E-051 **Rehabilitation process of tropical forest ecosystem through the interaction between plants and soil （Abstract of the Final Report）**

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[Abstract]

The tropical rainforests with the highest biodiversity and huge amount of carbon stock are quickly decreasing with forest fire, illegal logging etc. It is urgent necessity to find the way to conserve the remained forests and recover the damaged ones. The deforestation also destroys the soil structure. Forest plants grow with the symbiotic relationship with soil microorganisms. It is important to recover the relationship among plant, soil and soil microorganisms for the rehabilitation of the ecosystem of tropical rainforests. Our purpose of research is to clarify the way of forest rehabilitation through the recovery of symbiotic relationships among plants, soil, and soil microorganisms.

We conducted study in Bukit Bangkirai, East Kalimantan where the forest was severely damaged by forest fire in 1998 and reserved since then, and Padang, West Sumatra where illegal logging deteriorate forests. We got following results.

The forest structure was recovering in Bukit Bangkirai it may need 40-50 years for the recovery of basal area. But the recovery of species composition may need 200 years or more. The forests damaged repeatedly by illegal logging in Sumatra continued deterioration.

The effect of fire temperature limited to upper ca. 10 cm layer of soil. Most soil bacteria recovered less than 10 years after fire. The root nodule bacteria on legume trees also recovered quickly and seemed to contribute the nitrogen fixation. On the contrary, the recovery of fungi, including symbiotic mycorrhiza with Dipterocarpaceae, need years as long as the periods needed for trees.

Tropical rainforest have less species with regenerating ability from sprout than forests in dry or cool areas, but we found a few species vigorously recovered from sprout, such as *Cotylelobium melanoxylon* of Dipterocarpaceae and *F. splendidissima* of Leguminosae They are also host plant of mycorrhiza and root nodule bacteria, respectively, then they might support the recovery such microorganisms.

1. Introduction

The tropical rainforests are one of the most important ecosystems for the environment of the earth, which have the highest biodiversity and huge amount of carbon stock. They are, however, quickly degraded and decreased by forest conversion for agricultural land, forest fire, illegal logging and so on. Among tropical countries, Indonesia is the second most important after Brazil for its areas of tropical rain forests. At present, however, the areas of degraded forests in Indonesia have increased into about 101.73 million ha, and the rate of forest degradation is about 3.8 million ha per year. The extensive forest fires 1997-1998 alone, for example, degraded 116,984 $km^2$ (=30% of Japanese land area) forest of Indonesia（Tacconi, 2003). The rainforest in Indonesia along the equatorial line is the typical one, developing until the maximum, but damaged badly. It is urgent necessity to find the way to conserve the remained forests and recover the damaged ones.

The deforestation also destroys the soil structure. Forest plants grow with the symbiotic relationship with soil microorganisms. It is important to recover the relationship among plant, soil and soil microorganisms for the rehabilitation of the ecosystem of tropical rainforests. Our purpose of research is to clarify the way of forest rehabilitation through the recovery of symbiotic relationships among plants, soil, and soil microorganisms.

2. Research Objective

Our objectives of study is as follows,

(1) forest recovery process after damage by fire or logging.
(2) change of soil environment, soil bacteria, and mycorrhiza during the forest recovery.
(3) distribution of legume trees and its symbiotic root nodule bacteria in the recovering forest.
(4) change of fungus flora, which decay the plant debris and enhance the forest development.
(5) change of microenvironment, biodiversity during the forest recovery, and find indicator species of the level of recovery.
(6) recovering process of some representative species and groups as models of recovery.

3. Results and Discussion

**(1) Forest recovery process after damage by fire or logging**

We conducted the study in East Kalimantan and West Sumatra (Fig. 1). Forests of Bukit Bangkirai in East Kalimantan were damaged by fire in Feb. to March, 1998. We established six 1-ha plots: heavily burned (HD1, HD2), lightly burned (LD1, LD2), and unburned (K1, K2) plots from 2001 to 2006.HD plots lost most trees during the fire, and the tree number (DBH>4.8cm) recovered by 80% of K plots. K plot had little increase in biomass. HD1 plots The biomass in HD1 plot became 53 ton ha-1, and 92 ton ha-1. The species number (ha-1) in K1 was 253 in 2001 and 287 in 2007, and that in HD1 was 91 in 2001 and 131 in 2007.

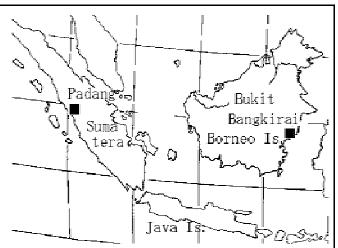

Fig. 1. Study sites on West Sumatra and East Kalimantan.

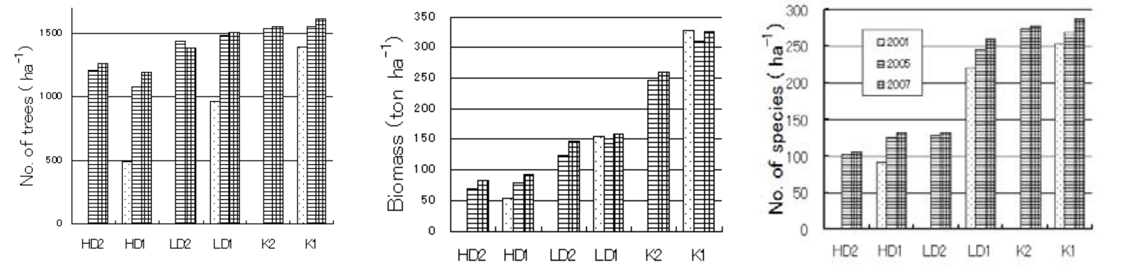


**Fig.2** No. of trees, biomass, and species number in six plots in 2001, 2005 and 2007 except HD2 whose data is in 2006 and 2007 at Bukit Bangkirai, East Kalimantan.

The unburned forest had species nearly 300 spp. which is similar value of highly diversified forest in Borneo (Suzuki 1999), but burned forest was around 130 spp. One of multivariate analyses (DCA) using basal area (BA) of each genus in plots from 2001 to 2007 (Fig. 3) showed the relationship between plots. The first and second axis seemed to indicate the successional and environmental trends, respectively. If we expect the recovery process from the changing speed of score value of the first axis, the heavily burned forest may need 200 years to become nearly same with the unburned forest (Fig. 4).

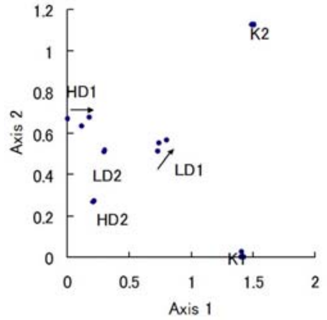


**Fig.3** Score of DCA analysis of each plot. Arrow shows change with time.

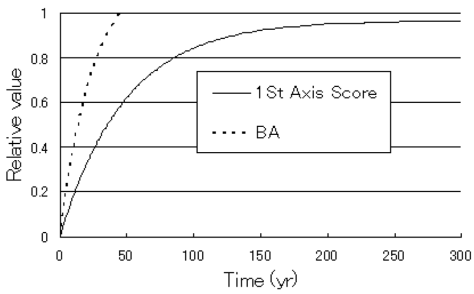


**Fig.4** Estimated change in DCA and BA with time (Relative value to undisturbed forest value).

In West Sumatra, we studied the effect of human disturbance on the structure and function of rainforest with the severe and abnormal dry climate (Yoneda et al. 2006). The forests from 600 m to 1780 m in alt were decreasing basal area of trees since the abnormal climate during El Niño in 1990s (Fig. 5). One of the reasons of the long effect of dry climate seemed the extension of gaps once established shown in Fig. 6.

The recent illegal logging, which cuts many tree species, increases the variance of spatial distribution of forest structure as well as decrease the biomass. These disturbances cause the fragmentation of forest, and probably decrease the ability of forest recovery. We measured the growth characteristics of many tree species in forest with different disturbance pressures, and clarified the change of composition of tree species with the change in disturbance strength. The net primary production of BA in selectively logged forest was similar to that in matured forest. That of biomass seemed to be less than the latter because of the diameter-height relationship, and specific gravity of woods.

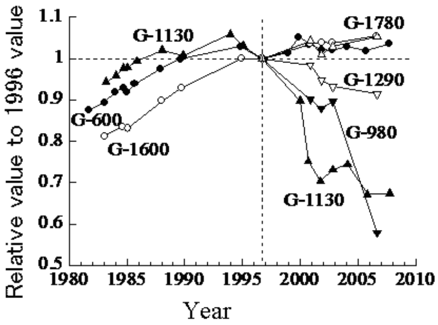


Fig.5 Change in BA of pots in Sumatra. Values in figure show the altitude.

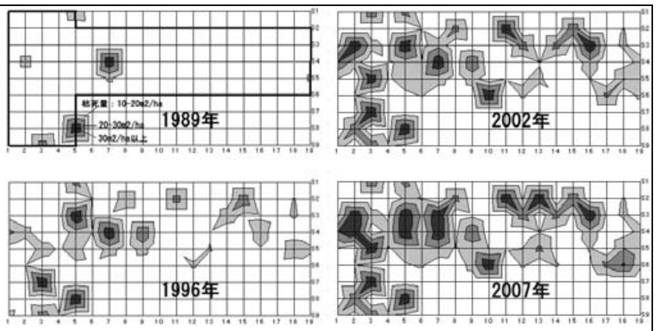


Fig.6 Change in accumulation of dead trees (=gap) of plot G-600. Each square is $100m^2$.

## (2) **Change of soil environment, soil bacteria, and mycorrhiza during the forest recovery**.

1)An experimental fire in laboratory, field soil survey, and monitoring of water dynamics in soil were conducted to estimate and reveal the effect of forest fire on soil of Bukit Bangkirai. The soil in upper 5 cm layer changed greatly in temperature, and lost water and organic matters when we heated the soil surface to 600-700°C (Fig. 7). The depth where the soil temperature exceeds 100°C was described with an equation $m\sqrt{t}$ where m=constant, t=heating time (minute). The value of m became smaller with more water content at beginning. We found the increase of pH and carbon content in soil layer below 10 cm in burned forest.

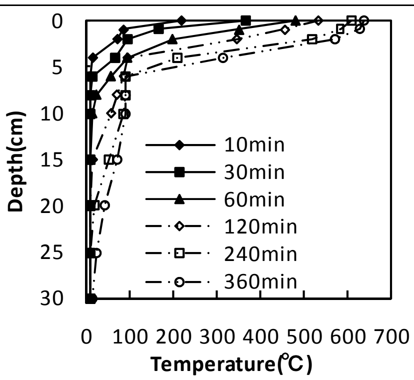


Fig.7 Change of soil temperature during experimental fire ($\theta_i$=0.32).

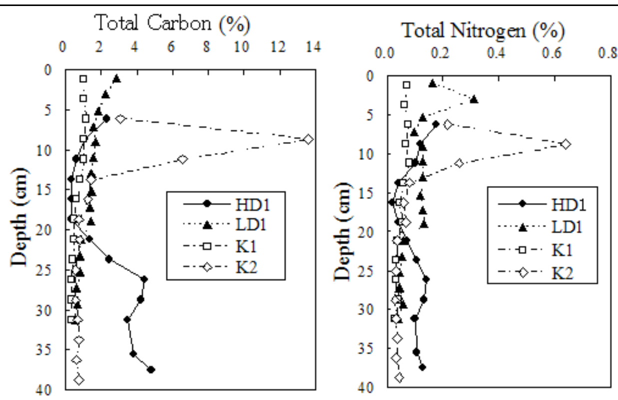


Fig.8 Vertical distribution of carbon and nitrogen in soil at plot HD1, LD1, K1 and K2.

2) We examined bacterial community structure in soil with basic chemical and enzymatic properties. The contents of total nitrogen and carbon, and the activities of cellulase and amirase of soil were not significantly different among plots with different fire effects (Fig. 9). The PCR-DGGE banding patterns of 16S rDNA (the V3 region) were similar among the plots (Fig. 10), and similar results were obtained with T-RFLP analyses. These data suggests that dominant bacteria in soil mostly recovered nine years after fire.

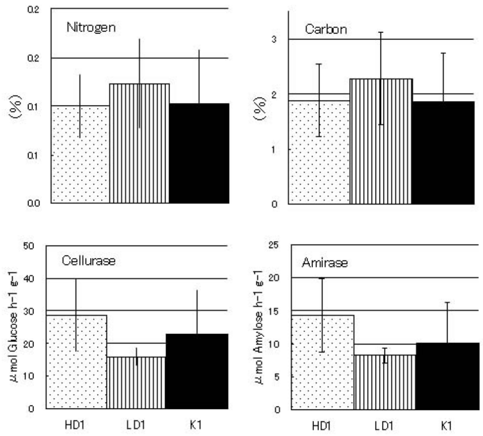


Fig.9 Weight percentages of total nitrogen and carbon, and activities of cellulase and amirase of soil in Plots HD1, LD1, and K1.

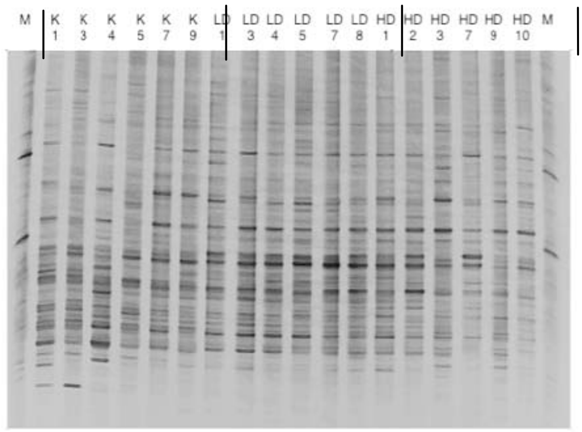


Fig.10 PCR-DGGE profiles of the V3 region of the 16S rDNA from soil bacteria in Plots HD1, LD1, and K1.

3) Nutrient acquisition of most plants largely depends on mycorrhizal fungi, which colonize fine roots of the plants symbiotically. Without such fungal symbionts, host plants, including all Dipterocarpaceae species, can not grow and survive in nature (Lee 1998). We studied mycorrhizal occurrence in soil samples collected from the six 1ha-plots. The dominance of mycorrhizae on forest floor was significantly correlated with the aboveground dominance of Dipterocarpaceae (Fig. 11). We also studied mycorrhizal fungal communities by applying molecular identification methods to individual mycorrhizal root tips in 331 soil samples. In the unburned area, mycorrhizal fungal community was dominated by Russulaceae and Thelephoraceae, and the total species richness estimated by Jack-knife method was 105 spp. In the burned area, mycorrhizal fungal community was significantly changed and dominated by a few fungal species including Scleroderma spp., which were not detected in the unburned area. The estimated species richness of mycorrhizal fungi in the burned area was 40 spp., which was significantly lower than that in the unburned areas. Of 24 *Cotylelobium melanoxylon* (Dipterocarpaceae) trees sprouting in the burned area, 22 were confirmed to be colonized by mycorrhizal fungi. But the colonization intensity (21±4% root tips were mycorrhizal) was significantly lower than that in the unburned area (nearly 100% in host root tips), indicating the difficulty of mycorrhizal infection in burned areas.

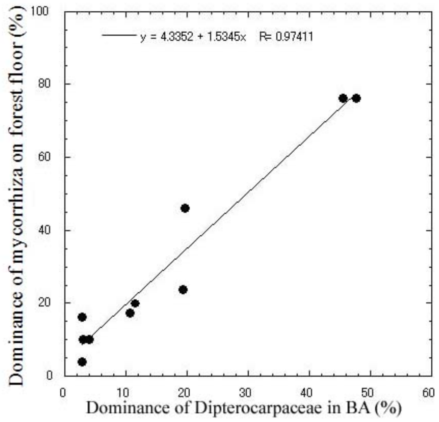


Fig.11 The correlation between the dominance of Dipterocarpaceae in BA and that of mycorrhizae on forest floor.

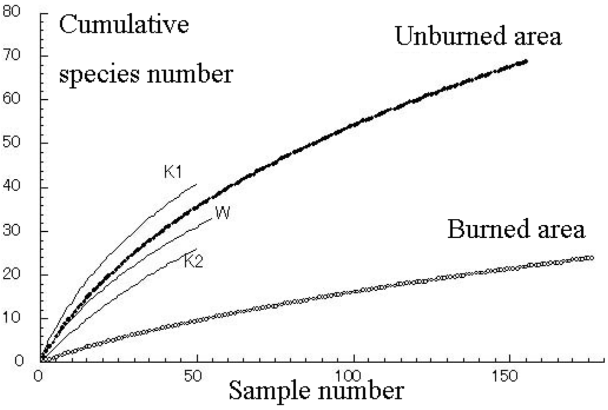


Fig.12 Species accumulation curve for mycorrhizal fungi detected in unburned and burned forests.

(3) **Symbiotic nitrogen fixation for recovering the fired forest**

The root nodules were counted on the wild grown young seedlings of *Fordia splendidissima* collected from each plot. Many nodules were observed in the heavily damaged (HD) area (Fig. 13). Symbiotic bacteria were isolated from the nodules of *Acacia mangium* and *F. splendidissima* grown in the each area. Phylogenetic analysis was carried out from the 16S rDNA partial sequences of several isolates. Couple of rhizospheric species for example, *Burkholderia*, *Microbacterium*, *Paenibacillus* and *Agrobacterium* were shown with high homology. These species are known as endophyte in rhizosphere, and *Burkholderia* is also reported as nitrogen fixing symbiotic strain. The conclusion at this stage, some rhizospheric bacteria establish symbiotic relation with leguminous trees in the forming root nodules as well as Rhizobiacere, and support the plant growth, resistance against plant disease and so on, during recovering the forest.

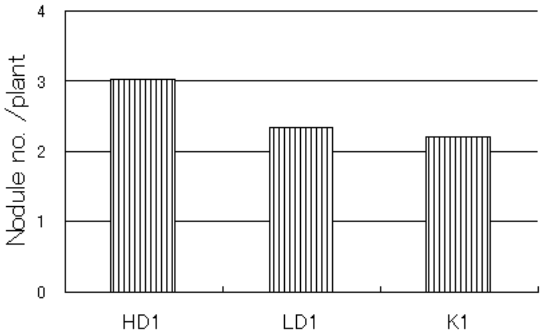


Fig.13 Average number of nodules per 239 saplings of *F. splendidissima*.

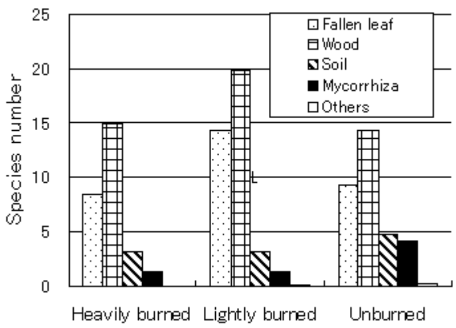


Fig.14 Species number of soft mushrooms on each substrate of each habitat

(4) **Change in fungus flora**

Figure 14 shows the number of mushrooms found on the forest floors in the plots. Wood decaying fungi were most frequent especially in LD1 where many trees had died. The species of mycorrhiza fungi were also decreased with increasing of the degree of damage by fire as the result of previous section (2). We made an experiment of wood decay using isolated wood decaying fungi

(Fig. 15). The decaying rate of *Shorea laevis* was very slow, it may need more than 10 years until compete decay. The observation of temperature in forest showed that the burned forest about10 years ago had still great difference in microenvironment from unburned forest (Fig. 16).

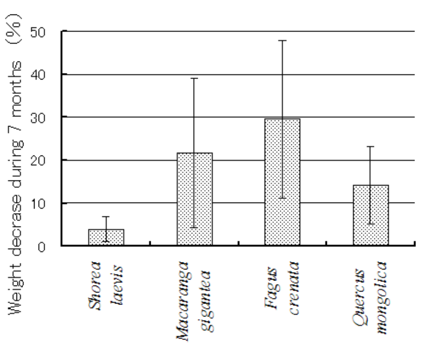


Fig.15 Durability of wood species for 14 wood-decay fungi.

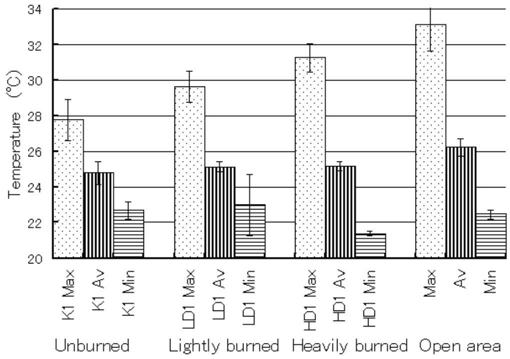


Fig.16 Differences in temperatures (daily maximum, average and minimum) in unburned and burned forests.

**(5) Change in microenvironment and biodiversity, and find indicator species of recovery.**

Species number of Bryophyta had no significant difference among different plots, though that of Marchantiophyta had: HD1< LD1<K1. The difference caused by the species growing on tree leaves, and their existence may be used as an indicator of wilderness of forest and/or forest recovery. The richness of mosses and lichens had no significant relation with that of trees, but related with microenvironment, especially air humidity. We compared the common ratio of species among plots, in bacteria, lichen, moss, liverwort, fungi and tree (Fig. 17). We used index of Jaccard index (=species number of common /sum of species number in each plot - common species number). Tree, fungi and liverwort had low ratio. They may need longer time for recovery than those with high ratio.

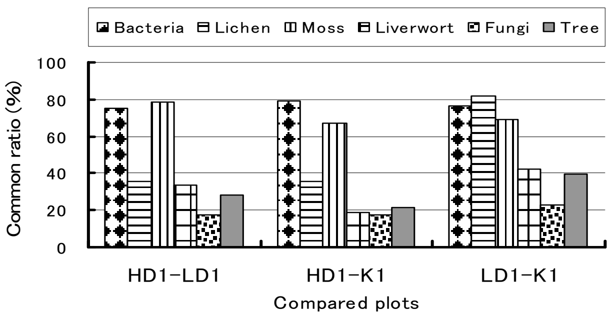


Fig. 17 Common ratio of species between plots. The data of bacteria is not species itself, but DNA band shown in Fig. 10.

**(6) Recovering process of some representative species and groups as models of recovery.**

1) The root system of pioneer species and climax species were studied for small saplings (Fig 18). Pioneer species had shallow and wide roots, meanwhile climax species had deep and narrow roots. Pioneer species can grow quickly because they have much of the root system close to the soil surface where nutrient is more abundant than deep under the soil. However, they would be vulnerable to damage by forest fire or exceptional dry climate. El Niño in future will damage the recovering forest comprised of pioneer trees.

2) The litter production decreased in more burned plots: 10.08, 9.12, 7.02 ton $ha^{-1}$, in K1,LD1, and HD1, respectively (Fig.19). The difference in litter production between burned and unburned forest is much less than that in biomass. The litter decay rate was more in pioneer species than climax species, and that of the same species was more in undamaged forest than in damaged forest.

3) Though *F. splendidissima* is a common shrub in climax forest, it regenerates vigorously after fire (Cleary 2005). The deep tap root of the species might allow the plant to survive during the fire (Fig. 18). Furthermore, the abilities of sprouting from survived root during fire (Fig. 20) and flowering on small plant (0.9m in height) would facilitate the recovery in burned forests.

4) The number of rattans including seedlings was much fewer in burned than in non-burned forest, meanwhile species richness was greater in burned forest for the number of stems. The animal-dispersed fruits of rattans might soon arrive from nearby non-burned forest. Then we can say that non-burned forests are very important as the seed sources even they cover small areas.

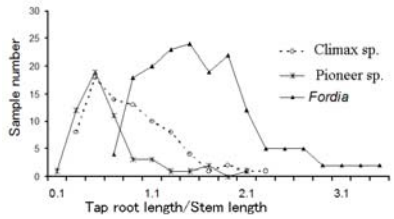


Fig. 18 Frequency of ration of tap root length to stem length in climax, pioneer and *F. splendidissima.*

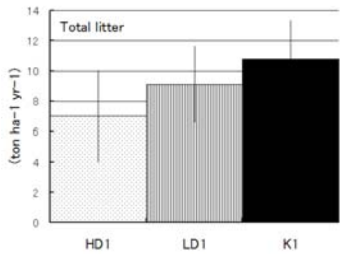


Fig. 19 Litter production in HD1, LD1 and K1 plots.

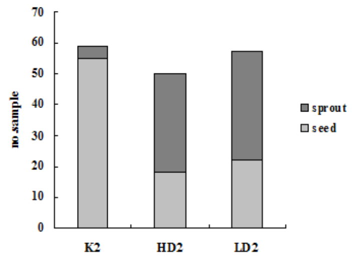


Fig. 20 Number of sprout and seed origin saplings of F. splendidissima around K2, HD2 and LD2 plots

5) We compared the sprouting ability of trees experimentally. Some species such as *Cotylelobium melanoxylon* (Dipterocarpaceae) and *F. splendidissima* (Leguminosae) had high ability of sprouting (Table 1), and contributed greatly in the forest regeneration. They are also host plant of mycorrhiza and root nodule bacteria, respectively, then they might support the recovery such microorganisms.

Table 1 Sprout ratio from cutting stumps and stems of each species.

Type: P:pioneer. S: Secondary forest species. C: Climax forest species

| Type | Fam | Species | Sprout ratio | Type | Fam | Species | Sprout ratio |
|---|---|---|---|---|---|---|---|
| P | Mela | *Clidemia hirta* | 0.94 | P | Euph | *Macaranga motleyana* | 0.57 |
| C | Legu | *Fordia splendidissima* | 0.90 | P | Euph | *Macaranga hypoleuca* | 0.52 |
| C | Dipt | *Cotylelobium melanoxylon* | 0.87 | P | Euph | *Macaranga trichocarpa* | 0.42 |
| S | Laur | *Litsea firma* | 0.82 | P | Meli | *Aglaia forbesii* | 0.33 |
| S | Thea | *Schima wallichii* | 0.74 | C | Dipt | *Dipterocarps confertus* | 0.23 |
| C | Euph | *Macaranga lowii* | 0.69 | C | Dipt | *Shorea laevis* | 0.08 |

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5) Watanabe, N., Simbolon, H. and Suzuki, E. (2008) Reestablishment of climbing palms, rattans after forest fire in East Kalimantan, Tropics (in press)