = 238.85t^{-1.556}$	0.8759
		CM	$M = 54.213\ln t + 357.75$	0.8102	$V = 84.711t^{-1.365}$	0.9056
		CP	$M = 127.98\ln t + 1129.7$	0.9325	$V = 152.45t^{-1.463}$	0.8183
缓坡 Gentle slope	未分解层 Undecomposed layer	CD	$M = 199.81\ln t + 1824.3$	0.9039	$V = 375.04t^{-1.458}$	0.7641
		CM	$M = 189.29\ln t + 1321.1$	0.975	$V = 218.76t^{-1.662}$	0.9457
		CP	$M = 105.44\ln t + 1690.7$	0.7805	$V = 551.68t^{-1.658}$	0.8806
CD		$M = 176.93\ln t + 1726.8$	0.9594	$V = 492.66t^{-1.643}$	0.8964	
CM		$M = 40.216\ln t + 362.52$	0.9659	$V = 44.847t^{-1.342}$	0.8915	
CP		$M = 179.1\ln t + 1079.9$	0.9709	$V = 300.6t^{-1.583}$	0.7605	
极陡 Extremely steep		CD	$M = 159.72\ln t + 1487.5$	0.952	$V = 399.37t^{-1.693}$	0.9248
		CM	$M = 61.994\ln t + 381.41$	0.9722	$V = 72.802t^{-1.425}$	0.9619
		CP	$M = 152.72\ln t + 1446.1$	0.9804	$V = 183.39t^{-1.606}$	0.9093

CD: 针阔混交林; CM: 针叶混交林; CP: 针叶纯林.
CD: Coniferous and broad-leaved mixed forest; CM: Coniferous mixed forest; CP: Coniferous pure forest.

表4 3个坡度枯落物持水量

Table 4 Water holding capacity of litter with different slopes

覆盖层 Cover layer	坡度 Slope	林分 Forest stand	自然含水率 Natural water rate ($R_0/\%$)	枯落物最大持水率 Maximum water holding rate of litter ($R_m/\%$)	枯落物最大持水量 Maximum water holding capacity of litter ($M_m/t\text{ hm}^{-2}$)	最大拦蓄量 Maximum storage capacity ($W_m/t\text{ hm}^{-2}$)	有效拦蓄量 Effective interception ($W/t\text{ hm}^{-2}$)
半分解层 Semi-decomposed layer	缓坡 Gentle slope	CD	32.91 ± 2.08A	256.82 ± 57.42A	4.59 ± 0.33A	5.26 ± 1.31B	4.39 ± 1.10B
		CM	10.19 ± 0.26B	234.25 ± 48.06A	3.89 ± 0.05A	3.72 ± 3.08A	3.13 ± 2.59A
		CP	18.03 ± 1.40C	198.57 ± 55.31A	5.85 ± 0.39A	3.98 ± 1.97A	3.29 ± 1.64A
	陡坡 Steep slope	CD	20.06 ± 0.23A	196.82 ± 80.99A	11.71 ± 0.28B	10.36 ± 4.07B	8.60 ± 3.43B
		CM	49.54 ± 2.85B	209.39 ± 15.49A	1.76 ± 0.42A	1.31 ± 1.36A	1.04 ± 1.10A
		CP	13.41 ± 8.62C	290.86 ± 1.36A	3.40 ± 0.67A	3.21 ± 1.02A	2.07 ± 0.82A
	极陡 Extremely steep	CD	16.92 ± 0.85A	206.38 ± 129.13A	10.64 ± 0.17B	9.72 ± 9.79B	8.13 ± 8.24B
		CM	64.39 ± 7.27B	228.33 ± 83.27A	1.65 ± 0.31A	1.24 ± 1.41A	0.99 ± 1.14A
		CP	19.18 ± 0.37C	182.12 ± 96.17A	3.70 ± 0.22A	3.33 ± 3.02A	2.77 ± 2.54A
未分解层 Undecomposed layer	缓坡 Gentle slope	CD	26.84 ± 0.88A	285.40 ± 120.09A	7.32 ± 0.98A	7.15 ± 2.87B	5.99 ± 2.41B
		CM	13.83 ± 1.95B	231.10 ± 32.77A	5.10 ± 1.06A	4.80 ± 2.90A	4.03 ± 2.14A
		CP	16.94 ± 2.15C	233.05 ± 141.37A	7.70 ± 0.96A	6.62 ± 2.57A	5.52 ± 2.14A
	陡坡 Steep slope	CD	13.69 ± 1.65A	239.34 ± 4.28A	12.23 ± 1.09B	11.62 ± 4.98B	9.77 ± 4.18B
		CM	62.68 ± 0.45B	223.61 ± 11.40A	1.96 ± 0.82A	1.35 ± 0.18A	1.06 ± 0.88A
		CP	17.13 ± 2.67C	183.98 ± 33.1A	5.26 ± 0.90A	4.69 ± 0.46A	3.90 ± 0.35A
	极陡 Extremely steep	CD	10.74 ± 0.98A	204.70 ± 100.34A	16.86 ± 0.89B	15.99 ± 4.78B	13.46 ± 4.04B
		CM	53.9 ± 14.20B	241.21 ± 1.70A	2.81 ± 1.01A	2.19 ± 1.29A	1.77 ± 1.04A
		CP	13.44 ± 2.19C	95.82 ± 3.20A	1.66 ± 0.89A	1.37 ± 2.97A	3.75 ± 2.50A

表中数据为平均值±标准偏差 ($N = 5$)。CD: 针阔混交林; CM: 针叶混交林; CP: 针叶纯林。不同大写字母均表示同一坡度不同林分间差异性显著 ($P < 0.05$)。

CD: Coniferous and broad-leaved mixed forest; CM: Coniferous mixed forest; CP: Coniferous pure forest. Different capital letters all indicate significant differences between different forest stands on the same slope ($P < 0.05$).

表5 3个坡度林地土壤孔隙状况及持水特性

Table 5 Soil porosity and water holding characteristics with different slopes forest land

坡度 Slope	林分 Stand type	土层 Soil layer (δ/cm)	容重 Bulk density ($\rho/\text{g cm}^{-3}$)	毛管孔隙度 Capillary porosity ($P/\%$)	非毛管孔隙度 Non-capillary porosity ($P/\%$)	总孔隙度 Total soil porosity ($P/\%$)
缓坡 Gentle slope	CD	0-20	0.98 ± 0.03A	40.22 ± 2.98A	13.05 ± 2.98A	53.26 ± 2.40A
		20-40	1.07 ± 0.06A	41.86 ± 0.86A	9.30 ± 2.50A	51.16 ± 2.88A
		40-60	1.22 ± 0.10A	39.51 ± 0.51A	9.25 ± 3.04A	48.76 ± 2.71A
	CM	0-20	1.18 ± 0.11B	38.68 ± 2.74A	12.43 ± 4.06A	51.11 ± 3.02B
		20-40	1.15 ± 0.10B	39.57 ± 2.71A	12.43 ± 4.04A	52.01 ± 2.76B
		40-60	1.24 ± 0.07B	39.73 ± 1.48A	8.34 ± 2.54A	48.07 ± 3.37B
	CP	0-20	0.92 ± 0.27A	38.51 ± 1.15A	17.77 ± 7.74A	56.27 ± 9.36A
		20-40	1.06 ± 0.05A	42.19 ± 0.39A	11.38 ± 1.55A	53.56 ± 1.45A
		40-60	1.06 ± 0.12A	41.44 ± 0.86A	12.12 ± 4.32A	53.56 ± 0.03A
陡坡 Steep slope	CD	0-20	1.03 ± 0.14A	44.56 ± 1.94A	11.38 ± 1.85A	55.94 ± 2.32A
		20-40	1.27 ± 0.04A	42.78 ± 1.48A	6.98 ± 2.33A	49.76 ± 1.55A
		40-60	1.18 ± 0.43A	39.92 ± 6.16A	3.62 ± 3.38A	42.04 ± 8.43A
	CM	0-20	1.15 ± 0.14B	37.88 ± 1.73A	11.75 ± 4.08A	49.63 ± 3.56B
		20-40	1.28 ± 0.11B	39.57 ± 2.64A	7.67 ± 2.93A	47.24 ± 2.81B
		40-60	1.30 ± 0.10B	37.66 ± 2.47A	5.59 ± 2.71A	43.25 ± 2.94B
	CP	0-20	1.28 ± 0.07AB	34.08 ± 1.04A	11.35 ± 5.43A	45.43 ± 5.06AB
		20-40	1.40 ± 0.06AB	36.83 ± 2.88A	5.81 ± 3.62A	42.64 ± 3.62AB
		40-60	1.39 ± 0.08AB	33.92 ± 4.51A	6.11 ± 4.53A	40.03 ± 4.53AB
极陡 Extremely steep	CD	0-20	1.29 ± 0.07A	30.87 ± 3.35A	12.44 ± 1.89A	43.31 ± 4.24A
		20-40	1.35 ± 0.06A	31.73 ± 5.21A	8.87 ± 5.56A	40.60 ± 2.52A
		40-60	1.34 ± 0.08A	34.98 ± 2.54A	8.83 ± 5.46A	43.81 ± 3.37A
	CM	0-20	1.26 ± 0.17B	39.33 ± 2.16A	7.00 ± 4.16A	46.33 ± 2.52B
		20-40	1.45 ± 0.17B	39.74 ± 3.71A	2.82 ± 2.41A	42.56 ± 5.51B
		40-60	1.41 ± 0.14B	38.57 ± 2.20A	2.77 ± 1.61A	41.34 ± 3.62B
	CP	0-20	1.14 ± 0.05AB	35.12 ± 2.71A	12.03 ± 4.56A	47.15 ± 3.75AB
		20-40	1.46 ± 0.06AB	36.70 ± 2.04A	2.13 ± 0.80A	38.83 ± 1.53AB
		40-60	1.38 ± 0.09AB	43.19 ± 2.77A	0.87 ± 0.23A	44.06 ± 3.33AB

表中数据为平均值±标准偏差 ($N = 3$)。不同大写字母均表示同一坡度不同林分间差异性显著 ($P < 0.05$)。CD: 针阔混交林; CM: 针叶混交林; CP: 针叶纯林。Different capital letters all indicate significant differences between different forest stands on the same slope ($P < 0.05$). CD: Coniferous and broad-leaved mixed forest; CM: Coniferous mixed forest; CP: Coniferous pure forest.

为针阔混交林显著大于其他两种林分类型,可以看出,在陡坡种植针阔混交林更有利于增加林地枯落物水源涵养能力。

3.4 林地土壤持水能力

3.4.1 土壤孔隙状况及持水特性 相关研究表明,林木根系通过生理习性对土壤施加影响,改良土壤结构,且由于土壤

微生物的活动,使得林地孔隙度增大,土壤容重变小,通气性好,持水能力强^[18]。由表5可知,3种林分在缓坡、陡坡和极陡坡土壤总孔隙度范围分别为48.07%-56.27%、40.03%-55.94%和38.83%-47.15%。同一坡度不同林分土壤容重表现为缓坡针叶混交林显著大于针阔混交林和针叶纯林,而土壤

总孔隙度则显著小于针阔混交林和针叶纯林。由图2-4可知, 3个坡度土壤最大持水量表现为缓坡(96.14-112.54 mm)、陡坡(80.06-111.88 mm)和极陡(77.66-94.30 mm), 可以看出, 缓坡土壤最大持水量大于陡坡。不同坡度土壤有效持水量表现为缓坡(18.50-35.54 mm)、陡坡(7.24-23.50 mm)和极陡(5.54-24.06 mm), 其中极陡坡土壤有效持水量表现为针阔混交林显著大于针叶纯林和针叶混交林。

3.4.2 土壤渗透系数 由图5可知, 3个坡度下土壤渗透系数均表现为针叶混交林>针阔混交林>针叶纯林, 整体表现为针叶混交林林下土壤的渗透系数显著大于针阔混交林和针叶

纯林, 其值为缓坡(2.23 mm/min)、陡坡(1.75 mm/min)、极陡(1.50 mm/min); 且针叶混交林的累积入渗量显著大于针叶纯林和针阔混交林, 其值为缓坡(27.55 mm)、陡坡(24.70 mm)、极陡(25.55 mm), 可以看出, 3种林分中针叶混交林的动态持水能力最佳, 针叶纯林最差。

3.5 枯落物层和土壤层持水能力综合分析

由图6可知3个坡度下不同林分综合最大持水量表现: 缓坡为(针叶纯林(326.87 mm)>针阔混交林(312.98 mm)>针叶混交林(302.47 mm)), 陡坡为针阔混交林(295.71 mm)>针叶混交林(280.28 mm)>针叶纯林(256.34 mm), 极

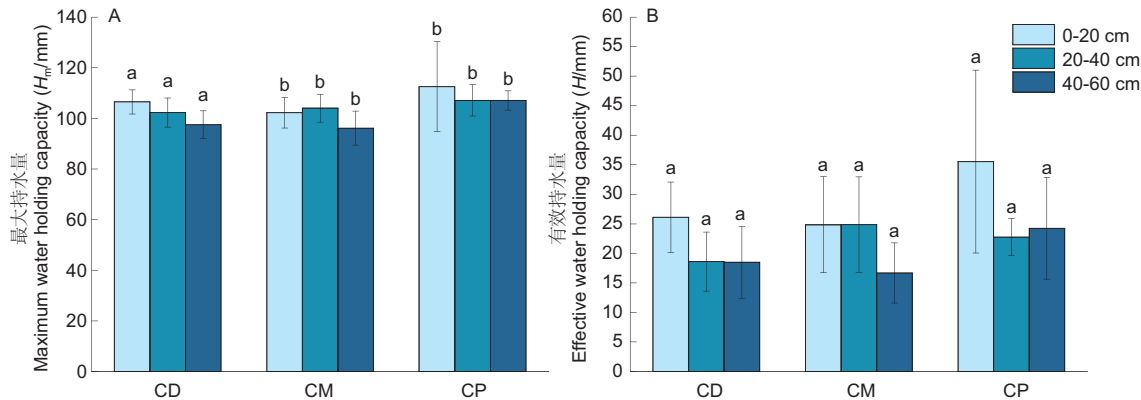


图2 缓坡林地土壤最大持水量(A)和有效持水量(B). 不同小写字母均表示同一坡度不同林分间差异性显著($P < 0.05$).

Fig. 2 Maximum soil water holding capacity (A) and effective water holding capacity (B) of gentle slope forest land. Different capital letters indicate significant differences between different forest stands on the same slope ($P < 0.05$).

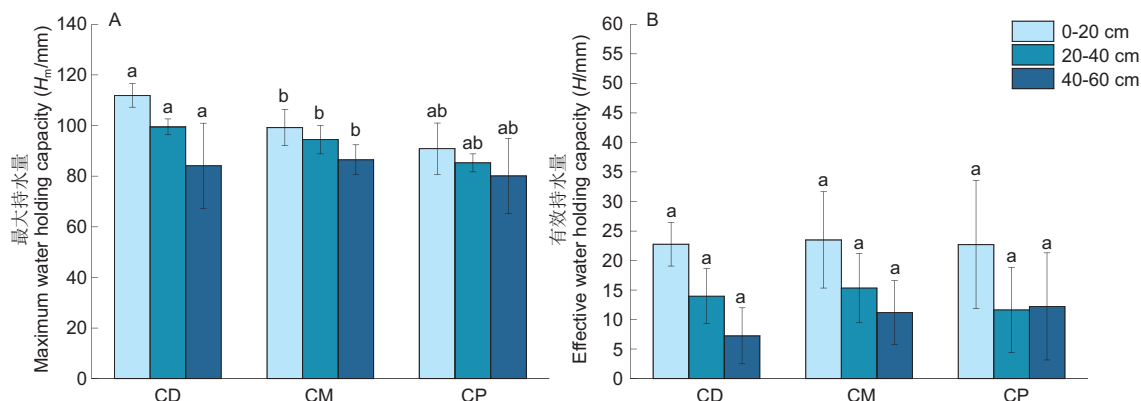


图3 陡坡林地土壤最大持水量(A)和有效持水量(B). 不同小写字母均表示同一坡度不同林分间差异性显著($P < 0.05$).

Fig. 3 Maximum soil water holding capacity (A) and effective water holding capacity (B) of steep slope forest land. Different lowercase letters indicate significant differences between different forest stands on the same slope ($P < 0.05$).

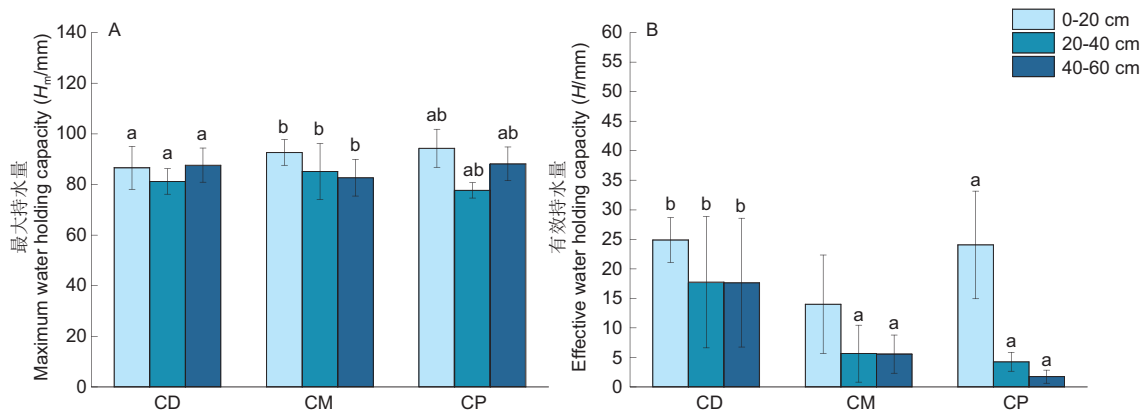


图4 极陡坡林地土壤最大持水量(A)和有效持水量(B). 不同小写字母均表示同一坡度不同林分间差异性显著($P < 0.05$).

Fig. 4 Maximum soil water holding capacity (A) and effective water holding capacity (B) of extremely steep slope forest land. Different lowercase letters indicate significant differences between different forest stands on the same slope ($P < 0.05$).

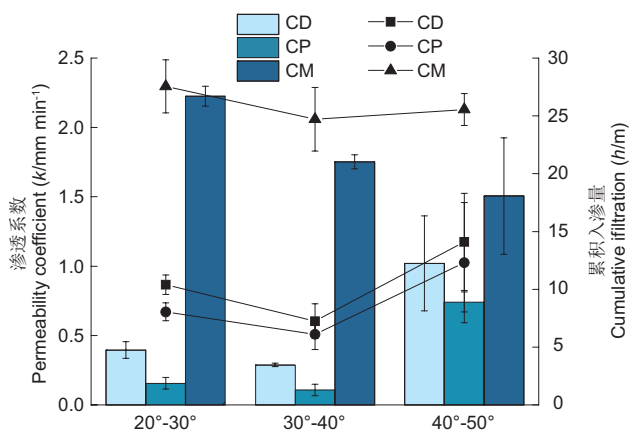


图5 3个坡度不同林分土壤渗透系数及累积入渗量。CD: 针阔混交林; CM: 针叶混交林; CP: 针叶纯林。

Fig. 5 Soil permeability coefficient and cumulative infiltration rate of three forests with different slopes. CD: Coniferous and broad-leaved mixed forest; CM: Coniferous mixed forest; CP: Coniferous pure forest.

陡为针叶混交林 (260.51 mm) > 针叶纯林 (260.13 mm) > 针阔混交林 (255.73 mm)。综合有效持水量表现: 缓坡为针叶纯林 (82.61 mm) > 针叶混交林 (66.47 mm) > 针阔混交林 (63.29 mm), 陡坡为针叶混交林 (50.04 mm) > 针阔混交林 (46.64 mm) > 针叶纯林 (44.14 mm), 极陡为针阔混交林 (60.50 mm) > 针叶纯林 (30.10 mm) > 针叶混交林 (25.21 mm)。可以看出, 缓坡和陡坡营造针叶纯林或针叶混交林水源涵养能力最佳, 极陡营造针阔混交林最佳。此外, 还可以看出土壤层是影响3个坡度下不同林分水源涵养能力的主体。

4 讨论

森林的枯落物层对降水的储蓄、产流及养分循环有着密切的关系, 枯落物层持水能力的大小与枯落物的组成、坡度、坡向、含水量、分解程度、积累量等因素密切相关^[1]。本研究表明, 缓坡针叶纯林总蓄积量显著大于针叶混交林和针阔混交林, 而在陡坡和极陡坡针叶纯林总蓄积量显著小于针叶混交林和针阔混交林。不同坡度枯落物蓄积量产生差异的原因主要是针叶纯林和针叶混交林凋落物自然含水量在缓坡较高, 微

生物活动频繁, 加快了凋落物分解速度, 而在陡坡和极陡坡坡面水分受重力作用, 使得凋落物自然含水量偏低, 凋落物分解速度缓慢, 造成不同坡度枯落物蓄积量有所不同^[19]; 此外, 由于不同林分类型枯落物组成的差异也会造成蓄积量的差异^[20]。

不同林分枯落物层持水能力与林分树种组成、枯落物自然含水量和蓄积量等多个因素密切相关^[21]。研究表明, 枯落物持水过程为吸水速率先迅速增加后逐渐减小, 直至饱和。这与梁晓娇等研究结果^[22-23]一致。此外, 本研究中3个林分陡坡和极陡坡处的枯落物最大持水量和最大拦蓄量均表现为针阔混交林显著大于其他两种林分, 这与赵锦梅等研究结果^[24]相同; 一方面原因是陡坡和极陡坡针阔混交林的蓄积量均比较大, 从而使得针阔混交林的最大持水量和拦蓄量均比较大。另一方面, 由于阔叶树种相比针叶拥有更大的表面积, 相同坡度下能够有效拦蓄降雨, 减少径流, 增加入渗^[25-26]。

土壤层作为森林生态系统水分储蓄的主要界面层, 其持水能力是度量退化坡地生态水文功能维持与恢复的重要指标^[27]。本研究中马尾松林持水能力的主体为土壤层, 这与王耀等人的研究结论^[28]一致。在缓坡和陡坡3种林分土壤最大持水能力大小排序依次为针阔混交林 > 针叶纯林 > 针叶混交林。这主要是针阔混交林中香樟大量的细根相较于针叶纯林更有利于维持其较高的养分和水分吸收能力^[29], 而杉木植被根系较浅, 不利于深层土壤水分的吸收, 因此针叶混交林土壤持水能力弱于针叶纯林和针阔混交林^[30-31]。土壤最大持水量对应总孔隙度, 研究结果表明极陡坡针叶纯林比针阔混交林土壤最大持水量大, 这主要是由于降雨过程中坡度越陡, 土壤越容易随水力搬运, 导致土壤持水能力下降^[32], 本研究中针叶纯林在极陡坡郁闭度相对较低, 林下灌草丰富, 土壤不容易受水流冲刷。研究表明在缓坡和陡坡针阔混交林土壤有效持水量小于针叶纯林和针叶混交林, 而极陡坡针阔混交林大于针叶混交林和针叶纯林, 这与贾秀红等对鄂中低丘山区针阔混交林土壤有效持水量大于针叶林的结果^[33]不同, 原因可能是缓坡和陡坡针阔混交林枯落物蓄积量较小, 且根系密度大, 土壤紧实, 使得非毛管孔隙度降低, 毛管孔隙度增加^[34]。凋落物分解后可促进土壤团粒的生成, 改善土壤结构, 提高土壤质地, 而土壤渗透系数的大小决定于土壤质地^[35], 本研究中土壤渗透系数表现为针叶混交林 > 针阔混交林 > 针叶纯林, 说明针

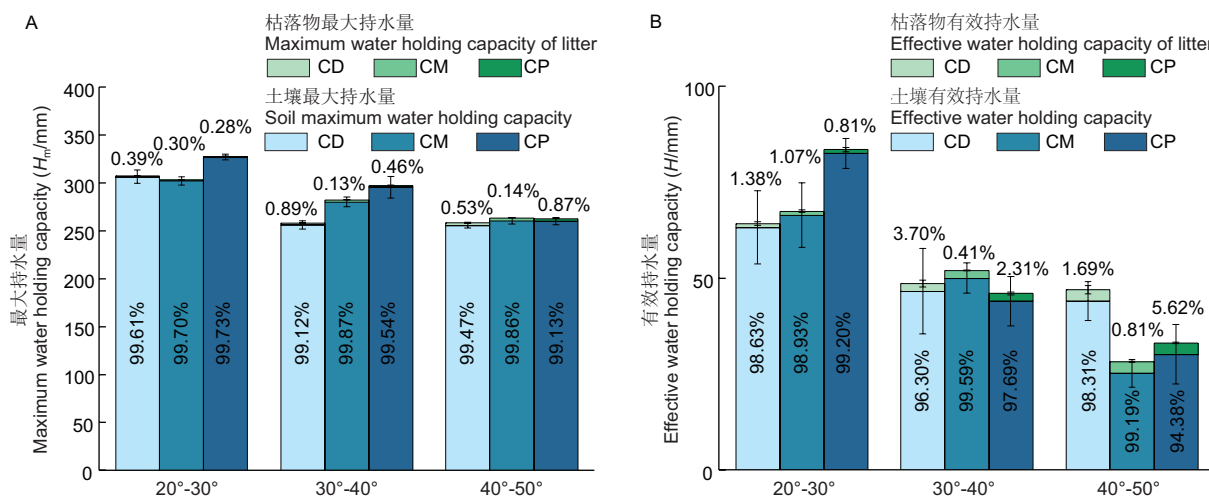


图6 3个坡度不同林分枯落物与土壤层最大持水量 (A) 和有效持水量 (B) 综合分析。CD: 针阔混交林; CM: 针叶混交林; CP: 针叶纯林。

Fig. 6 Comprehensive analysis of the maximum water holding capacity (A) and effective water holding capacity (B) of the litter and soil layer of three forests with different slopes. CD: Coniferous and broad-leaved mixed forest; CM: Coniferous mixed forest; CP: Coniferous pure forest.

叶混交林的凋落物分解程度大于针阔混交林和针叶纯林;而杉木根系较浅,浅层土壤根系密集,根系对水的吸收能力强,这也可能是导致土壤渗透系数增大的原因^[36-37]。

5 结论

(1) 在缓坡针叶纯林总蓄积量最大,而陡坡和极陡坡分别是针阔混交林和针叶混交林最大。不同坡度和分解层次枯落物最大拦蓄量和有效拦蓄量均为针阔混交林最大。

(2) 3个坡度土壤有效持水量为缓坡针叶纯林最大、陡坡针叶混交林最大和极陡坡针阔混交林最大。3个坡度土壤渗透系数均为针叶混交林最大,针阔混交林次之。

(3) 3个坡度不同林分综合有效持水量表现为缓坡针叶

纯林最高,陡坡针叶混交林最高,极陡坡针阔混交林最高。整体来说,3种林分水源涵养能力表现为缓坡和陡坡针叶混交林最佳,极陡坡针阔混交林最佳。

综上所述,本研究通过综合分析3个坡度下不同马尾松林分类型的枯落物和土壤层持水能力,结果表明,3种林分综合水源涵养能力在20°-40°坡针叶混交林和纯林更佳,在40°-50°坡针阔混交林最佳。研究结论将为实现坡面植被对位配置提供指导意见。但本研究林分枯落物和土壤层水文特征不仅受林分类型和坡度的影响,还与林龄和气候等外在因素有关,且本研究中采用的枯落物浸泡试验在反映林地枯落物的水文特征方面具有一定的局限性,因此,对于马尾松林地枯落物层和土壤层真实持水能力尚需进一步研究。

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