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The impacts of selective logging and clear-cutting on woody plant diversity after 40 years of natural recovery in a tropical montane rain forest, south China

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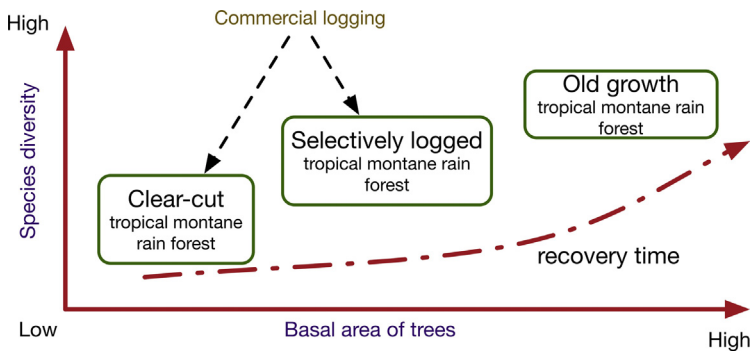
HIGHLIGHTS

- Relatively rapid rate of species richness recovery existed in a tropical montane rain forest after commercial logging.
- The community composition and structure of two logged forests were distinct from an old growth forest after 40 years.
- Selectively logged forest had faster recovery rate than clear-cut forest.
- Logged montane rain forest has a higher conservation potential than other disturbed secondary forests.

GRAPHICAL ABSTRACT



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ABSTRACT

Historically, clear-cutting and selective logging have been the commercial logging practices. However, the effect of these pervasive timber extraction methods on biodiversity in tropical forests is still poorly understood. In this study, we compared abiotic factors, species diversity, community composition, and structure between ca. 40-year-old clear-cut (MCC); ca. 40-year-old selectively logged (MSL); and tropical old growth montane rain forests (MOG) on Hainan Island, China. Results showed that there were a large number of trees with a diameter at breast height (DBH) <30 cm in the two logged forests. Additionally, the two logged forests only had 40% of the basal area of the large trees (DBH ≥ 30 cm) found in the old growth forest. The species richness and Shannon-Wiener diversity indices generally showed no difference among the three forest types. MCC had 70% of the species richness of the large trees in the MOG, whereas MSL and MOG had similar species richness. High value timber species had similar species richness among the three forest types, but a lower abundance and basal area of large trees in MCC. The species composition was distinct between the three forests. Large trees belonging to the family Fagaceae dominated in the logged forests and played a more important role in the old growth forest. Huge trees (DBH ≥ 70 cm) were rare in MCC, but were frequently found in MSL. Most abiotic factors varied inconsistently among the three forest types and few variables related to species diversity, community structure and composition. Our study indicated that MSL had a relatively faster recovery rate than MCC in a tropical montane rain forest after 40 years, but both logged forests had a high recovery potential over a long-term.

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1. Introduction

In tropical regions, commercial logging is one of the leading factors causing extensive deforestation, degradation, and most significantly, changes in community composition and structure after logging (Chazdon, 2014; Edwards et al., 2014b; Putz et al., 2012). Variations in logging practices, disturbance intensity, and environmental factors might lead to a varied recovery rate and trajectory of forests (Chazdon, 2014; Edwards et al., 2014a). Thus, the impacts of logging on species diversity are still largely debated (Zimmerman and Kormos, 2012; Xu et al., 2015).

Clear-cutting was a common practice in early timber harvesting history (Barlow et al., 2016; Putz et al., 2012). The removal of forest canopy cover post clear-cutting causes extreme changes in the biotic and abiotic environment. Controlled burning of clear cuts is also a common practice after timber harvests. However, because of limited data on clear-cutting, forest recovery after this widespread timber-harvesting practice is poorly understood. Selective logging has garnered more attention and several studies have been conducted on this aspect, as compared to clear-cutting (Edwards et al., 2012; Putz et al., 2012; Wilcove et al., 2013). Selective logging involves the harvest of valuable timber trees, skidding of logs, and road construction while maintaining some mature seed trees. The forest recovery rate of community structure and species composition after selective logging is relatively fast because, to some extent, the forest structure is retained (Zang et al., 2010). However, with intensive logging or repeated logging, the forest recovery process can be inhibited (Martin et al., 2015; Putz et al., 2012). Most research on tropical forests span a relatively short period of time after logging (Cannon et al., 1998; Edwards et al., 2012) and the recovery of logged forests usually requires several decades (Chazdon, 2014). We still know little about the medium- to long-term effects of forest harvesting on the recovery rate of the community composition and structure of tropical forests. This is especially true in tropical Asia where many important timber-yielding tree species occur (Putz et al., 2012) and there is extensive anthropogenic land-use change (Edwards et al., 2012; Wilcove et al., 2013). It is very important to study the recovery process of a variety of forest types, logged using different practices based on relatively long-term data.

In tropical forest areas in China, clear-cutting was once the dominating timber-harvesting practice, but it was replaced gradually by selective logging in the 1970s. This change in logging practices provides a great opportunity to compare the recovery process of forest ecosystems after different logging practices. Here, we analyzed the effects of clear-cutting and selective logging after 40 years on the species diversity and community structure recovery of a tropical montane rain forest (TMRF) on Hainan Island, China. We hypothesized that: (1) Selectively logged forests recover at a faster rate than clear-cut forests because of their different disturbance intensities; (2) The species composition of selectively logged forests is more similar to that of old growth forests than clear-cut forests because of the remaining mature seed trees post logging.

2. Material and methods

2.1. Study area

The study area was located in the Bawangling Forest Region (BFR; 18°52′–19°12′ N, 108°53′–109°20′ E) on Hainan Island, the largest tropical island in China. The mean annual temperature (MAT) and precipitation (MAP) of the TMRF is 19.4 °C and 2806 mm, respectively, at an elevation of 1000 m. Precipitation is distributed seasonally with a wet season (precipitation ≥100 mm/month) from May to October and a dry season (precipitation <100 mm/month) from November to April. Tropical lowland rain forest and TMRF are the main vegetation types in the BFR, but the distribution of the lowland rain forest has decreased because of long-term cultivation and intensive logging (Ding et al., 2012). Consequently, the TMRF plays a more important role in conserving biodiversity and providing ecosystem services on this island (Zang et al., 2010).

2.2. Data collection

In order to compare the effects of clear-cutting and selective logging on the long-term (ca. 40 years) recovery of community structure and ecosystem functioning, six, 1-ha (100 m × 100 m) forest dynamic plots (FDPs) were established in 2010 and 2011. These FDPs included two clear-cut (MCC1 and MCC2), two selectively logged (MSL1 and MSL2), and two old growth forest plots (MOG1 and MOG2). In each plot, all woody stems with ≥1 cm diameter at breast height (DBH) were tagged, mapped, and their DBH was measured. All woody stems were identified to the species or morphological species level according to the Flora of China (http://www.efloras.org).

MCC1 and MCC2 were clear-cut in 1966 and immediately burned after logging. Approximately five to eight large trees were left intentionally as seed trees in the clear-cutting area. Subsequently, two high commercial value trees (*Vatica mangachapoi* and *Homalium ceylanicum*) were planted. These two species are associated with tropical lowland rain forests and have a low tolerance to the low temperatures experienced during winter in the montane area. The planted trees were gradually replaced by montane rain forest species with a natural recovery from the 1970s (local worker pers. comm.). The two selectively logged plots (MSL1 and MSL2) were harvested in 1975. According to the timber quality in BFR, the tree species were categorized into six classes. During timber harvesting, at least 15 trees from the top class to the third class were left intentionally as seed trees in each hectare. The intensity of selective logging on Hainan is higher than in other tropical regions with at least 60% of the timber volume harvested during this process. In this study, we took the trees listed in the first three classes as high value timber trees, including 29 species in our plots (Appendix Table A1).

Soil samples (0–20 cm) were collected in each 20 × 20 m subplot of each FDP for analysis. All soil samples were air-dried after field collection, and transported to a soil laboratory at the Southwest University in Chongqing, China for analysis. Analyses included tests for pH, soil organic matter (SOM), total nitrogen (TN), total phosphorus (TP), available nitrogen (AN), available phosphorus (AP), and available potassium (AK). A soil core sample (100 cm^2) was collected in each subplot using a cutting ring to determine the two important physical properties, including soil water content and soil bulk density. The canopy openness was calculated using HemiView (HMV1v8, Delta-T Devices Ltd., Cambridge, UK) to take hemispherical canopy photographs at 1.5 m above ground level on the center points in each 20 × 20 m subplot of each 1-ha FDP.

2.3. Data analysis

All woody stems in the plots were categorized into three different size groups: (1) small (1 cm ≤ DBH <10 cm), (2) medium (10 cm ≤ DBH <30 cm), and (3) large trees (DBH ≥ 30 cm). The rate of increase in species diversity between the different logging practices was compared using the rarefaction method. To eliminate the influence of abundance on the number of species, we used individual species abundance curves to compare species richness. Abiotic variables, abundance, species richness, the Shannon-Wiener index, and basal area were compared by forest type using an analysis of variance (ANOVA) and Tukey's honest significant difference test. The associations of abiotic and biotic variables (e.g., abundance, basal area, and species diversity) were analyzed using the Pearson correlation coefficient. The variations in abundance, basal area, and species richness of high value timber trees and Fagaceae trees among the three forest types were also compared using the same method. Using a Chi-square test, we compared the DBH size distribution among the forest types. We used the non-metric multidimensional scaling (NMDS) method to test variations in species composition and associations with abiotic variables based on species

abundance and basal area data with the Chao similarity coefficient. We used an analysis of similarities (ANOSIM) to test whether the species composition differed among the three forest types. The NMS and ANOSIM were conducted using the "metaMDS" and "anosim" functions in the "vegan" package (Oksanen et al., 2016) in the R program (R Core Team, 2016). In order to explore the proportion of old growth forest species distributed in the logged forests, the correlation of abundance and basal area of species between logged forests (MCC or MSL) and old growth forests was examined using a linear regression in the R program.

3. Results

3.1. Species diversity and community structure

The selectively logged forest had the greatest abundance and basal area of small trees (1 cm ≤ DBH < 10 cm) (Fig. 1). The abundance and basal area of medium trees (10 cm ≤ DBH < 30 cm) in the two logged forests were significantly higher than in the old-growth forest. There was no significant difference ($P = 0.31$) in the abundance of large trees (DBH ≥ 30 cm), but the basal area of large trees was significantly different ($P < 0.05$) among the three forest types. The two logged forests only had 40% of the large tree basal area of the old-growth forest. Species richness of small and medium trees did not significantly differ between the three forest types. The species richness of large trees in selectively logged forest was similar to that of the old growth forest, but the clear-cut forest had only 70% of the species richness of the old-growth forest. There were no significant differences in the Shannon-Wiener indices among the three forest types across the three tree sizes (Fig. 1).

The abundance and basal area of high value timber trees within the small and medium size classes in the selectively logged forest was greater than in the clear-cut and old growth forests (Fig. 2). However, the old growth forest had more, large high value timber trees. The species richness of high value timber trees was similar among the three forest types (Fig. 2).

Species area and abundance curves showed no differences in small trees between both logged forests and the old growth forests (Fig. 3). The accumulation rate of medium trees in the selectively logged forest was faster than in the old growth forest. However, the species accumulation rate of large trees in the selectively logged forest was similar to

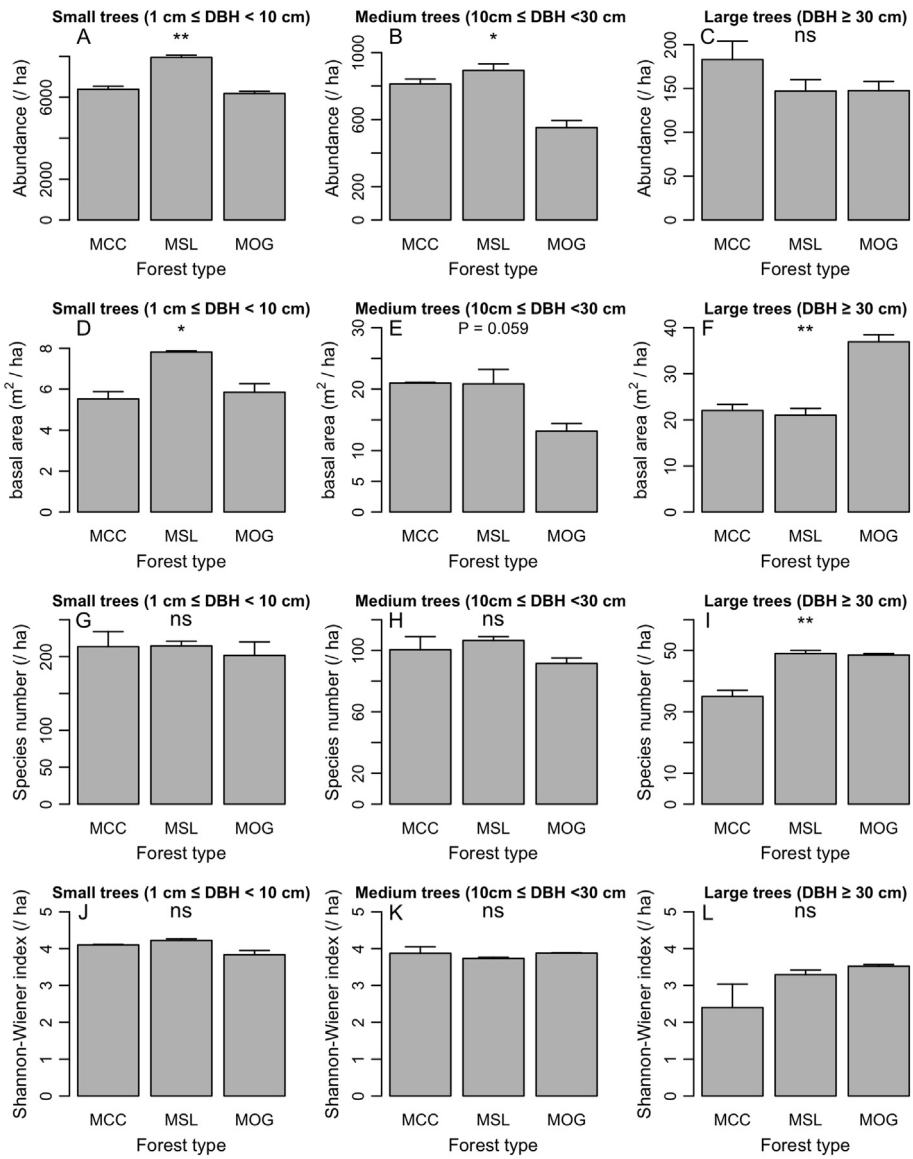

Fig. 1. Variations in abundance (A, B, C), basal area (D, E, F), and species richness (G, H, I) and Shannon-Wiener index (J, K, L) among the three forest types (clear-cut, selective logged, and old growth forest) for small trees (1 cm ≤ DBH < 10 cm), medium trees (10 cm ≤ DBH < 30 cm) and large trees (DBH ≥ 30 cm). DBH, diameter at breast height. One-way ANOVA test and number of replicates $N = 2$. *, $P < 0.05$; **, $P < 0.01$; ns, $P > 0.05$.

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that of the old growth forest. There were more obvious dominant, large tree species in the clear-cut forest (Fig. 3I).

There were significant differences in DBH size distribution for small ($\chi^2 = 245.65$, $P < 0.001$) and medium trees ($\chi^2 = 30.56$, $P < 0.05$) among the three forest types (Fig. 4). The selectively logged forest had more stems with 1–3 cm DBH than the clear-cut and old growth forests. There were more medium trees distributed in the logged forests, especially in the selectively logged forest. The difference in large tree DBH size distribution was the greatest; there were more trees with 30–50 cm DBH in the clear-cut forest than in the other two forest types. However, fewer huge trees (DBH ≥ 70 cm) occurred in both the clear-cut and selectively logged forests than in the old growth forest.

3.2. Species composition

The first NMS axis reflected the effect of different tree sizes on the variations in species composition, and the second showed changes in the species composition among the different forest types (Fig. 5). The NMS analysis showed that as the tree DBH class increased, the distances between the different forests decreased. Based on the abundance data, there was a significant difference in the species composition ($F = 2.33$, $P < 0.05$) for large trees and a marginal difference for small ($F = 2.11$, $P = 0.07$) and medium trees ($F = 2.14$, $P = 0.07$). There was also a marginal difference in the species composition (all $P < 0.08$) between the three tree sizes based on basal area data.

Most species that occurred in the old growth forest also occurred in the clear-cut and selectively logged forests (Fig. 6). The correlations in abundance data were most similar between the two logged forests and old growth forest. The correlations of basal area data between the two logged forests and old growth forest were relatively weak ($b = 0.28$–0.45, $P < 0.001$). The basal area of large tree species in the selectively logged forest had a more positive correlation ($b = 0.88$, $P < 0.001$) with old growth forests than with clear-cut forests ($b = 0.66$, $P < 0.001$).

3.3. Dominant species and Fagaceae species

Among the 10 most abundant small trees (Table 1), *Psychotria rubra* and *Gironniera subaequalis* were dominant in both logged forests. *Mallotus hookerianus* and shrub species *Saprosma ternatum*, *Prismatomeris tetrandra*, and *Memecylon ligustrifolium* were distributed in the old growth and selectively logged forests. *Cryptocarya chinensis* was the most dominant species in the selectively logged forests. *Castanopsis carlesii* var. *spinulosa*, *C. chinensis*, *Syzygium araiocladum*, and *Engelhardia roxburghiana* were the dominant medium tree species in the logged forests, with the highest abundance in the selectively logged forest. The dominant species (*G. subaequalis*, *C. chinensis*, and *S. araiocladum*) in the logged forests also dominated the old growth forest. However, *M. hookerianus*, the most dominant medium tree species in the old growth forest, only occurred in the selectively logged forest. In both logged forests, *C. carlesii* var. *spinulosa*, *Alniphyllum fortunei*, and *E. roxburghiana* were the dominant large tree species. Large trees, including *Alseodaphne hainanensis*, *Xanthophyllum hainanense*, *G. subaequalis*, and *Lithocarpus fenzelianus*, were dominant in the old growth forest (Fig. 6).

The Fagaceae species had a greater abundance and basal area of small and medium trees in the two logged forests than in the old growth forest (Fig. 7). However, large trees of the Fagaceae species had a greater abundance and basal area in the old growth forest. Among the large trees, Fagaceae species represented 9%, 17%, and 27% of the abundance and 10%, 27%, and 42% of the basal area in clear-cut, selectively logged, and old growth forests respectively.

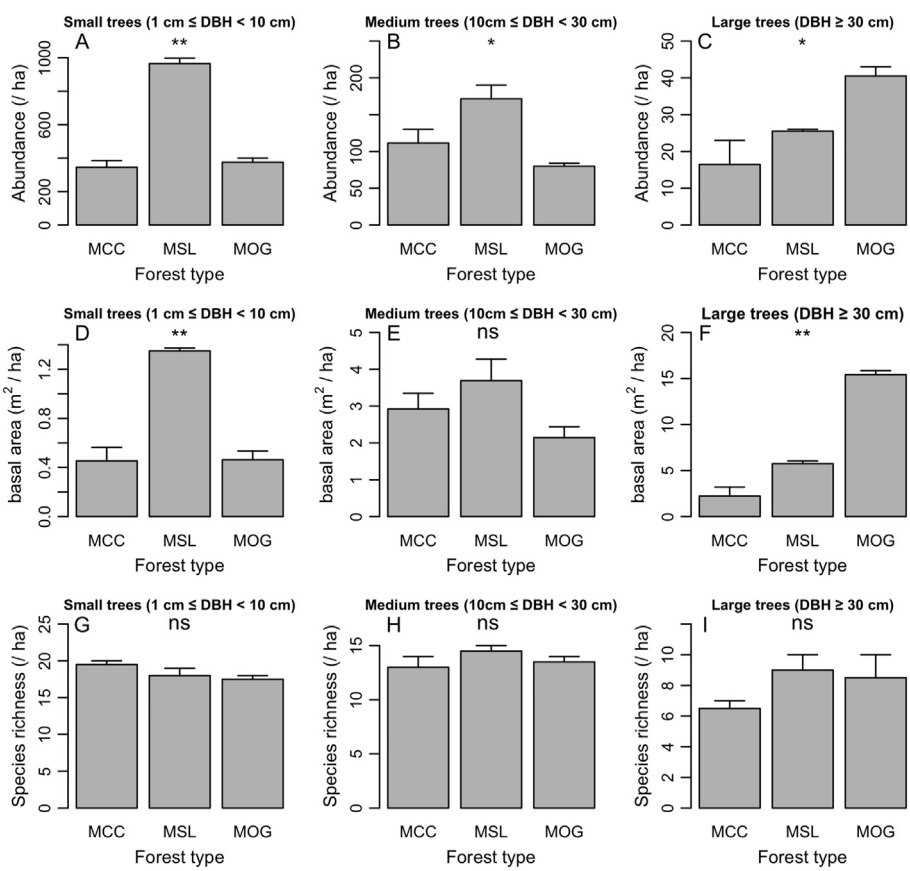

Fig. 2. Variations in abundance (A, B, C), basal area (D, E, F), and species richness (G, H, I) of high value timber species among the three forest types (clear-cut, selective logged, and old growth forest) for small trees (1 cm ≤ DBH <10 cm), medium trees (10 cm ≤ DBH <30 cm) and large trees (DBH ≥ 30 cm). DBH, diameter at breast height. One-way ANOVA test and number of replicates $N = 2$. *, $P < 0.05$; **, $P < 0.01$; ns, $P > 0.05$.

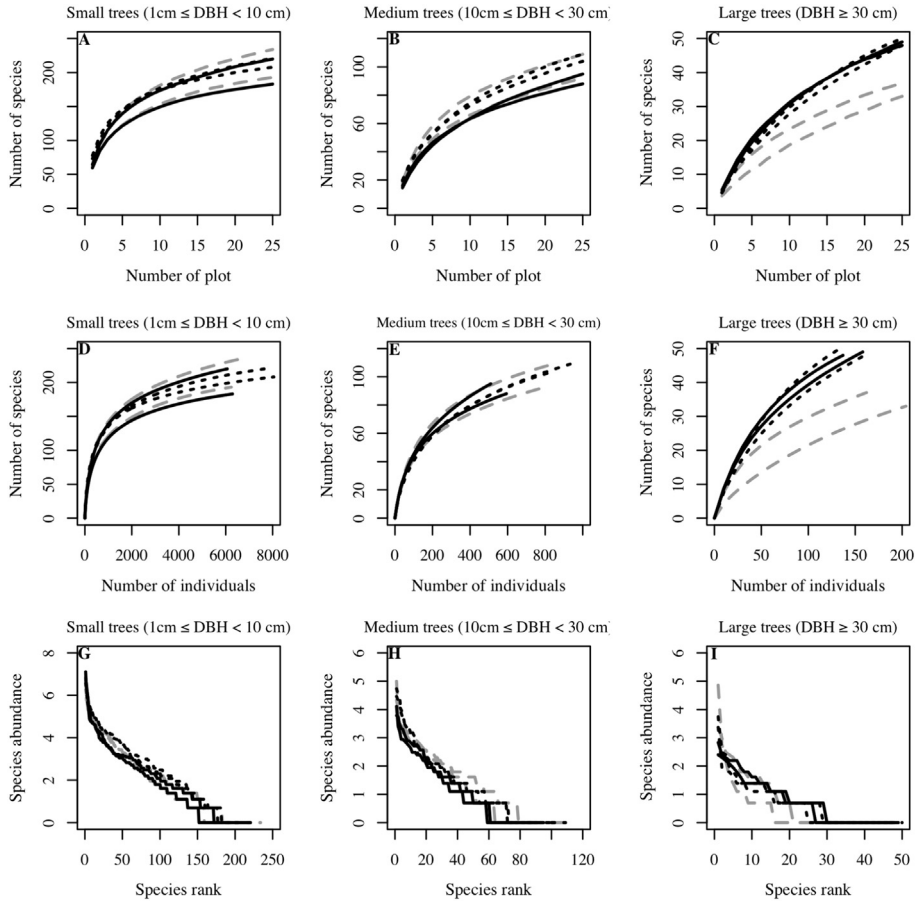

Fig. 3. The species-area accumulation curves, species-abundance accumulation curves, and species rank-abundance distribution curves for small trees (A, D, G), medium trees (B, E, H), and large trees (C, F, I) among the three forest types (clear-cut, selective logged, and old growth forest). Small trees, 1 cm ≤ DBH < 10 cm; medium trees, 10 cm ≤ DBH < 30 cm; large trees, DBH ≥ 30 cm. DBH, diameter at breast height. Gray dashed lines represent forest dynamic plots after clear-cut (MCC); black dotted lines represent forest dynamic plots after selective logged (MSL); black lines represent old growth forest plots (MOG).

3.4. Abiotic factors and association with species diversity and composition

There were significant differences between the effects of the nine abiotic variables except soil water content among the three forest types (Table 2). The two, logged forests had less canopy openness and a lower pH than the old growth forests. Soil organic matter, total nitrogen, total phosphorus, and maximum water holding capacity reached the greatest values in selectively logged forests. The old growth forests had relatively high available nutrients in the soil (nitrogen and phosphorus) as well as a good soil physical structure (bulk density). Soil available potassium in clear-cut forests was greatest among the three forest types and had a higher soil organic matter and total nitrogen than the old growth forests. The associations of abiotic variables with four diversity variables and compositions varied greatly among the three tree sizes. Only a few abiotic variables (soil organic matter, total nitrogen, and total phosphorus) related to partial variations in diversity variables (Appendix Table A2). The abiotic variables hardly affected the species composition in NMDS across the forest types (Appendix Table A3).

4. Discussion

4.1. The recovery process of post-logged forests

The rate and trajectory of forest recovery after deforestation directly affects tropical forest biodiversity conservation and global climate change (Barlow et al., 2016; Chazdon, 2014; Putz et al., 2012). Our results show that forests logged using two different practices have high recovery rates. The species richness of small and medium trees reached the level of old-growth forests after 40 years of recovery and there was no significant difference in the Shannon-Wiener indices among the three forest types. The high resilience of tropical montane rainforests is supported by previous work on the island of Hainan (Ding et al., 2012; Xu et al., 2015) and other tropical forests (Cannon et al., 1998; Carreño-Rocabado et al., 2012; Martin et al., 2015; Putz et al., 2012). For example, after 8 years of recovery, post commercial selective logging in an Indonesian tropical rain forest, the number of species and rarefied species richness was the same as in an old-growth forest (Cannon et al., 1998). In an additional Indonesian study, selective logging significantly reduced the stems of mature trees, but tree abundance, number of species, and diversity indices reached the level of an old-growth forest after only 15 years of recovery (Slik et al., 2002). Verburg and van Eijk-Bos (2003) found that forest diversity 20 years post selective logging showed no differences in species diversity. In a Brazilian tropical forest, selective logging significantly reduced the density of trees with ≥30 cm DBH, but after 5 years, the mature stem density, species richness, and diversity indices were comparable to that of an old growth forest (Villela et al., 2006).

Variations in the habit quality of different sites might influence forest recovery (Chazdon, 2014), but this effect may be very minor in our study area. Water is usually the primary important limiting factor of tree growth and distribution in tropical regions (Engelbrecht et al., 2007). The relatively high precipitation and fog in the winter dry season may ameliorate water stress in the TMRF (Zang et al., 2010) and can consequently eliminate seasonal drought. Our results also found that soil water content was the only factor that showed no significant

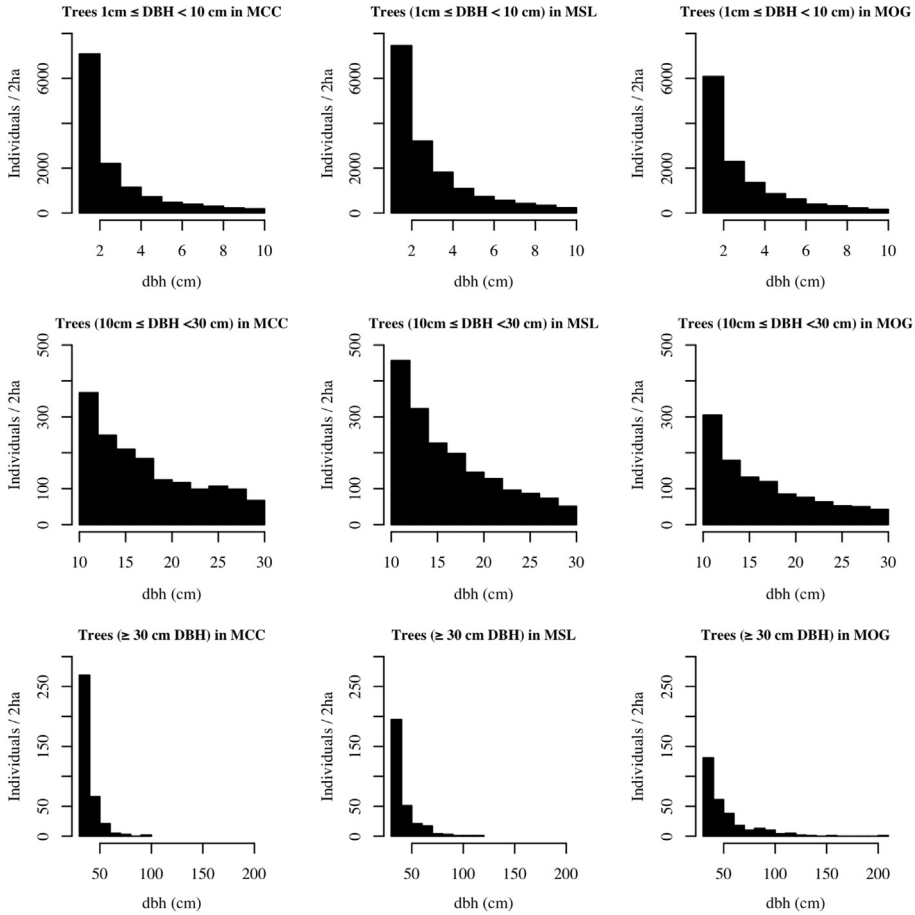

Fig. 4. The frequency distribution of stem DBH (diameter at breast height) of small trees (1 cm ≤ DBH < 10 cm), medium trees (10 cm ≤ DBH < 30 cm), and large trees (DBH ≥ 30 cm) among the three forest types (clear-cut, selective logged, and old growth forest). DBH, diameter at breast height.

difference among the forest types, and all forests had a relatively high level (ca. 30%). However, other abiotic variables including soil nutrients did not show consistent patterns among the three forests. Few abiotic variables were found to be related with community diversity, structure, and composition (Appendix Table A2 and A3), which indicated that disturbance intensity related to different logging methods, could play a more important role in determining the recovery rate and trajectory of a logged forest, as previously suggested (Carreño-Rocabado et al., 2012; Ding et al., 2012).

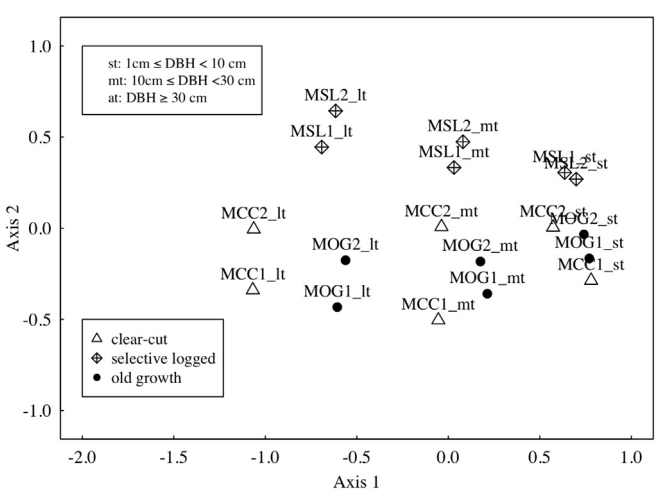

Fig. 5. Non-metric multidimensional scaling (NMS) for small trees (st), medium trees (mt), and large trees (at) among the three forest types (clear-cut, selective logged, and old growth forest) based on abundance data. Small trees, 1 cm ≤ DBH < 10 cm; medium trees, 10 cm ≤ DBH < 30 cm; large trees, DBH ≥ 30 cm. DBH, diameter at breast height.

Another important factor that impacts tropical forest restoration is the distance between disturbed lands and remnant intact old growth forests (Chazdon, 2014). In our study area, when conducting the logging practices, some patches of old growth forests were left unlogged for various reasons, such as a rugged topography, conditions of log transportation, or for animal use. The undisturbed old growth forests at the ridges usually have many parent seed trees and the seeds of old-growth forest species spread directly into clear-cut areas. Moreover, seed trees intentionally left after clear-cutting further provided seeds and accelerate the natural recovery process (Zahawi et al., 2013). Many secondary forests rarely reach the biodiversity levels of mature forests after a high disturbance, even after more than a century of succession (Chazdon, 2014). However, research shows that forests distributed within a short distance from natural or pristine forests have a much higher regeneration potential (Norden et al., 2009). The intensity of logging is relatively lighter than that of other agricultural disturbances and therefore has a greater recovery potential (Cannon et al., 1998; Chazdon, 2003).

This study also showed that after selective logging, species richness within three size classes reached the level of old-growth forests after 40 years of recovery. However, the recovery rate of species richness in the clear-cut forest was much slower, especially for trees ≥30 cm DBH. This difference is likely caused by the fact that some large diameter seed trees were retained in selectively logged forests, resulting in a more rapid recovery rate (Cannon et al., 1998; Chazdon, 2014).

Recent studies have consistently shown the relative high recovery rate of clear-cut forests (Xu et al., 2015; Zimmerman and Kormos,

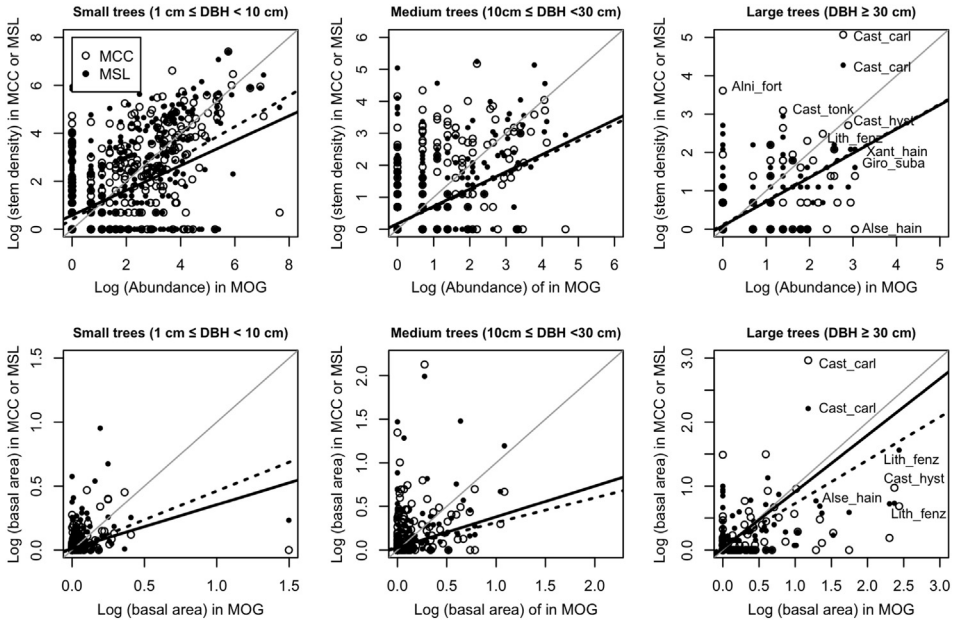

Fig. 6. Relationship between abundance and basal area of different size trees in clear-cut forests (MCC), selectively logged forests (MSL) and old growth forests (MOG). Small trees, 1 cm ≤ DBH <10 cm; medium trees, 10 cm ≤ DBH <30 cm; large trees, DBH ≥ 30 cm. DBH, diameter at breast height. Alni_fort, *Alniphyllum fortunei* (Hemsl.) Makino; Alse_hain, *Alseodaphne hainanensis* Merr.; Cast_carl, *Castanopsis carlesii* (Hemsley) Hayata var. *spinulosa* W.C. Cheng & C.S. Chao; Cast_hyst, *Castanopsis hystrix* J. D. Hooker et Thomson ex A. De Candolle; Cast_tonk, *Castanopsis tonkinensis* Seemen; Giro_suba, *Gironniera subaequalis* Planch; Lith_fenz, *Lithocarpus fenzelianus* A. Camus; Xant_hain, *Xanthophyllum hainanense* Hu.

Table 1
The abundance (trees number of 2 ha) of 10 most abundant species of small trees, medium trees, and large trees among the three forest types. MCC, clear-cut; MSL, selectively logged; MOG, old growth forest. S, shrub; ST, small tree; TT, tall tree. DBH, diameter at breast height.

	Growth form	MCC	MSL	MOG
Small trees (1 cm ≤ DBH < 10 cm)				
Psychotria rubra (Lour.) Poir.	S	1651	1636	315
Mallotus hookerianus (Seem.) Muell. Arg.	ST	1	160	2102
Saprosma ternatum Hook. f.	S	110	619	1158
Prismatomeris tetrandra (Roxb.) K. Schum	S	383	359	1029
Cryptocarya chinensis (Hance) Hemsl.	TT	265	1183	219
Memecylon ligustrifolium Champ.	S	358	362	708
Ardisia quinquegona Blume	S	404	270	357
Diospyros cathayensis Steward	ST	642	9	375
Gironniera subaequalis Planch	TT	745	177	39
Blastus cochinchinensis Lour.	S	240	294	221
Medium trees (10 cm ≤ DBH < 30 cm)				
Castanopsis carlesii (Hemsley) Hayata var. *spinulosa* W.C. Cheng & C.S. Chao	TT	176	189	8
Cryptocarya chinensis (Hance) Hemsl.	TT	35	169	43
Gironniera subaequalis Planch	TT	40	94	58
Syzygium araiocladum Merr. et Perry	ST	13	154	0
Symplocos adenopus Hance	ST	56	20	57
Engelhardia roxburghiana Wall.	TT	30	95	2
Mallotus hookerianus (Seem.) Muell. Arg.	ST	0	18	103
Alniphyllum fortunei (Hemsl.) Makino	TT	63	45	0
Cinnamomum tsoi Allen	TT	42	53	12
Syzygium chunianum Merr. et Perry	ST	19	56	29
Large trees (dbh ≥ 30 cm)				
Castanopsis carlesii (Hemsley) Hayata var. *spinulosa* W.C. Cheng & C.S. Chao	TT	158	71	15
Alniphyllum fortunei (Hemsl.) Makino	TT	36	2	0
Engelhardia roxburghiana Wall.	TT	13	18	3
Castanopsis hystrix J.D. Hooker et Thomson ex A. De Candolle	TT	14	2	17
Castanopsis tonkinensis Seemen	TT	21	6	3
Alseodaphne hainanensis Merr.	TT	0	7	20
Cyclobalanopsis blakei (Skan) Schottky	TT	7	8	12
Gironniera subaequalis Planch	TT	3	4	20
Xanthophyllum hainanense Hu	TT	1	7	18
Lithocarpus fenzelianus A. Camus	TT	3	7	12

2012). The high available light and relatively intact soil after clear-cutting create ideal conditions for the recruitment of long-lived generalist pioneer species, such as *Castanopsis carlesii* and *Alniphyllum fortunei*. Moreover, the practice of controlled burning after clear-cutting provides abundant nutrients for those rapid resource-use pioneer species. A recent study found a dominance of long-lived pioneer species (*Campnosperma brevipetiolata*) in the Solomon Islands, 50 years after selective logging (Katovai et al., 2016). However, the rapid change in understory light availability may not be suitable for late successional species growth (Chazdon, 2014). In contrast, selective logging, which maintains some original vegetation and creates gaps, provides a regeneration niche for understory late successional species (Zang et al., 2005), thereby increasing the number of small trees. With the increasing density of tree stems in selectively logged forests, the direct competition for light (aboveground competition), soil moisture, and nutrients (belowground competition) increases (Coomes and Grubb, 2000). Only tree species with a strong competitive advantage (e.g., efficient nutrient utilization capacity, and rapid growth capacity) will regenerate and grow under the canopy of selectively logged forests.

4.2. The importance of huge trees and Fagaceae species on forest recovery

The remaining huge trees (DBH ≥ 70 cm) in selectively logged forests are important drivers of forest community restoration and ecosystem functioning after disturbance (Lindenmayer et al., 2012; Sist et al., 2014). Very large trees directly accelerate forest regeneration by providing essential recruitment conditions through an effect known as the "tree island" (Zahawi et al., 2013). Tree islands are especially important for the regeneration of late successional species because changes in the microenvironment of the understory can reduce soil temperatures while the tree islands maintain similar pre-logging conditions, resulting in a less negative effect on the survival and growth of seedlings. At the same time these very large trees could accelerate the recovery rate by directly providing seeds and attracting birds or other animals for dispersal (Lindenmayer et al., 2012). Thus, the composition of very large seed trees dictates the species composition of recovering forests.

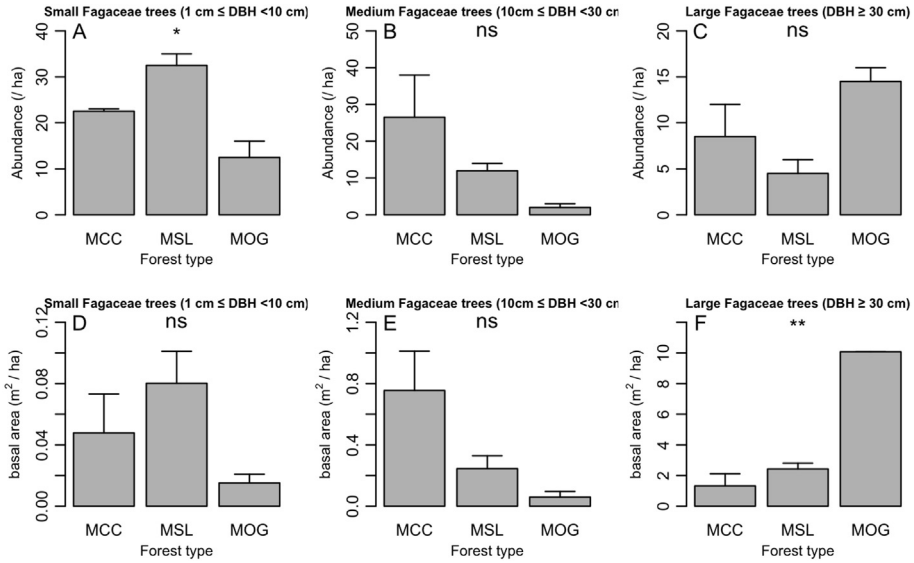

Fig. 7. Variations in abundance (A, B, C), basal area (D, E, F), and species richness (G, H, I) of Fagaceae species among the three forest types (clear-cut, selective logged, and old growth forest) for small trees (1 cm ≤ DBH <10 cm), medium trees (10 cm ≤ DBH <30 cm) and large trees (DBH ≥ 30 cm). DBH, diameter at breast height. One-way ANOVA test and number of replicates $N = 2$. *, $P < 0.05$; **, $P < 0.01$; ns, $P > 0.05$.

Fagaceae trees are an important component in tropical montane forests (ter Steege and Hammond, 2001) and they can account for >50% of the forest biomass (Culmsee et al., 2010). In this study, species from Fagaceae consisted of 17% and 42% of the abundance and basal area of large trees in old growth forests (DBH ≥ 30 cm). Moreover, large Fagaceae tree species (*Castanopsis carlesii*, *C. hystrix*, and *C. tonkinensis*) were abundant in both logged forests, especially in the clear-cut forest plots. These species generally have a high seed yield, strong germination ability, fast growth rates (Team Workers for Studies on the Hainan Timbers, 1966) and can recruit in most disturbed areas of the BFR (Ding et al., 2012). Therefore, these long-lived pioneer species not only increase the recovery rate of species richness after disturbance, but also help to maintain a stable community structure. Two shade-tolerant Fagaceae species (*Cyclobalanopsis blakei* and *Lithocarpus fenzelianus*) also recovered after logging, but the abundance of large trees was still less than in old growth forests. In a Bolivian tropical forest, intensive silviculture treatments had positive effects on long-lived pioneers, but not shade-tolerant species (Peña-Claros et al., 2008). Unfortunately, the most valuable large size timber species (*Alseodaphne hainanensis*), which dominate in old growth forests do not recover in clear-cut forests, but do so in selectively logged forests. This result demonstrates the negative effect of clear-cutting on the recruitment of important timber species.

5. Conclusions

Our study demonstrates the relatively rapid recovery rate of species diversity in a TMRF after commercial logging. However, some important forest features (e.g., community composition and structure) were influenced by human disturbance even after a nearly 40-year natural period. Our results clearly showed that the community composition and structure of the two logged forests were distinct from those of old growth forest. However, the recovery rate in species composition and structure of selectively logged areas was greater in clear-cut areas than in old growth forests, and this difference was greater with an increasing tree size. Despite a good recovery, some large trees of high value timber species regenerated very slowly in the clear-cut forest. Regardless, our results suggest that the logged montane rain forest has a higher conservation potential than other disturbed forests, such as secondary forests, after shifting cultivation.

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Table 2
The abiotic variables (mean ± standard error) of canopy openness and soil features among the three forest types (MCC, clear-cut; MSL, selectively logged; MOG, old growth forest). One-way ANOVA test and number of replicates $N = 2$.

Abiotic variables	MCC	MSL	MOG	*F* value
Canopy openness (%)	8.52 ± 0.31	8.64 ± 0.44	11.76 ± 0.47	20.02***
pH value	4.45 ± 0.04	4.31 ± 0.02	4.47 ± 0.04	6.03**
Soil organic matter (g/kg)	55.11 ± 1.15	63.60 ± 0.79	43.47 ± 0.85	13.8***
Soil total nitrogen (g/kg)	2.24 ± 0.06	3.06 ± 0.11	1.87 ± 0.06	58.09***
Soil total phosphorus (g/kg)	0.24 ± 0.01	0.36 ± 0.03	0.34 ± 0.01	12.14***
Soil available nitrogen (mg/kg)	130.16 ± 4.43	152.05 ± 2.95	182.99 ± 4.11	46.74***
Soil available phosphorus (mg/kg)	5.91 ± 0.51	11.48 ± 0.51	13.61 ± 1.08	28.11***
Soil available potassium (mg/kg)	152.12 ± 3.49	137.93 ± 5.73	132.75 ± 4.69	4.51*
Soil water content (%)	28.46 ± 0.01	30.02 ± 0.01	29.11 ± 0.01	0.88ns
Soil bulk density (g/cm^2)	1.02 ± 0.02	0.93 ± 0.02	1.09 ± 0.02	23.31***

*** $P < 0.001$.
** $P < 0.01$.
* $P < 0.05$.
ns $P \geq 0.05$.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.scitotenv.2016.11.185.

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