

# Long-term response of living forest biomass to extensive logging in subtropical China

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Received: 8 September 2017 / Accepted: 9 October 2017 / Published online: 19 July 2018  
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**Abstract** Forest disturbance and recovery are critical ecosystem processes, but the temporal patterns of disturbance have not been studied in subtropical China. Using a tree-ring analysis approach, we studied post-logging above-ground (ABG) biomass recovery dynamics over a 26-year period in four plots with different degrees of logging disturbance. Before logging, the ABG biomass ranged from 291 to 309 t ha<sup>-1</sup>. Soon after logging, the plots in primary forest, secondary forest, mixed forest and single-species forest had lost 33, 91, 90 and 100% of their initial ABG biomass, respectively. Twenty-six years after logging, the plots had regained 147, 62, 80 and 92% of their original ABG biomass, respectively. Over the 26 years following logging, the mean  $C_{AI}$  (Current annual increment) were 10.1, 5.5, 6.4 and 10.8 t ha<sup>-1</sup> a<sup>-1</sup> and the average  $M_{AI}$  (Mean annual increment) 8.7, 2.5, 5.6 and 7.8 t ha<sup>-1</sup> a<sup>-1</sup> for the four forest types, respectively. The results indicate that subtropical forests subjected to moderate logging or disturbances do not require intensive management and single-species plantings can rapidly restore the above-ground biomass to levels prior to heavy logging.

**Keywords** Biomass · Forest management · Harvest intensity · Subtropical evergreen broad-leaved forest · Jiulianshan Nature Reserve

## Introduction

Forest disturbance and recovery are critical but poorly quantified mechanisms for transferring carbon between the land and the atmosphere (Houghton 1999; Pacala et al. 2001). Forests are major contributors to terrestrial ecosystem carbon sinks and their associated economic benefits (Canadell and Raupach 2008; Zhang et al. 2016). Subtropical forests play an important role in regional and global carbon balances (Fang et al. 2001; Piao et al. 2009; Ren et al. 2016). One of the most common terrestrial biomes on Earth, subtropical evergreen broad-leaved forests, cover most parts of China (Kira 1991; Wu 1980). Because natural resource exploitation is becoming more aggressive, large areas of these primary forests have been destroyed and converted to secondary forests and plantations (Li 2004; Wang et al. 2007). Forests in China are large carbon sinks, especially the subtropical forests of southern China (Pan et al. 2011; Piao et al. 2009). One option to rapidly increase biomass after logging these forests is to plant single-species stands with appropriate site preparation (Zhou et al. 2016). Restoring the forest structure to an undisturbed state will increase carbon storage in disturbed forests (Lin et al. 2015).

Various man-made disturbances such as thinning, heavy cutting and mechanical site preparation are applied at stand initiation to reduce competing vegetation and improve crop tree growth (Miller et al. 2009). In subtropical China, shrub clearing, controlled burning and soil preparation before planting are conventional practices to improve the survival

The online version is available at <http://www.springerlink.com>

Corresponding editor: Zhu Hong.

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rate and growth of crop trees (Yang et al. 2005). The long-term effects of logging on the growth and cumulative biomass of forests are very complex. The forest structure of selective cutting forest ecosystems is relatively simple, consisting of a single, large-diameter canopy layer and little development of the understory to allow light to reach the herbaceous ground layer (Hanberry et al. 2014). However, with continued low rates of forest disturbance, the current biomass per ha will likely increase to historical levels as the most competitive trees become larger and the mean number of trees per ha decreases due to competition and self-thinning (Hanberry et al. 2016).

For sustainable forest management practices, accurate field data are needed. Tree ring analysis is an efficient and practical tool that can quickly provide information on growth rates by estimating the ages and ring width of trees (Brienen and Zuidema 2006; Lieberman and Lieberman 1985; López et al. 2013). This study focuses on above-ground living biomass, including total biomass, current annual increments, mean annual increments, biological rotation ages, average recovery rates compared to the original biomass, and biomass changes in stem diameter classes with different levels of cutting using tree ring analysis.

## Materials and methods

The study site is in the Jiulianshan Nature Reserve in the eastern Nanling Mountains, the greatest mountain range in South China. The forest is evergreen broad-leaved 20–30 m in height. Rolling topography is a common feature and the elevation is 400–1430 m, a.s.l. Temperatures average 16.8 °C and annual precipitation averages 2024.7 mm (Zhou et al. 2016), with a distinct wet season between March and September. Before 1988, the forest (9128.1 ha) was subjected to heavy logging in which all trees > 7 cm diameter at breast height (DBH) were removed. Fortunately, an additional 4283.5 ha area was reserved as a natural protected area in 1975 but some mushroom cultivation activities were allowed to continue. After logging, forest restoration process took three main forms with different site preparations: secondary forest with site clearing, a single-species planting with a controlled burn, and planting a mixed forest with a site clearing. By the late 1980s, a large area of logged land had been reforested or afforested using coniferous species (Liu et al. 2002; Toshio et al. 2001). The primary forest, located in the core zone of the Reserve, has not been affected by major disturbances within the last 90 years except for some timber harvesting for mushroom cultivation (Liu et al. 2002; Toshio et al. 2001). The planted species were usually Chinese-fir (*Cunninghamia lanceolata* (Lamb.) Hook),

Masson's pine (*Pinus massoniana* Lamb.) and slash pine (*Pinus elliottii* Engelm.). In this study area, Chinese-fir was the main species for planting.

## Plot selection

Based on the investigation of typical forest sites, four plots representing different degrees of recovery after logging were selected in the core zone of forests with primary disturbance, secondary forests, mixed forests and single-species forests (Fig. 1). The plot sizes were 100 m × 100 m per ha and all plots were similar in topography. The primary forest plot was disturbed with moderate logging disturbance and other plots had been logged seriously. The post-logging ABG (above-ground) biomass was 70, 10, 9 and 0% of the original pre-logging biomass for the primary, secondary, mixed, and single-species forest plots, respectively.

The primary forest plot, located in the core zone of the Nature Reserve, had never been heavily logged except for a few trees for mushroom cultivation before 1988. The Chinese fir in the mixed and single-species plots, also located in the core zone of the Reserve, was planted in 1979 and 1989, respectively, after the plots were heavily logged. The secondary forest plot, located in the experimental zone of the Reserve, was heavily logged 26 years ago and all trees > 10 cm DBH were removed. After logging, all shrubs, lianas and weeds were cleared and residual trees were kept in the secondary forest and mixed forest plots. All vegetation was burned before planting Chinese-fir in the single-species plot.

Table 1 shows the physical and chemical soil characteristics for each plot (Yang et al. 2015). The soils are typically upland yellowish red soil rich in potassium. No significant differences were observed in soil physical characteristics among plots. There were slight differences in soil chemical characteristics. These site differences have not been considered in this study due to limited labour and for economic reasons.

## Data collection

From 2014 to 2015, species of all living trees  $\geq 1.0$  cm DBH and all snags were recorded in each plot. Seven hundred and forty-six saplings (diameters 1.0–5.0 cm) and 40 trees (diameters 5.0–50.2 cm) were harvested by destructive sampling to develop allometric equations. For estimating the living biomass after logging between 1988 and 2015, 232, 58, 61 and 37 1.0 cm diameter increment cores were taken in the primary forest, secondary forest, mixed forest and single-species forest plots, respectively. Considering the complexity of the primary forest, the



**Fig. 1** Forest structure: **a** the primary forest (approximately 90 years old); **b** the secondary forest after 26 years; **c** the mixed forest after 36 years, and **d** the single-species plantation after 26 years

**Table 1** Physical and chemical soil characteristics for each plot

Forest types	Water content (%)	Bulk density ( $\text{g cm}^{-3}$ )	pH	C/N	AP ( $\text{mg kg}^{-1}$ )
Single-species	$31.88 \pm 5.35$	$1.02 \pm 0.10$	$4.73 \pm 0.09$	$14.17 \pm 0.56$	$25.88 \pm 5.99$
Mixed forest	$32.91 \pm 3.47$	$1.13 \pm 0.07$	$4.58 \pm 0.10$	$14.04 \pm 0.68$	$41.99 \pm 17.58$
Secondary forest	$29.91 \pm 12.40$	$1.19 \pm 0.12$	$4.40 \pm 0.15$	$17.35 \pm 1.88$	$25.92 \pm 6.13$
Primary forest	$47.96 \pm 2.65$	$1.02 \pm 0.04$	$4.72 \pm 0.11$	$14.64 \pm 0.62$	$38.41 \pm 11.27$
Forest types	AN ( $\text{mg kg}^{-1}$ )	AK ( $\text{mg kg}^{-1}$ )	TN ( $\text{g kg}^{-1}$ )	TC ( $\text{g kg}^{-1}$ )	
Single-species	$59.12 \pm 5.71$	$155.46 \pm 44.84$	$1.93 \pm 0.36$	$0.03 \pm 0.005$	
Mixed forest	$57.37 \pm 5.34$	$125.97 \pm 25.44$	$2.22 \pm 0.31$	$0.03 \pm 0.003$	
Secondary forest	$67.78 \pm 4.67$	$81.73 \pm 6.54$	$1.09 \pm 0.19$	$0.02 \pm 0.005$	
Primary forest	$78.18 \pm 3.99$	$199.04 \pm 34.49$	$2.76 \pm 0.26$	$0.04 \pm 0.005$	

C/N is the carbon to nitrogen ratio, AP, AN, AK, TN and TC are available phosphorus, available nitrogen, available potassium, total nitrogen and total carbon, respectively

increment cores were also taken according to dominant tree species.

The ABG (above-ground) biomass before logging was obtained from Toshio et al. (2001). Based on the pre-logging inventory and the former studies, the ABG biomass estimates were  $309 \text{ t ha}^{-1}$  for the primary forest,  $291 \text{ t ha}^{-1}$  for the secondary forest and  $306 \text{ t ha}^{-1}$  for the single-species forest plots. Pre-logging (1979) ABG

biomass estimates for the mixed forest plot was  $309 \text{ t ha}^{-1}$ . Soon after logging (1980 and 1989), the plots subjected to moderate logging (primary forest plot), lost 33%, heavy logging (the mixed and secondary forest plots) lost 91 and 90%, respectively, and clear cutting (100%) of their original ABG biomass, respectively (Fig. 5).

## Data treatment

The DBH size-class groupings of all species for each plot were determined statistically. All sampled data were pooled to develop allometric equations by using wood density, DBH and height. The best allometric equations were chosen using  $R^2$  and standard errors of estimate (SEE). The best equations were as follows:

$$W_{\text{AGB}} = 0.1060D^{2.4520} \quad (R^2 = 0.99, n = 33, 5 \leq D \leq 50.2 \text{ cm}) \quad (1)$$

where  $W_{\text{AGB}}$  is the dry weight of the individuals whose DBH was  $\geq 5$  cm and  $\leq 50.2$  cm;  $D$  is the DBH (cm). Using the tree ring analysis, the proportion of annual tree width in each increment core was calculated to determine the DBH in any year (Zhou et al. 2016). The ABG (above-ground) living biomass of each sample tree was calculated and scaled up according to the number of stems per hectare as recommended by UNFCCC (2011). For trees larger than the maximum allowed in the calculation of the allometric equation ( $> 50.2$  cm DBH; 78 of the 6968 trees sampled), biomass values were calculated by extrapolation (West et al. 2014). Chinese-fir biomass was calculated from previously published allometric equations (Wang et al. 2015). As a result, the ABG living biomass ( $W$ ) of the forest in any year ( $i$ ) may be calculated as:

$$W_i = \sum_{j=1}^n n_{ij} w_{ij} \quad (2)$$

where  $W_i$  is ABG (above-ground) living biomass of the  $i$ th year;  $n_{ij}$  is the number of individuals in the  $i$ th year with  $j$  DBH size-class;  $w_{ij}$  is ABG biomass of individuals in the  $i$ th year with  $j$  DBH size-class;  $j = 5.0, 6.0, 7.0, 8.0$  cm, ..., max DBH size-class of a plot. The current annual increment ( $C_{\text{AI}}$ ) and mean annual increment ( $M_{\text{AI}}$ ) computation can be expressed as:  $C_{\text{AI}}$  is ABG biomass at the end of the year-ABG biomass at the beginning of the year, and  $M_{\text{AI}}$  is ABG biomass per hectare/age of stand. The rate of growth for forest living ABG biomass can be determined using the following equations:

$$R(\%) = (B_t - B_{t-1})/B_{t-1} \times 100\% \quad (3)$$

where  $R_g$  is rate of growth,  $B_t$  represents forest living ABG (above-ground) biomass at the end of the  $t$  year and  $B_{t-1}$  represents forest living ABG biomass at the beginning of the  $t$  year.

In this study, the biological rotation ages (BRAs) of the four plots were estimated using the trends in the  $C_{\text{AI}}$  and  $M_{\text{AI}}$  (Zhou et al. 2016). Given no replication, differences in the mean  $C_{\text{AI}}$  and  $M_{\text{AI}}$  of each plot from the year after cutting to 2015 were assessed using one-way analysis of variance (ANOVA), followed by an LSD (least significant

difference) test (data not shown). Additionally, the annual forest living biomass was separated into diameter classes to evaluate changes in forest structure (West et al. 2014).

## Results

### Structure of the plots

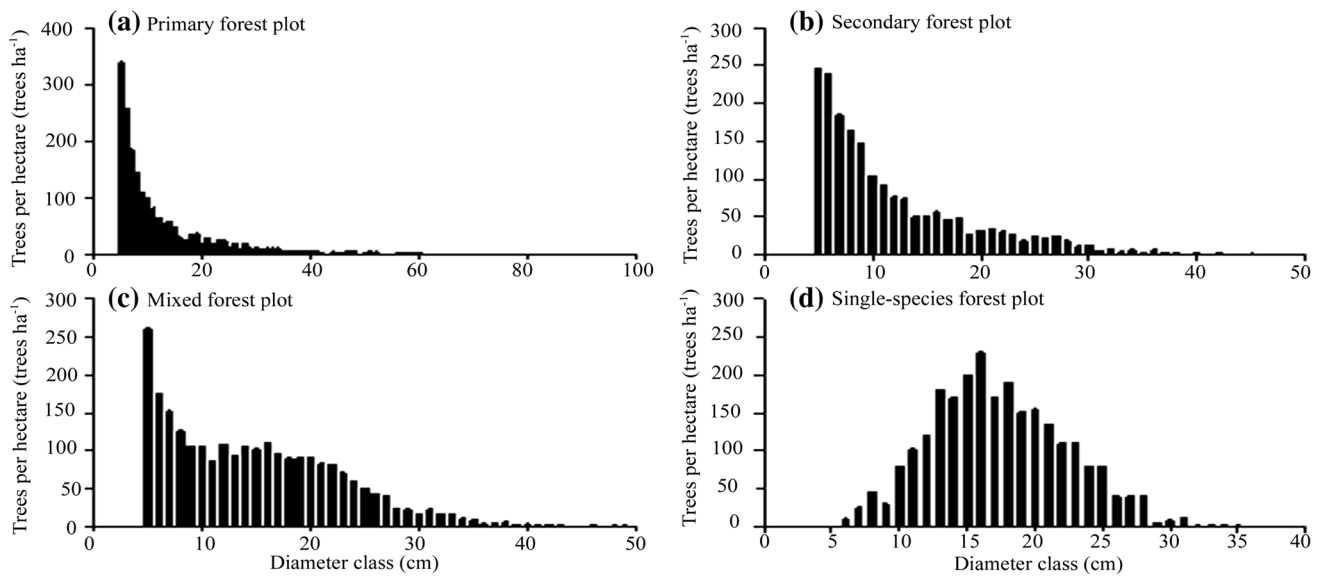
In 1988, the number of trees for the four plots was between 1220 and 1562 trees per hectare. The average pre-logging DBH of the four plots as described in the literature ranged from 10.6 to 18.1 cm, and the basal areas ranged from 30.2 to 48.6  $\text{m}^2 \text{ha}^{-1}$ . After 26 years, the number of trees per hectare varied from 1930 to 2494; the average DBH ranged from 10.3 to 15.8 cm, and the basal areas ranged from 32.9 to 75.0  $\text{m}^2 \text{ha}^{-1}$ .

The DBH size-class groupings of all species  $\geq 5$  cm for the primary and secondary forests exhibited a typical reverse-J shape indicating abundant regeneration. For the mixed forest and single-species forest plots, the DBH size-class grouping of all species  $\geq 5$  cm was a normal or approximately normal distribution (Fig. 2).

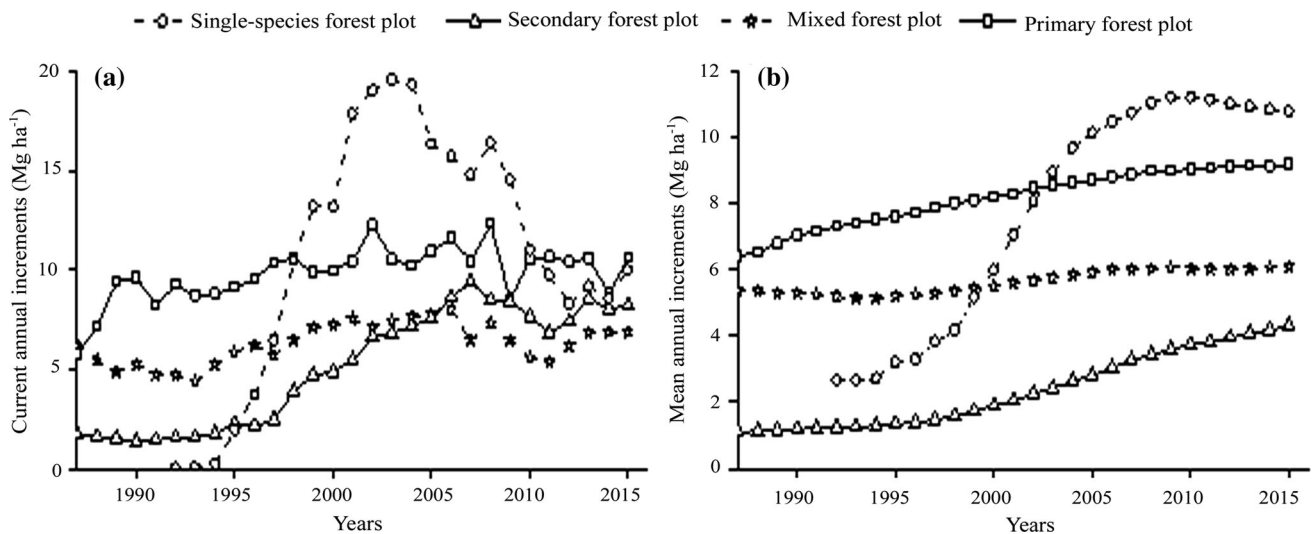
### Biomass $C_{\text{AI}}$ and $M_{\text{AI}}$

From 1988 to 2015, the biomass  $C_{\text{AI}}$  (current annual increment) of the secondary forest and single-species forest plots increased rapidly then dropped to between 8.2 and 9.9  $\text{t ha}^{-1}$  (Fig. 3a). The biomass  $M_{\text{AI}}$  (mean annual increment) of the two plots followed the same trend but was more stable (Fig. 3b). Over the same period, biomass  $C_{\text{AI}}$  and  $M_{\text{AI}}$  of the primary and mixed forests showed stable changes with little fluctuation between 5 and 11  $\text{t ha}^{-1}$ . For the primary forest and single-species forests, biomass  $C_{\text{AI}}$  declined dramatically in 2009. By restricting the recovery period after logging to 1988–2015, the average  $C_{\text{AI}}$  in this period were 10.1, 5.5, 6.4 and 10.8  $\text{t ha}^{-1} \text{a}^{-1}$  (primary, secondary, mixed, and single-species forests, respectively). Over the subsequent 26 years, the average  $M_{\text{AI}}$  were 8.7, 2.5, 5.6 and 7.8  $\text{t ha}^{-1} \text{a}^{-1}$  for the same forests, respectively.

Based on biomass increments, we estimated that the average biological rotation ages (BRAs) for the mixed forest and single-species plots were 35 and 18 years, respectively (Fig. 4b, d). For the primary and secondary plots, there was not a clear reduction in the number of trees over 80 and 35 years which prevents a precise determination of their BRAs. However, the mean BRAs of the two plots would be greater than 100 years, according to the trends in  $C_{\text{AI}}$  and  $M_{\text{AI}}$  (Fig. 4a, c).



**Fig. 2** The diameter distribution of the primary forest (a), secondary forest (b), mixed forest (c), and single-species forest (d)

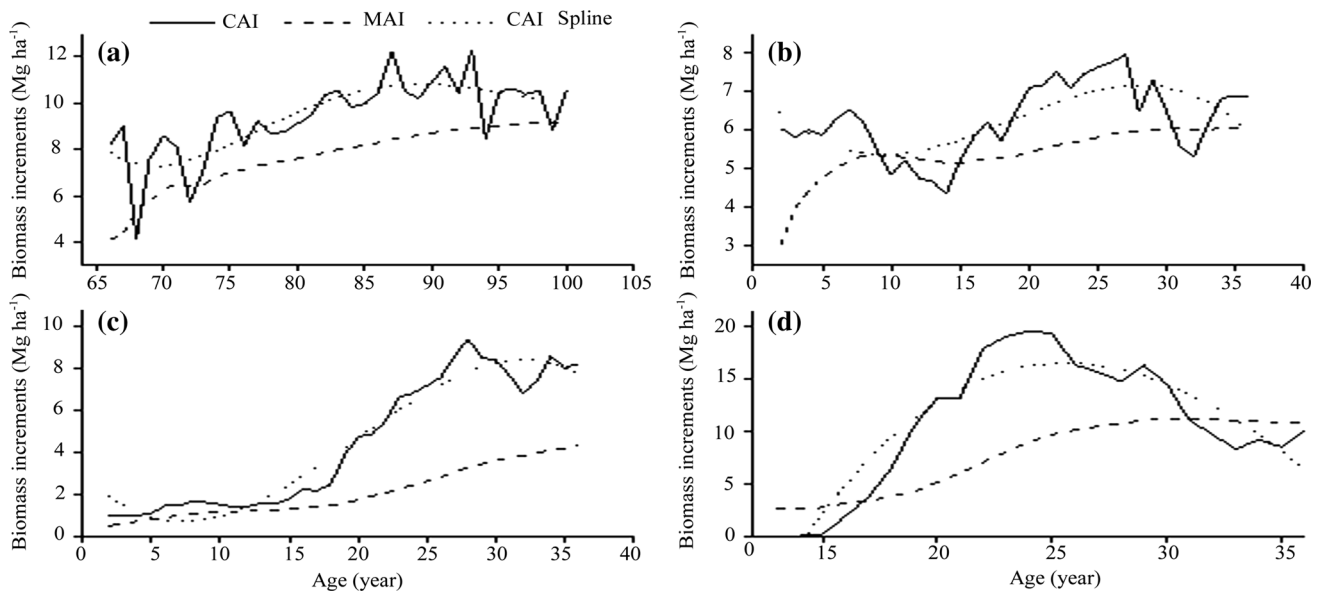


**Fig. 3** Current annual (a) and mean annual increments (b) for the forest plots in Jiuliashan Nature Reserve

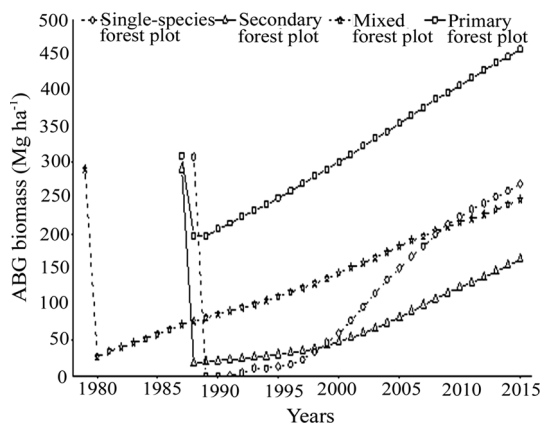
**Dynamic changes in ABG (above-ground) biomass**

The changes in the ABG biomass of each plot after logging are shown in Fig. 5. Soon after logging, the primary, secondary, mixed, and single-species forest plots had lost 33.0, 91.0, 90.0 and 100.0% of their initial ABG biomass, respectively. In 2015, the ABG biomass was 459, 164, 248 and 270 t ha<sup>-1</sup> for primary, secondary, mixed, and single-species plots, respectively. Figure 6 shows the biomass growth rates for the four plots; the average growth rates between 1988 and 2015 were 3.7, 8.9, 6.4 and 15.2% for primary, secondary, mixed, and single-species plots, respectively.

Table 2 shows the proportion of ABG (above-ground) biomass before and 26 years after logging based on diameter class for each plot. Twenty-six years after light logging (illegal logging and mushroom harvesting), the plot recovered 47% of its original ABG biomass, of which 46% was contributed by trees with DBH > 50 cm. In contrast, the secondary forest recovered 62% of its original biomass over the same period; 63% was contributed by trees with DBH 20–40 cm (Table 2). From 1980 to 2015, the mixed forest plot recovered 80% of its original ABG biomass. From 1989 to 2015, the single-species plot recovered 92% of its ABG biomass. Clearly, 26 years after logging, large trees (DBH > 40 cm) contributed a substantially smaller proportion of the ABG biomass except in

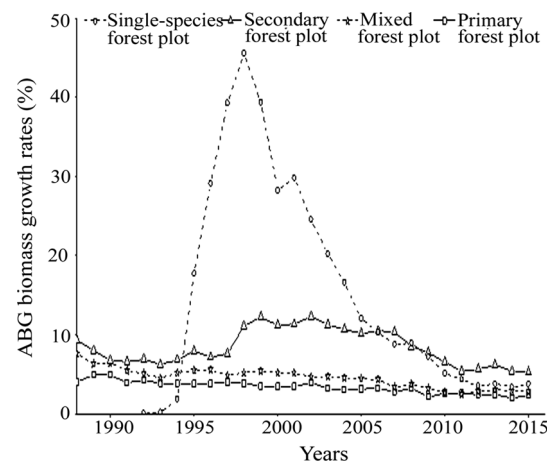


**Fig. 4** Current ( $C_{AI}$ ) and mean ( $M_{AI}$ ) annual biomass increments in relation to age for primary forest (a); mixed forest with clearing (b), secondary forest (c) and single-species forest (d). Dotted lines represent the  $C_{AI}$  spline curve with 3 order polynomial fit



**Fig. 5** ABG (above-ground) biomass dynamics of the forest types in the Jiulianshan Nature Reserve subtropical evergreen broad-leaved forest. For the mixed forest plot, logging occurred between 1978 and 1979, and for the other three plots between 1987 and 1989

the primary forest (54%). Over the same period, the biomass of trees 20–40 cm DBH significantly increased in the single-species, mixed and secondary forests, whereas biomass of trees 10–30 cm DBH decreased in the primary forest plot (Table 2). It is important to note that the above-ground biomass of all size classes, except for < 10 cm, decreased in the secondary forest when compared to pre-logging levels; in the primary forest, trees > 50 cm diameter increased by 46% (Table 2).



**Fig. 6** ABG (above-ground) biomass growth rates for the four forest types

## Discussion

### Effects of harvest intensity

Details about number, species and size of trees pre-logging were not available. Fortunately all this information could be reasonably concluded from previous studies. The number of trees per hectare for each plot was more than before logging due partly to activities in forests for gathering mushrooms or fuel wood affecting the growth of seedlings. After logging, the forests were preserved in 2003 as a national nature reserve and activities such as fuel wood gathering were banned completely.

**Table 2** Proportion of the ABG (above-ground) biomass before and 26 years after logging based on stem diameter class in the primary, secondary, mixed and single-species forest plots

Treatments	Proportional change in ABG biomass from 1988 to 2015						
	5–10 cm (%)	10–20 cm (%)	20–30 cm (%)	30–40 cm (%)	40–50 cm (%)	>50 cm (%)	Total (%)
Primary forest	1	– 2	– 8	– 9	8	46	47
Mixed forest	2	11	3	– 21	– 5	– 7	– 20
Secondary forest	6	– 2	– 14	– 39	– 7	– 5	– 38
Single-species forest	– 1	31	12	– 37	– 8	– 7	– 8

The differences in  $C_{AI}$  and  $M_{AI}$  under different harvest intensities were significant and the effect of cutting intensity was great. Since all large trees were cleared in the single-species and secondary forest plots,  $C_{AI}$  and  $M_{AI}$  fluctuated considerably for the first 15 years. However, with large trees preserved in the primary and mixed forest plots after logging,  $C_{AI}$  and  $M_{AI}$  were more stable.  $C_{AI}$  fluctuation for each plot had no significant correlation with harvest intensity. The  $C_{AI}$  in 2008 before ice damage was 12.3 and 16.4 t ha<sup>-1</sup> in the primary and single-species plots, respectively. After ice damage in 2009, the values decreased to 8.5 and 14.5 t ha<sup>-1</sup>, respectively. The secondary and mixed forest plots were not affected by the extreme low temperatures because of their relatively lower elevations. Therefore, the  $C_{AI}$  of the ABG (above-ground) biomass remained fairly stable before and after the ice damage (Fig. 3).

The results suggest a negative impact of harvest intensity on subsequent growth of living biomass in the secondary forest whereas for the primary forest, subjected to moderate harvesting, disturbance was a positive effect. The reason for this may be that biomass growth was stimulated by moderate disturbances such as logging and stump and mushroom harvesting (Hyvönen et al. 2016; Karlsson et al. 2002; Saksa 2013). Pre-logging, 33% of the ABG biomass was fixed in trees > 50 cm diameter in the primary and mixed forest plots, while this was 14% in the secondary and single-species plots. Losses in the single-species, mixed and secondary forests were mostly due to extensive logging. Planting single- or mixed species after heavy logging could return the ABG biomass to original levels over the subsequent 30 years. Many experimental recovery biomass rates are higher than in real-world applications (Evelyn et al. 2014). Removing more biomass from a stand through extensive logging also has the potential to make site preparation and planting more efficient (Saarinen 2006).

The mean growth rate in ABG (above-ground) biomass for the primary forest plot [(7.7 ± 1.4) t ha<sup>-1</sup> a<sup>-1</sup>] was similar to that of a 60-year-old premature stand in eastern China (approximately 7.0 t ha<sup>-1</sup> a<sup>-1</sup>, calculated from

Zhang et al. 2010). It is also close to the rate reported in an earlier study of our study area (9.9–10.8 t ha<sup>-1</sup> a<sup>-1</sup>) by Toshio et al. (2001). The average recovery rate of the secondary forest with site clearing [(2.1 ± 1.2) t ha<sup>-1</sup> a<sup>-1</sup>] was close to the rate of dry tropical forests 2–25 years-of-age (2.3–3.4 t ha<sup>-1</sup> a<sup>-1</sup>), and close to that of a previously logged forest in southeast China (3.24 ± 0.36 t ha<sup>-1</sup> a<sup>-1</sup>) (Yang et al. 2005).

### Restoration practices in forest management

The pre-logging ABG (above-ground) biomass values reported by Toshio et al. (2001) for the four plots (308–396 t ha<sup>-1</sup>) were close to the estimates of Yang et al. (2003) for subtropical evergreen broad-leaved forests near this study site (247–358 t ha<sup>-1</sup>). In 2015, the ABG biomass in the four plots ranged from 164 to 459 t ha<sup>-1</sup> which was similar to the estimates of Zhang et al. (2010) for a subtropical secondary forest (143–422 t ha<sup>-1</sup>). These calculated biomass values were within the range of biomass values for evergreen broad-leaved forests of similar age in subtropical China (136–500 t ha<sup>-1</sup>) (Feng et al. 1999). The moderately logged forest plot contained greater ABG biomass than before logging due to large trees that generally preserve the forest state even after logging. After logging, the surviving large trees contributed the highest proportion of the ABG biomass (54%). Moderate disturbance in the primary forest plot might stimulate large trees to a greater ABG biomass more quickly than other plots in which all large trees were removed. Large trees can promptly make full use of newly available resources such as sunlight and space (Hanberry et al. 2016). The increased biomass of the primary and single-species Chinese-fir plots are almost identical (272 and 269 t ha<sup>-1</sup>), and likewise for the mixed and secondary forest plots (171 and 155 t ha<sup>-1</sup>). Large trees can have a great resource advantage after logging, increasing biomass where only large trees or Chinese-fir occur. A crucial aspect of logging operations lies in determining how the forest should or should not be harvested. Tree ring analysis showed that trees between 30 and 60 cm diameter had the highest productivity (14.2 kg a<sup>-1</sup>

per tree), followed by trees  $\geq 60$  cm diameter ( $10.2 \text{ kg a}^{-1}$  per tree) and  $\leq 30$  cm diameter ( $4.5 \text{ kg a}^{-1}$  per tree) in the study area. Because of modest human disturbance in the primary forest plot, the improved access to light made the reserved 30–60 cm diameter trees grow faster than before disturbance. As such, 46% of the ABG biomass was fixed in trees  $> 50$  cm from 1988 to 2015 in the primary plot. However, no trees  $> 20$  cm in the secondary forest after logging could result in fixing more ABG biomass in saplings or herbs in the early years of stand growth. This was similar to the mixed forest plot. In the single-species plot, tending in the sapling stage allowed the stand to close quickly such that all resources were pooled in the growth of the single species. Therefore, leaving a sufficient number of large trees (70% of the total ABG biomass) or planting a single species may rapidly restore the ABG biomass to its initial state.

Biomass variations occurred due to a lack of disturbance with different site preparations and the practices of tending young forests. Tree cutting periodically removes trees from a given site, typically at least every 100 years (Hanberry et al. 2016; Masek et al. 2008). Although the above ground biomass in the single-species plot almost fully recovered within 26 years after heavy logging, the tree species diversity that would make the forest more stable was obviously lower than in other plots. In contrast, the ABG biomass was between 63 and  $239 \text{ t ha}^{-1}$  for secondary evergreen broad-leaved forests in Japan and 16–50-year-old secondary forests located throughout the tropics (Brown and Lugo 1990). Globally, the ABG pre-logging biomass of tropical forests ranges from 300 to  $475 \text{ t ha}^{-1}$  (Mazzei et al. 2010; Saatchi et al. 2007). These comparisons show that evergreen broad-leaved forests in subtropical China have an ability to maintain relatively high growth rates of ABG biomass.

The differences between past and present ABG biomass provide an estimate of the additional biomass that current forests could accumulate in the absence of disturbance (Hanberry et al. 2016). Although site preparation and the practice of tending young forests do not remove large trees, these control measures can prevent the growth of smaller diameter trees that replace canopy trees after mortality, resulting in lower densities rather than the maximization of available growing space. This transition in forest stand development over time is caused by competition among trees and the resultant self-thinning (Oliver and Larson 1990). In the absence of disturbance, the continued growth of current forest stands will result in fewer but larger trees per hectare and may create forests with greater density, smaller tree diameters, and less biomass than now.

## Conclusion

Tree-ring analysis is a valuable tool for the sustainable management of natural and planted forests (De Ridder et al. 2013). The above-ground biomass, as measured by tree-ring analysis, was greater in the primary forest (moderate logging disturbance) and single-species forest than in the mixed and secondary forests. After only 26 years, the primary forest fully recovered to its original state, confirming that subtropical forests subjected to moderate logging do not require intensive management. The above-ground living biomass based on individual growth rates show that planting a single-species coniferous species could quickly recover the biomass to a slightly higher level than other forest regeneration patterns between 26 and 36 years after extensive logging. Compared to the single-species and mixed forest plots, the above-ground biomass in the secondary forest plot was still 38% below pre-logging values after 26 years of recovery. Therefore, it is worthwhile to consider the results of this study in the context of local forest management. While the biomass recovered rapidly after a single-species planting, further studies are needed on the effects on biodiversity of biomass recovery when planting mixed and natural forests (Ouyang et al. 2016).

**Acknowledgements** Our fieldwork was aided by the Administration Bureau of Jiulian Mountain National Nature Reserve, which granted us permission to conduct surveys and procure samples in the forest. We thank Zhong Hao, Zhong Yuanchang, Liang Yuelong, Hu Hualin and Fu Qinglin for providing logistical support. This manuscript was improved by anonymous reviewers.

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