Comparative Study of Carbon Storage and Allocation Characteristics of Mature Evergreen Broad-leaved Forest

Zhangquan ZENG, Canming ZHANG*, Yandong NIU, Xiquan LI, Zijian WU, Jia LUO

Hunan Academy of Forestry/Hengshan Research Station of Forest Ecosystem, Changsha 410004, China

Abstract Evergreen broad-leaved forest is an important forest type in China. This paper analyzes the allocation characteristics of vegetation and soil carbon pool of evergreen broad-leaved forest, to understand the current status of research on the carbon storage of evergreen broad-leaved forest as well as shortcomings. In the context of global climate change, it is necessary to carry out the long-term research of evergreen broad-leaved forest, in order to grasp the formation mechanism of evergreen broad-leaved forest productivity, and the impact of climate change on the carbon sequestration function of evergreen broad-leaved forest ecosystem.

Key words Evergreen broad-leaved forest, Vegetation carbon pool, Soil carbon pool, Carbon allocation, Carbon storage

Forest is a major part of terrestrial ecosystems, and its biomass accounts for about 90% of total terrestrial biomass[1]. The world's forests and soils store a total of 1146 Pg C[2], accounting for 46% of the total global terrestrial carbon pool (2477 Pg C)[3]. The rational management of forest ecosystems can increase the carbon storage, equivalent to the carbon sink effect; if it is destroyed, it will release large amounts of CO_2. There is degradation in the global forest in varying degrees[4], Houghton estimated that in the 1980s there was release of 0.6 Pg C in tropical regions every year because of forest degradation[4]; FAO also reported that the carbon released in tropical regions of Asia due to forest degradation was equivalent to the carbon released arising from deforestation[5]. The Chinese subtropical evergreen broad-leaved forest is severely damaged, and the natural broad-leaved forest has been very little. However, due to the high productivity and rich biodiversity, evergreen broad-leaved forest ecosystem has long been the focus of attention. In Guangdong's Dinghushan[6-7] and Heishiding[8], Chongqing's Luoyunshan[9], Zhejiang's Tiantaishan[10], Hunan's Huitong[11-12] and Fujian's Wanmulin[13], the in-depth study was carried out about biomass, productivity, carbon cycle and population dynamics of evergreen broad-leaved forest. In previous studies, the research on forest carbon storage was mainly focused on the macro level, there was a shortage of researches on the allocation characteristics of regional carbon storage, and in particular few researches were on the carbon storage of subtropical evergreen broad-leaved forest.

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* Corresponding author. E-mail: zhang6664733@aliyun.com

Therefore, through the comprehensive analysis of changes in the evergreen broad-leaved forest vegetation, soil and the entire forest ecosystem carbon storage in the subtropical regions, we expounded the factors influencing the carbon storage of evergreen broad-leaved forest, in order to provide the scientific basis and reference for the carbon storage estimate and carbon cycle study on a regional scale.

1 The vegetation carbon pool allocation characteristics of evergreen broad-leaved forest

The forest carbon pool mainly includes vegetation and soil carbon pool. The vegetation carbon pool includes arborous layer, understory vegetation, woody debris and litter. The vegetation carbon pool of evergreen broad-leaved forest is an important carbon pool. There are differences in the vegetation carbon pool size for different types of evergreen broad-leaved forest, which is mainly related to the forest stand types, forest age, and soil fertility conditions. Sheng Hao et al[13] reported that the vegetation carbon pool of *Altingia gracilipes* natural forest in Fujian reached 425 Mg/hm^2, slightly different from that of temperate old-growth forest (500 years old) (348 – 448 Mg/hm^2)[14]; the vegetation carbon pool of 150-year-old subtropical *Castanopsis kawakamii* natural forest was 255 Mg/hm^2; the vegetation carbon pool of 400-year-old monsoon-influenced evergreen broad-leaved forest in the south subtropical zone was 245 Mg/hm^2; the vegetation carbon pool of evergreen broad-leaved forest in Hunan's Yingzuijie was 129 Mg/hm^2; the vegetation carbon pool of tropical pristine rainforest in Hainan's Jianfengling was 340 Mg/hm^2; the vegetation carbon pool of the tropical regeneration forests was 234 Mg/hm^2; the vegetation carbon pool of temperate broad-leaved Pinus koraiensis natural forest was 55 – 102 Mg/hm^2[7, 12, 15-16].

1.1 Carbon pool of arborous layer In the vegetation carbon storage of evergreen broad-leaved forest, the carbon storage of arborous layer occupies a major part, and it is the main body of forest carbon sink.

Chen et al[17] reported that the biomass carbon pool of arborous layer of *Castanopsis kawakamii* natural forest in the mid-subtropical zone accounted for 97.2% of vegetation carbon pool. Sheng Hao *et al*. reported that the carbon storage of arborous layer of Fujian *Altingia gracilipes* natural forest accounted for most of the vegetation carbon pool (99.56%)[13]. Wang Hua et al[18] reported that the vegetation carbon of secondary evergreen broad-leaved forest in the Huitong area was mainly concentrated in the arborous layer, accounting for more than 95% of the entire vegetation carbon storage function. The carbon pool of arborous layer of the evergreen broad-leaved forest is related to the tree age. The study results of Huang Rong et al[19] showed that the carbon storage of 47-year-old evergreen broad-leaved forest was 115.03 Mg/hm^2, while the carbon storage of 120-year-old evergreen broad-leaved forest was 224.43 Mg/hm^2, indicating that there was a positive correlation between the carbon storage and tree age. The carbon storage allocation of arborous layer of evergreen broad-leaved forest mainly includes the spatial allocation (DBH, height allocation) and tree variety allocation. Zeng et al reported that during the succession process of coniferous forest to evergreen broad-leaved forest, the allocation of the carbon storage of arborous layer in various organs was changed (the proportion of trunk declining from 55.2% to 45.1%, and the proportion of branches and roots increasing from 12.5% to 16.4% and from 12.9% to 17.3%, respectively[12], which might be more conducive to the forest carbon accumulation of evergreen broad-leaved forest.

As to the carbon density of evergreen broad-leaved forest in Hunan Yingzuijie, the forest with DBH of greater than 30 cm has the highest carbon density, amounting to 62.41 Mg/hm^2, accounting for 50.08% of the total carbon density[12]. The study results of Huang Rong et al showed that the 47-year-old evergreen broad-leaved forest with DBH greater than 15 cm but smaller than 17 cm, had the highest carbon storage, amounting to 34.25 Mg/hm^2, accounting for 29.77% of total carbon storage; the 120-year-old evergreen broad-leaved forest with DBH greater than 41 cm, had the highest carbon storage, amounting to 60.03 Mg/hm^2, accounting for 26.78% of total carbon storage; the maximum carbon storage of 47-year-old evergreen broad-leaved forest appeared in the height level of 15 – 17 m, while the maximum carbon storage of 120-year-old evergreen broad-leaved forest appeared in the height level of 17 – 19 m[19], indicating that the impact of carbon storage by DBH and tree height was greater than the number of plants.

The vast majority of carbon storage of evergreen broad-leaved forest is concentrated in a few tree species, and most species contribute little to the carbon storage. The study results of Huang Rong et al showed that the number of 47-year-old forest species at the rich or important stage accounted for 25% of the total number of plant species, but their contribution to the total carbon storage was 30.5%; the number of 120-year-old forest species at the rich or important stage accounted for 13.9% of the total number of plant species, but their contribution to the total carbon storage was 36.7%[19].

Compared with other forest stand in the same region, the carbon density of evergreen broad-leaved forest is large. The carbon density of arborous layer of evergreen broad-leaved forest in Hunan Yingzuijie is 129.34 Mg/hm^2[12], higher than the carbon density of arborous layer of local mixed broad-leaved conifer forest (95.83 Mg/hm^2), and the carbon density of arborous layer of Pinus massoniana forest (85.27 Mg/hm^2), also higher than the average carbon density of arborous layer of the Chinese forest vegetation (57.07 Mg/hm^2)[20]. Wang Hua et al[18] also reported that the carbon storage function of the secondary evergreen broad-leaved forest vegetation was the strongest in the Huitong area (96.28 Mg/hm^2), higher than that of pure broad-leaved stand and other forest types in this area.

1.2 Carbon pool of understory vegetation The forest plants include the arborous layer and understory vegetation layer. Due to little understory vegetation biomass, the traditional studies generally ignore the role of understory vegetation[21].

However, with the land use change, the role of understory vegetation is re-valued. The total biomass of understory plants of subtropical evergreen broad-leaved forest is 1.8 Mg/hm^2[22]. The understory vegetation carbon density of Fujian Wanmulin evergreen broad-leaved forest is 1.86 $Mg.hm^2$[13], and the understory vegetation carbon density of Hunan Yingzuijie evergreen broad-leaved forest is only 0.69 Mg/hm^2, smaller than that of *Pinus massoniana* (2.7 Mg/hm^2) and mixed broad-leaved conifer forest (2.14 Mg/hm^2)[12], probably because the understory parts of evergreen broad-leaved forest and mixed broad-leaved conifer forest are restricted by insufficient sunlight, and the understory layer can not be fully developed.

1.3 Carbon pool of woody debris The woody debris (WD) includes coarse woody debris (CWD) and fine woody debris (FWD). CWD is the main body of forest woody debris, including downed log, dead standing tree, rootstock and limb; FWD mainly refers to the litter sprigs. CWD is an integral part of the forest ecosystem, and an important carbon pool within the system[23].

The CWD storage of moist evergreen broad-leaved forest in Ailaoshan of Southwest China reaches 98.46 Mg/hm^2[24]. The WD carbon pool storage of Fujian *Altingia gracilipes* natural forest is 2.37 Mg/hm^2[13], the WD carbon pool storage of Dinghushan mixed broad-leaved conifer forest is 5.24 Mg/hm^2[25], and the WD carbon pool storage of Hunan Yingzuijie evergreen broad-leaved forest is 3.78 Mg/hm^2[12], less than that of the 500-year-old subtropical monsoon-influenced evergreen broad-leaved forest (13.2 Mg/hm^2), and Ailaoshan primitive evergreen broad-leaved forest (36.56 Mg/hm^2)[27].

Studies have shown that in the forest, CWD accounts for 13% – 43% of the aboveground biomass[28]. The CWD storage of evergreen broad-leaved forest is low, possibly due to the forest stand composition, bole nature, local climate and other factors: when the superior tree species forming CWD are in the growth phase, there are few fallen trees; in the subtropical regions, the temperature is high and the rainfall is abundant, so that the woody debris is easy to decompose and difficult to accumulate.

1.4 Carbon pool of litter In different climatic zones, the carbon storage of litter layer varies widely. The litter layer carbon storage of Hunan Yingzuijie evergreen broad-leaved forest is 2.11 Mg/hm^2[12]; the litter layer carbon storage of southern subtropical broad-leaved forest, mixed forest and coniferous forest is 1.6, 3.38 and 5.89 Mg/hm^2[29]; the litter layer carbon storage of Fujian *Altingia gracilipes* natural forest is 3.79 Mg/hm^2[13]. Yang Yusheng et al[30] derived the litter layer carbon storage of subtropical *Castanopsis kawakamii* forest at 4.02 Mg/hm^2. Local climate, human disturbance and forest age are the important factors affecting the litter layer carbon storage.

2 Soil carbon pool allocation characteristics of evergreen broad-leaved forest

The global forest soil organic carbon storage is 402 – 787 Pg C, accounting for 25% – 50% of the world's terrestrial soil carbon storage[31], 2 to 3 times that of aboveground part of forest ecosystem[32]. It is the largest carbon pool in the terrestrial ecosystem.

The soil carbon density of Hunan Yingzuijie evergreen broad-leaved forest is 90.49 Mg/hm^2[12]; the soil carbon density of northern subtropical natural secondary forest communities is 61.81 – 96.45 Mg/hm^2[33]; the soil carbon density of the eastern evergreen broad-leaved forest is 117.6 Mg/hm^2[34]; the deep soil carbon storage of Fujian *Altingia gracilipes* natural forest is 130.02 Mg/hm^2[13]. The possible reasons about the difference of soil carbon are as follows:

(i) The spatial heterogeneity of soil and different forest soil layer thickness directly affect the estimation of forest soil carbon pool.

(ii) The heat is rich and rainfall is abundant in the subtropical regions throughout the year, so the biological cycle is strong, and the organic substance undergoes fast metabolism, not conducive to the accumulation of soil organic matter[35].

The 0 – 20 cm and 0 – 40 cm soil carbon of Yingzuijie evergreen broad-leaved forest contributes 61.69% and 85.49%, respectively[12]. The soil carbon storage of Fujian *Altingia gracilipes* natural forest is mainly concentrated in the 0 – 20 cm deep soil, accounting for 53% of total soil carbon storage[13]. The proportion of topsoil carbon storage of evergreen broad-leaved forest is high, reflecting that the soil is more fragile and human disturbance activity is more likely to cause soil carbon losses.

Therefore, it is necessary to strengthen the protection of subtropical natural secondary forest, reduce human disturbance on forests, therefore increase the organic carbon retention of forest ecosystem.

3 Ecosystem carbon pool allocation characteristics of evergreen broad-leaved forest

The study on the ecosystem carbon pool allocation characteristics of subtropical evergreen broad-leaved forest is conducive to the forest carbon cycle understanding. Overall, the carbon storage of evergreen broad-leaved forest is high. For example, the carbon pool of Fujian *Altingia gracilipes* natural forest is 561.39 Mg/hm^2[13], the carbon storage of central subtropical *Castanopsis kawakamii* natural forest is 399.1 Mg/hm^2, and the carbon pool of 400-year-old southern subtropical evergreen broad-leaved forest is 245 Mg/hm^2. The average carbon storage of forest ecosystem in China (258.83 Mg/hm^2) is lower than that of the 500-year-old temperate forest (618.99 Mg/hm^2)[14, 17, 36].

The carbon pool storage of ecosystem is affected by plants, soil, climate and other factors, and the mutual comparison of different ecosystems is difficult to reveal the dominant factors influencing the carbon storage of ecosystem. Compared with other local forest types, the ecosystem carbon pool of evergreen broad-leaved forest is large.

The organic carbon density of Hunan Yingzuijie evergreen broad-leaved forest ecosystem reaches 225.36 Mg/hm^2, higher than the organic carbon density of mixed broad-leaved conifer forest (170.96 Mg/hm^2) and *Pinus massoniana* natural forest (154.20 Mg/hm^2) ecosystems[12]. The vegetation carbon density of Hunan Yingzuijie evergreen broad-leaved forest accounts for 59.85% of total carbon density, and the soil carbon density accounts for 40.15% of total carbon density, indicating that the proportion of vegetation and soil carbon density is very high[12].

4 Prospect of the study on evergreen broad-leaved forest carbon pool

Currently, many researchers have carried out a lot of studies on the carbon storage and allocation of evergreen broad-leaved forest. However, for the evergreen broad-leaved forest with high productivity and rich biodiversity, the present studies are still inadequate.

In order to reveal the mechanism of response of carbon sequestration function of evergreen broad-leaved forest ecosystem to the global change, we can conduct the following studies:

(i) Through the establishment of large-scale fixed sample plot, it is necessary to carry out long-term positioned research regularly, to grasp the formation mechanism of evergreen broad-leaved forest productivity and dynamic changes in the spatial distribution pattern.

(ii) It is necessary to carry out the study on the relations between forest biodiversity and carbon storage, and especially the research of the effect of forest species diversity (such as richness, abundance) on the carbon storage as well as the dynamic changes in the relationship between species, to master the effect of climate change on the structure and function of evergreen broad-leaved forest ecosystem, and especially the effect on carbon sequestration function.

(iii) Based on the complex interaction among soil, climate and vegetation as well as the high spatial heterogeneity in the biogeochemical process of evergreen broad-leaved forest ecosystem, we can use high-density sampling, and geostatistical method, to explore the spatial pattern of soil organic carbon and its influencing factors[37].

5 Conclusions and discussions

This study makes a comprehensive analysis of allocation characteristics of vegetation and soil carbon pool of evergreen broad-leaved forest, to understand the research status of evergreen broad-leaved forest in the subtropical regions as well as the defects in the studies. In the context of global climate change, it is necessary to carry out the long-term positioned studies on evergreen broad-leaved forest, in order to grasp the formation mechanism of evergreen broad-leaved forest productivity and dynamic changes in the spatial distribution pattern, as well as the effect of climate change on the ecosystem structure and carbon sequestration function of evergreen broad-leaved forest. It is also necessary to understand the spatial variation of soil carbon pool and its influencing factors through the high-density sampling of soil.

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