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Review

On the Management of Large-Diameter Trees in China's Forests

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Abstract: Large-diameter trees have mainly been used for timber production in forestry practices. Recently, their critical roles played in biodiversity conservation and maintenance of ecosystem functions have been recognized. However, current forestry policy on the management of large-diameter trees is weak. As China is the biggest consumer of large-diameter timbers, how to maintain sustainable large-diameter timber resources as well as maximize ecological functions of the forests is a critical question to address. Here we summarize historical uses, distribution patterns, and management strategies of large-diameter trees in China. We found that large-diameter trees are mainly distributed in old-growth forests. Although China's forest cover has increased rapidly in the past decades, large-diameter trees are rarely found in plantation forests and secondary forests. We suggest that knowledge of large-diameter trees should be widely disseminated in local forestry departments, especially their irreplaceable value in terms of biodiversity conservation and ecosystem functions. Protection of large-diameter trees, especially those in old-growth forests, is critical for sustainable forestry. To meet the increasing demand of large-diameter timbers, plantation forests and secondary forests should apply forest density management with thinning to cultivate more large-diameter trees.

Keywords: large-diameter trees; large-diameter timber; biodiversity; policy; old-growth forest

1. Introduction

Large-diameter trees, defined as trees in the upper end of the size distribution in the local area, in many cases, trees with diameters at breast height (DBH) ≥ 60 cm, are important ecological features of old-growth forests [1,2]. They have high commercial value in terms of high-quality timber used for building, construction and other purposes [3], but are considered to have lower biomass growth rates and carbon sequestration ability [4,5]. For these reasons, traditional forestry practices in many countries support cutting large-diameter trees for timber resources and replacing them with younger trees regularly [1,6]. Consequently, there is a rapid global loss of large-diameter trees [7].

Recent studies are challenging previous understanding on large-diameter trees [8,9]. For example, some studies found that large-diameter trees continue to have higher growth rates compared to smaller ones, in terms of stand basal area [10], biomass growth rates [11], and wood production [12]. Moreover, scientific studies on large-diameter trees are accumulating due to their irreplaceable ecological, social, and cultural values [1,9,13], in addition to their economic values. Large-diameter trees play an important role in supporting forest biodiversity. First, larger trees produce more flowers and fruits that are food resources for a wide range of taxa [1]. They have tree cavities, which support up to 30% of all vertebrate species as nesting sites and shelters [14]. For example, large-diameter trees in Australia are home to about 300 species [1]. Therefore, even past selective logging of large-diameter trees can have a time-delayed effect on contemporary declines of old-forest dependant species [15]. Second, large-diameter trees can modulate microclimate, change soil physical and chemical components [16,17]; such environmental changes induced by the presence of large-diameter trees can increase habitat heterogeneity and facilitate species coexistence [18]. Lastly, retained large trees in commercially logged forests, function as refugia for canopy woody plants [19], and can accelerate forest restoration [20]. Even dead trees can support high species diversity, providing stepping stones or sources for seed dispersers, pollinators and pathogens that promote species coexistence [21]. Large-diameter trees are also important components of ecosystem functions. For example, large-diameter trees (DBH ≥ 60 cm) comprise 41% of the mature forest biomass worldwide [2]. They are key elements driving carbon dynamics within natural forests and managed forests after selective logging [22,23]. Moreover, large trees contribute disproportionally to decomposition, drive below- and aboveground structural heterogeneity [16,24], determine microhabitat densities [25], modulate microclimate [17], and combat climate change [26,27]. Loss of large-diameter trees result in a rapid decay of ecosystem functioning. For example, forest fragmentation kills large trees in tropical rainforest and leads to almost one third loss of carbon storage [28,29].

Following these novel findings, diversity and density of large old trees have been studied globally. For example, studies have reported the status of beech trees (*Fagus sylvatica* L.) DBH ≥ 80 cm in an old-growth forest of Belgium [30], large old trees in a wood-pasture of Romania [31], and large trees DBH > 40 cm in Finland at the national scale [32]. Unfortunately, large-diameter trees are threatened worldwide. For example, nine of the oldest and largest baobab trees (*Adansonia digitate* L.) in Africa have died in the past 12 years [33], and large trees DBH > 45 cm have declined dramatically in the boreal forests of central Sweden [34]. Considering that the scope of forest service in terms of economic values (e.g., wood production) has shifted towards their ecological values [12], the management of large-diameter trees in forestry practices should be re-evaluated. Yet forestry policy to manage large-diameter trees often is weak in most countries [9], especially in China, where management on large-diameter trees has received little attention. Here, we reviewed related literatures on this topic written in both English and Chinese. Our aim is to describe the evolution of large-diameter trees management in China, report the current distribution pattern and protection status of large-diameter trees. Subsequently, we propose practical strategies for sustainable management of large-diameter trees in different forest types.

2. Results and Discussions

2.1. Status of Large-Diameter Trees in China

China has a large number of large-diameter tree species. More than 700 species can grow to be large and older than 100 years in human-dominated landscapes [35,36]. Ancient *Ginkgo biloba* L., *Ficus religiosa* L., *Cinnamomum camphor* L., and many tropical tree species have extremely large diameters that DBH > 60 cm. For example, there are 93 species DBH > 49.8 cm in a 20-ha forest plot in Xishuangbanna, including one of the tallest species in China, *Parashorea chinensis* (Dipterocarpaceae), and the largest 1% individuals have contained 159.6 Mg per ha, 57% of the total biomass [2]. China has 2.08 million km^2 of forest, mostly distributed in South, Southwest, and Northeast China [37]. Large intact old-growth forests in these forest lands, such as those in Yunnan province, are also home to some of the tallest and oldest trees in the world [38,39], indicating that China should be home to many large-diameter trees. Unfortunately, large-diameter trees are not common in this country due to long term overexploitation [40,41]. For example, large-diameter timber (DBH >37 cm) only account for 5.7% of the total timber volume in Anhui province [42].

Historically, China's natural forests were considered as private property and lacked sustainable management. Large-diameter trees are among the first sources of timber extraction, especially when forests are not under strict protection [43] and are located in regions with low enforcement [41]. Local people build houses [3], tombs [44], and other forms of buildings with large-diameter trees as an expression of wealth and power. In addition, large-diameter trees were logged for making boats, war wagons, and used as fuelwood, resulting a sharp decline of large-diameter trees [41,43]. For example, millions of large-diameter trees were cut down to make iron during the Great Leap Forward in the 1960s, and DBHs of the largest trees in many regenerating forests today are less than 50 cm [45]. In recent decades, large-diameter timbers were mainly used for industrial uses [46], furniture [47], chopping blocks [41], and musical instruments [48]. These timber logs are not from domestic markets, rather they are mainly imported from Southeast Asia, Africa, and Russia [49].

Large-diameter trees are common in old-growth forests (Figure 1a). For example, the density of large-diameter trees (DBH ≥ 60 cm) in an old-growth forest (25 ha) of Changbaishan Nature Reserve is about 34 stems per ha, and it is 24 stems per ha, 19 stems per ha, and 14 stem per ha in a tropical montane rainforest (60 ha) in Hainan Island, a tropical rainforest (20 ha) of Xishuangbanna and a humid subtropical forest (25 ha) in Fushan, respectively [2]. The densities of large-diameter trees in these forests are comparable to those reported in a temperate mixed-conifer forest in the Yosemite National Park, USA (19.1 trees DBH ≥100 cm per ha; [50]), a lowland beech forest of Brussels, Belgium (34.3 trees DBH ≥ 80 cm per ha; [30]), and a temperate broadleaf woodland at Wytham Woods, UK (18 trees DBH ≥ 60 cm per ha; [2]). Though old-growth forests are critical habitats for many endangered species [51], the area of old-growth forests in China is small, with about 116,000 km^2 in area compared to 1.17 million km^2 of secondary forests [37]. These old-growth forests are more frequently found in east Qinghai-Tibetan Plateau, mountainous areas of Southwest and Northeast China where human accessibility is low [52]. Extremely large and old trees can be found only in remote, high elevation regions [39]. While China has strict regulations on biodiversity conservation, many of these forests have been protected under national protection programs. Yet some of them are fragmented and are disappearing [53,54]. Given that large-diameter trees in natural forests are vulnerable to habitat loss and fragmentation [29], atmospheric drought and other anthropogenic disturbances [35], the fate of large-diameter trees in these forests still hangs in the balance.

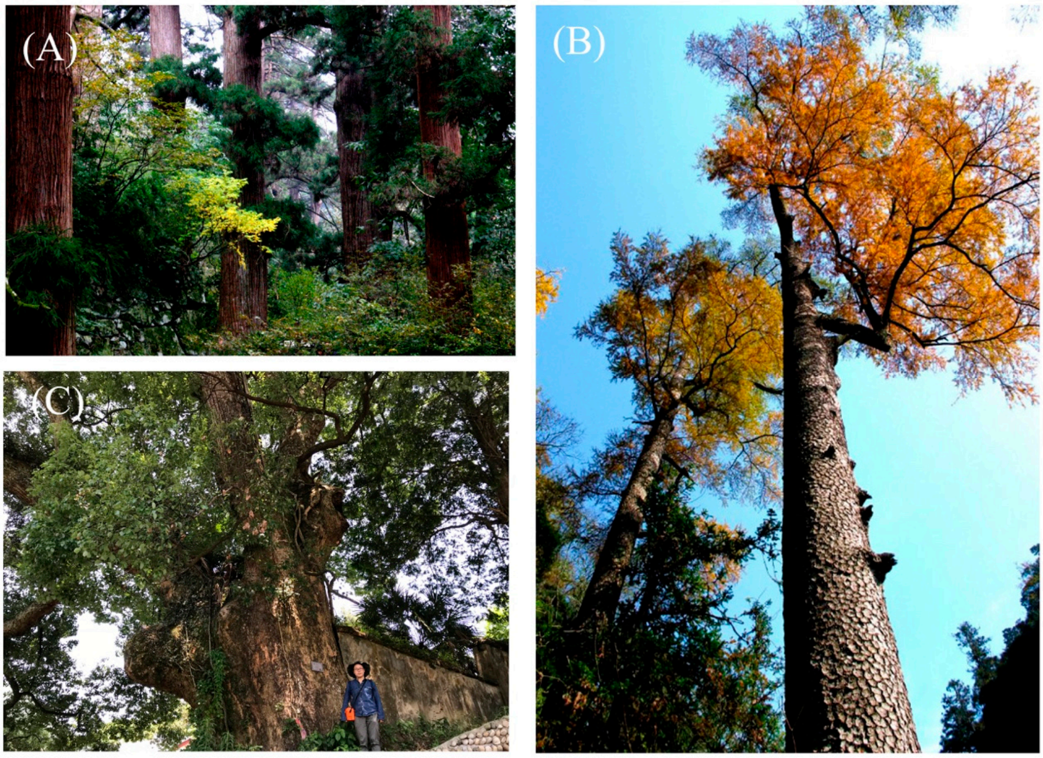

Figure 1. Large-diameter trees in (**A**) an old-growth *Cryptomeria fortune* Hooibrenk forest of Tianmushan National Nature Reserve, Zhejiang province; (**B**) a plantation forest of *Pseudolarix amailis* (J. Nelson) Rehder in Tianmushan National Nature Reserve, Zhejiang province; (**C**) a village of Kaihua County, Zhejiang province with an ancient *Cinnamomum camphora* (L.) Presl. tree.

Large-diameter trees are occasionally found in secondary forest (Figure 1b). Secondary forests in China are dominated by regenerating forests that stay in early successional stages with few large-diameter trees [52,55]. For example, there are few trees DBH > 40 cm in the Thousand Island Lake region in Zhejiang province [45], and Baiyun Mountain in Guangdong province, which are representatives of China's forests regenerated from the 1960s [56]. However, some secondary forests can harbour large-diameter trees after a long period of recovery. For example, the density of large-diameter trees (DBH > 60 cm) in a secondary evergreen broadleaf forest (24 ha) in Gutianshan National Nature Reserve is 2 stems per ha even after a secondary succession over a hundred years. Similarly, the density is 3 stems per ha in a secondary forest (20 ha) in Hong Kong after a succession of about 60 years [2]. In a secondary forest (9 ha) in Wuyanling Nature Reserve, the density of large-diameter trees (DBH > 50 cm) is 6.67 trees per ha, though these trees are mainly survivors from the disturbance about 50 years ago [57]. Hence, secondary forests have less large-diameter trees than old-growth forests.

The situation is even worse in human-dominated landscapes. For example, a recent study found about 682,730 large-diameter trees ≥ 100 years old from 198 city-level regions of China, with only 0.36 trees per km^2 at the national level [35]. The density of large-diameter tree varies substantially from 0.002 trees/km^2 (Tongyu County) to 24.18 trees/km^2 (Macao). These trees are mainly individually distributed in villages and urban areas, and clustered in some plantation forests. However, most plantation forests are dominated by fast growing species with short rotation periods that are typically less than 30 years [58], which prevents the development of large-diameter tree stands.

2.2. Management of Large-Diameter Trees in China

To develop a sustainable society, China has implemented the world's largest forest restoration program and invested more than US$378.5 billion on 16 sustainability programs since 1998 [59]. Unfortunately, the government policy focuses on forest cover [58] rather than the restoration of old-growth forests, and large-diameter trees have received little attention in China's current forestry policy. One reason might be that forests with stand age < 40 years old account for 63% of total forested area of China [52], and large-diameter trees are not common in these forests.

2.3. Large-Diameter Trees in Human-Dominated Landscapes

Large-diameter trees in human-dominated regions are known for their high cultural and socioeconomical values [1,13,35]. For example, large *Ginkgo biloba* and *Ficus religiosa* trees are regarded as sacred symbols that have important spiritual value to Chinese people [40] and followers of Buddhism [13]. Hence, citizens showed a high willingness to pay for the conservation of these large-diameter trees [60]. In addition, large-diameter trees that exceed 100 years old in these regions have received high conservation efforts after the establishment of the *Regulation on the Protection and Management of Ancient and Famous Trees* by the State Forestry Administration [36]. Trees have been legally protected, tagged, and managed by local forestry administrations. However, most of the large-diameter trees in new cities were uprooted and transplanted from natural forests starting in the 1990s. For example, 149,652 trees were transplanted to Guangzhou City in 1990–1994, resulting in a huge loss of large-diameter tree resources in natural forests [61]. Moreover, large-diameter trees transplanted to human dominated landscapes die rapidly due to insufficient management, unsuitable habitat, and those which survive transplanting are vulnerable to climate warming, severe drought and air pollution [35,62]. This calls for urgent action on the sustainable management of large-diameter trees in human-dominated landscapes.

2.4. Large-Diameter Trees in Commercial Forests

China, as the world's largest importer of timber, has an increasing demand of large-diameter logs from domestic markets [42,46]. A strict logging ban in natural forests after the implementation of the Natural Forest Conservation Program has made commercial forests, especially plantation forests, the major domestic sources of large timber productions in China. China has about 79 million ha plantation forests [37], but timber from plantation forests is considered to be low in tree size and quality.

Some studies have focused on the cultivation of large-diameter trees in commercial forests through density management with thinning, which is an effective way to facilitate the retention of large-diameter trees [63]. For example, *Pinus massoniana* Lamb. plantation is the most important conifer used for timber production in China. If *Pinus massoniana* was thinned to a density of 70%, the retained trees in the transformed forests would be significantly larger than that in the forests without thinning [64]. In addition, a shift from even-aged silviculture to uneven-aged forest management has increased the number of large-diameter trees [65]. Notably, large-diameter trees are more likely to be present in regions characterized by high water availability and moderate temperatures, with deep soil and less disturbances [23,66,67]. Hence, site conditions should also be considered when planning to cultivate large-diameter trees.

2.5. Large-Diameter Trees in Non-Commercial Forests

Non-commercial forest refers to forest that has been protected from human intervention to maintain forest ecosystem functions [55]. The area of non-commercial forest in China is roughly 85 million ha [37], and composed mainly by secondary forests regenerated from the 1960s, with few large-diameter trees [54]. These forests usually have lower species diversity and structural complexity compared to old-growth forests [55]. Yet China's forestry policy on these forests is to forbid human disturbances and have them undergo natural succession. However, natural succession is a long process which may take centuries to recover its full species composition [68] and reach high canopy cover. To accelerate secondary succession, close-to-nature management might be an effective solution to promote the growth of targeted large-diameter trees. Unfortunately, appropriate studies in China are quite limited [69].

Old-growth forests account for a low proportion of non-commercial forest but have the highest conservation value and contain most of the large-diameter trees [51]. Generally, large-diameter trees in old-growth forests are legally protected in national nature reserves. Additional small patches of old-growth forest occur outside the national protection system and large trees in these forest fragments are threatened. For example, large-diameter trees in some holy hills in Xishuangbanna have been used by local people for coffins [70]. To address this question, it has been suggested that fine-scale conservation efforts are needed to conserve large-diameter trees as small natural features [71].

3. Conclusions

China's forestry administrations concentrate on forest cover and timber production and have neglected the importance of large-diameter trees. Since the role of forests is changing in recent decades, it is critical to spread the knowledge on the importance of large-diameter trees in forestry practices for at least three reasons. First, economically, China is the biggest consumer of global timber, and importing large-diameter timber is both expensive and environmentally unsustainable [46,49]. Second, ecologically, large-diameter trees play an irreplaceable role in biodiversity conservation [1], carbon sequestration [2,11,23], and other ecosystem functions [26,27]. Third, large-diameter trees can be seen as a conservation icon to link humanity to nature for their social and cultural significance [35], attracting more tourists to forests, and improving human well-being.

To have sustainable high-quality timber production, maintain forest functions, and promote human–nature interactions, it is necessary to consider large-diameter trees in forestry policy [9]. First, it is critical to strengthen protection for remaining large-diameter trees in forestry practice, e.g., the preservation of the biggest trees with DBH > 60 cm [22], even dead ones [21,27]. Second, cultivation of large-diameter trees is urgently required. Forest thinning management is a promising strategy to cultivate big trees.

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C.W., B.J. and J.L led the writing and all authors contributed critically to the drafts and gave final approval for publication. All authors have read and agreed to the published version of the manuscript.

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