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Biomass increment and mortality losses in tropical secondary forests of Hainan, China

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Abstract Secondary forests, created after heavy logging, are an important part of China's forests. We investigated forest biomass and its accumulation rate in 38 plots in a tropical secondary forest on Hainan Island. These secondary forests are moderate carbon sinks, averaging 1.96–2.17 t C ha^{-1} a^{-1}. Biomass increment is largely by medium-sized (10–35 m) trees. Tree mortality accounts for almost 30% of the biomass and plays a negligible role in biomass accumulation estimates. Mortality rate is highly dependent on tree size. For small trees and seedlings, it is related to competition due to elevated irradiance after logging. Regarding prospective biomass and rates of accumulation, recovery is not as rapid as in secondary forests of cleared land. Therefore, tropical forests are susceptible to logging operations and need careful forest management.

Keywords Tropical secondary forest management · Carbon sink · Inventory · Dynamic plot · Logging

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Introduction

Secondary forests created following intense logging, are an important component of China's tropical forests, part of the ecotone from tropical Southeast Asia to East Asia with lowland rainforests, seasonal rainforests, and mountain rainforests. In the decades prior to the 2000s, secondary forests or plantations replaced most of primary rainforests. Intense logging gave rise to secondary forests, currently enclosed in nature reserves. Reduced impact logging has limited or minor effects on an ecosystem's biophysical or biogeochemical processes (Miller et al. 2011). However, it is not the same for severely logged forests, which is what has occurred in tropical China.

Studies on tropical secondary forests have focused on early stages of secondary growth on cleared land (Brown and Lugo 1990). Little information is available for tropical secondary forests resulting from heavy logging. The heavily logged secondary forest has few large trees but still contains several in a medium growth stage with a nearly closed, though not dense, canopy.

Logging of large trees stimulates the growth of understory trees by enhancing available sunlight. To what extent this stimulation occurs is still unknown. Brown and Lugo (1990) suggested that biomass accumulation is rapid in the first 15 years of secondary growth (up to 100 t ha^{-1}). In an Amazon logging experiment, this was in a range from 2.5 to 4.5 t ha^{-1} a^{-1} (Figueira et al. 2008). Moreover, small trees predominantly contribute to the increase in biomass. The logging example in the Amazon is moderate, logging 15% of the trees with a DBH above 35 cm. How biomass increment and mortality losses respond to heavy or intense logging, as is the case in tropical China, needs quantification. In this study we report inventory data from 38

permanent sample plots to show how intense logging affects biomass increment and mortality.

Materials and methods

Diaoluoshan National Natural Reserve

This study was carried out in Diaoluoshan National Nature Reserve (DNNR) located in the southeast of Hainan Island (18°40′–49′N, 109°45′–57′E). Climate seasonality is due to a tropical monsoon climate. In general, late May through October is the rainy season and November to early May the dry season. Mean annual temperature is 24.6 °C, with the lowest in January (15.3 °C) and highest in July (28.4 °C) (Hu 1997). Annual rainfall is relatively high up to 2160 mm.

The DNNR was approved as a national nature reserve in January 2008. Its total area is 183.87 km^2, with 78.41 km^2 as core, 84.56 km^2 as buffer, and 20.90 km^2 an experimental zone (http://dlsnr.forestry.gov.cn/). The lowest point is approximately 100 m.a.s.l.), and the highes 1499 m.a.s.l. Approximately 2126 species, belonging to 239 families of vascular plants, have been recorded. The design of the DNNR aimed to: (1) conserve tropical rainforests; (2) protect rare or endangered species and their habitats; (3) maintain forest biodiversity; and, (4) conserve landscape and tourism resources.

Before the 1980s, DNNR was a forestry centre famous for timber production and the main vegetation classified as tropical rainforest. Forests below 700 m) flourish with species of the Dipterocarpaceae family, such as *Vatica mangachapoi* Blanco (Hu 1997). These ecosystems are tropical lowland rainforests; ecosystems on mountaintops are short montane moss forests. Between them lies tropical mountain rainforests. Montane moss forests are difficult to access and have limited available quality timber, and logging is therefore not severe. Lowland rainforests with their valuable timber, have been heavily logged. An old engineer, who lives and works in the DNNR, recalled that trees with a DBH above 20 cm were cut for timber before the establishment of the Nature Reserve (*personal communication, Mr Yiwen Liang, a local people*). The tropical mountain forests intensely with a few old trees randomly distributed were logged intensely.

The inventory plots

A total of 38 plots (50 × 50 m) were established in 2010 (Fig. 1). A re-census was carried out in plots #1–#15 in 2015. The elevation of these plots ranges from 245 to 1255 m.a.s.l. (Table 1). The forest type was determined as: (1) 17 plots with trees belonging to the Dipterocarp family

was tropical lowland forest (TLF); (2) one plot without Dipterocarps but with *Dacrydium pierrei* Hickel was montane moss forest (MMF); and, (3) 20 plots were tropical mountain forest (TMF). Soil of the TLF and TMF plots is latosol; the MMF plot has mountainous yellow soil. Trees H > 2 cm DBH labeled and identified to species. A total of 26,725 trees were recorded. The DBH was measured with a measuring tape and tree height was also recorded.

Biomass allometric equations

The biomass allometry principle indicates that there is a relationship between biomass and tree size (Niklas 1994; Gower et al. 1999). The most common expression for this relationship is the power function:

$$y = a(x)^b \tag{1}$$

where y is biomass, x tree size, a and b fitted parameters and may be species specific. It is impractical to collect allometric data for all species, which might be over 200–300 per plot in tropical rain forests. Development of mixed-species allometric equations is necessary for this application. Kira et al. (1967) is the pioneer study to use mixed allometric equations for tropical forests. Some mixed-species equations are also available for our study region. The typical one used is that of Li (1993), which was developed based on samplings of 102 trees and more than 70 species, and diameter sizes from 5 cm to 80 cm, heights from less than 8 to 32 m:

$$W_{AG} = 0.040213((DBH)^2H)^{0.97268} \tag{2}$$

where W_{AG} is aboveground biomass (kg), DBH diameter at breast height (cm) and H height (m). The parameters are similar to those used by Brown et al. (1989) from world-wide data for moist tropical forests:

$$W_{AG} = 0.044418((DBH)^2H)^{0.9719} \tag{3}$$

We thus adopted the Li (1993) equation for aboveground biomass estimation.

Belowground allometric equations, including fine roots, however, are rare compared to aboveground ones. We collected four allometric equations for comparison purposes in this study:

(1) Belowground biomass allometry derived in the same region (Li 1993):

$$W_{BG} = 0.003612((DBH)^2H)^{1.11527} \tag{4}$$

where W_{BG} is belowground biomass (kg).

(2) Allometry collected in Xishuangbanna prefecture of China for TMF (Zheng et al. 2006):
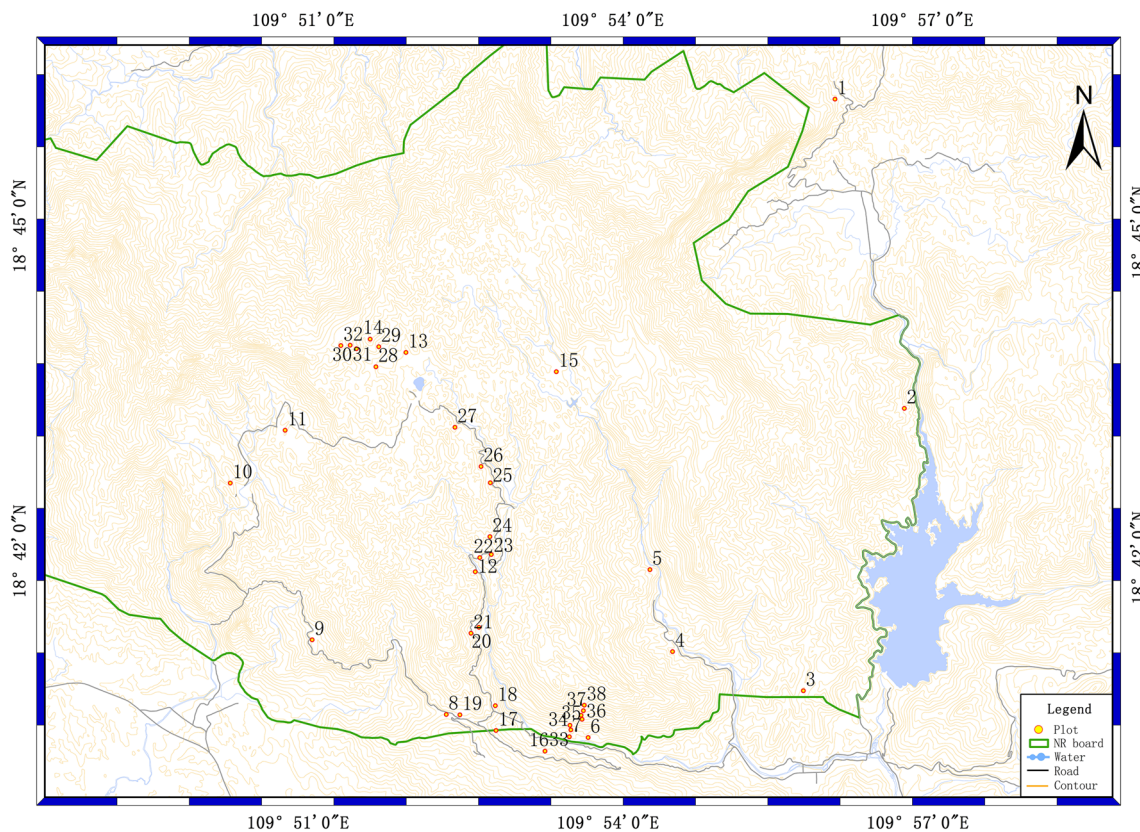
Fig. 1 Distribution of plots in the Diaoluoshan National Nature Reserve

$$W_{BG} = 0.003612((DBH)^2 H)^{1.11527} \qquad (5)$$

(3) Allometry collected in Xishuangbanna of China for a tropical seasonal rainforest (Feng et al. 1998):

$$\begin{cases} W_{BG} = 0.0112((DBH)^2 H)^{0.9045}, \ DBH \leq 20 \ cm \\ W_{BG} = 0.0069((DBH)^2 H)^{0.9781}, \ DBH > 20 \ cm \end{cases}$$

$$(6)$$

(4) Allometry collected in Thailand for a tropical seasonal rainforest (Kira et al. 1967):

$$W_{BG} = 0.0264((DBH)^2 H)^{0.775} \qquad (7)$$

Biomass increment, recruitment, mortality, and total accumulation

Relative growth rate (RGR) is calculated as:

$$RGR = \frac{2(DBH_{i+1} - DBH_i)}{DBH_{i+1} + DBH_i} \times 100 \qquad (8)$$

where DBH_i and DBH_{i+1} are diameter at breast height in the ith and i + 1th censuses. Mortality rate (MR) is calculated as:

$$MR = \frac{N_M}{N_T} \qquad (9)$$

where N_M is the number of tree mortalities in a specific DBH class and N_T is total trees in that class. Biomass increment (ΔB) is calculated as:

$$\Delta B = W_i - W_{i+1} \qquad (10)$$

where W_i and W_{i+1} are total biomass of live trees in ith and i + 1th census We tracked individual trees to calculate ΔB (Clark et al. 2001); thus, only live trees in both the ith and i + 1th censuses were used for calculations. Recruitment (R) and mortality (M) biomass were calculated as biomass of dead trees and recruitment of trees during the census time. Total biomass accumulation (C_b) is calculated as:

$$C_B = \Delta B + R - M \qquad (11)$$

Results

Stand biomass

The heavily logged forests had occasional large and medium- sized trees. Only 22 trees had a DBH above 70 cm

Table 1 General information about the plots

Plot No.	Elevation (m)	Type	Tree number	Mean DBH (cm)	Maximum DBH (cm)	Aboveground biomass (T/ha)	Belowground biomass (T/ha)	Ratio[a]
1	475	TMF	748	9.84	44.3	140.09	40.00	0.286
2	250	TLF	750	7.70	43.2	82.00	22.54	0.275
3	245	TLF	605	10.75	80.2	163.27	52.31	0.320
4	270	TLF	630	8.71	80.0	112.75	35.15	0.312
5	395	TLF	1199	7.74	60.8	153.01	43.70	0.286
6	255	TLF	996	8.15	86	147.65	44.98	0.305
7	265	TLF	992	7.72	25.0	68.69	16.26	0.237
8	515	TMF	838	7.14	66.1	190.79	60.19	0.315
9	555	TLF	1645	6.50	68.7	128.85	35.12	0.273
10	640	TLF	595	10.98	139.0	372.03	157.70	0.424
11	750	TMF	550	11.32	119.0	300.65	122.95	0.409
12	665	TMF	871	8.67	47.7	159.55	46.70	0.293
13	940	TMF	888	9.19	54.8	171.32	54.53	0.318
14	1130	TMF	965	8.73	67.3	197.76	60.37	0.305
15	935	TMF	1624	7.34	31.5	182.81	48.28	0.264
16	355	TMF	346	12.28	63.2	113.33	36.33	0.321
17	405	TLF	416	13.19	88.9	208.70	75.28	0.361
18	455	TLF	375	12.63	108.0	194.77	70.33	0.361
19	505	TLF	505	10.84	61.8	157.57	50.75	0.322
20	555	TMF	328	12.49	110.0	175.83	68.28	0.388
21	605	TMF	460	9.65	49.3	114.16	37.10	0.325
22	655	TMF	458	11.99	47.7	176.16	55.97	0.318
23	705	TMF	604	9.80	47.7	160.05	49.40	0.309
24	755	TMF	697	10.63	72.7	200.55	61.72	0.308
25	805	TMF	463	10.88	56.1	144.56	47.01	0.325
26	855	TMF	436	10.64	50.8	117.30	36.13	0.308
27	905	TMF	512	9.92	69.2	123.84	38.59	0.312
28	1005	TMF	622	10.77	117.1	222.96	81.29	0.365
29	1055	TMF	331	15.00	128.5	213.96	78.50	0.367
30	1155	TMF	718	10.27	87.0	170.20	52.43	0.308
31	1205	TMF	771	9.95	73.0	167.27	53.71	0.321
32	1255	MMF	613	10.71	40.3	93.08	25.12	0.270
33	305	TLF	805	8.46	90.5	111.78	33.59	0.301
34	355	TLF	757	9.18	47.3	134.10	39.72	0.296
35	405	TLF	551	9.60	55.7	150.39	50.73	0.337
36	455	TLF	600	10.28	70.0	169.71	55.45	0.327
37	505	TLF	846	8.83	108.0	171.17	57.05	0.333
38	555	TLF	615	10.38	76.3	180.86	59.63	0.330

TLF tropical lowland forest, *TMF* tropical mountain forest, *MMF* montane moss forest biomass ton dry matter/ha
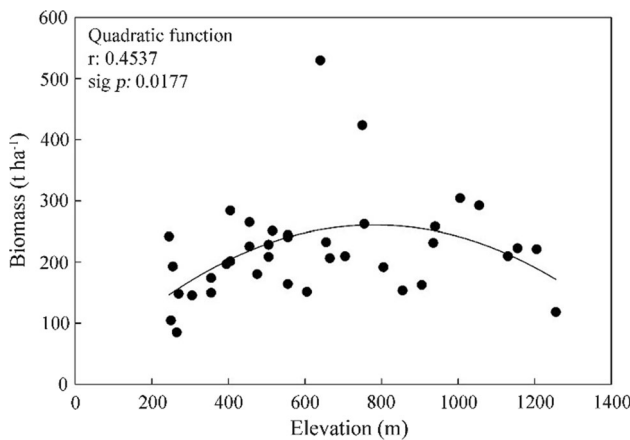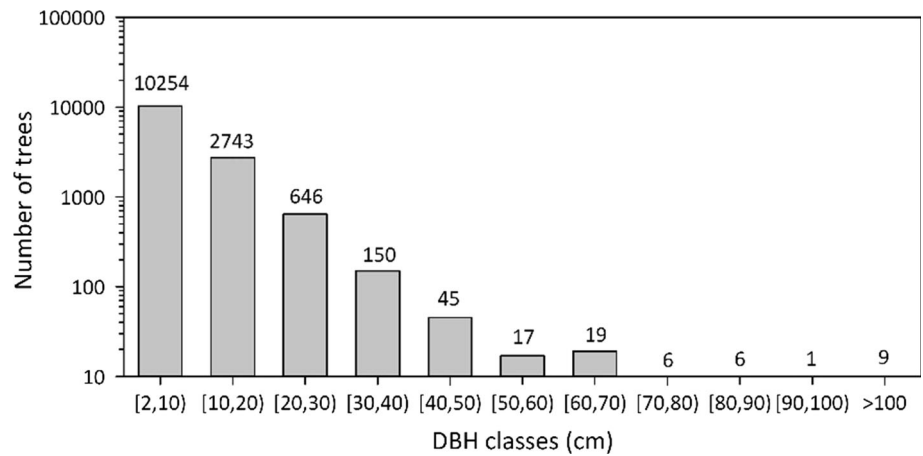
[a]Ratio = (Belowground biomass/Aboveground biomass)

from 13896 individuals for plots #1–#15 (< 0.2%) (Fig. 2). The number of medium size trees (10–35 cm DBH was 132 (< 1%).

Mean biomass for all 38 plots was 218.6 ± 80.8 t ha^{-1} (Table 1). Mean biomass was higher in TMF (228.6 ± 63.9 t ha^{-1}) than in TLF (212.2 ± 97.1 t ha^{-1}). A *t* test between TLF and TMF was not significant ($p = 0.542$). The single MMF plot showed a biomass of 118.2 t ha^{-1}. There was an altitude trend in biomass distribution (Fig. 3). Biomass peaked in middle altitudes, with

**Fig. 2** Frequency distribution in different diameter classes based on the plots #1–#15

Fig. 3 Estimated stand biomass in relation to elevation
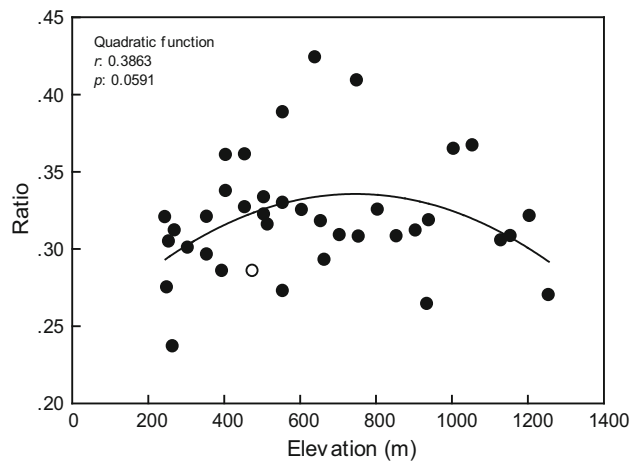
Fig. 4 Ratio of belowground and aboveground biomass in relation to elevation

lower and higher altitudes with low biomass. The ratio of belowground and aboveground biomass is 0.32 on average, and it has a relation to elevation (Fig. 4).
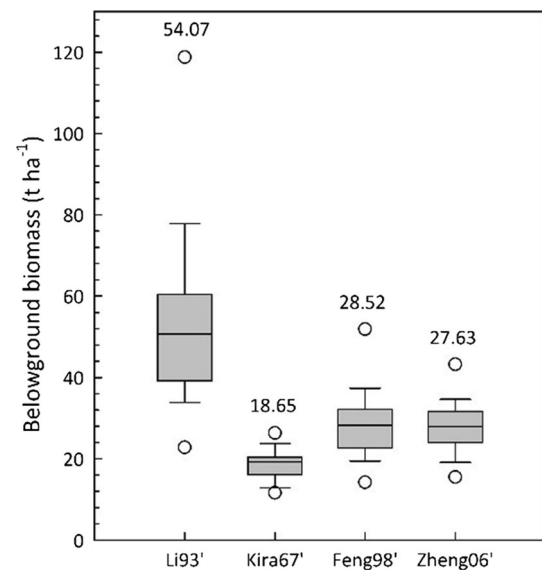

Fig. 5 Comparison of belowground biomass estimated with different allometric equations

Belowground biomass, estimated with different allometric equations, varied strongly (Fig. 5). The allometry derived in the same region (Li 1993) gave the highest estimated biomass (54.1 t ha^{-1}). Allometric equations from the Xishuangbanna prefecture of China gave medium levels of estimated biomass of 28.5 t ha^{-1} (Feng et al. 1998), and 27.6 t ha^{-1} (Zheng et al. 2006)). Biomass estimated with allometry equations calculated for forests further from the site (Kira et al. 1967) was lowest (18.6 t ha^{-1}).

Tree growth and biomass increment

Relative growth rates (RGR) tend to decrease with DBH (Fig. 6). Large trees (> 35 cm) showed low RGR, usually less than 5.0% (Mean RGR was 3.4%), while RGR of
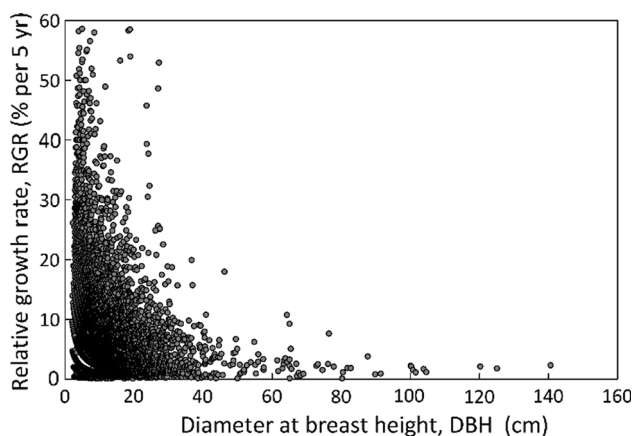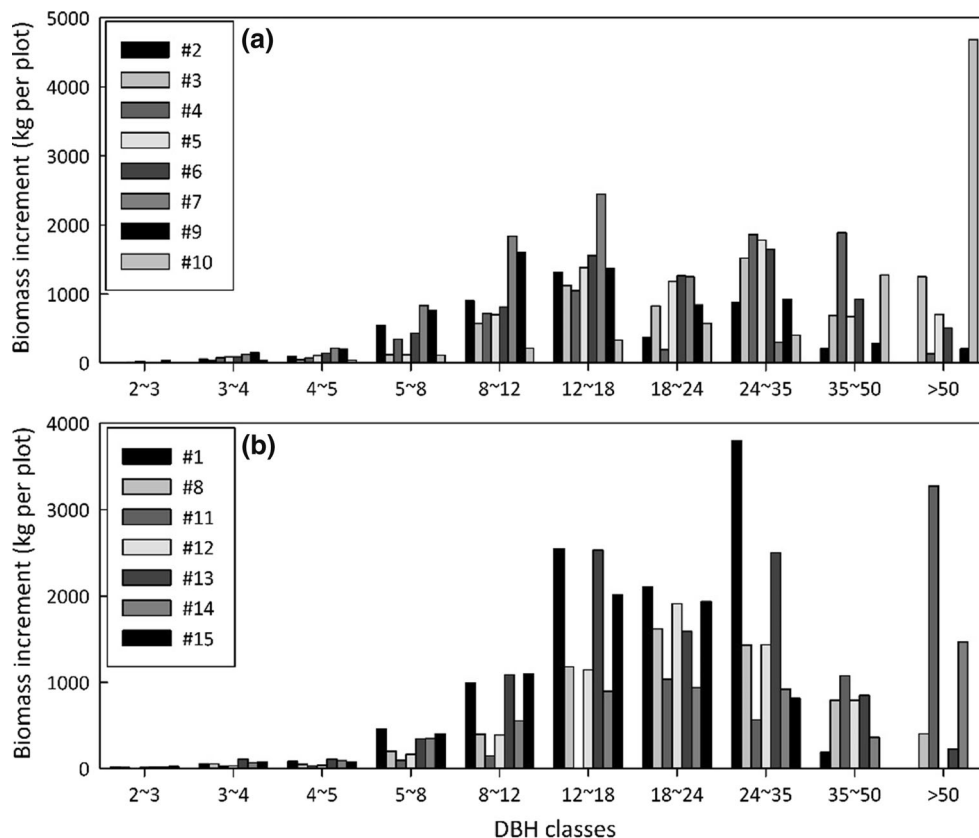
Fig. 6 Relative growth rate compared to diameter

smaller trees (< 10 cm) varied strongly with a mean value of 7.3%. The mean RGR of medium-sized trees was 6.1%.

The distribution of biomass increment (ΔB) under different DBH classes is shown in Fig. 7. Despite accounting for nearly half of the total number of trees, individuals with a DBH < 5 cm contributed slightly to the ΔB of both lowland and mountain forests. The mean contribution to total ΔB was highest in DBH classes 12–18 cm for TLF, whereas the highest contribution for the TMF were 24–35 cm DBHs. The pie chart of the contributions of small ([2,10]), medium-sized ([10,35]) and large trees ([35, ∞]) to total ΔB is shown in Fig. 8. Medium-sized trees contribute most to total ΔB, and this is especially obvious in TMF. Large trees, with only a small portion of the number of trees, contribute comparable to that of small trees.
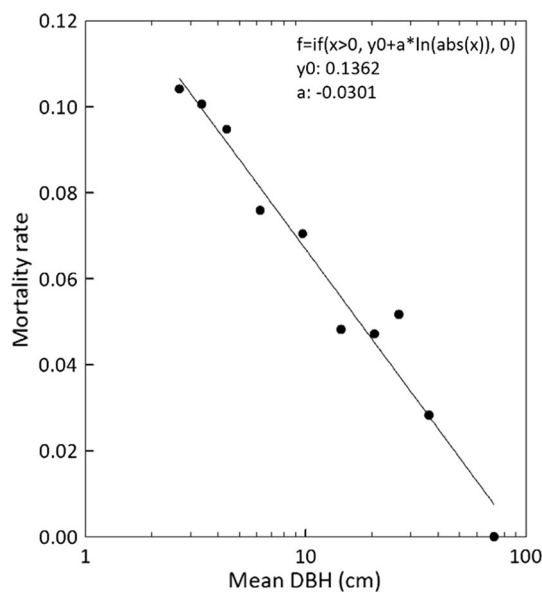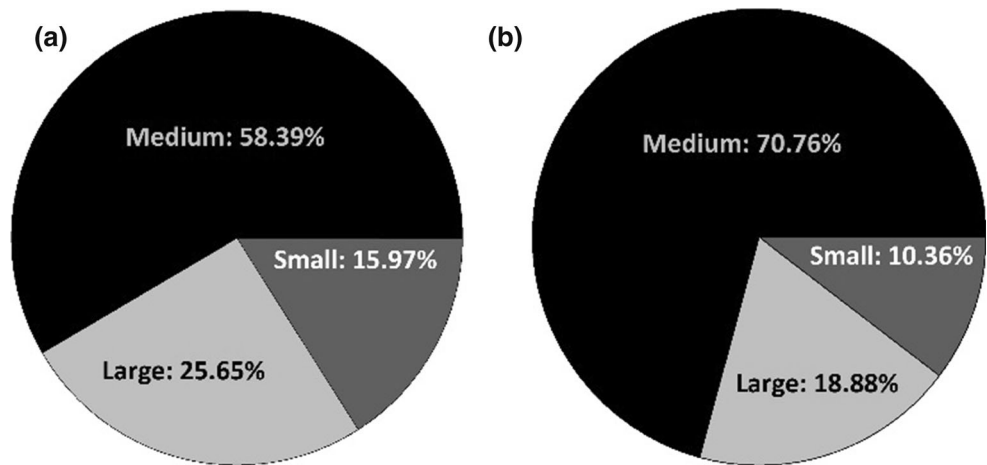
Mortality rate

Therate of mortality was highly dependent on tree size (Fig. 9). No tree with a DBH > 50 cm died during the investigation period. More than 1100 trees, including five with DBH > 35 cm, died during the study period. The overall mortality rate was 0.015 per year.

Total biomass accumulation

There were no trends found in biomass increment, recruitment, mortality losses, or total biomass accumulation due to altitude (Fig. 10). The mean biomass increment was 5.2 ± 0.8 and 5.7 ± 1.5 t ha^{-1} a^{-1} for TLF and TMF, respectively. Mean recruitment had little effect on total biomass accumulation with mean values of 0.3 for TLF and for TMF. Mortality loss was similar in both with a value of 1.6 t ha^{-1} a^{-1} (Fig. 11). Overall, the net biomass accumulation was slightly higher in TMF (4.3 ± 1.5 t ha^{-1} a^{-1})

Fig. 7 Biomass increment in different DBH classes

Fig. 8 Pie chart depicting the contribution of different size classes to stand biomass increment Small: DBH < 10 cm; Medium: 10–35 cm; Large : DBH > 35 cm

Fig. 9 Tree morality rate plotted against mean size (Data of horizontal axis based on mean DBH of 10 DBH classes)

than TLF (3.9 ± 1.4 t ha^{-1} a^{-1}). A t-test of C_b between TLF and TMF was not significant ($p = 0.612$).

Discussion and conclusions

Stand vegetation accumulated carbon at moderate rates in the tropical secondary forests under study. If the biomass is converted into carbon with a conversion factor of 0.5, the mean vegetation carbon sink was 2.17 and 1.96 t C ha^{-1} a^{-1} for mountain and lowland forests, respectively. This estimation is similar to results from a logged forest in the Philippines (1.4 t C ha^{-1} a^{-1}; Lasco et al. 2006), and in Borneo (1.2 t C ha^{-1} a^{-1}; Berry et al. 2010). This is higher than that of primary forests in the same region (0.56–0.62 t C ha^{-1} a^{-1}; Chen et al. 2010), in

the Amazon (0.98 t C ha^{-1} a^{-1}; Baker et al. 2004), and in Africa (0.63 t C ha^{-1} a^{-1}; Lewis et al. (2009), but not as large as secondary forests on cleared land (Brown and Lugo 1990).

Medium-sized trees were major contributors to biomass increment in the forests in this study (Fig. 8). This is different from a logging experiment in the Amazon which suggested small trees play a leading role in biomass increment (Figueira et al. 2008). This could be explained by the history of our Nature Reserve. The last logging operation took place in the DNNR in 2001 (*personal communication, Mr Yiwen Liang, a local people*). Forests were strictly protected after 2001 which means there was already at least 10 years of secondary growth before we established the plots. Selective logging of large trees could rapidly increase the level of sunlight to understory trees. After more than 10 years of change, most of these small-size trees have grown into medium-sized ones. This was the major reason for the differences between our forests and the Amazon logging experiment.

The degree of logging intensity plays an important role in both biomass amount and its rate of accumulation in secondary forests. Similar dipterocarp forests in Xishuangbanna, Thailand, and Malaysia showed high biomass (Ogawa et al. 1965; Terakunpisut et al. 2007; Tan et al. 2015). In general, the low-elevation site usually has higher temperatures than higher altitude sites. If water is not a limiting factor, warmer sites have higher biomass. In our study, biomass was highest in the middle elevation plot of the mountain forest (Fig. 3). The low elevation lowland forests did not have a high biomass, and possibly experienced more disturbance by logging. The biomass increment across DBH classes was low. The highest DBH class contributing to biomass was smaller in TLF (12–18 cm) than in mountain forest (24–35 cm) (Fig. 7).

Mortality, accounting for approximately 30% of biomass increase, should be in biomass carbon accumulation
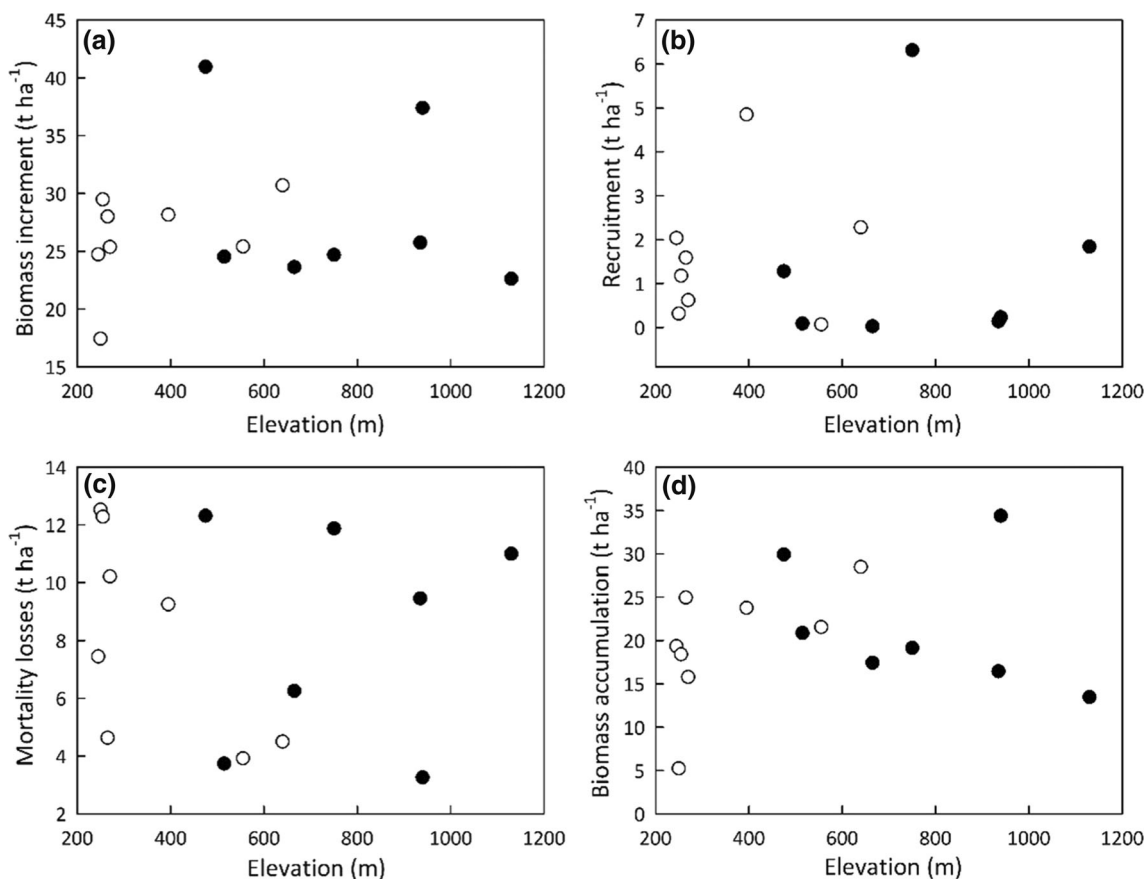
Fig. 10 Altitude effects on biomass increment, recruitment, mortality losses, and total biomass accumulation (TLF, open symbols; TMF, closed symbols)
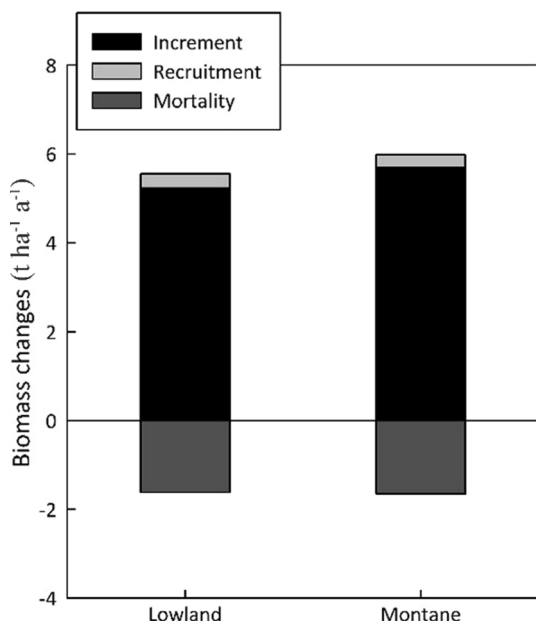
Fig. 11 Net biomass accumulation rate and its components

estimates. The overall mortality was 0.015 trees per year. This is comparable to that of primary forests in Pasoh,

Malaysia (King et al. 2006). Mortality is strongly dependent on tree size (Fig. 9). This is consistent with previous inventories (Lieberman et al. 1985) and models (Pinard and Cropper 2000). Most importantly, no tree died with a DBH > 50 cm over the 5-year investigation; however, mortality of seedlings and small trees was relatively high. Logging of large trees may increase the level of understory radiance to seedlings and small trees. This could also result in strong competition and subsequent high mortality.

The ratio of belowground and aboveground biomass is important to estimate total forest biomass. The mean ratio was 0.319, almost twice as high than a similar logged forest in SW China (0.165; Tang et al. 1998) and Malaysia (0.172; Pinard and Putz 1996). This ratio is similar to results from primary tropical forests in Brazil (0.252; Russell 1983; 0.255; Salomão et al. 1996, and Columbia (0.263; Saldarriaga et al. 1988). Methodology is a critical element in estimating belowground biomass, and varied strongly with different allometric equations (Fig. 5). On the one hand, there are less allometric equations available for belowground biomass compared to that for aboveground. On the other, most of the allometric equations are derived for primary forests. The allometric equation based

on the same region gave the highest belowground estimate, followed by equations from Xishuangbanna, China, and the lowest with equations from Thailand.

Overall, the logged secondary forest showed some differences in biomass and its rate of accumulation compared to primary forests in the tropics. Biomass recovery is not as rapid as in secondary forests established on cleared land. Given this, mean biomass accumulation rate could be maintained in subsequent years; recovery of 100 t ha^{-1} needs at least 50 years. In reality, this accumulation rate could hardly be maintained due to disturbance and increasing canopy cover. Therefore, tropical forests are sensitive to logging operations and need careful forest management.

References

Baker TR, Phillips OL, Malhi Y, Almeida S, Arroyo L, Fiore AD et al (2004) Increasing biomass in Amazonian forest plots. Philos Trans R Soc B Biol Sci 359:353–365

Berry NJ, Phillips OL, Lewis SL, Hill JK, Edwards DP, Tawatao NB, Ahmad N, Magintan D, Khen CV, Maryati M, Ong RC, Hamer KC (2010) The high value of logged tropical forests: lessons from northern Borneo. Biodivers Conserv 19:985–997

Brown S, Gillespie AJR, Lugo AR (1989) Biomass estimation methods for tropical forests with applications to forest inventory data. For Sci 35:881–902

Brown S, Lugo AE (1990) Tropical secondary forests. J Trop Ecol 6:1–32

Chen DX, Li YD, Liu HP, Xu H, Xiao WF, Luo TS, Zhou Z, Lin MX (2010) Biomass and carbon dynamics of a tropical mountain rain forest in China. Sci China Ser C Life Sci 53:798–810

Clark DA, Brown S, Kicklighter DW, Chambers JQ, ThomlinsonNi JR, Ni J (2001) Measuring net primary production in forests: concepts and field methods. Ecol Appl 11:356–370

Feng Z, Zheng Z, Zhang J, Cao M, Sha L, Deng J (1998) Biomass and its allocation of a tropical wet seasonal rain forest in Xishuangbanna, China. Acta Phytoecol Sin 22:481–488

Figueira AMS, Miller SD, de Sousa CAD, Menton MC, Maia AR, da Rocha HR, Goulden ML (2008) Effects of selective logging on tropical forest tree growth. J Geophys Res 113:G00B05. https://doi.org/10.1029/2007jg000577

Gower ST, Kucharik CJ, Norman JM (1999) Direct and indirect estimation of leaf area index, $F_{(APAR)}$, and net primary production of terrestrial ecosystems. Remote Sens Environ 70:29–51

Hu Y (1997) The dipterocarp forest of Hainan island, China. J Trop For Sci 9:477–498

King DA, Davies SJ, Noor NSM (2006) Growth and mortality are related to adult tree size in a Malaysian mixed dipterocarp forest. For Ecol Manag 223:152–158

Kira T, Ogawa H, Yoda K, Ogino K (1967) Comparative ecological studies on three main types of forest vegetation in Thailand. IV. Dry matter production, with special reference to the Khao Chong rain forest. Nat Life Southeast Asia 5:149–174

Lasco RD, MacDicken KG, Pulhin FB, Guillermo IQ, Sales RF, Cruz RVO (2006) Carbon stocks assessment of a selectively logged dipterocarp forest and wood processing mill in the Phillipines. J Trop For Sci 18:166–172

Lewis SL, Lopez-Gonzalez G, Sonke B, Affum-Baffoe K, Baker TR, Ojo LQ (2009) Increasing carbon storage in intact African tropical forests. Nature 457:1003–1006

Li Y (1993) Comparative analysis for biomass measurement of tropical mountain rain forest in Hainan Island, China. Acta Ecol Sin 13:313–320

Lieberman D, Lieberman M, Peralta R, Hartshorn GS (1985) Mortality patterns and stand turnover rates in a wet tropical forest in Costa Rica. J Ecol 73:915–924

Miller SD, Goulden ML, Hutyra LR, Keller M, Saleska SR, Wofsy SC, Figueira AMS, da Rochar HR, de Camargo PB (2011) Reduced impact logging minimally alters tropical rainforest carbon and energy exchange. In: Proceedings of the National Academy of Sciences of United States of America, 108, 19431v19435

Niklas KJ (1994) Plant allometry: the scaling of form and processes. University of Chicago Press, Chicago

Ogawa H, Yoda K, Kira T (1965) Comparative ecological studies on three main type of forest vegetation in Thailand. II. Plant biomass. Nat Life Southeast Asia 4:49–80

Pinard MA, Cropper WP (2000) Simulated effects of logging on carbon storage in dipterocarp forest. J Appl Ecol 37:267–283

Pinard MA, Putz FE (1996) Retaining forest biomass by reduced logging damage. Biotropica 28(3):278–295

Russell CE (1983) Nutrient cycling and productivity of native and plantation forests at Jari Florestal, Para, Brazil. Doctoral thesis, University of Georgia. University Microfilms International, Ann Arbor, MI

Saldarriaga JG, West DC, Tharp ML, Uhl C (1988) Long-term chronosequence of forest succession in the Upper Rio Negro of Colombia and Venezuela. J Ecol 76:938–958

Salomão RP, Nepstad DC, Vieira IC (1996) Biomass and structure of tropical forests and the greenhouse effect. Ciencia Hoje 21:38–47

Tan ZH, Deng XB, Hughes A, Tang Y, Cao M, Zhang WF, Wang XF, Sha LQ, Song L, Zhao JF (2015) Partial net primary production of a mixed dipterocarp forest: spatial patterns and temporal dynamics. J Geophys Res Biogeosci 120:570–583

Tang JW, Zhang JH, Song QS, Cao M, Feng ZL (1998) A preliminary study on the biomass of secondary tropical forest in Xishuangbanna. Acta Phytoecol Sin 22(6):489–498

Terakunpisut J, Gajaseni N, Ruankawe N (2007) Carbon sequestration potential in aboveground biomass of Thong Pha Phum national forest, Thailand. Appl Ecol Environ Res 5:93–102

Zheng Z, Liu H, Feng ZL (2006) Biomass of tropical montane rain forest in Xishuangbanna of Southwest China. Chin J Ecol 25:347–353