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南亚热带典型森林演替类型粗死木质残体贮量及其对碳循环的潜在影响

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摘 要 森林生态系统中的粗死木质残体(Coarse woody debris, CWD)不仅能够为其它生物提供生境,维持森林结构,而且对生物地球化学循环起着不可忽视的作用,CWD作为森林生态系统中重要的结构和功能元素,已经引起广泛关注。然而,华南地区典型亚热带森林生态系统中CWD的结构和功能方面的研究很少。该文报道了鼎湖山自然保护区内典型南亚热带森林生态系统中CWD的贮量及其特征,所选择的森林包括马尾松(*Pinus massoniana*)林、针阔叶混交林和季风常绿阔叶林,它们分别代表该气候区域内处于森林演替早期、中期和后期3个阶段的森林类型。其中马尾松林和针阔叶混交林都起源于20世纪30年代人工种植的马尾松纯林,由于长期受到包括收割松针、CWD和林下层植物等在内的人为活动的干扰,到2003年调查时马尾松林仍属于针叶林;而混交林样地自种植之后就未受到人为活动的干扰,自然过渡为针阔叶混交林类型。人为干扰对马尾松人工林的结构和功能产生了巨大的影响,马尾松林的生物量仅为针阔叶混交林生物量的35%。组成马尾松林、针阔叶混交林和季风常绿阔叶林CWD的树种数量分别为7、18和29;马尾松林中几乎没有CWD存在(贮量仅为0.1 Mg C·hm^{-2}),针阔叶混交林CWD的贮量为8.7 Mg C·hm^{-2},季风常绿阔叶林CWD的贮量为13.2 Mg C·hm^{-2},分别占地上部分生物量的9.1%和11.3%;针阔叶混交林和季风常绿阔叶林中只有将近10%的CWD以枯立的方式存在。该区域内CWD的分解速率较快,在区域碳循环中将扮演重要角色,保留林地中的CWD是维持本区域森林生产力和森林可持续管理的重要举措。

关键词 森林演替 碳贮量 人类干扰 亚热带森林 鼎湖山自然保护区

COARSE WOODY DEBRIS BIOMASS AND ITS POTENTIAL CONTRIBUTION TO THE CARBON CYCLE IN SUCCESSIONAL SUBTROPICAL FORESTS OF SOUTHERN CHINA

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Abstract Coarse woody debris (CWD) in forest ecosystems provides critical habitat for many organisms, maintains a healthy forest structure, and is important in the biogeochemical cycling of carbon and nutrients. However, the characteristics and ecological functions of CWD are poorly documented and understood in the subtropical forests of southern China. In this study, the amount and characteristics of CWD in three typical forest ecosystem types in southern China were investigated at the Dinghushan Nature Reserve. These forests were selected to form a successional sequence with a *Pinus massoniana* forest, a mixed coniferous broad-leaved forest, and a monsoon evergreen broad-leaved forest representing early-, mid-, and advanced-successional stages, respectively. Both the *Pinus massoniana* and the mixed coniferous broad-leaved forests developed on artificial *Pinus massoniana* plantations planted in the 1930s. Nevertheless, these two forests were at different successional stages. The *Pinus massoniana* forest was harvested for leaf/needle litterfall, CWD, and undergrowth until 1990 whereas human interventions were excluded in the mixed coniferous broad-leaved forest. Results indicated that human disturbance dramatically altered the successional process of the *Pinus massoniana* forest and its ecological functions. Total aboveground biomass was just 35% of that of the mixed coniferous broad-leaved forest. The number of tree species that contributed to CWD increased along the successional sequence with 7, 18, and 29 species in the *Pinus massoniana*, mixed coniferous broad-leaved, and monsoon evergreen broad-leaved forest sites, respectively. There was almost no CWD (0.1 Mg C·hm^{-2}) in the *Pinus*

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massoniana forest, while CWD amounted to 8.7 Mg C·hm^{-2} in the mixed coniferous broad-leaved forest and 13.2 Mg C·hm^{-2} in the monsoon evergreen broad-leaved forest, representing 9.1 % and 11.3 % of the total aboveground biomass, respectively. Only about 10 % of the CWD was standing in the mixed coniferous broad-leaved and the monsoon evergreen broad-leaved forests, suggesting that sudden forest canopy gaps created by falling or snapping of trees might be more important than gradual gaps formed by standing dead trees in the succession of these forests in this region. Although the decomposition rate of CWD was relatively fast, it was still comparable to that of the soil organic carbon in the region, suggesting that CWD can play an important role in the global carbon cycle. Keeping CWD on the forest floor is a critical strategy for maintaining forest productivity and implementing sustainable forest management in southern China.

Key words Forest succession, Carbon storage, Human impact, Subtropical forest, Dinghushan Nature Reserve

随着森林可持续经营管理的发展,粗死木质残体(Coarse woody debris, CWD)受到了广泛的关注。在全球范围内不同的森林类型、地形结构、年龄结构和干扰格局等前提下,围绕CWD的特征及其对生物量的贡献已经进行了大量研究(Harmon *et al*., 1986; Harmon & Chen, 1991; Spies *et al*., 1988; Hughes *et al*., 2000; Clark *et al*., 2002)。在CWD众多生态功能中,最为突出的是为其它生物提供生境以维持生物多样性和延续生物地球化学过程(Bowman *et al*., 2000; McKenny & Kirkpatrick, 1999; Harmon *et al*., 1990, 1994; Crowford *et al*., 1997; Amaranthus *et al*., 1994; Nakamura & Swanson, 1994)。

大量研究早已证明CWD是森林生态系统中的重要组成成分,在成熟森林中CWD的贮量往往占地上部分生物量的10 %~20 %(Muller & Liu, 1991; Harmon *et al*., 1993; Delaney *et al*., 1998),但在计算森林碳贮量的时候这一组分往往被忽略(Brown, 2002)。近20年来,全球范围内对CWD的研究迅速增加,相关的研究主要集中在中高纬度地区(如北美洲太平洋西北海岸的温带森林)(Carmona *et al*., 2003)和热带地区(Chambers *et al*., 2000, 2001)。相比之下,北回归线附近的森林CWD的相关报道较少(魏平等, 1997; 温达志等, 1998; 唐旭利等, 2003b)。

自20世纪50年代以来,在鼎湖山自然保护区围绕演替序列上的不同森林生态系统的组成、结构和动态早已开展了大量研究工作。早期关于森林动态的研究表明,由于受内源性干扰(如衰老和竞争引起的死亡)和外源性干扰(如台风和病虫害的爆发)(魏平等, 1997; 温达志等, 1998; 唐旭利等, 2003b)的综合影响,南亚热带典型森林生态系统的林地表面有大量CWD聚集。

本文报道了鼎湖山自然保护区中处于不同演替阶段的南亚热带典型森林生态系统CWD的贮量和特征。所选择的3个典型森林生态系统为:马尾松(*Pinus massoniana*)林、针阔叶混交林和季风常绿阔叶林,分别代表该区域处于演替早期、中期和后期的森林类型。其中马尾松林和针阔叶混交林均起源于20世纪30年代人工种植的马尾松林。马尾松林长期受到包括收集CWD、凋落物和收割林下层植物在内的人为活动的干扰(孔国辉和莫江明, 2002; 莫江明等,1997, 2001),这些干扰直到1990年才停止,而针阔混交林自种植以来就未受到过人为活动的干扰。基于上述背景,本研究的目的包括:1)量化这些森林生态系统中CWD的贮量及其特征,包括种类组成、分解状态等;2)初步评估长期的人为干扰(如收割CWD和凋落物)对森林演替和碳贮量可能的影响;3)研究演替序列上CWD贮量和特征的变化及对生态功能可能产生的影响。

1 研究地和方法

1.1 研究地概况

本研究在鼎湖山自然保护区内进行,鼎湖山自然保护区位于广东省中部(112°30′39″~33′41″E, 23°09′21″~23°11′30″N),西距广州84 km,保护区面积1 133 hm^2。鼎湖山自然保护区属于典型的南亚热带季风气候区,年平均降雨量1 927 mm,其中80 %分布在雨季(4~9月),旱季(10月~翌年3月)降雨量仅为年降雨量的20 %。年均温度21.4 ℃和相对湿度80 %。保护区内共有1 843种植物分属于267科877属(Kong *et al*., 1993)。

本文涉及到演替序列上的3种主要植被类型:演替初期的马尾松林,中期的针阔叶混交林和后期的季风常绿阔叶林。

1.2 CWD的调查

CWD的野外调查于2003年3月进行。调查在鼎湖山森林生态系统定位站所设立的3个永久样地内进行(表1)。本研究沿用前人的定义(魏平等,

1997; 温达志等,1998),将林地表面直径 ≥2.5 cm、长度 ≥1 m 的木质残体定义为 CWD,按调查时的存在状态分为枯立木和倒木 2 种类型。倒木测量长度和中央直径,枯立木测量胸径和高度。同时记录分解状态并鉴定树种。

我们沿用魏平等(1997)和温达志等(1998)研究季风常绿阔叶林 CWD 时在 Sollins(1982)的基础上制定的 5 级分类标准(表 2)。为了便于在不同演替阶段森林之间对 CWD 进行比较,本研究将分解等级为Ⅰ、Ⅱ的 CWD 合并为"轻度分解",Ⅲ、Ⅳ的 CWD 合并为"中度分解",这样本文涉及到 3 个分解等级:"轻度分解(表 2 中 Ⅰ、Ⅱ级)"、"中度分解(表 2 中 Ⅲ、Ⅳ级)"、和"高度分解(表 2 中 Ⅴ级)"。

1.3　CWD 的体积和贮量

CWD 的体积按圆柱体公式计算,贮量用体积和平均密度换算(温达志等,1998; 魏平等, 1997),C 贮量由贮量和平均 C 含量换算而成,本研究取平均 C 含量 51.02 %。

2　结　果

2.1　CWD 贮量

鼎湖山不同演替阶段森林 CWD 的碳贮量变化范围在 0.1～13.2 Mg C·hm^{-2}(表 3)之间。CWD 贮量变化与生物量相似,表现为随演替进程而增加的趋势,处于演替初期的马尾松林无论生物量还是 CWD 贮量都最小,而处于演替后期的顶级森林类型

表 1　样地概况
Table 1　Description of study sites

林型 Forest type	演替阶段 Successional stage	林龄 Stand age (a)	受保护时间 Years under protection (a)	样地面积 Plot size (m^2)	生物量 Biomass (Mg·hm^{-2})
马尾松林 *Pine massoniana* forest	早期 Early-succession	70	～14 (莫江明等, 1997, 2001; 孔国辉和莫江明, 2002)	10 000	60～80 (彭少麟和方炜, 1995)
针阔叶混交林 Mixed coniferous broud-leaved forest	中期 Mid-succession	70	70	1 200	261～283 (彭少麟和张祝平, 1994; 方运霆等, 2003)
季风常绿阔叶林 Monsoon evergreen broad-leaved forest	后期 Advanced-succession	> 400	> 400 (魏平和温达志, 1999)	10 000	308[1)]

1) 根据彭少麟和方炜(1995),彭少麟和张祝平(1994),温达志等(1997)报道生物量的结果计算的平均值 Mean biomass calculated based on Peng & Fang (1995), Peng & Zhang (1994), Wen *et al*. (1997)

表 2　鼎湖山 CWD 分解等级划分标准[1)]
Table 2　Classification system of CWD decay classes in forests at Dinghushan Nature Reserve

特征 Character	分解等级 Decay class				
	轻度分解 Early		中度分解 Intermediate		高度分解 Advanced
	Ⅰ	Ⅱ	Ⅲ	Ⅳ	Ⅴ
叶 Leaves	存在 Present	-	-	-	-
枝 Branches and twigs	直径小于 3 cm 的细枝尚存,粗枝完整 Twigs less than 3 cm present, large branches keep intact	直径小于 3 cm 的细枝部分存在,粗枝完整 Twigs less than 3 cm partly present, large branches keep intact	无细枝,粗枝部分存在,大部分断裂 Absent of twigs, large branches present, but mostly broken	无细枝,粗枝部分存在 Absent of twigs, large branches partly present	-
皮 Bark	完整,坚固 Intact, tight	基本完整,坚固 Intact on the whole, tight	部分存在,松弛 Partly present, loose	少量,松弛 Trace present, loose	-
木质结构 Wood consistency	坚固 Solid	坚固 Solid	较坚固 Semi-solid	部分坚固,易破裂 Party solid, breakable	松软,易破碎为粉末状 Soft, powdery
苔藓和真菌 Moss and fungi	-	覆盖面积小于表面积的 25 % Cover less than 25 % of surface area	覆盖面积为表面积的 25 %～50 % Cover 25 % - 50 % of surface area	覆盖面积超过表面积的 50 % Cover more than 50 % of surface area	覆盖面积超过表面积的 50 % Cover more than 50 % of surface area
根系入侵 Invading root	-	-	-	边材部分可见 In sapwood	心材部分可见 In heartwood

1) 根据温达志等(1998)和魏平等 (1997)基于 Sollins(1982)制定的标准 Adapted from Sollins (1982) and following Wen *et al*. (1998) and Wei *et al*. (1997)

表 3 鼎湖山演替序列典型森林生态系统 CWD 的贮量

Table 3 Estimation CWD biomass in successional forests at Dinghushan Nature Reserve

		演替阶段 Successional stage		
		早期(马尾松林) Early (*Pine massoniana* forest) 1)	中期(针阔叶混交林) Middle (Mixed coniferous broad-leaved forest)	后期(季风常绿阔叶林) Advanced (Monsoon evergreen broad-leaved forest) 2)
植被碳贮量 Total living biomass (Mg C·hm^{-2})		40.605	116.180	147.80
CWD 碳贮量 CWD biomass (Mg C·hm^{-2})	枯立木 Snags	0.054 (0.071)	0.885 (0.604)	1.896 (0.026)
	倒木 Logs	0.048 (0.068)	7.827 (5.814)	11.316 (0.239)
	合计 Total	0.102 (0.095)	8.712 (5.672)	13.210 (0.239)

1) 数据引自彭少麟和方炜 (1995) Data from Peng & Fang (1995) 2) 数据引自温达志等 (1997) Data from Wen *et al*. (1997) 括号内数值为标准差 Standard error in parenthesis

季风常绿阔叶林拥有最大生物量和 CWD 贮量。CWD 作为一个 C 库,其重要性亦随森林演替进程而趋显著: CWD 的贮量占地上部分生物量在马尾松林、针阔叶混交林、季风常绿阔叶林中的比例分别为 0.3 %,9.1 %和 11.3 %。

2.2 枯立木与倒木的比例

不同森林类型 CWD 的存在形式有较大差异:马尾松林中枯立木与倒木的贮量比例接近 1,枯立木的贮量占 CWD 总贮量的 53 %,倒木的贮量占总贮量的 47 %。针阔叶混交林和季风常绿阔叶林中倒木所占的比例较大,倒木的贮量分别占 CWD 总贮量的 90 %和 87 %。

2.3 CWD 的贮量的腐烂等级分布特征

CWD 的分解格局随演替进程而变化(图 1),总体上中度分解 CWD(表 2 中 III、IV级)的比例随演替序列呈增加的趋势,马尾松林中等分解状态 CWD 的比例仅为 3.5 %,针阔叶混交林和季风常绿阔叶林中等分解状态 CWD 分别占 CWD 总量的 36.1 %和 66.7 %。马尾松林中超过 95 %的 CWD 都处于轻度分解状态(表 2 中 I、II级),调查中没有发现处于高度分解状态的 CWD。针阔叶混交林高度腐烂状态(表 2 中 V级) CWD 占 CWD 总贮量的 49 %,比季风常绿阔叶林高,后者仅为 6 %。

2.4 CWD 的组成结构

马尾松林、针阔叶混交林、季风常绿阔叶林 CWD 的分别由 7、18、29 种树种组成。每个森林类型的 CWD 贮量都由少数"优势种"控制(表 4)。马尾松林 CWD 的主要优势种为马尾松,占 CWD 总贮量的 88 %,其次为桃金娘(*Rhodomyrtus tomentosa*) 和三叉苦(*Evodia lepta*) 分别占 CWD 总贮量的 6 %和 4 %,其余 4 个种的 CWD 仅占总贮量的 2 %。针阔叶混交林 CWD 库的主要"优势种"亦为马尾松,占总贮量的 79 %,阔叶树种占的比例较少,如豺皮樟(*Litsea rotundifolia*) 和黄果厚壳桂(*Cryptocarya concinna*) 占 CWD 总贮量比例分别为 7 %和 5 %。季风常绿阔叶林 CWD 的主要优势种为黄果厚壳桂,占系统 CWD 贮量的 47 %,其次为锥栗(*Castanpsis chinensis*)、厚壳桂(*Cryptocarya chinensis*)、荷木(*Schima superba*) 和其它 25 种,占 CWD 贮量的比例分别为 26 %、13 %、8 %和 6 %。

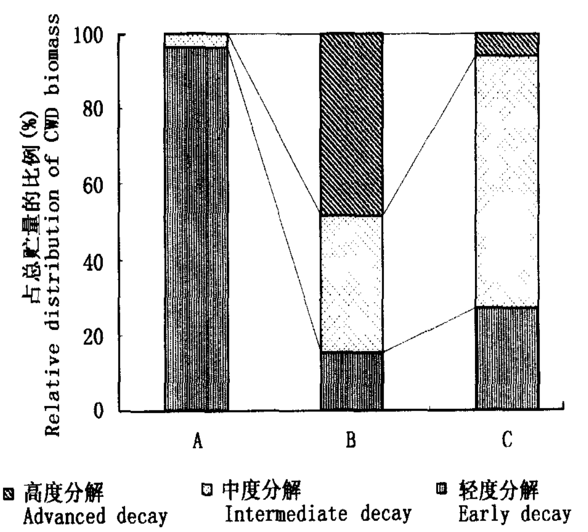

图 1 不同分解状态 CWD 的比例

Fig. 1 Relative distribution of CWD biomass among decay states in successional forests at Dinghushan Nature Reserve

A: 马尾松林 *Pinus massoniana* forest B: 针阔叶混交林 Mixed coniferous broad-leaved forest C: 季风常绿阔叶林 Monsoon evergreen broad-leaved forest

马尾松是马尾松林和针阔叶混交林 CWD 库的主要"优势种",但二者在分解状态上存在较大的差异,马尾松林中超过 95 %的马尾松 CWD 都处于轻度分解状态,中等分解状态的马尾松 CWD 不足 5 %,针阔叶混交林马尾松 CWD 中 61 %处于高度分解状态,33 %处于中度分解状态,轻度分解状态的仅

表4　CWD的种类组成
Table 4　Species classification of CWD

林型 Forest type	树种 Species	CWD 贮量 CWD biomass ($Mg\ C \cdot hm^{-2}$)	比例 Percentage (%)
马尾松林 *Pine massoniana* forest	马尾松 *Pinus massoniana*	0.088	88
	桃金娘 *Rhodomyrtus tomentosa*	0.006	6
	三叉苦 *Evodia lepta*	0.004	4
	其余4种 Other 4 species	0.002	2
针阔叶混交林 Mixed Coniferous broad-leaved forest	马尾松 *Pinus massoniana*	6.900	79
	豺皮樟 *Litsea rotundigfolia*	0.600	7
	黄果厚壳桂 *Cryptocarya concinna*	0.500	5
	其余15种 Other 15 species	0.800	9
季风常绿阔叶林 Monsoon evergreen broad-leaved forest	黄果厚壳桂 *Cryptocarya concinna*	6.200	47
	锥栗 *Castanpsis chinensis*	3.400	26
	厚壳桂 *Cryptocarya chinensis*	1.700	13
	荷木 *Schima superba*	1.000	8
	其余25种 Other 25 species	0.900	6

占6%。

2.5　CWD的径级结构

本研究涉及的3个林型中枯立木和倒木的数量都随径级的增加而减少。针阔叶混交林的倒木和枯立木,以及季风常绿阔叶林的倒木数量都随径级增加呈指数减少,季风林倒木数量的径级变化趋势不太明显(图2)。

直径小于10cm的木质残体是演替初期阶段森林CWD的主要构成元素,随着演替地进行,其优势度下降。马尾松林中,直径小于10 cm的木质残体占枯立木总量的89%,倒木总量的96%;针阔叶混交林中,相应的比例为82%和75%;季风常绿阔叶林则为29%和61%。

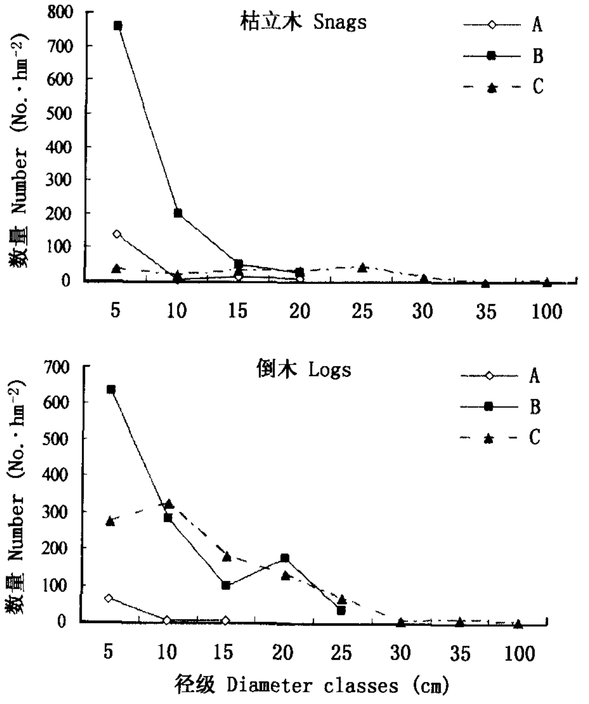

图2　不同演替阶段森林CWD数量的径级分布格局
Fig.2　The number of CWD by diameter classes in successional forests at Dinghushan Nature Reserve
A、B、C:见图1 See Fig.1

3　讨　论

3.1　CWD的特征与森林演替

本研究报道的倒木最大碳贮量(即演替顶级的季风常绿阔叶林的倒木贮量)为11.32 $Mg\ C \cdot hm^{-2}$(表5),这一结果介于北美洲的针叶林、北美落叶阔叶林和南美落叶阔叶林倒木贮量之内(Spies *et al*., 1988;Harmon *et al*., 1986;Carmona *et al*., 2002),高于澳大利亚低地热带雨林的倒木贮量(Grove, 2001),亦高于委内瑞拉除热带山地湿润林以外其它5种热带雨林的平均值(Delaney *et al*., 1998)。

本文所报道的3种演替阶段森林枯立木的贮量低于热带、温带和寒带地区其它森林类型的报道结果,说明本区域的干扰格局不同于其它地区。据报道,由积雪覆盖、积压,以及病虫害等因素引起的树木死亡是导致中高纬度森林存在大量枯立木的主要原因(Veblen & Alaback, 1996; Dobbertin *et al*., 2001)。台风和山体滑坡是鼎湖山自然保护区最常见的灾害性环境干扰因子,在引起树木倒塌死亡的同时,常常伴随突发性林窗的形成。因此,在鼎湖山自然保护区森林演替过程中,突发性林窗的重要性远远超过渐进的树木死亡而形成的林窗,这一结果与热带森林中的研究结论一致(Clark *et al*., 2002)。

表5 不同森林生态系统CWD贮量的比较

Table 5 Comparison of CWD biomass in various forest ecosystems

地区及森林类型 Region and forest type	演替阶段 Successional stage	CWD贮量 CWD biomass (Mg C·hm^{-2}) 倒木 Logs 平均值 Mean	倒木 Logs 范围 Range	枯立木 Snags 平均值 Mean	枯立木 Snags 范围 Range	参考文献 References
北美(西海岸)针叶林 Coniferous forest, North American (West coast)	早期-中期 Early-mid (40～195)	16.50	7.00～26.00	13.50	9.50～20.00	Spies *et al*., 1988
	老龄 Old-growth (200～900)	31.50	27.00～36.80	27.00	20.50～31.50	Spies *et al*., 1988
北美落叶林 Deciduous forest, North American	早期-中期 Early-mid (10～83)	8.00	2.50～16.00	3.50	2.00～6.00	Harmon *et al*., 1986
	老龄 Old-growth (200 to >300)	12.50	8.00～19.00	5.50	-	Harmon *et al*., 1986
美国(Harvard森林)针叶林和落叶林 Coniferous and deciduous forest, America (Harvard forest)	针叶林 Coniferous forest (N/A)	20.40	-	-	-	Currie & Nadelhoffer, 2002
	落叶林 Deciduous forest (N/A)	13.80	-	-	-	Currie & Nadelhoffer, 2002
智利常绿阔叶林 Evergreen broad-leaved forest, Chile	早期-中期 Early-mid (11～112)	15.00	4.50～21.00	29.50	2.50～84.00	Carmona *et al*., 2002
	老龄 Old-growth (133～200)	23.50	15.50～32.50	63.00	6.50～174.50	Carmona *et al*., 2002
中国华南地区南亚热带演替序列森林 Successional subtropical forests, Southern China	早期 Early (70～80)	0.05	-	0.05	-	本文 This study
	中期 Middle (70～80)	7.80	-	0.90	-	本文 This study
	老龄 Old-growth (>400)	11.30	-	1.90	-	本文 This study
澳大利亚低地热带雨林 Lowland tropical rainforest, Australian	老龄 Old-growth (N/A)	4.70	-	1.80	-	Grove, 2001
	砍伐后森林 Forest after logging (N/A)	3.60	-	4.70	-	Grove, 2001
	次生林 Secondary forest (>90)	2.50	-	1.80	-	Grove, 2001
委内瑞拉热带荆棘林 Tropical thorn woodland, Venezuela		0.70	0.06～1.37	1.20	0.33～2.10	Delaney *et al*., 1998
委内瑞拉热带干热森林 Tropical very dry forest, Venezuela		1.45	0.99～1.66	2.40	2.09～2.70	Delaney *et al*., 1998

表 5 (续)　Table 5 (continued)

地区及森林类型 Region and forest type	演替阶段 Successional stage	CWD 贮量 CWD biomass (Mg C·hm⁻²)				参考文献 References
		倒木 Logs		枯立木 Snags		
		平均值 Mean	范围 Range	平均值 Mean	范围 Range	
委内瑞拉热带干湿过渡森林 Tropical moist transition dry forest, Venezuela		1.40	0～5.70	3.30	1.26～6.95	Delaney *et al*.,1998
委内瑞拉热带湿润森林 Tropical moist forest, Venezuela		7.40	0～22.60	16.70	10.90～27.60	Delaney *et al*.,1998
委内瑞拉热带低山湿润森林 Tropical lower montane moist forest, Venezuela		10.70	4.10～26.30	21.20	10.32～38.31	Delaney *et al*.,1998
委内瑞拉热带山地湿润森林 Tropical montane wet forest, Venezuela		13.20	2.95～23.40	17.30	6.73～27.73	Delaney *et al*.,1998

表 6　不同森林类型土壤微生物数量及其组成(10^6 ·g⁻¹干土) (引自周丽霞等, 2002)

Table 6　Amount and composition of soil microbes in successional forests (10^6 ·g⁻¹ dry soil) (from Zhou *et al*., 2002)

土壤微生物 Soil microbe		马尾松林 *Pinus massoniana* forest	针阔叶混交林 Mixed coniferous broad-leaved forest	季风常绿阔叶林 Monsoon evergreen broad-leaved forest
微生物数量 Microbe amount		1.168 0	1.365 0	2.085 0
细菌 Bacteria	数量 Amount	1.034 0	1.157 0	1.953 0
	百分比 Percentage (%)	88.53	84.76	93.67
真菌 Fungi	数量 Amount	0.097 3	0.122 0	0.066 0
	百分比 Percentage (%)	8.30	8.94	3.17
放线菌 Actinomycetes	数量 Amount	0.036 9	0.086 2	0.066 0
	百分比 Percentage (%)	3.17	6.30	3.17

对处于不同演替阶段森林 CWD 贮量的研究表明,CWD 的贮量随演替的进行呈增加的趋势。这一结果与温带森林类似研究报道的结果存在差异,温带森林 CWD 的最高贮量出现在刚刚受到干扰森林(Idol *et al*.,2001; Spetich *et al*., 1999; Spies *et al*., 1988; Carmona *et al*., 2002)。这一差异一方面与前述导致 CWD 形成的干扰因素有关,另一方面也与干扰的频率有关。本研究中的马尾松林受到持续的人为干扰长达 60 年之久。

根据早期报道,一个由锥栗倒伏形成的面积为 270 m² 的林窗范围内 CWD 的贮量为 3.8 Mg C(唐旭利等,2003b)。在调查过程中也发现林下 CWD 的量远少于林窗范围内 CWD 的量。这与温带老龄森林中 CWD 的发生频率呈偏态分布趋势一致(Muller, 2003)。

季风常绿阔叶林 CWD 的种类组成也反映出林冠上层树种的竞争,但是这种关系不显著。锥栗是季风常绿阔叶林上层优势乔木,其生物量占地上部分总生物量的 31 %(唐旭利等,2003a),但其对 CWD 库的贡献居于黄果厚壳桂之后。这一结果与 Muller (2003) 报道的温带老龄森林的结果一致。

3.2　长期收获 CWD 对系统结构和功能的影响

早期关于人类活动对 CWD 影响的研究侧重于木材收获(皆伐和择伐)引起的结果(Harmon *et al*., 1986; Spies *et al*., 1988; Sturtevant *et al*., 1997; Carmona *et al*., 2002; Rouvinen *et al*., 2002),尚未见长期连续收获 CWD 和凋落物(落叶)对生态系统演化过程中的结构和生态功能的影响的报道。CWD 和凋落物是世界上很多地区,尤其是华南地区薪柴的主要来源(Smil, 1983; Brown *et al*., 1995; Kimoto *et al*., 2002),本研究所报道的结果在一定程度上有助于评价这一常见的人类活动所引起的生态后果。针阔叶混交林 CWD 的贮量可以反映本区域内 20 世纪 30 年代人工种植的马尾松纯林在未受到人为干扰(收获 CWD 和收割林下凋落物)情况下 CWD 的水平。马尾松林 CWD 的贮量则可以代表自 20 世纪 30 年代种植以来至 20 世纪 90 年代初期持续受人类活动干扰的马尾松林 CWD 的水平。

大量的研究表明,CWD 是维持森林生态系统生物多样性的重要组分(Harmon *et al*.,1986; Aumen, 1990; France ,1997)。本研究区域内,针阔叶混交林的生物多样性指数远远高于马尾松林的生物多样性指数,据报道二者的 Shanner-Wiener 指数分别为 2.7 和 1.1(黄忠良等,1998);土壤微生物总量和细菌在 3 大类微生物中所占的比例亦是针阔叶混交林高于马尾松林(周丽霞等,2002)(表 6);针阔叶混交林地表无脊椎动物的多样性指数(1.94)是马尾松林(0.42)的 4 倍(徐国良等,2002)。上述比较表明收获 CWD 可能减少本区域森林生态系统植物、微生物和土壤动物的生境。

3.3 CWD 的分解速率

我们利用本次调查的资料结合早期报道的结果(魏平等, 1997; 温达志等, 1998),运用单指数衰减方程 $k = -\ln(X_t/X_0)/t$ (Olson, 1963)估算 CWD 的分解速率 k。式中 X_0 是起始时间 CWD 的贮量,在这里为 1992 年 CWD 贮量, t 时刻 CWD 的贮量 X_t 在这里为 2003 年 CWD 贮量(本文报道的结果)。估算出 CWD 的分解速率常数为 0.031 a^{-1},CWD 的平均周转时间为 32 年。这一结果高于大多数研究报道的结果(Johnson & Greene, 1991; Busse, 1994; Graham & Cromack, 1982; Grier, 1978; Means *et al*., 1985; Fahey, 1983; Foster & Lang, 1982; Tyrrell & Crow, 1994),但低于用 Chambers 公式(Chambers *et al*., 2000)计算得到的结果(0.102 a^{-1})。我们认为 Chambers 公式没有考虑降水对分解的影响,仅将温度作为影响 CWD 分解的限制因子,对全球区域范围内进行 CWD 分解速率进行对比研究忽略降水的影响是可行的,然而,对于小尺度范围内的 CWD 分解的研究,有必要将温度和降水结合起来考虑。

3.4 CWD 对碳循环潜在的影响

大量的研究表明成熟森林 CWD 贮量占地上部分生物量的 10 %～20 % (Muller & Liu, 1991; Harmon *et al*., 1993; Delaney *et al*., 1998)。本研究的结果亦证明 CWD 是处于不同演替阶段森林,尤其是地带性顶级植被类型季风常绿阔叶林不可忽略的 C 库。

CWD 作为碳库,其重要性不仅仅体现在贮量方面,由于 CWD 的分解速率较慢,在林地表面存留时间相对较长。Mackensen 和 Jürgen (2003)报道澳大利亚 57 %以上的 CWD 的分解时间都超过 40 年,这一结果远远大于 IPCC 计算分解采用的默认分解时间(默认值为 10 年)。本研究的计算结果(32 年)亦比 IPCC 采用的默认时间长。由此可见,CWD 对森林生态系统 C 循环的影响是一个缓慢的过程,有必要对其进行长期的量化研究。

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