

# 天童国家森林公园植被碳储量估算\*

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**摘要** 以典型木荷-栲树群落、含苦槠的木荷-栲树群落、含杨梅叶蚊母树的木荷-栲树群落、披针叶茴香-南酸枣群落、枫香-马尾松群落、黄毛耳草-毛竹群落 6 种群落类型样地实测数据为基础,结合文献资料汇总,采用生物量相对生长方程法,研究了天童国家森林公园森林生态系统的植被碳储量、碳密度及其组分和空间分布特征。结果表明:野外调查的 6 种群落类型中,含苦槠的木荷-栲树群落碳储量(12113.92 Mg C)和碳密度(165.03 Mg C · hm<sup>-2</sup>)均最高,披针叶茴香-南酸枣群落碳储量最低(680.95 Mg C),其碳密度为 101.26 Mg C · hm<sup>-2</sup>。各群落类型中,常绿树种的碳储量均显著高于落叶树种,其碳密度范围分别为 76.08 ~ 144.95 和 0.16 ~ 20.62 Mg C · hm<sup>-2</sup>。各群落类型的乔木层各组分中,植株干的碳储量均最高。各林分类型中,常绿阔叶林碳储量最高,为 23092.39 Mg C,占天童林区森林生态系统碳储量的 81.7%,碳密度为 126.17 Mg C · hm<sup>-2</sup>。天童国家森林公园植被总碳储量为 28254.22 Mg C,碳密度为 96.73 Mg C · hm<sup>-2</sup>。

**关键词** 生物量 植被碳储量 碳密度 生物量相对生长方程 常绿阔叶林

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**Estimation for vegetation carbon storage in Tiantong National Forest Park.** GUO Chun-zi<sup>1,2,3</sup>, WU Yang-yang<sup>1,2,3</sup>, NI Jian<sup>1,2,3</sup> (<sup>1</sup>Department of Environmental Science, East China Normal University, Shanghai 200241, China; <sup>2</sup>Zhejiang Tiantong National Forest Ecosystem Observation and Research Station, Ningbo 315114, Zhejiang, China; <sup>3</sup>State Key Laboratory of Environmental Geochemistry, Institute of Geochemistry, Chinese Academy of Sciences, Guiyang 550002, China). -Chin. J. Appl. Ecol., 2014, 25(11): 3099-3109.

**Abstract:** Based on the field investigation and the data combination from literature, vegetation carbon storage, carbon density, and their spatial distribution were examined across six forest community types (*Schima superba* - *Castanopsis fargesii* community, *S. superba* - *C. fargesii* with *C. sclerophylla* community, *S. superba* - *C. fargesii* with *Distylium myricoides* community, *Illicium lanceolatum* - *Choerospondias axillaris* community, *Liquidambar formosana* - *Pinus massoniana* community and *Hedyotis auricularia* - *Phylostachys pubescens* community) in Tiantong National Forest Park, Zhejiang Province, by using the allometric biomass models for trees and shrubs. Results showed that: Among the six communities investigated, carbon storage and carbon density were highest in the *S. superba* - *C. fargesii* with *C. sclerophylla* community (storage: 12113.92 Mg C; density: 165.03 Mg C · hm<sup>-2</sup>), but lowest in the *I. lanceolatum* - *C. axillaris* community (storage: 680.95 Mg C; density: 101.26 Mg C · hm<sup>-2</sup>). Carbon storage was significantly higher in evergreen trees than in deciduous trees across six communities. Carbon density ranged from 76.08 to 144.95 Mg C · hm<sup>-2</sup>, and from 0.16 to 20.62 Mg C · hm<sup>-2</sup> for evergreen trees and deciduous trees, respectively. Carbon storage was highest in stems among tree tissues in the tree layer throughout communities. Among vegetation types, evergreen broad-leaved forest had the highest carbon storage (23092.39 Mg C), accounting for 81.7% of the total carbon storage in all forest types, with a carbon density of 126.17 Mg C · hm<sup>-2</sup>. Total carbon storage for all vegetation types in Tiantong Na-

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tional Forest Park was 28254.22 Mg C, and the carbon density was 96.73 Mg C · hm<sup>-2</sup>.

**Key words:** biomass; vegetation carbon storage; carbon density; allometric biomass equation; evergreen broad-leaved forest.

全球气候变暖已经成为全球变化中最主要的环境问题,森林作为地球上面积最大、碳储量最高的陆地生态系统,在生物圈与大气圈的物质循环中起着决定性作用,巨大的储碳能力和高效的生产力使森林生态系统在全球碳循环中处于主导地位<sup>[1]</sup>.为了有效控制温室气体排放、减缓全球变暖进程,必须进一步明确森林碳库的现状及其在当前和未來全球碳循环中的地位<sup>[2]</sup>.

全球尺度的碳研究已成为研究者关注的热点问题<sup>[2-4]</sup>.美国和欧洲的研究者用不同方法分别对不同地区陆地生态系统碳储量和碳吸收进行估算<sup>[5-7]</sup>,并探讨自然和人为因素对碳汇和碳循环的影响.在过去的20年里,我国的生态学者也根据野外调查资料,运用不同方法和手段,估算了中国森林生态系统以及各省份森林植被的生物量、碳储量和碳密度,并对其变化特征进行分析<sup>[8-14]</sup>.目前,国内外应用最广泛的森林碳储量估算方法主要有样地生物量调查法、森林清查法、涡度相关法和应用遥感等新技术的模型模拟法<sup>[15]</sup>.其中,基于样地实测数据的生物量调查法和森林资源清查法应用广泛,前者基于标准木的生物量相对生长方程,能够在小尺度上精确估算森林植被生物量,从而获取其碳储量和碳密度;后者利用换算因子连续函数法估算区域尺度的森林生物量及碳储量,并得到了普遍应用和较高评价<sup>[9,16]</sup>.然而,由于研究区域的广泛性与复杂性以及计量方法的差异性,导致对全球范围或大尺度区域森林碳储量的估算差异较大<sup>[10,17-18]</sup>.因此,分别研究不同区域和不同植被类型的碳储量,对大尺度区域碳储量估算至关重要<sup>[19]</sup>.在样地尺度上基于野外监测数据,利用生物量相对生长方程估算群落类型的生物量和碳储量,从而估算较大尺度的植被碳储量,将为更加精确地估算区域尺度碳储量(包括土壤碳储量)奠定良好的数据和方法基础.

我国东部常绿阔叶林群落结构复杂,具有丰富的生物多样性和巨大的环境效益<sup>[20]</sup>.由于东部地区人口稠密、经济发达,常绿阔叶林的存在与发展对于保持该地区的水土、调节区域生态系统平衡以及减少温室气体的排放等都具有重要作用.因此,准确估算该地区森林生态系统的碳储量现状,对其固碳潜力作出评价,既可为制定森林增汇措施提供理论依

据,又有利于促进林业碳汇交易的发展.为此,本文以我国东部中亚热带常绿阔叶林区域为研究对象,选择浙江省东部天童国家森林公园为研究区域,在样地实测数据的基础上,利用生物量相对生长方程,对天童林区的森林生态系统碳储量现状进行估算,并对其碳密度和碳储量空间分布进行分析,旨在为我国区域尺度的森林碳储量和碳循环研究提供基础数据.

## 1 研究地区与研究方法

### 1.1 研究区概况

天童国家森林公园(29°48' N, 121°47' E)位于中国中东部沿海,属浙东丘陵和宁绍平原的一部分,面积349 hm<sup>2</sup>.公园三面环山,主峰太白山,海拔约653.3 m,园内平均海拔约300 m.坡度主要在10~30°,鲜有45°以上陡坡.该地区属典型亚热带季风气候,年均温度16.2℃,年均降水量1374.7 mm.由于长期以来人为干扰相对较少,气候和土壤条件相对比较优越,自然植被保存较好,因此该区域成为浙江省东部丘陵地区地带性植被类型的代表地段.区域内的主要群落类型可划分为(图1):常绿阔叶林、常绿落叶阔叶混交林、落叶阔叶林、常绿针叶林、毛竹林和次生山地灌丛<sup>[21]</sup>.

### 1.2 样地设置与调查

在天童国家森林公园中选择6种代表性森林群落类型:典型木荷-栲树群落、含苦槠的木荷-栲树群落、含杨梅叶蚊母树的木荷-栲树群落、披针叶茴香-南酸枣群落、枫香-马尾松群落、黄毛耳草-毛竹群落.采用标准样方调查法,2012年7—9月开展详细的群落调查.每种群落类型设置3个20 m × 20 m标准样地,共计18个样地(图1),同时每个标准样地中设置4个灌木层样方,面积5 m × 5 m;在每个灌木层样方中设置草本样方1个,面积2 m × 2 m.记录样地海拔、地理位置、地形、坡度等样地基本信息.调查分乔木层、灌木层和草本层3层进行.乔木层调查记录树高≥1.3 m植株的种类、枝下高、高度、胸径、基径和冠幅;灌木层记录植株的种类、高度、基径和盖度;草本层记录植株种类、高度和盖度.本次调查中未涉及层间植物.群落组成、结构和生物多样性的变化特征见文献<sup>[22]</sup>.本文重点探讨群落与植被生

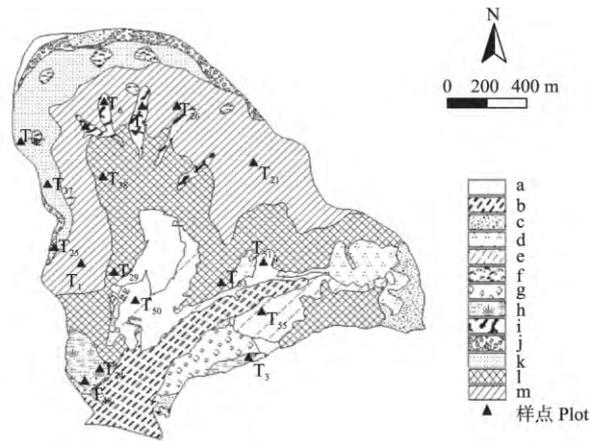


图1 天童国家森林公园植被类型及样地位置

Fig.1 Vegetation and location of sampling sites in Tiantong National Forest Park.

a) 非林区 Non-forest area; b) 杜鹃-白栎群落 *Rhododendron simsii* - *Quercus fabric* community; c) 马尾松人工幼林 *Pinus massoniana* young plantation; d) 枫香-杉木群落 *Liquidambar formosana* - *Cunninghamia lanceolata* community; e) 黄毛耳草-毛竹群落 *Hedyotis auricularia* - *Phyllostachys pubescens* community; f) 长叶石栎-雷公鹅耳枥群落 *Lithocarpus henryi* - *Carpinus viminea* community; g) 化香-枫香群落 *Platycarya strobilacea* - *L. formosana* community; h) 枫香-马尾松群落 *L. formosana* - *P. massoniana* community; i) 披针叶茴香-南酸枣群落 *Illicium lanceolatum* - *Choerospondias axillaris* community; j) 长叶石栎-云山青冈群落 *Lithocarpus henryi* - *Cyclobalanopsis sessilifolia* community; k) 含杨梅叶蚊母树的木荷-栲树群落 *Schima superba* - *Castanopsis fargesii* with *Distylium myricoides* community; l) 含苦槠的木荷-栲树群落 *S. superba* - *C. fargesii* with *C. sclerophylla* community; m) 典型木荷栲树群落 *S. superba* - *C. fargesii* community.

物量和碳储量的特征.

### 1.3 群落生物量的估算

样地各层生物量均采用生物量相对生长方程法进行估算. 生物量相对生长方程, 也称为异速生长方程或维量分析法, 是对植株结构和功能特征指标 (如材积、生物量等) 与易于测量的植株形态学变量 (如胸径、树高等) 间数量关系的统称<sup>[23-25]</sup>. 在森林生态系统的生物量和生产力估算中, 相对生长方程是最常见的方法<sup>[26]</sup>. 国内外科学家已经广泛使用相对生长方程来测定全球不同区域的各种森林类型的生物量. 针对亚热带常绿阔叶林树种, 研究者们建立了大量不同物种的生物量相对生长方程. 通过查阅大量文献, 收集和总结了适用于我国东部典型常绿阔叶林的生物量相对生长方程, 包括部分灌木和草本植物, 作为本研究中植被生物量估算的基础 (表1). 由于这些模型不能涵盖天童林区所有物种, 因此按照简单易操作的原则, 根据叶候、生活型、冠层将研究区域内的物种划分为若干植物功能型 (plant functional types, PFTs), 对缺失生物量相对生长方程的物种用同一植物功能型物种的模型来代替, 减少

物种参数, 优化模型结构, 提高了模型的可行性和运算效率. 通过这些处理, 样地调查中所有出现的物种都有相应的相对生长方程来估算其生物量. 由于各模型变量的单位不尽相同, 在具体计算过程中需要进行单位转换.

植株生物量由地上生物量和地下生物量组成, 对于缺少地下生物量模型的植株, 其地下生物量值采用李高飞和任海<sup>[27]</sup>所计算的亚热带常绿阔叶林地上与地下生物量比值 (4.39) 进行估算.

### 1.4 森林生态系统植被碳储量的计算

森林生态系统的植被碳储量包含乔木层、灌木层和草本层的碳储量. 森林碳储量为森林生物量 (干质量) 乘以转换系数 (即含碳率), 本文采用目前国际上常用的转换系数 0.5, 所计算的森林植被碳储量未包含凋落物碳储量. 根据样地碳储量估算值和群落面积, 可估算出不同群落类型的乔木层、灌木层和草本层碳储量, 最后累加得到各林分类型与天童林区森林生态系统碳储量.

对于研究区域中没有实测数据的其他林分类型, 其碳储量采用发表文章中的碳密度乘以林分面积估算. 其中, 次生山地灌丛单位面积生物量平均值取  $19.76 \text{ Mg} \cdot \text{hm}^{-2}$ <sup>[28]</sup>, 含碳率取 0.5; 非林地 (农田、茶园等经济林) 单位面积生物量平均值取  $23.7 \text{ Mg} \cdot \text{hm}^{-2}$ <sup>[39]</sup>, 含碳率取 0.5; 马尾松人工林碳密度取值为  $26.67 \text{ Mg C} \cdot \text{hm}^{-2}$ <sup>[29]</sup>; 本研究区域的落叶阔叶林主要为化香-枫香群落, 其碳密度取枫香林实测平均值  $24.83 \text{ Mg C} \cdot \text{hm}^{-2}$ <sup>[29]</sup>.

### 1.5 数据处理

生物量和碳储量的计算由 Excel 完成. 使用 SPSS 19.0 软件, 采用 Duncan 新复极差测验对每种群落类型 3 个样地的均值进行多组样本间差异显著性分析.

## 2 结果与分析

### 2.1 不同群落类型各层生物量、碳储量和碳密度

野外调查的 6 种群落类型生物量和碳储量差异较大, 其中, 含苦槠的木荷-栲树群落最高, 其生物量和碳储量分别为  $24227.84 \text{ Mg}$  和  $12113.92 \text{ Mg C}$ ; 其次为典型木荷-栲树群落和含杨梅叶蚊母树的木荷-栲树群落; 披针叶茴香-南酸枣群落的生物量和碳储量最低, 分别为  $1361.90 \text{ Mg}$  和  $680.95 \text{ Mg C}$  (表2).

各群落碳密度大小顺序为含苦槠的木荷-栲树群落 > 典型木荷-栲树群落 > 枫香-马尾松群落 > 披针叶茴香-南酸枣群落 > 含杨梅叶蚊母树的木荷-栲树

表 1 我国东部亚热带常绿阔叶林的生物量相对生长方程

Table 1 Allometric biomass equations for the subtropical evergreen broad-leaved forests in Eastern China

| 植物种/功能型<br>Species/PFTs                                    | 研究地点<br>Study site             | 森林类型<br>Forest type                                                   | 组分<br>Component           | 回归模型<br>Regression model     | r                     | 文献<br>Reference |
|------------------------------------------------------------|--------------------------------|-----------------------------------------------------------------------|---------------------------|------------------------------|-----------------------|-----------------|
| 檫木 <sup>1)</sup><br><i>Loropetalum chinense</i>            | 江西千烟洲<br>Qianyanzhou, Jiangxi  | 亚热带人工林<br>Subtropical plantation                                      | 地上部 Aboveground           | $W = 0.0024(GH)^{1.0973}$    | 0.8436                | [30]            |
|                                                            |                                |                                                                       | 枝 Branch                  | $W = 0.000796(GH)^{1.1878}$  | 0.8515                |                 |
|                                                            |                                |                                                                       | 叶 Leaf                    | $W = 0.0114(GH)^{0.7581}$    | 0.5713                |                 |
| 木荷<br><i>Schima superba</i>                                | 浙江天童<br>Tiantong, Zhejiang     | 典型常绿阔叶林<br>Typical evergreen broad-leaved forest                      | 地上部 Aboveground           | $W = 0.1619D^{2.2993}$       | 0.9987                | [31]            |
|                                                            |                                |                                                                       | 干 Stem                    | $W = 0.0916D^{2.3612}$       | 0.9957                |                 |
|                                                            |                                |                                                                       | 枝 Branch                  | $W = 0.0483D^{2.261}$        | 0.9933                |                 |
|                                                            |                                |                                                                       | 叶 Leaf                    | $W = 0.182e^{0.1672D}$       | 0.9976                |                 |
| 米槠<br><i>Castanopsis carlesii</i>                          | 浙江天童<br>Tiantong, Zhejiang     | 典型常绿阔叶林<br>Typical evergreen broad-leaved forest                      | 地上部 Aboveground           | $W = 0.7597e^{0.3518H}$      | 0.9741                | [31]            |
|                                                            |                                |                                                                       | 干 Stem                    | $W = 0.5113e^{0.3516H}$      | 0.9791                |                 |
|                                                            |                                |                                                                       | 枝 Branch                  | $W = 0.1465e^{0.3712H}$      | 0.9496                |                 |
|                                                            |                                |                                                                       | 叶 Leaf                    | $W = 0.1133e^{0.2627H}$      | 0.9688                |                 |
| 栲树<br><i>Castanopsis fargesii</i>                          | 浙江天童<br>Tiantong, Zhejiang     | 典型常绿阔叶林<br>Typical evergreen broad-leaved forest                      | 地上部 Aboveground           | $W = 0.3343e^{0.4064H}$      | 0.9916                | [31]            |
|                                                            |                                |                                                                       | 干 Stem                    | $W = 0.2393e^{0.404H}$       | 0.9868                |                 |
|                                                            |                                |                                                                       | 枝 Branch                  | $W = 0.0503e^{0.4434H}$      | 0.9903                |                 |
|                                                            |                                |                                                                       | 叶 Leaf                    | $W = 0.0398e^{0.3179H}$      | 0.9844                |                 |
| 石栎 <sup>2)</sup><br><i>Lithocarpus glaber</i>              | 浙江天童<br>Tiantong, Zhejiang     | 典型常绿阔叶林<br>Typical evergreen broad-leaved forest                      | 地上部 Aboveground           | $W = 0.449e^{0.2932D}$       | 0.9908                | [31]            |
|                                                            |                                |                                                                       | 干 Stem                    | $W = 0.1583D^{2.2171}$       | 0.9924                |                 |
|                                                            |                                |                                                                       | 枝 Branch                  | $W = 0.0716e^{0.3136D}$      | 0.9845                |                 |
|                                                            |                                |                                                                       | 叶 Leaf                    | $W = 0.047e^{0.2393D}$       | 0.9372                |                 |
| 细叶青冈 <sup>3)</sup><br><i>Cyclobalanopsis myrsinaefolia</i> | 浙江天童<br>Tiantong, Zhejiang     | 典型常绿阔叶林<br>Typical evergreen broad-leaved forest                      | 地上部 Aboveground           | $W = 0.0109H^{3.8461}$       | 0.9887                | [31]            |
|                                                            |                                |                                                                       | 干 Stem                    | $W = 0.0102H^{3.6991}$       | 0.9909                |                 |
|                                                            |                                |                                                                       | 枝 Branch                  | $W = 0.0368e^{0.5097H}$      | 0.9846                |                 |
|                                                            |                                |                                                                       | 叶 Leaf                    | $W = 0.0109e^{0.1387D}$      | 0.9854                |                 |
| 赤楠<br><i>Syzygium buxifolium</i>                           | 江西井冈山<br>Jinggangshan, Jiangxi | 中亚热带湿润常绿阔叶林<br>Middle subtropical moist evergreen broad-leaved forest | 全株 Whole plant            | $W = 4.299 + 0.004Dr^2H$     | 0.968                 | [32]            |
|                                                            |                                |                                                                       | 杜茎山 <i>Maesa japonica</i> | 全株 Whole plant               | $W = 0.165Dr^{2.646}$ |                 |
| 鹿角杜鹃 <sup>4)</sup><br><i>Rhododendron latoucheae</i>       |                                |                                                                       | 全株 Whole plant            | $W = 27.602 + 0.004Dr^2H$    | 0.966                 |                 |
| 拟赤杨<br><i>Alniphyllum fortunei</i>                         |                                |                                                                       | 全株 Whole plant            | $W = 1.262 + 0.002Dr^2H$     | 0.941                 |                 |
| 箬竹 <sup>5)</sup><br><i>Indocalamus tessellatus</i>         |                                |                                                                       | 全株 Whole plant            | $W = 0.319Dr^{2.552}$        | 0.950                 |                 |
| 铁凉伞 <sup>6)</sup><br><i>Ardisia crenata</i>                |                                |                                                                       | 全株 Whole plant            | $W = -2.804 - 2.909Dr + 1.$  | 0.991                 |                 |
| 野漆树<br><i>Toxicodendron succedaneum</i>                    |                                |                                                                       | 全株 Whole plant            | $W = 1.253 + 0.004Dr^2H$     | 0.916                 |                 |
| 白栎<br><i>Quercus fabri</i>                                 | 湖北长阳                           | 亚热带天然灌丛草地                                                             | 地上部 Aboveground           | $W = 1.1214G$                | 0.9003                | [33]            |
| 水锦树 <sup>7)</sup><br><i>Wendlandia wariifolia</i>          | Changyang, Hubei               | Subtropical shrubby grassland                                         | 地上部 Aboveground           | $W = 0.7714G$                | 0.9662                |                 |
| 麻栎<br><i>Quercus acutissima</i>                            |                                |                                                                       | 地上部 Aboveground           | $W = 1.0232G$                | 0.9243                |                 |
| 黄檀 <sup>8)</sup><br><i>Dalbergia hupeana</i>               |                                |                                                                       | 地上部 Aboveground           | $W = 1.1464G$                | 0.9195                |                 |
| 菝葜 <sup>9)</sup><br><i>Smilax china</i>                    |                                |                                                                       | 地上部 Aboveground           | $W = 0.7915G$                | 0.9659                |                 |
| 盐肤木<br><i>Rhus chinensis</i>                               | 江西千烟洲                          | 亚热带人工林                                                                | 全株 Whole plant            | $W = 3.43 + 0.501Dr^2G$      | 0.991                 | [34]            |
| 白檀<br><i>Symplocos paniculata</i>                          | Qianyanzhou, Jiangxi           | Subtropical plantation                                                | 全株 Whole plant            | $W = 8.559 + 0.49Dr^2H$      | 0.967                 |                 |
| 山莓<br><i>Rubus corchorifolius</i>                          | 江西千烟洲                          | 亚热带人工林                                                                | 全株 Whole plant            | $W = 0.1685(Dr^2H)^{0.6165}$ | 0.843                 | [35]            |
| 紫珠 <sup>10)</sup><br><i>Callicarpa bodinieri</i>           | Qianyanzhou, Jiangxi           | Subtropical plantation                                                | 全株 Whole plant            | $W = 4.6484 + 0.0028Dr^2H$   | 0.942                 |                 |
| 樟树 <sup>11)</sup><br><i>Cinnamomum camphora</i>            | 湖南会同<br>Huitong, Hunan         | 亚热带常绿阔叶林<br>Subtropical evergreen broad-leaved forest                 | 干 Stem                    | $W = 20.583(D^2H)^{1.069}$   | 0.9775                | [36]            |
|                                                            |                                |                                                                       | 枝 Branch                  | $W = 33.366(D^2H)^{0.6806}$  | 0.6866                |                 |
|                                                            |                                |                                                                       | 叶 Leaf                    | $W = 29.959(D^2H)^{0.8664}$  | 0.7038                |                 |
|                                                            |                                |                                                                       | 皮 Skin                    | $W = 4.6996(D^2H)^{1.1397}$  | 0.9501                |                 |
|                                                            |                                |                                                                       | 根 Root                    | $W = 26.789(D^2H)^{0.9108}$  | 0.9348                |                 |
| 杜英 <sup>12)</sup><br><i>Elaeocarpus decipiens</i>          | 湖南会同<br>Huitong, Hunan         | 亚热带常绿阔叶林<br>Subtropical evergreen broad-leaved forest                 | 干 Stem                    | $W = 126.55(D^2H)^{0.4929}$  | 0.9691                | [36]            |
|                                                            |                                |                                                                       | 枝 Branch                  | $W = 36.356(D^2H)^{0.5317}$  | 0.7810                |                 |
|                                                            |                                |                                                                       | 叶 Leaf                    | $W = 51.924(D^2H)^{0.5559}$  | 0.9892                |                 |
|                                                            |                                |                                                                       | 皮 Skin                    | $W = 23.391(D^2H)^{0.3742}$  | 0.9596                |                 |
|                                                            |                                |                                                                       | 根 Root                    | $W = 84.776(D^2H)^{0.4974}$  | 0.9805                |                 |

续表 1  
Table 1 Continued

| 植物种/功能型<br>Species/PFTs                                                                     | 研究地点<br>Study site            | 森林类型<br>Forest type                                      | 组分<br>Component                   | 回归模型<br>Regression model            | r      | 文献<br>Reference |
|---------------------------------------------------------------------------------------------|-------------------------------|----------------------------------------------------------|-----------------------------------|-------------------------------------|--------|-----------------|
| 常绿伴生亚乔木 <sup>13)</sup><br>Evergreen companion<br>subtrees                                   | 浙江建德<br>Jiande, Zhejiang      | 亚热带常绿阔叶林<br>Subtropical evergreen<br>broad-leaved forest | 全株 Whole plant                    | $W = 136.175(D^2H)^{0.7897}$        | 0.9987 | [37]            |
|                                                                                             |                               |                                                          | 地上部 Aboveground                   | $W = 248.253 + 33.3112D^2H$         | 0.9992 |                 |
|                                                                                             |                               |                                                          | 地下 Underground                    | $W = 68.564(D^2H)^{0.643}$          | 0.9971 |                 |
|                                                                                             |                               |                                                          | 干 Stem                            | $W = 40.756(D^2H)^{0.9199}$         | 0.9978 |                 |
|                                                                                             |                               |                                                          | 枝 Branch                          | $W = D/(0.022 - 0.0032D)$           | 0.9951 |                 |
|                                                                                             |                               |                                                          | 叶 Leaf                            | $W = 20.335e^{0.5544D}$             | 0.9840 |                 |
|                                                                                             |                               |                                                          | 根 Root                            | $W = 35.07(D^2H)^{0.6499}$          | 0.9966 |                 |
| 落叶亚乔木 <sup>14)</sup><br>Deciduous subtrees                                                  | 浙江建德<br>Jiande, Zhejiang      | 亚热带常绿阔叶林<br>Subtropical evergreen<br>broad-leaved forest | 全株 Whole plant                    | $W = 86.589(D^2H)^{0.8699}$         | 0.9876 | [37]            |
|                                                                                             |                               |                                                          | 地上部 aboveground                   | $W = -22.704 + 35.686D^2H$          | 0.9926 |                 |
|                                                                                             |                               |                                                          | 地下 Underground                    | $W = 74.066(D^2H)^{0.5827}$         | 0.9950 |                 |
|                                                                                             |                               |                                                          | 干 Stem                            | $W = 28.579(D^2H)e^{-0.000309D^2H}$ | 0.9915 |                 |
|                                                                                             |                               |                                                          | 枝 Branch                          | $W = 2.222(D^2H)^{1.1548}$          | 0.9897 |                 |
|                                                                                             |                               |                                                          | 叶 Leaf                            | $W = 4.551D^{2.3727}$               | 0.9946 |                 |
|                                                                                             |                               |                                                          | 根 Root                            | $W = 38.031(D^2H)^{0.5902}$         | 0.9925 |                 |
| 枫香 <sup>15)</sup><br>Chinese sweet gum                                                      | 浙江 Zhejiang                   | 亚热带常绿阔叶林<br>Subtropical evergreen<br>broad-leaved forest | 地上部 Aboveground                   | $W = 34.514(D^2H)^{1.0037}$         | 0.9549 | [38]            |
|                                                                                             |                               |                                                          | 地上部 Aboveground                   | $W = 60.143(D^2H)^{0.9274}$         | 0.9608 |                 |
| 苦槠 <i>Castanopsis sclerophylla</i>                                                          | 浙江 Zhejiang                   | 亚热带常绿阔叶林<br>Subtropical evergreen<br>broad-leaved forest | 地上部 Aboveground                   | $W = 94.594(D^2H)^{0.8666}$         | 0.9053 |                 |
| 浙江常绿阔叶林其他种 <sup>16)</sup><br>Other species in the evergreen broad-leaved forest in Zhejiang | 浙江 Zhejiang                   | 亚热带常绿阔叶林<br>Subtropical evergreen<br>broad-leaved forest | 地上部 Aboveground                   | $W = 94.594(D^2H)^{0.8666}$         | 0.9053 |                 |
| 硬阔 II <sup>17)</sup><br>Hardwood ( II )                                                     | 浙江 Zhejiang                   | 常绿阔叶林<br>Evergreen broad-leaved forest                   | 干 Stem                            | $W = 0.0803H^{0.7815}D^{1.8056}$    |        | [39]            |
|                                                                                             |                               |                                                          | 冠 Crown                           | $W = 0.286D^{1.0968}G^{0.945}$      |        |                 |
|                                                                                             |                               |                                                          | 根 Root                            | $W = 0.247H^{0.1745}D^{1.7954}$     |        |                 |
| 毛竹 <i>Phyllostachys pubescens</i>                                                           | 浙江 Zhejiang                   | 常绿阔叶林<br>Evergreen broad-leaved forest                   | 干 Stem                            | $W = 0.0398H^{0.5778}D^{1.854}$     |        | [39]            |
|                                                                                             |                               |                                                          | 冠 Crown                           | $W = 0.28D^{0.8357}G^{0.274}$       |        |                 |
|                                                                                             |                               |                                                          | 根 Root                            | $W = 0.371H^{0.1357}D^{0.9817}$     |        |                 |
| 杂竹 Other species of Bambusoideae                                                            | 浙江 Zhejiang                   | 常绿阔叶林<br>Evergreen broad-leaved forest                   | 全株 Whole plant                    | $W = 0.015189Dr^{0.6305}H^{2.0687}$ |        | [39]            |
| 草本 Herb                                                                                     | 浙江 Zhejiang                   | 常绿阔叶林<br>Evergreen broad-leaved forest                   | 单位面积总量 Total amount per unit area | $W = 0.05492H^{0.803}C^{1.0877}$    |        | [39]            |
| 狗脊 <sup>18)</sup><br><i>Wookwardia japonica</i>                                             | 江西千烟洲<br>Qianyanzhou, Jiangxi | 亚热带人工针叶林<br>Subtropical conifer plantation               | 地上部 Aboveground                   | $W = 2.518(Dr^2H)^{0.616}$          |        | [40]            |

1) 杨梅叶蚊母树 *Distylium myricoides*; 2) 长叶石栎 *Lithocarpus henryi*; 3) 褐叶青冈 *Cyclobalanopsis stewardiana*、青冈 *Cyclobalanopsis glauca*、云山青冈 *Cyclobalanopsis nubium*; 4) 马银花 *Rhododendron ovatum*、米饭花 *Vaccinium mandarinorum*; 5) 苦竹 *Pleioblastus amarus*、五节芒 *Miscanthus floridulus*; 6) 红凉伞 *Ardisia crenata*、朱砂根 *Ardisia crenata*; 7) 狗骨柴 *Tricalysia dubia*、虎刺 *Damnacanthus indicus*、胡颓子 *Elaeagnus pungens*; 8) 花榈木 *Ormosia henryi*; 9) 薯蓣 *Dioscorea opposita*; 10) 大青 *Clerodendrum cyrtophyllum*、豆腐柴 *Premna microphylla*; 11) 红楠 *Machilus thunbergii*、华东楠 *Machilus leptophylla*、细叶香桂 *Cinnamomum subavenium*、豹皮樟 *Litsea coreana*、黄丹木姜子 *Litsea elongata*、紫楠 *Phoebe sheareri*、天竺桂 *Cinnamomum japonicum*; 12) 薯豆 *Elaeocarpus japonicus*; 13) 红叶树 *Helicia cochinchinensis*、虎皮楠 *Daphniphyllum oldhamii*、杨梅 *Myrica rubra*、浙江新木姜子 *Neolitsea aurata*、光叶石楠 *Photinia glabra*、披针叶茴香 *Illicium lanceolatum*、含笑 *Michelia figo*、山矾 *Symplocos sumuntia*、披针叶山矾 *Symplocos lancifolia*、四川山矾 *Symplocos setchuensis*、总状山矾 *Symplocos heishanensis*、薄叶山矾 *Symplocos anomala*、黄牛奶树 *Symplocos laurina*、老鼠矢 *Symplocos stellaris*、细枝铃 *Eurya loquaiana*、格药铃 *Eurya muricata*、窄基红褐铃 *Eurya rubiginosa*、连蕊茶 *Camellia fraterna*、油茶 *Camellia oleifera*、山茶 *Camellia japonica*、厚皮香 *Ternstroemia gymnanthera*、杨桐 *Cleyera japonica*; 14) 野鸦椿 *Euscaphis japonica*、苕麻 *Boehmeria nivea*、天仙果 *Ficus erecta*、山油麻 *Helicteres angustifolia*、卫矛 *Euonymus alatus*、百齿卫矛 *Euonymus centidens*、红脉钓樟 *Lindera rubronervia*、野桐 *Mallotus tenuifolius*、赛山梅 *Styrax confusus*、野茉莉 *Styrax japonicus*、山鸡椒 *Litsea cubeba*、白花苦灯笼 *Tarenna mollissima*; 15) 橄榄槭 *Acer olivaceum*、锐角槭 *Acer acutum*、三角槭 *Acer buergerianum*; 16) 檫木 *Sassafras tzumu*、茅栗 *Castanea seguinii*、化香树 *Platycarya strobilacea*、无患子 *Sapindus mukorossi*、刺楸 *Kalopanax septemlobus*、油桐 *Vernicia fordii*、雷公鹅耳枥 *Carpinus viminea*、厚壳树 *Ehretia thyrsoiflora*、南酸枣 *Choroospondias axillaris*、华东野胡桃 *Juglans cathayensis*; 17) 冬青 *Ilex purpurea*、大叶冬青 *Ilex latifolia*、光枝刺缘冬青 *Ilex hylonoma*、厚叶冬青 *Ilex elmerilliana*、深山含笑 *Michelia maudiae*、华东木樨 *Osmanthus cooperi*、苦槠木 *Fraxinus insularis*; 18) 蕨 *Pteridium aquilinum*、里白 *Diplazium glaucum*、贯众 *Cyrtomium fortunei*、海金沙 *Lygodium japonicum*。W: 生物量 Biomass; D: 胸径 Diameter at breast height; Dr: 基径 Basal diameter; H: 高度 Height; G: 冠幅 Crown diameter; C: 盖度 Coverage。

群落 > 黄毛耳草-毛竹群落。含苦槠的木荷-栲树群落碳密度高达 165.03 Mg C · hm<sup>-2</sup>，这与其高生物量和碳储量相符；而碳密度最低的群落为人工林黄

毛耳草-毛竹群落，仅为 43.09 Mg C · hm<sup>-2</sup>。

不同群落类型中乔木层生物量、碳储量和碳密度占群落总量的比重均最大。乔木层、灌木层和草本

表 2 天童国家森林公园不同群落类型各层生物量、碳储量和碳密度

Table 2 Biomass, carbon storage and carbon density of different communities in Tiantong National Forest Park (mean ± SD)

| 群落类型<br>Community<br>type | 群落面积<br>Area<br>(hm <sup>2</sup> ) | 乔木层 Tree               |                                    |                                                        | 灌木层 Shrub              |                                    |                                                        | 草本层 Herb               |                                    |                                                        | 群落 Community           |                                    |                                                        |                   |
|---------------------------|------------------------------------|------------------------|------------------------------------|--------------------------------------------------------|------------------------|------------------------------------|--------------------------------------------------------|------------------------|------------------------------------|--------------------------------------------------------|------------------------|------------------------------------|--------------------------------------------------------|-------------------|
|                           |                                    | 生物量<br>Biomass<br>(Mg) | 碳储量<br>Carbon<br>storage<br>(Mg C) | 碳密度<br>Carbon<br>density<br>(Mg C · hm <sup>-2</sup> ) | 生物量<br>Biomass<br>(Mg) | 碳储量<br>Carbon<br>storage<br>(Mg C) | 碳密度<br>Carbon<br>density<br>(Mg C · hm <sup>-2</sup> ) | 生物量<br>Biomass<br>(Mg) | 碳储量<br>Carbon<br>storage<br>(Mg C) | 碳密度<br>Carbon<br>density<br>(Mg C · hm <sup>-2</sup> ) | 生物量<br>Biomass<br>(Mg) | 碳储量<br>Carbon<br>storage<br>(Mg C) | 碳密度<br>Carbon<br>density<br>(Mg C · hm <sup>-2</sup> ) | 变异系数<br>CV<br>(%) |
| A                         | 76.65                              | 17204.66<br>±7598.24   | 8602.33 ±<br>3799.12               | 112.23 ±<br>49.57                                      | 885.99<br>±420.49      | 442.99 ±<br>210.24                 | 5.78 ±<br>2.74                                         | 202.41<br>±150.10      | 101.20 ±<br>75.05                  | 1.32 ±<br>0.98                                         | 18293.06               | 9146.53                            | 119.33ab                                               | 40                |
| B                         | 73.40                              | 22610.68<br>±12582.70  | 11305.34 ±<br>6291.35              | 154.02 ±<br>85.71                                      | 988.34<br>±424.05      | 494.17 ±<br>212.03                 | 6.73 ±<br>2.89                                         | 628.82<br>±188.83      | 314.41 ±<br>94.42                  | 4.28 ±<br>1.29                                         | 24227.84               | 12113.92                           | 165.03b                                                | 54                |
| C                         | 25.02                              | 4253.50<br>±1489.83    | 2126.75 ±<br>744.92                | 85.00 ±<br>29.77                                       | 246.30<br>±101.84      | 123.15 ±<br>50.92                  | 4.92 ±<br>2.04                                         | 210.72<br>±49.70       | 105.36 ±<br>24.85                  | 4.21 ±<br>0.99                                         | 4710.52                | 2355.26                            | 94.14ab                                                | 30                |
| D                         | 6.73                               | 1286.88<br>±759.89     | 643.44 ±<br>379.94                 | 95.68 ±<br>56.50                                       | 54.85<br>±5.02         | 27.42 ±<br>2.51                    | 4.08 ±<br>0.37                                         | 20.16<br>±7.93         | 10.08 ±<br>3.97                    | 1.50 ±<br>0.59                                         | 1361.90                | 680.95                             | 101.26ab                                               | 56                |
| E                         | 8.69                               | 1793.44<br>±588.58     | 896.72 ±<br>294.29                 | 103.19 ±<br>33.87                                      | 38.77<br>±7.73         | 19.39 ±<br>3.86                    | 2.23 ±<br>0.44                                         | 107.20<br>±21.28       | 53.60 ±<br>10.64                   | 6.17 ±<br>1.22                                         | 1939.41                | 969.71                             | 111.59ab                                               | 30                |
| F                         | 26.06                              | 2124.34<br>±245.70     | 1062.17 ±<br>122.85                | 40.76 ±<br>4.71                                        | 42.37<br>±5.29         | 21.19 ±<br>2.64                    | 0.81 ±<br>0.10                                         | 79.15<br>±42.59        | 39.58 ±<br>21.29                   | 1.52 ±<br>0.82                                         | 2245.86                | 1122.93                            | 43.09a                                                 | 9                 |

A: 典型木荷-栲树群落 *Schima superba* - *Castanopsis fargesii* community; B: 含苦槠的木荷-栲树群落 *Schima superba* - *Castanopsis fargesii* with *C. sclerophylla* community; C: 含杨梅叶蚊母树的木荷-栲树群落 *Schima superba* - *Castanopsis fargesii* with *Distylium myricoides* community; D: 披针叶茴香-南酸枣群落 *Illicium lanceolatum* - *Choerospondias axillaris* community; E: 枫香-马尾松群落 *Liquidambar formosana* - *Pinus massoniana* community; F: 黄毛耳草-毛竹群落 *Hedyotis auricularia* - *Phyllostachys pubescens* community. 同列不同小写字母表示差异显著 ( $P < 0.05$ ) Different small letters in the same column meant significant difference at 0.05 level. 下同 The same below.

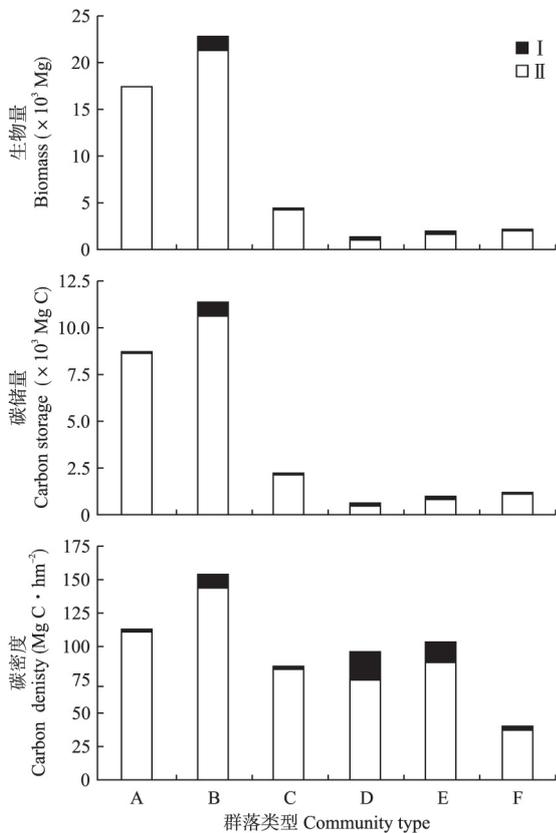


图 2 天童国家森林公园不同群落类型常绿和落叶木本植物生物量、碳储量和碳密度

Fig. 2 Biomass, carbon storage and carbon density of evergreen and deciduous trees of different communities in Tiantong National Forest Park.

A ~ F: 群落类型 (见表 2) Community type (Saw Table 2). I: 落叶树种 Deciduous tree; II: 常绿树种 Evergreen tree.

层的碳储量分别为 643.44 ~ 11305.34、19.39 ~ 494.17、10.08 ~ 314.41 Mg C. 群落面积较大、植株高大的含苦槠的木荷-栲树常绿阔叶林群落各层碳储量和碳密度均在 6 种群落类型中最高. 乔木层和灌木层碳密度最小的为黄毛耳草-毛竹群落, 但该群落草本层含大量植株幼苗, 故而碳密度并不是 6 种群落类型中最小的.

### 2.2 不同群落类型常绿和落叶木本植物生物量、碳储量和碳密度

6 种群落类型中, 常绿树种的生物量和碳储量均显著高于落叶树种 (图 2). 在各群落中, 尤其是在典型木荷-栲树群落中, 常绿与落叶木本植物的树种数和植株数相差较大, 常绿树种碳储量为落叶树种的 3.7 ~ 707.9 倍. 含苦槠的木荷-栲树群落常绿树种和落叶树种的生物量和碳储量均最高; 常绿树种生物量和碳储量最低的群落为披针叶茴香-南酸枣群落, 属常绿落叶阔叶混交林, 故该群落也是常绿树种碳储量与落叶树种碳储量差值最小的群落; 落叶树种生物量和碳储量最低的群落为典型木荷-栲树群落. 总体来看, 常绿树种在天童林区植被碳储过程中占据主导地位, 这是其作为亚热带代表性植被类型的重要特征. 不同群落类型的常绿树种和落叶树种的碳密度范围分别为 76.08 ~ 144.95 和 0.16 ~ 20.62 Mg C · hm<sup>-2</sup>. 其中, 常绿树种碳密度最高的群落为含苦槠的木荷-栲树群落, 落叶树种碳密度最高的群落为披针叶茴香-南酸枣群落.

### 2.3 不同群落类型乔木层各组分生物量、碳储量和碳密度

不同群落类型乔木层各组分(枝、干、叶、地下)的生物量和碳储量也不尽相同(表3)。由于用于估算个别树种生物量的相对生长方程不包含植株各组分生物量的估算模型,所以本研究对乔木层各组分碳储量的对比仅包含可以估算出其各组分生物量的树种。6种群落类型的乔木层植株各组分中,干生物量、碳储量和碳密度均最大,其生物量占乔木层总生物量的33.6%~62.7%,表明植株的树干储存着乔木层大部分碳;枝和地下部分的生物量和碳储量居于其次,其碳储量分别占乔木层总碳储量的8.6%~30.0%和16.7%~35.1%;叶碳储量所占比例较小,约2.0%~22.5%。由于黄毛耳草-毛竹群落为人工林,其乔木层基本为单一毛竹树种,偶见枫香植株,对其各组分碳储量的分析主要为对毛竹干、

冠、根碳储量的分析,其各组分碳储量分别占总碳储量的62.7%、12.3%、25.1%。各组分中典型木荷-栲树群落乔木层干碳密度最大,含杨梅叶蚊母树的木荷-栲树群落乔木层叶碳密度最小。

### 2.4 天童林区森林生态系统植被总碳储量和碳密度

天童国家森林公园植被总碳储量为28254.22 Mg C,碳密度为96.73 Mg C·hm<sup>-2</sup>(表4)。常绿阔叶林是该地区森林植被碳储量的最主要承担者,其碳储量占天童林区森林生态系统碳储量的81.7%,其碳密度也在各林分类型中最大,远高于该地区总碳密度。常绿针叶林与毛竹林碳储量分别占天童林区总碳储量的8.0%和4.0%。主要林分类型碳密度大小顺序为常绿阔叶林>常绿针叶林>常绿落叶阔叶混交林>毛竹林,前三者均大于林区总碳密度,毛竹林作为人工林,碳密度约为总碳密度的45%。

表3 天童国家森林公园不同群落类型乔木层各组分生物量、碳储量和碳密度

Table 3 Biomass, carbon storage and carbon density in tree layer of different communities in Tiantong National Forest Park (mean ± SD)

| 群落类型<br>Community<br>type | 枝 Branch               |                                    |                                                      | 干 Stem                 |                                    |                                                      | 叶 Leaf                 |                                    |                                                      | 地下 Underground         |                                    |                                                      | 总碳储量<br>Total<br>carbon<br>storage<br>(Mg C) |
|---------------------------|------------------------|------------------------------------|------------------------------------------------------|------------------------|------------------------------------|------------------------------------------------------|------------------------|------------------------------------|------------------------------------------------------|------------------------|------------------------------------|------------------------------------------------------|----------------------------------------------|
|                           | 生物量<br>Biomass<br>(Mg) | 碳储量<br>Carbon<br>storage<br>(Mg C) | 碳密度<br>Carbon<br>density<br>(Mg C·hm <sup>-2</sup> ) | 生物量<br>Biomass<br>(Mg) | 碳储量<br>Carbon<br>storage<br>(Mg C) | 碳密度<br>Carbon<br>density<br>(Mg C·hm <sup>-2</sup> ) | 生物量<br>Biomass<br>(Mg) | 碳储量<br>Carbon<br>storage<br>(Mg C) | 碳密度<br>Carbon<br>density<br>(Mg C·hm <sup>-2</sup> ) | 生物量<br>Biomass<br>(Mg) | 碳储量<br>Carbon<br>storage<br>(Mg C) | 碳密度<br>Carbon<br>density<br>(Mg C·hm <sup>-2</sup> ) |                                              |
| A                         | 4489.53 ± 2944.78      | 2244.77 ± 1472.39                  | 29.29 ± 19.21                                        | 9301.45 ± 3166.83      | 4650.72 ± 1583.41                  | 60.68 ± 20.66                                        | 528.30 ± 268.30        | 264.15 ± 134.15                    | 3.45 ± 1.75                                          | 2867.16 ± 1333.68      | 1433.58 ± 666.84                   | 18.70 ± 8.70                                         | 8593.22                                      |
|                           | 6068.62 ± 5496.84      | 3034.31 ± 2748.42                  | 41.34 ± 37.44                                        | 8420.07 ± 6496.48      | 4210.04 ± 3248.24                  | 57.36 ± 44.25                                        | 2323.17 ± 1948.29      | 1161.58 ± 974.14                   | 15.82 ± 13.27                                        | 3434.77 ± 1543.47      | 1717.39 ± 771.74                   | 23.40 ± 10.51                                        |                                              |
| C                         | 949.22 ± 486.30        | 474.61 ± 243.15                    | 18.97 ± 9.72                                         | 2285.15 ± 904.48       | 1142.58 ± 452.24                   | 45.67 ± 18.08                                        | 81.95 ± 46.85          | 40.98 ± 23.42                      | 1.64 ± 0.94                                          | 880.44 ± 206.57        | 440.22 ± 103.28                    | 17.59 ± 4.13                                         | 2098.38                                      |
|                           | 255.70 ± 210.99        | 127.85 ± 105.49                    | 19.01 ± 15.69                                        | 355.66 ± 95.32         | 177.83 ± 47.66                     | 26.44 ± 7.09                                         | 238.22 ± 297.86        | 119.11 ± 148.93                    | 17.71 ± 22.15                                        | 208.49 ± 113.61        | 104.24 ± 56.81                     | 15.50 ± 8.45                                         |                                              |
| E                         | 136.09 ± 33.44         | 68.05 ± 16.72                      | 7.83 ± 1.92                                          | 840.94 ± 388.07        | 420.47 ± 194.04                    | 48.39 ± 22.33                                        | 46.83 ± 46.47          | 23.41 ± 23.23                      | 2.69 ± 2.67                                          | 554.12 ± 224.39        | 277.06 ± 112.19                    | 31.88 ± 12.91                                        | 788.99                                       |
|                           | 246.30 ± 41.92         | 123.15 ± 20.96                     | 4.73 ± 0.80                                          | 1256.44 ± 130.44       | 628.22 ± 65.22                     | 24.11 ± 2.50                                         | -                      | -                                  | -                                                    | 502.55 ± 29.81         | 251.27 ± 14.90                     | 9.64 ± 0.57                                          |                                              |

表4 天童国家森林公园不同林分类型碳储量和碳密度

Table 4 Carbon storage and carbon density of different forest types in Tiantong National Forest Park

| 林分类型<br>Forest type                                            | 林分面积<br>Area<br>(hm <sup>2</sup> ) | 碳储量<br>Carbon storage<br>(Mg C) | 碳密度<br>Carbon density<br>(Mg C·hm <sup>-2</sup> ) | 百分比<br>Percentage |
|----------------------------------------------------------------|------------------------------------|---------------------------------|---------------------------------------------------|-------------------|
| 常绿阔叶林 Evergreen broad-leaved forest                            | 183.03                             | 23092.39                        | 126.17                                            | 81.7              |
| 常绿落叶阔叶混交林<br>Evergreen and deciduous broad-leaved mixed forest | 9.71                               | 983.20                          | 101.26                                            | 3.5               |
| 落叶阔叶林 Deciduous broad-leaved forest                            | 8.39                               | 208.39                          | 24.83                                             | 0.7               |
| 常绿针叶林 Evergreen coniferous forest                              | 20.13                              | 2246.56                         | 111.59                                            | 8.0               |
| 毛竹林 Moso bamboo forest                                         | 26.06                              | 1122.93                         | 43.09                                             | 4.0               |
| 次生山地灌丛 Shrubland                                               | 24.27                              | 239.76                          | 9.88                                              | 0.9               |
| 马尾松人工幼林 <i>Pinus massoniana</i> artificial young forest        | 7.98                               | 212.69                          | 26.67                                             | 0.8               |
| 非林地 Non-forest                                                 | 12.52                              | 148.30                          | 11.85                                             | 0.5               |
| 总和 Total                                                       | 292.08                             | 28254.22                        | 96.73                                             | 100               |

### 3 讨 论

#### 3.1 天童常绿阔叶林植被生物量、碳储量和碳密度的比较

在区域尺度上,森林碳储量的多少与植被生物量密切相关<sup>[10]</sup>,而植株的高度和胸径作为影响植株生物量的重要因子进而影响到森林碳储量。由研究区 6 种群落的物种组成性质和数量特征信息<sup>[22]</sup>可知 3 种常绿阔叶林群落乔木层优势种为栲树、木荷,灌木层优势种为连蕊茶、箬竹、细枝柃等,各高度级和胸径级植株数目均较多,且大高度级和大径级植株的数目也较多。群落优势种植株数目多,具有较大的高度级和胸径级。群落处于演替后期,群落生物量和碳储量较大。披针叶茴香-南酸枣群落的优势种为黄丹木姜子,其植株多集中在中小高度级和胸径级。群落中高大植株数目少,对群落生物量的大小产生不利影响。枫香-马尾松群落优势种为深山含笑和苦竹,小高度级和小径级植株数目多,群落生物量小。黄毛耳草-毛竹群落植株虽主要集中于大高度级和大径级,但该群落为人工林,植株数目较少且物种组成单一,很大程度上限制了群落的生物量和碳储量。

样地所处的小生境也在一定程度上决定着群落特征,从而决定植被生物量和碳储量的大小。在相同气候条件下,地形、海拔和土壤条件作为主要的生境特征影响着群落植被的生物量和碳储量。3 种木荷-栲树群落作为天童森林公园内代表性的常绿阔叶林,分布范围广,在低海拔至 500 m 以上的山坡上皆有分布,所在地一般坡度较平缓,除山坡上部外土层均较深厚,这有利于植株光合作用的增强和光呼吸强度的降低,并能为植株提供更丰富的矿质养分,促进生物量和碳储量的积累;同时人类活动干扰对其影响较小也有利于碳储量的积聚。披针叶茴香-南酸枣群落主要分布于海拔 270~330 m 的山沟中,生境土层浅薄多石,结构松散,不利于群落内植株的有机物生产和养分吸收,群落生物量和碳储量小。枫香-马尾松群落主要分布在人类活动较频繁的低海拔山坡下部,多为常绿阔叶林演替过程中的一个过渡阶段;黄毛耳草-毛竹群落为人工种植林,密度和株数有一定限制,受人为因素影响大,且林下层由于经常清理造成灌木层和草本层无明显界限<sup>[21]</sup>,土壤条件得益于人为干扰,对群落植被生物量和碳储量的积累有一定帮助。

不同群落的物种组成和数量特征差异,以及不

同群落小生境的差异,都会影响植被的碳储量,内部和外部因子的共同作用,导致天童国家森林公园不同森林类型、起源和林种的植被生物量和碳储量差异显著。阔叶林和常绿林分布范围广,物种多样性丰富,生物量和碳储量大;针叶林和落叶林分布范围小,植株高度级和胸径级小,生物量和碳储量小。天然林群落结构复杂,生物量和碳储量大;人工林群落结构单一,生物量和碳储量小。在天童国家森林公园的各种林分类型中,阔叶林面积约为天童林区面积的 65.5%,但其碳储量占总碳储量的 82.5%,其中以常绿阔叶林的碳储量最大,占阔叶林总碳储量的 99.1%。人工林主要为毛竹林、马尾松人工幼林和茶园等经济林,其中,毛竹林是该区域最主要的经济林。人工林碳储量为 1483.93 Mg C,占总碳储量的 5.3%。

森林碳密度作为影响森林质量的重要因子,与森林面积共同决定了森林的储碳能力<sup>[41]</sup>。本研究中,阔叶林和常绿林(包括常绿落叶阔叶混交林)碳密度均高于总碳密度,表明其相较于针叶林和落叶林在固碳能力上具有绝对优势。天童国家森林公园作为自然保护区,由于良好的森林保护政策和措施,该区域森林生态系统仍以天然林为主,人工林所占比例甚小,且都处于保护区边缘地带。相较于人工林,天然林具有更大的生产力和储碳能力。本研究中,毛竹林的碳密度仅为总碳密度的一半左右,表明其固碳能力较弱;天然林作为主要林种,且森林年龄结构也多接近成熟林,故其碳密度较大。

#### 3.2 我国亚热带常绿阔叶林碳储量和碳密度比较

与我国亚热带地区其他研究结果(表 5)比较可以看出,天童国家森林公园的植被碳密度高于三峡库区和赣中亚热带区,表明该区域森林具有较高的碳储能力;但低于西双版纳、鼎湖山和哀牢山地区,这与随着纬度的增加植被碳密度递减的研究结果<sup>[42-43]</sup>相符。Fang 等<sup>[9]</sup>基于森林清查资料估算的我国森林植被碳密度为 44.91 Mg C · hm<sup>-2</sup>,李海奎和雷渊才<sup>[40]</sup>估算我国森林植被乔木林碳密度为 42.82 Mg C · hm<sup>-2</sup>,周玉荣等<sup>[44]</sup>估算我国森林植被平均碳密度为 57.07 Mg C · hm<sup>-2</sup>。本研究中,天童国家森林公园植被碳密度为 96.73 Mg C · hm<sup>-2</sup>,远高于我国森林碳密度的平均水平和世界平均水平<sup>[11]</sup>(86.00 Mg C · hm<sup>-2</sup>)。森林主要林分因子和海拔、坡度等立地因子的差异,以及人类活动的干扰,都对森林生态系统植被平均碳密度造成影响,随着森林植被保护措施的完善和生态系统的演替,天童国家

表 5 中国亚热带和热带区域植被碳密度

Table 5 Vegetation carbon density of different study areas in subtropical and tropical China

| 研究地点<br>Study site                      | 森林类型<br>Forest type                                   | 海拔<br>Altitude<br>(m) | 地理位置<br>Geographical location                     | 坡度<br>Slope<br>(°) | 植被碳密度<br>Vegetation carbon density<br>(Mg C · hm <sup>-2</sup> ) | 文献<br>Reference   |
|-----------------------------------------|-------------------------------------------------------|-----------------------|---------------------------------------------------|--------------------|------------------------------------------------------------------|-------------------|
| 西双版纳<br>Xishuangbanna                   | 季节雨林<br>Tropical seasonal rain forest                 | 730                   | 21°57'39.4" N,<br>101°12'00.4" E                  | 22                 | 154.67                                                           | [45]              |
| 鼎湖山<br>Dinghu Mountain                  | 常绿阔叶林<br>Evergreen broad-leaved forest                | 300                   | 23°10'9.9" N,<br>112°32'22.64" E                  | 30                 | 149.45                                                           | [45]              |
| 哀牢山<br>Ailao Mountain                   | 中山湿性林<br>Moist evergreen broad-leaved forest          | 2488                  | 24°32'53" N,<br>101°01'41" E                      | 15                 | 239.40                                                           | [45]              |
| 浙江天童<br>Tiantong, Zhejiang Province     | 亚热带常绿阔叶林<br>Subtropical evergreen broad-leaved forest | 300                   | 29°48' N,<br>121°47' E                            | 10~30              | 96.73                                                            | 本研究<br>This study |
| 三峡库区<br>The Three Gorges Reservoir Area | 亚热带常绿阔叶林<br>Subtropical evergreen broad-leaved forest | 1080~1920             | 30°10'58"—31°24'14" N,<br>108°23'28"—110°30'51" E | 5~40               | 42.80                                                            | [46]              |
| 赣中<br>Central Jiangxi Province          | 亚热带常绿阔叶林<br>Subtropical evergreen broad-leaved forest | 83~1041               | 26°29'17"—26°51'49" N,<br>114°06'39"—115°04'10" E | 15~35              | 43.00                                                            | [42]              |

森林公园将发挥更大的碳汇作用。

### 3.3 基于相对生长方程估测碳储量的优缺点及其不确定性

森林生态系统碳储量的研究涉及森林宽广的时间和空间尺度以及森林生态系统的内部联系,对其储碳能力的研究存在很大的困难和不确定性<sup>[47]</sup>。不同方法均具有各自的优缺点。本研究选用的利用生物量相对生长方程估算森林生态系统生物量、进而估测碳储量的方法直接、明确且技术简单,其建立在研究区域样地调查基础上的优势,对较小区域尺度上森林碳储量的估算具有更高的精确度。但在实际样地调查时,考虑到调查的难度以及人为因素的影响,一般都选取生长较好的地段进行测定,其结果往往高估了森林植被的整体碳储量<sup>[10]</sup>。同时,由于在估算过程中选用的生物量相对生长方程的适用性不同,对估算结果也可能造成一定影响。在选择生物量相对生长方程时,虽然遵照了各树种生长的土壤条件和气候条件尽可能相似的原则,但其准确性也不能完全替代在研究区域样地中通过砍伐标准木建立的实地相对生长方程。各模型对根系生物量和地下生物量概念的模糊也影响估测的精确度,可能造成估算结果偏大。本研究选取植物平均含碳率为 0.5,但顾凯平等<sup>[48]</sup>认为,不同树种应根据其化学组成及化学分子式来确定其含碳率,固定含碳率值会影响对碳汇估算的精确程度。

虽然生物量相对生长方程法和森林清查法的方程都是基于实测数据获得,但森林清查法估算森林生物量和碳储量较粗放,只涉及森林乔木层,且由于林业上树木分类较粗糙,在实际工作中建立的蓄积量-生物量转换函数存在缺陷<sup>[49]</sup>;而相对生长方程方法基于标准样地调查数据,所涉及到的植物种更全面,方程及方法更精细,具有更高的准确性。在适

用范围方面,森林清查法多用于区域、国家和洲际乃至全球尺度森林生物量和碳储量的估算,相对生长方程法只适用于小尺度局地地区生物量和碳储量的研究。鉴于大尺度样地数据获得的困难度,该方法并不适用于大尺度区域。

森林生态系统的碳储量不仅包括立木碳储量,也包括凋落物碳储量,土壤碳储量也需要考虑在内。本研究没有考虑到凋落物的碳储量,也未涉及土壤碳库,因此,对天童国家森林公园整个生态系统碳储量的研究还需要进一步详细的调查和深入。

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