Stand Structure, Floristic Composition and Diversity of Tropical Lowland Rain Forests in Sabah, Malaysia under Different Managements

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Introduction

Timber exploitation, which accelerated from the 1950s to 1970s by the introduction of mechanized methods, has been altering the tropical lowland forests of Sabah, Malaysian Borneo (Sabah Forestry Department 1989). For sustainable production of low-volume, high-quality and high-priced timbers, reduced-impact logging (RIL), a low impact logging technique of timber harvesting, was introduced in Sabah in 1989 (Lagan et al. 2007). It is believed that RIL is an adequate method for the sustainable management of tropical forests, because RIL can reduce the damages to the forests compared to the conventional logging method. However, there are relatively limited data to justify the sustainability of RIL in terms of full recovery of species composition, diversity and biomass after timber harvest (Pinard and Putz 1996; Bertault and Sist 1997; Sist and Nguyen-The 2002; Bischoff et al. 2005). Can the tropical forests after RIL approach the pre-harvest, old-growth status in the course of secondary succession? To answer this question, we compared the recovery processes of logged-over forests subjected to RIL and to a conventional method (high-impact logging) in terms of structure, floristic composition and diversity.

Materials and Methods

Eleven research plots of 0.2 ha area (100 m x 20 m or 50 m x 40 m, depending on the availability of similar topography) were established in Deramakot Forest Reserve (DFR) and the neighboring Tangkulap Forest Reserve (TFR), Sabah, Malaysian Borneo (5°N 117°E), under different forest managements (Table 1). DFR and TFR had been selectively logged in the 1950s-1980s with similar overall intensity. The minimum trunk diameter for harvesting was 60cm, but this rule does not appear to be necessarily followed. This resulted in very heterogeneous condition of remaining forests at the small spatial scale. After this period, DFR was selected as a focal site for the application of RIL in 1989, while TFR receives persistent pressure of conventional logging. In DFR, we established two plots in each of following four groups of forest management in May 2003. (1) Residual primary forest that appeared to be unaffected by logging,

(2) old-growth forest that was not logged after 1980s, (3) forests logged by RIL in 1995-1997, (4) forests logged by RIL in 1999-2000. The distinction between groups (1) and (2) was based on the proximity to logging roads or skid trails and on the presence or absence of stamps in the plot. Forests of groups (3) and (4) were identified by the management record of DFR (Lagan et al. 2007). In TFR, in May 2003, we established two plots in the forest that had been intermittently logged by the conventional method, and added one more plot in the same forest in March 2005. In the following analyses and discussion, we used three broad categories of forest management status as follows. Old-growth forests including (1) and (2), forests harvested by RIL including (3) and (4), and forests harvested by conventional logging (5).

All plots were divided into contiguous twenty 10-m x 10-m subplots. The location and altitude of the plots were measured by using a portable receiver of global positioning system (GPS III plus, Garmin, Olathe, USA). All living trees larger than 30 cm in trunk girth at 1.3 m above ground were measured first in May 2003 and re-measured in March 2005. Diameter at breast height (DBH) was calculated as girth divided by 3.14 (thus minimum DBH was 9.6 cm). Dead trees were checked at the tree census in March 2005. For comparison among the three categories of forest management, we incorporated the 2005 data to increase the sample size of the forest logged by conventional method. Buttressed or stilt-rooted trees were measured for trunk diameter at above the protrusions but not at 1.3m above the ground. Multiple trunks were separately recorded for DBH. Leaf area index (LAI), which is defined as the sum of leaf area per unit ground area, was measured at five plots using LAI-2000 Canopy Analyzer (LI-COR, Lincoln, USA) in June 2003. The five plots were PRI-1, 80s-2, RIL00-2, RIL05-1, and CV-1 (see Table 1 for the abbreviation of the plot). LAI was estimated based on ten measurements at corners of 10-m x 10-m subplots in each plot. This was repeated three times in different parts of the plot, from which the mean LAI was calculated.

Above-ground biomass (AGB, kg) of individual stem was estimated by using the following equations obtained by Brown (1997) and Chave et al. (2005) as:

$$AGB = \exp(-2.134+2.530 \ln(DBH)), \qquad (1)$$

and

$$AGB = \rho \times \exp(-1.499 + 2.148 \ln(DBH) + 0.207(\ln(DBH))^2 - 0.0281(\ln(DBH))^3), \qquad (2)$$

respectively, where ρ is wood density (g cm^{-3}). The stand-level AGB density (kg m^{-2}) was derived by the summation of individual stem biomass divided by plot area. For equation (2), the use of stand-level average was recommended by Chave et al. (2005) if species-specific wood density was unavailable as in our case. Brown (1997) reported that mean wood density for 428 Asian tropical tree species was 0.57 g cm^3. If this value was used, biomass estimates by equation (2) was almost identical to those by equation (1). For simplicity, we reported the results based on equation (1) only.

To identify species, we collected leaves for voucher specimens, using a clipper and a catapult for tall trees. Species identification was based on the leaf specimens and bark characters. Voucher specimens were stored at the laboratory in DFR. We have not yet finished the matching of species between plots, so that floristic comparison among plots was done at the genus level. Four and 18 stems (0.3 and 1.4% of total number of stems) could not be identified to family and genus, respectively, and these were excluded from the calculation of number of taxa. Floristic diversity of each plot was evaluated by numbers of family, genus and species. Logged forests may have smaller numbers of taxa simply because stem density is reduced by logging. To allow for this, an index that represents diversity in terms of number of species relative to number of stem was calculated:

$$S = \alpha \ln (1+N/\alpha),$$

where S is the number of species, N is the number of stems, and α is a constant known as Fisher's diversity index (Fisher et al. 1943). To take into account the equitability of species abundance, Shannon's indices of diversity and evenness were also calculated (Magurran 2004). For floristic comparison among plots, detrended correspondence analysis (DCA) was conducted using relative basal area of genus in 2005, which was log (x+1) transformed before analysis (ter Braak & Smilauer 2002). The method of detrending used was by segments.

Dipterocarpaceae trees are dominant climax species in tropical lowland forest in Southeast Asia, and this family is well known as important commercial timber (Whitmore 1984). On the other hand, most of observed *Macaranga* (Euphorbiaceae) species were characterized as a gap-dependent species in regeneration (Slik et al. 2003). Their regeneration requires large canopy opening, and is abundant on disturbed soils (Whitmore 1984). Thus, we examined the dominances of the Dipterocarpaceae and *Macaranga* as indicators for disturbance.

Results

Stem density (number of stems per plot) and mean DBH was not significantly different among the three broad categories of forest management, although stem density tended to be lower in the forests harvested by conventional method than those in the other categories (Tukey multiple comparison tests, both $P > 0.05$, Fig. 1). Basal area, maximum DBH and AGB density were smaller in the forests harvested by conventional logging than in the rest ($P < 0.05$), while those of the old-growth forests and the forests harvested by RIL did not differ statistically from each other. AGB density of old-growth forests exceeded 48 kg m^{-2}, that of the forests harvested by RIL ranged from 31.8 to 48.1 kg m^{-2}, and that of the forests harvested by the conventional method from 9.6 to 28.4 kg m^{-2}. LAI was greater in old-growth forests than in the other categories, although this difference could not be tested statistically due to small sample size. DBH distribution of the forests harvested by RIL and the old-growth forests showed clearly L-shaped pattern (Fig. 2). DBH distributions of the forests harvested by conventional method showed the lack of larger trees (> 80 cm DBH) due to logging.

A total of 339 species belonging to 146 genera and 52 families (excluding unidentified stems) were found among 1333 stems ≥ 9.6 cm DBH, although the number of species may be reduced if matching of species in different plots was completed. The numbers of the observed taxa (families, genera and species) in the old-growth forests and the forests harvested by RIL were similar to each other, and were higher than those of the forests harvested by conventional method (Tukey multiple comparison tests, all $P < 0.05$; Fig. 3). The index of species richness of Fisher's α in the old-growth forests and the forests harvested by RIL was higher than that in the forests harvested by the conventional method (all $P < 0.05$). The α of the old-growth forests and the forests harvested by RIL overlapped greatly, all being greater than 50, while that of the forests harvested by conventional method was less than 40. The maximum value of α was 119.3 in the old-growth forest at PRI-1 and the minimum value was 17.6 in the forest harvested by conventional method at CV-3. Both of Shannon's indices of species diversity and evenness showed similar trends as number of taxa and Fisher's α.

The first and second axes of DCA cumulatively explained 24.4% of variance (eigenvalues, 0.34 and 0.21, respectively). Floristics of the three forest categories evaluated by genus composition clearly differentiated along the axis 1 (Fig. 4). The ranges of axis 1 scores of old-growth forests and the forests harvested by RIL partly overlapped, but the forests harvested by conventional logging were separated from the other two categories. Therefore, a most striking difference in species composition was found between the forests harvested by the conventional method and the rest. Among four abundant genera, two (*Dipterocarpus* and *Shorea*) that belong to Dipterocarpaceae were biased towards old-growth forests. Two genera of Euphorbiaceae showed contrasting patterns: *Macaranga* were abundant in disturbed sites while *Mallotus* were so in well-developed forests.

Old-growth forests and the forests harvested by RIL were dominated by Dipterocarpaceae trees, while the forests harvested by conventional method were by *Macaranga* trees (Fig. 5). According to the pattern of DBH distribution, Dipterocarpaceae contained many small-diameter trees in both the old-growth forests and the forests harvested by RIL, indicating a good regeneration (Fig. 2). On the other hand, *Macaranga* trees regenerated well in the forests harvested by the conventional method.

Discussion

Our results suggest that RIL is an efficient method to reduce logging impacts on forest structure, floristic composition and diversity compared with the conventional logging method. Commercially-logged forests occupy large tracts in tropical regions where human impacts are becoming increasingly greater, yet they have a high potential to protect biodiversity if managed properly (Cannon et al. 1998). The size of canopy opening by logging (i.e. creation of canopy gap) affected regeneration patterns and species composition elsewhere (Denslow 1980; Pickett and White 1985). RIL operation regulates the amount of logged trees and their size (DBH), location, and transportation of harvested logs (Sabah Forestry Department and European Union 2000). Consequently, RIL operation creates a smaller number of canopy gaps probably with a smaller mean size than the conventional logging does. Shade-tolerant trees can regenerate under a darker light condition. Therefore, these trees could have regenerated under small-sized canopy gaps in the forests harvested by RIL due to their physiological tolerance for reduced light. In contrast, the regeneration of shade-intolerant trees requires a sunnier condition (Turner 2001). Response to light condition associated with the difference in gap sizes caused a greater similarity of species composition and diversity between the old-growth forests and the forests harvested by RIL, and facilitated the regeneration of dipterocarp trees in the forests harvested by RIL (Sist and Nguyen-The 2002; Bischoff et al. 2005).

Differences of forest managements were related to the differences in the disturbance regime and regeneration patterns. For example, bulldozers heavily disturb topsoils by pulling out logged trees on the forest floor in the forests harvested by conventional method (Pinard et al. 2000). In our study, the forests harvested by conventional method were dominated by pioneer species of the genus *Macaranga*. *Macaranga* trees are known to regenerate under large canopy gaps often with disturbed soil conditions (Davies et al. 1998; Davies 2001). Moreover, an operation of the conventional method would have left a greater damage to the surrounding trees. On the other hand, RIL operation is gentle to forest with a minimum damage to soils and surrounding trees. This was achieved by both pre-harvest and harvest operations, including careful planning and construction of skid trails or skylines, directional felling, and appropriate skidding and landing (Sabah Forestry Department and European Union 2000). Our analysis dealt with two to three decades of a secondary succession only, and whether the species composition and structure of the forest including shrubs and herbs (that we do not include in our current analysis) can fully recover to a pre-harvest condition is still not known. To confirm the sustainability of the structure and floristic composition of tropical rain forests in DFR managed by RIL, long-term ecological monitoring is needed.

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Table 1. Description of the research plots.

Plot name	Abbreviation	Plot size (m)	Altitude (m)	Management status
Old-growth unlogged since the 1980s				
Ecological trail	PRI-1	100 x 20	248	Primary forest
ET antenna	PRI-2	50 x 40	248	Primary forest
ET jauh	80s-1	50 x 40	248	Unlogged since the 1980s
C54	80s-2	50 x 40	195	Unlogged since the 1980s
RIL				
Mannan	RIL95-1	100 x 20	196	8-10 years after RIL
Domingo	RIL95-2	100 x 20	200	8-10 years after RIL
C63 bawah	RIL00-1	100 x 20	195	5-6 years after RIL
C63 atas	RIL00-2	100 x 20	221	5-6 years after RIL
Conventional method				
Tangkulap 1	CV-1	100 x 20	109	Conventional logging
Tangkulap 2	CV-2	50 x 40	76	Conventional logging
Tangkulap 3	CV-3	100 x 20	52	Conventional logging

RIL indicates reduced-impact logging, and the time after logging is as of 2005.

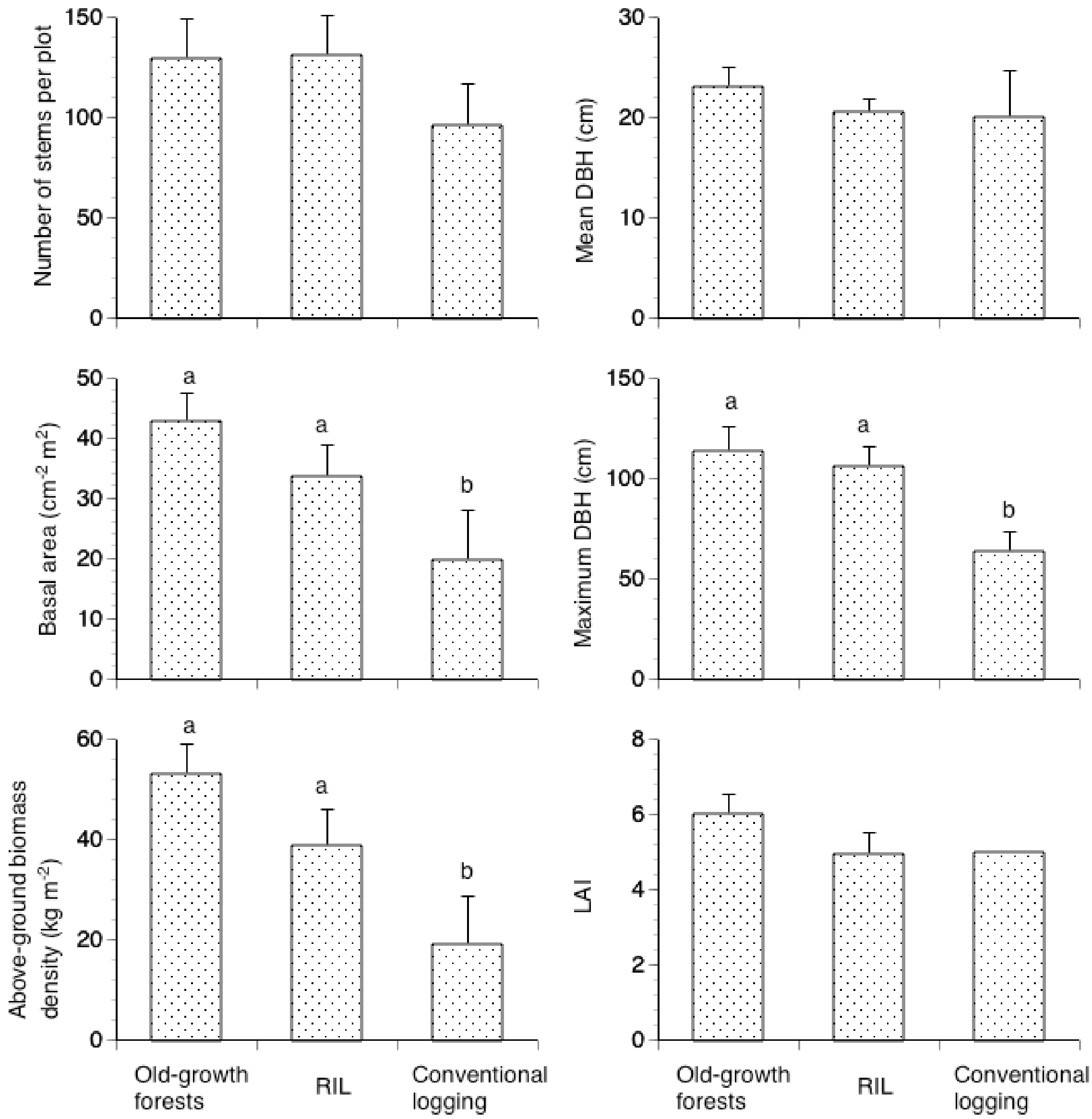

Figure 1. Stand structure in relation to management status in the tropical lowland forest in Deramakot, Sabah, Malaysia. RIL and conventional logging indicate the forests harvested by reduced-impact logging and by conventional logging, respectively. Forest categories that do not share the same letters differ at $P < 0.05$ by Tukey multiple comparison test. Vertical lines indicate standard deviation.

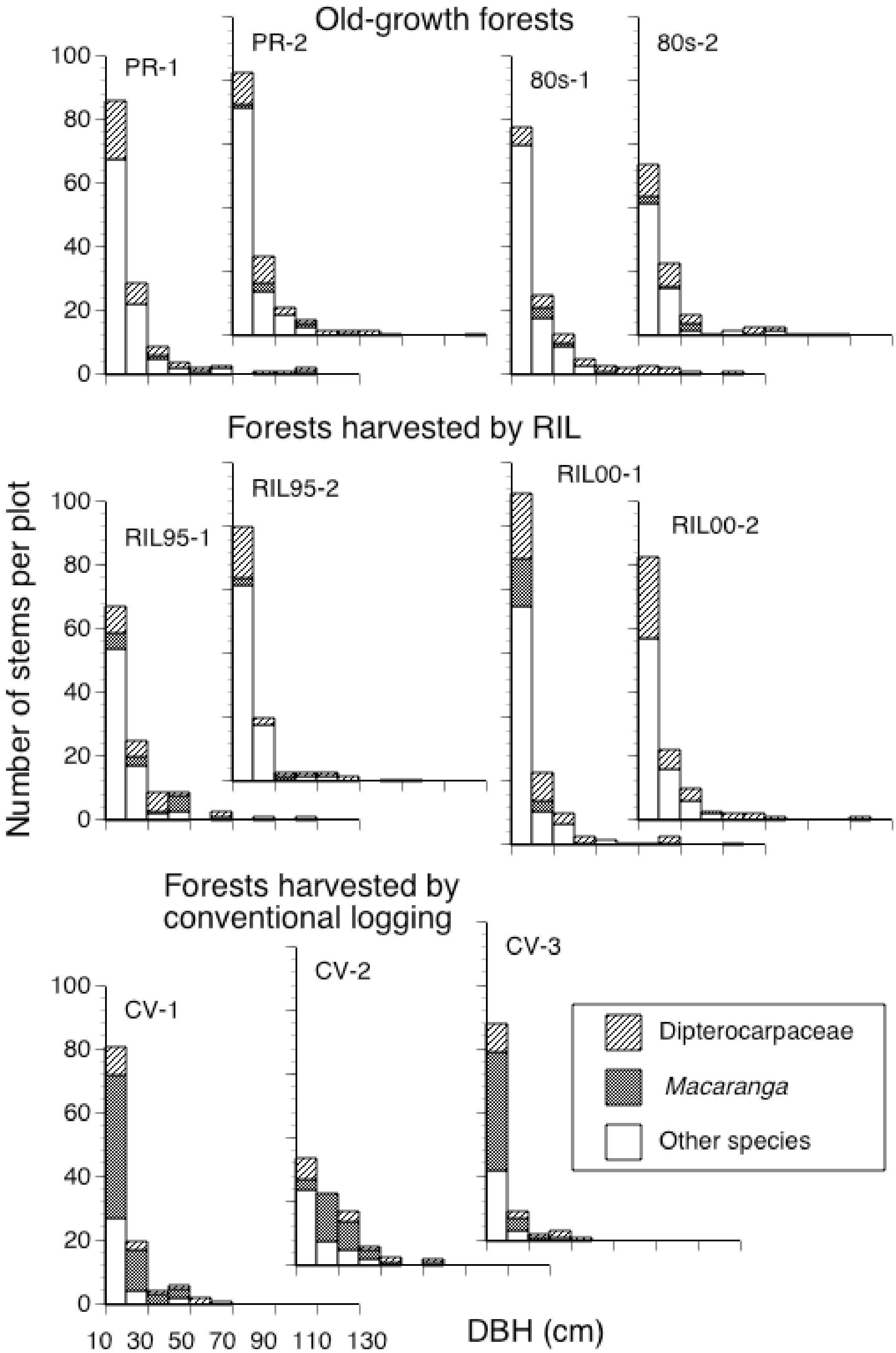

Figure 2. DBH distribution of trees in the 11 study plots, showing the fractions occupied by two dominant taxa, Dipterocarpacea and *Macaranga* (Euphorbiaceae). Stems < 10 cm DBH were excluded. See Table 1 for the plot abbreviations.

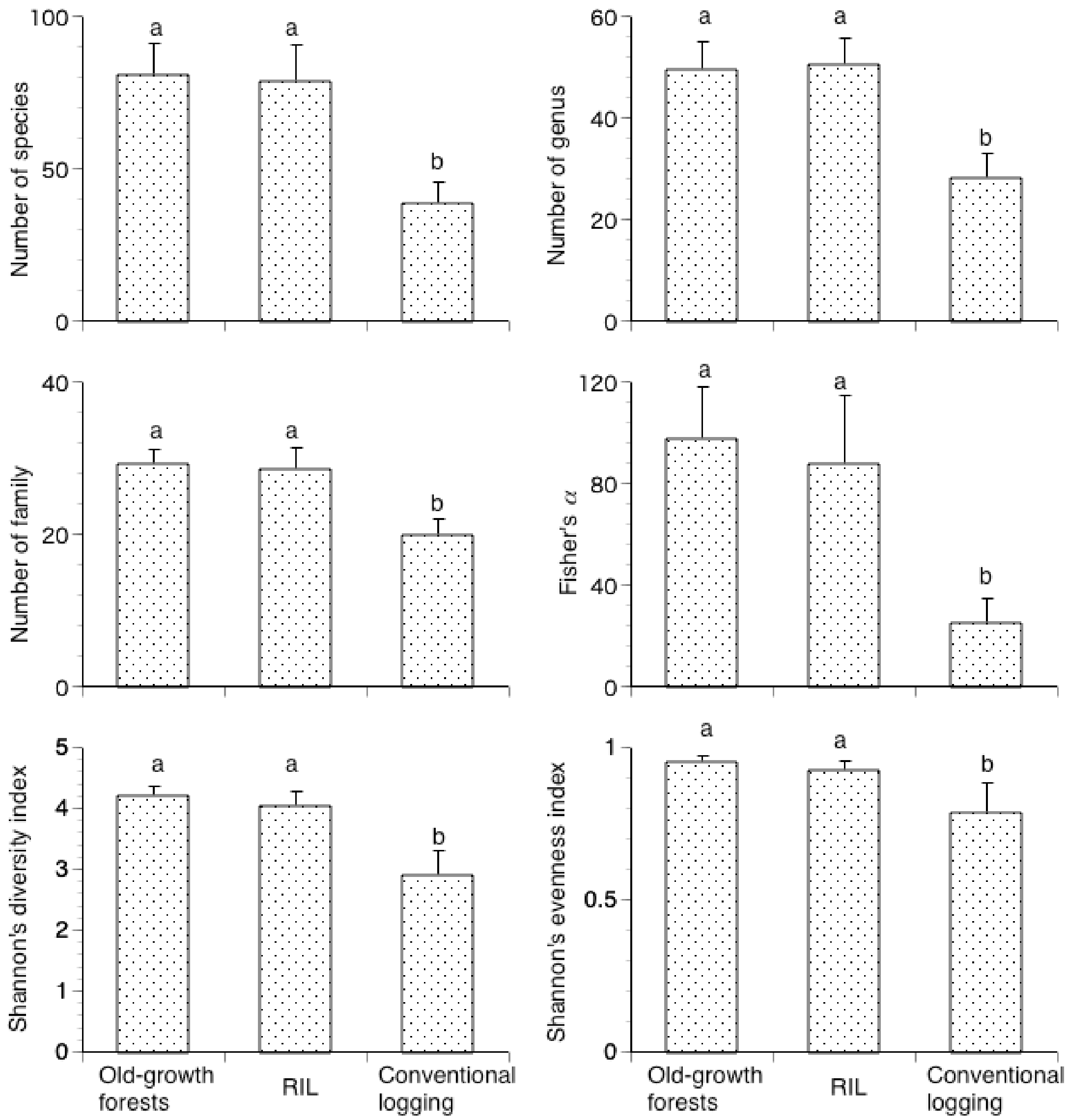

Figure 3. Tree diversity in relation to management status in the tropical lowland forest in Deramakot, Sabah, Malaysia. RIL and conventional logging indicate the forests harvested by reduced-impact logging and by conventional logging, respectively. Forest categories that do not share the same letters differ at $P < 0.05$ by Tukey multiple comparison test. Vertical lines indicate standard deviation.

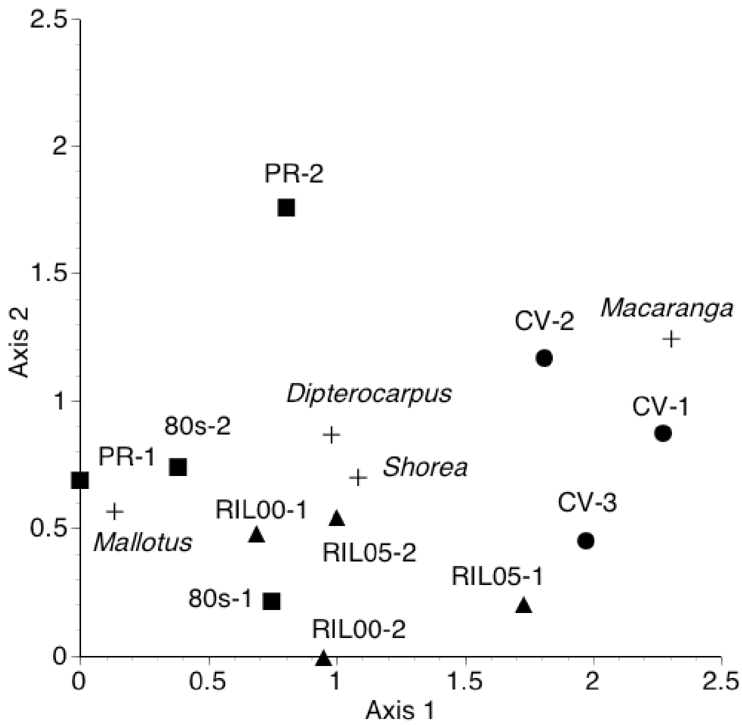

Figure 4. DCA diagram based on relative basal area of genus. Scores of four abundant genera were also shown. Square, old-growth forests; triangle, forests harvested by reduced-impact logging; circle, forests harvested by conventional method; cross, genus. See Table 1 for the plot abbreviations.

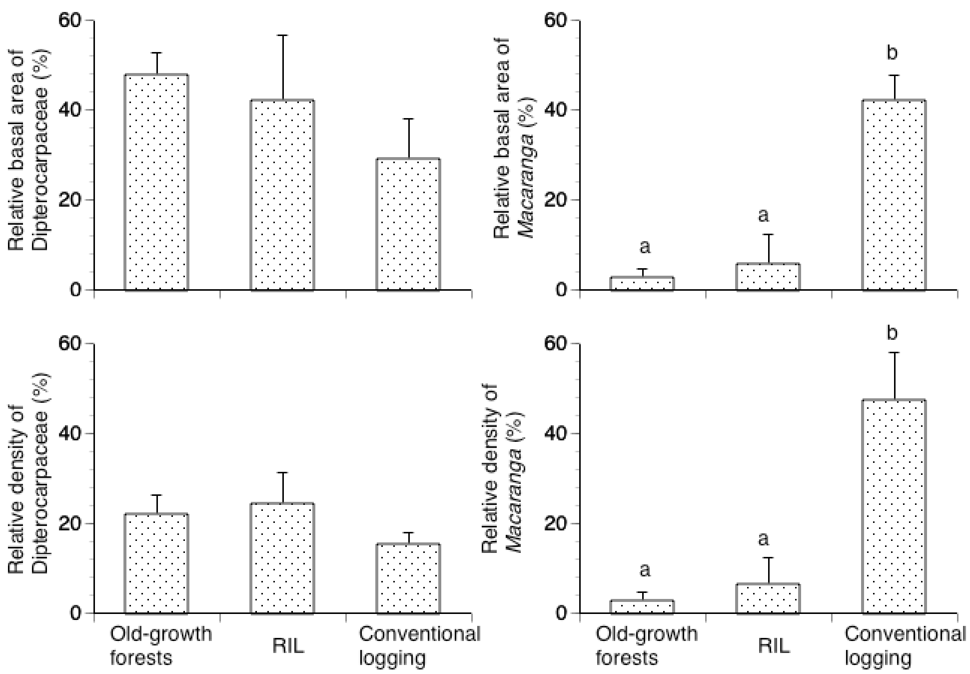

Figure 5. Dominance of Dipterocarpaceae and *Macaranga* (Euphorbiaceae) in terms of basal area and stem number in the three categories of forest management. RIL and conventional logging indicate the forests harvested by reduced-impact logging and by conventional logging, respectively. Forest categories that do not share the same letters differ at $P < 0.05$ by Tukey multiple comparison test. Vertical lines indicate standard deviation.