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Tree Species and Soil Properties in Selectively Logged Papua Rainforest

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Keywords:	tropical forest, logging, soil property

SCHOLARONE MANUSCRIPTS

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Abstract

Logging in tropical forests has been practised for decades and is likely to have altered forest conditions in many places. The objective of this research was to compare changes in tree species and soil characteristics between unlogged and logged forests in a small region of southern Papua, Indonesia. Data on tree and soil properties were collected in 166 plots consisting of 46 in unlogged forest and 120 in logged forest (each of one-year, five-year, ten-year, and fifteen-year logged forest was 30 plots). The result revealed that seedlings remained the most abundant stem class after logging. In terms of species dominance, most of the forests were dominated by the genera *Hopea, Vatica,* and *Syzygium*. However, after logging, pioneer species, such as *Macaranga bifoveata*, became more abundant, indicating the successional process. Soil conditions, including soil organic matter, C/N, litterfall C content, and litter dry weight, were not significantly different between unlogged and logged forests, indicating that logging did not significantly alter soil properties. However, studies of forest dynamics should be conducted to better understand the forest recovery process after logging, an artificial disturbance.

Keywords: tropical forest, logging, soil property, soil organic matter, silviculture.

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Introduction

Tropical rainforests can provide various services, including timber and non-timber forest products (Zimmerman and Kormos 2012). In particular, in Papua, many people still rely on the forest ecosystem for their livelihood. Despite local people's dependence on forest products and services, many tropical countries, including Indonesia, continue to exploit forests to meet domestic and international timber demand. To meet the timber demand, selective logging permits for new concession areas are still being issued. Selective logging targets commercial trees of specific sizes, while other trees are left to grow as future crop trees. This process can result in a fragmented forest, with some parts almost undisturbed and others heavily degraded, depending on the logging intensity (Putz et al. 2012). After logging, the forest changes ecological conditions, including increased light penetration and soil erosion (Brown et al. 2022, Steur et al. 2021).

As a consequence, a successional trajectory is initiated that can last for decades or centuries (Lozada et al. 2012) and which slowly alters the forest tree composition (Chazdon et al. 2010, Duah-Gyamfi et al. 2014). Alterations in logged forests generally affect the abundance of dominant species, tree mortality, recruitment and growth rates, and forest structure (Bohlman and Pacala 2012, Yamada et al. 2013). The actual successional pathway of a selectively logged forest may depend on many variables, with harvesting intensity and changes in soil conditions due to erosion being the main factors. Over time, tropical rainforests can be altered by natural (Crausbay and Martin 2016) and anthropogenic causes (de Avila et al. 2015, Huth et al. 2004). In this study, the focus is on alteration resulting from selective logging as an anthropogenic cause, which can alter the condition of tropical rainforests. The biotic and abiotic conditions of this forest before selective logging will differ from those after selective logging (Edwards et al. 2014). Tree composition and structure, as biotic elements, change during the logging period of the forest (Asase et al. 2014). Moreover, soil nutrients and litterfall can differ between pre- and post-logging conditions (Chiti et al. 2016, Hattori et al. 2013, Yamada et al. 2014). Many researchers have studied those phenomena in tropical rainforests.

In many tropical areas, such as South Papua, Indonesia, logging has been taking place for decades (Kuswandi et al. 2015, Kuswandi and Murdjoko 2015, Murdjoko 2013, Murdjoko et al. 2016a, Relawan 2014). In contrast, there were a few publications concerning the effect of selective logging in southern Papua. Hence, this study focused on the alteration of tree species composition, structure, and some soil factors resulting from selective logging. Furthermore, the objective of this research was to compare the alterations of tree species composition, structure, and soil characteristics between unlogged and logged forests in southern Papua, Indonesia.

Materials and Methods

Study Area

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The location was within a logging concession owned by PT Tunas Timber Lestari in southern Papua. The Indonesian selective logging system was implemented, in which trees with a minimum cutting diameter of 40 cm are cut, with a 35-year cutting cycle. After that, the results were generalized to the southern lowland area of Papua, where the topography is relatively flat. Geographically, the study area was between 140° 21'– 140°59' E and 05°50' – 06° 42' S. This logging concession was located near the border of Indonesia and Papua New Guinea, between the Muyu and Uwim Merah Rivers in the west and the Fly River in the east. The northern part is a mountainous area, and the southern part is the ex-timber concession.

Here, we placed plots in unlogged and logged forests, with the logged forests divided into four time points (1, 5, 10, and 15 years after logging). Plots were distributed based on logging blocks in this logging concession. Five locations were singled out as representing unlogged forest (logging block of 2016), 1 year (logging block of 2014), 5 years (logging block of 2010), 10 years (logging block of 2005), and 15 years (logging block of 2000) after logging. Hence, the total was 166 plots, with 46 in unlogged forest and 120 in logged forest (each of one-year, five-year, ten-year, and fifteen-year logged forest was 30 plots).

Climatically, the annual mean rainfall ranged from 3,000 to 4,000 mm, and the environment was quite moist, with daily moisture between 75 and 85%. The average maximum temperature is 32°C. The southern part of Papua consists of coastal plains, and the geological factor is alluvium. Trees were dominated by families of *Dipterocarpaceae*, *Lauraceae,* and *Myrtaceae* (Gandhi and Mitlöhner 2014, Kuswandi et al. 2015, Murdjoko et al. 2016).

[here Fig 1]

Data Collection and Sampling

Tree species were divided into four phases: seedlings, saplings, poles, and trees. Seedlings are typically characterized by a height of less than 1.5 m. Saplings are characterized by a height greater than 1.5 m and a diameter of less than 10 cm. Poles are described to have a diameter between 10 and 20 cm. Trees are typically characterised by a diameter greater than 20 cm. In this study, plot sizes were divided into four categories: 2 m x 2 m for seedlings; 5 m x 5 m for saplings; 10 m x 10 m for poles; and 20 m x 20 m for trees. Those plots were arranged in a nested layout. Then, the data taken for each plot are: species - every individual was identified according to the scientific name. Species identification was performed by two vegetation identifiers from the herbarium technician. Unidentified samples were set as voucher specimens and sent to Herbarium Papuense "*Balai Penelitian Kehutanan Manokwari*" and Herbarium Manokwariense (MAN) *Pusat Penelitian Keanekaragaman Hayati Universitas Papua* (*PPKH-UNIPA*). The validation name of species and family was checked online at Plants of the World Online (https://powo.science.kew.org/ accessed in December 2025); the number of species, where the number of

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each species in the plot will be documented, and Diameter - diameter at breast height (1.3 m) or 20 cm above buttress was tallied for trees or individuals > 5 cm. Besides, soil was sampled to compare organic matter and nitrogen content and to differentiate the decomposition process resulting from forest alteration. Then, soil samples were collected from each 20 m x 20 m plot, taking four from each corner and one from the centre. Then, the five soil samples were combined into a single sample. The soil sample was topsoil. Litterfall was also collected using a 1 m x 1 m plot within a 20 m x 20 m tree plot, which was randomly placed within the plot. The litterfall was weighed in the field and packed as a litterfall sample. The soil and litterfall samples were analysed in the laboratory of *Balai Pengkajian Teknologi Pertanian Yogyakarta, Indonesia*.

Data Analysis

Diversity index. Diversity among locations was tested using the diversity index. The Shannon-Wiener diversity index was singled out as a parameter. Besides measuring diversity among locations, the index was also used to describe the distribution of each species by computing evenness (E) and the number of individuals. The diversity index was calculated as $H' = -\sum p_i \, ln \, (p_i)$ where H' is the Shannon-Wiener diversity index, p_i is the number of samples where tree species *i* is present. Evenness among locations was measured using $E = H'/(ln\,(S))$ in which S is the number of species for each area (Pielou 1966, Shannon 1948, Spellerberg and Fedor 2003). The F test was applied to compare diversity and evenness between unlogged and logged forests. *Importance value index (IVI).* The importance value index was calculated to determine the dominance of each tree species. The index for tree and pole was determined by adding relative frequency, relative density, and relative dominance as $IV_i = RFr_i + RDe_i + RDo_i$ where IV_i is important value index of tree species *i,* RFr_i is relative frequency of tree species *i,* RDe_i is relative density of tree species *i,* RDo_i is the relative dominance of tree species *i.* The index for the seedling and sapling was $IV_i = RFr_i + RDe_i$ (Curtis and McIntosh 1950). *Tree structure based on DBH distribution.* Distribution of DBH was analysed using the Kolmogorov–Smirnov test, with DBH grouped into class diameter (CD) classes. Then, the number of individuals was placed cumulatively as F(X), representing the observed frequency. After that, FN (X) was defined as the theoretical frequency and computed as $FN(X) = k.e^{-a.CD_i}$ where $FN\,(X)$ is the theoretical frequency, k is the coefficient, e is 2.718, a is the slope of a regression of the natural logarithm, CD_i is i th diameter class. The Kolmogorov–Smirnov test was computed as $d = D_max/N$ where d_{max} is the maximum absolute value between F(X) and FN (X), and N is the number of individuals. The *d* is the observed value compared to the critical value. If the *d* derived from the computation was less than the critical value in the Kolmogorov–Smirnov distribution, it indicated that the theoretical and observed frequencies of the DBH distribution were statistically similar (Durbin 1975, Nascimento et al. 2014). Moreover, analysis of variance (F test) with Tukey's post hoc test was used to compare edaphic

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conditions between unlogged and logged forests. Statistical analysis was computed using R version 4.5.1. (R Core Team 2025).

Results

Tree Diversity and Structure Pre- and Post-Logging Condition

We documented 176 species and 49 families in this tropical rain forest. Then, those species and families were grouped by their logging status: unlogged forest comprised 126 species and 45 families; one-year logged included 92 species and 38 families; five-year logged consisted of 110 species and 43 families; ten-year logged contained 113 species and 40 families; and fifteen-year logged covered 110 species and 38 families. Seemingly, tree diversity decreased, but in the fifth and tenth years after logging, it increased slightly, then dropped for the remainder of the post-logging period. However, there were no significant differences (F test, P>0.05) between the unlogged forest and logged forest in terms of tree diversity (Tab. 1) based on Shannon-Weiner (H'). Moreover, evenness (E) between the unlogged forest and logged forest did not show a significant difference (F test, P>0.05). The value of evenness (E) among those forests was about 0.9, suggesting that the number of species was evenly distributed in each forest.

[here Tab 1]

[here Tab 2]

In this forest, seedlings were the most abundant in both unlogged and logged forests compared to other phases (Tab. 2). However, the number of individuals decreased after logging, with the reduction measured as the difference between the numbers in logged and unlogged forests. In the first year after logging, there was about a 14 per cent reduction in seedling numbers, but this increased by about 13 per cent in the fifth year post-logging. Furthermore, the number of seedlings in the tenth and fifteenth years after logging was reduced by approximately 35% and 19%, respectively, compared to pre-logging levels. The number of saplings generally decreased after logging. The drop in sapling numbers was about 30, 23, and 6 per cent in the first, fifth, and tenth years after logging, respectively, and rose by about 20 per cent in the fifteenth year after logging. The comparison of pole numbers between unlogged and logged forests showed a clear decrease. The proportions of poles in unlogged forest to logged forest were about 64 per cent for the first year, 36 per cent for the fifth year, 31 per cent for the tenth year, and 44 per cent for the fifteenth year. The number of trees after logging showed a declining trend, with drops of about 28 per cent in the first year, about 3 per cent in the fifth year, about 18 per cent in the tenth year, and about 24 per cent in the fifteenth year.

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Dominant Species of Trees in the Understory and Upperstory

The five most dominant species were selected based on their importance value index (IVI) for each phase, where the seedlings and samplings were grouped as understory. The upper story consisted of poles and trees. The understory condition was characterized by the dominant species of seedlings (Fig. 2) in unlogged forests, namely *Hopea celtidifolia* Kosterm. (IVI=19.07 %), *Vatica rassak* Blume (IVI=14.44 %), *Hopea iriana* Slooten (IVI=14.00 %), *Lasianthus* sp. (IVI=13.63 %) and *Syzygium anomalum* Lauterb. (IVI=13.28 %). In the first year after logging, the dominant seedling species was *Syzygium anomalum* Lauterb. (IVI=27.42 %), *Macaranga bifoveata* J.J.Sm (IVI=21.27 %), *Hopea iriana* Slooten (IVI=12.32 %), *Canarium asperum* Benth. (IVI=10.65 %) and *Blumeodendron tokbrai* (Blume) Kurz (IVI=8.12 %). In the five-year logged forest, seedlings of *Hopea celtidifolia* Kosterm. were dominant. (IVI=21.31 %), *Syzygium anomalum* Lauterb. (IVI=15.37 %), *Vatica rassak* Blume (IVI=15.09 %), *Goniothalamus* sp. (IVI=11.10 %), and *Canarium asperum* Benth. (IVI=9.63 %). In a ten-year-old logged forest, seedlings were abundantly covered by *Syzygium anomalum* Lauterb. (IVI=20.38 %), *Vatica rassak* Blume (IVI=19.32 %), *Hopea celtidifolia* Kosterm. (IVI=10.62 %), *Canarium hirsutum* Willd. (IVI=10.17 %) and *Canarium asperum* Benth. (IVI=8.21 %). In the fifteenth year after logging, the most dominant seedlings were *Vatica rassak* Blume (IVI=30.79 %), *Hopea iriana* Slooten (IVI=15.38 %), *Hopea celtidifolia* Kosterm. (IVI=9.84 %), *Syzygium anomalum* Lauterb. (IVI=9.38 %) and *Calophyllum* sp. (IVI=9.07 %). Moreover, as shown in Figure 3, the species such as *Syzygium anomalum* Lauterb. (IVI=16.77 %), *Canarium asperum* Benth. (IVI=9.68 %), *Vatica rassak* Blume (IVI=9.43 %), *Gymnacranthera farquhariana* (Hook.f. & Thomson) Warb. (IVI=7.91 %) *Hopea iriana* Slooten (IVI=7.66 %) was abundant in unlogged forests, ranking among the top five dominant species. In the logged forest, the dominant sapling species were *Aglaia argentea* Blume (IVI=17.48 %) and *Syzygium anomalum* Lauterb. (IVI=15.82 %), *Gymnacranthera farquhariana* (Hook.f. & Thomson) Warb. (IVI=14.49 %), *Macaranga bifoveata* J.J.Sm. (IVI=11.28 %) and *Vatica rassak* Blume (IVI=10.21 %). After five years of logging, the forest was dominated by *Macaranga bifoveata* J.J.Sm. (IVI=22.62 %), *Syzygium anomalum* Lauterb. (IVI=17.28 %), *Canarium asperum* Benth. (IVI=11.79 %), *Aglaia argentea* Blume (IVI=7.91 %) and *Vatica rassak* Blume (IVI=7.75 %). The dominant species of saplings in a 10-year-old logged forest were *Vatica rassak* Blume (IVI = 11.27%) and *Syzygium anomalum* Lauterb. (IVI=10.43 %), *Virola surinamensis* (Rol. ex Rottb.) Warb. (IVI=9.92 %), *Gymnacranthera farquhariana* (Hook.f. & Thomson) Warb. (IVI=8.77 %) and *Macaranga bifoveata* J.J.Sm. (IVI=8.49 %). In the fifteenth year after logging, saplings were *Vatica rassak* Blume (IVI = 21.47%) and *Hopea celtidifolia* Kosterm. (IVI=12.06 %), *Blumeodendron tokbrai* (Blume) Kurz (IVI=11.71 %), *Syzygium anomalum* Lauterb. (IVI=11.16 %) and *Knema* sp. (IVI=9.14 %).

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The dominant species of poles (Fig. 4) in unlogged forest were *Gymnacranthera farquhariana* (Hook.f. & Thomson) Warb. (IVI=29.05 %), *Hopea celtidifolia* Kosterm. (IVI=23.10 %), *Gironniera subaequalis* Planch. (IVI=18.18 %), *Blumeodendron tokbrai* (Blume) Kurz (IVI=15.70 %) and *Syzygium anomalum* Lauterb. (IVI=15.46 %). After one year of logging, the dominant species were *Gymnacranthera farquhariana* (Hook.f. & Thomson) Warb. (IVI=47.41 %), *Hopea celtidifolia* Kosterm. (IVI=26.50 %), *Melicope elleryana* (F. Muell.) T.G. Hartley (IVI=21.57 %), *Blumeodendron tokbrai* (Blume) Kurz (IVI=21.17 %) and *Canarium asperum* Benth. (IVI=17.92 %). In a logged forest over 5 years, species such as *Macaranga bifoveata* J.J.Sm. (IVI=30.60 %), *Canarium asperum* Benth. (IVI=19.29 %), *Gymnacranthera farquhariana* (Hook.f. & Thomson) Warb. (IVI=15.61 %), *Gironniera subaequalis* Planch. (IVI=12.60 %) and *Blumeodendron tokbrai* (Blume) Kurz (IVI = 11.24%) grew abundantly. The species of *Pimelodendron amboinicum* Hassk. (IVI=31.03 %), *Aglaia argentea* Blume (IVI=20.53 %), *Blumeodendron tokbrai* (Blume) Kurz (IVI=19.97 %), *Lithocarpus rufovillosus* (Markgr.) Rehder (IVI=17.83 %) and *Gymnacranthera farquhariana* (Hook.f. & Thomson) Warb. (IVI=16.36 %) became the most frequent in the tenth year after logging. In the fifteen-year logged forest, the dominant species of poles were *Blumeodendron tokbrai* (Blume) Kurz (IVI=29.49 %), *Vatica rassak* Blume (IVI=21.83 %), *Melicope elleryana* (F. Muell.) T.G. Hartley (IVI=18.36 %), *Syzygium anomalum* Lauterb. (IVI=13.92 %) and *Canarium asperum* Benth. (IVI=13.67 %).

The tree species (Fig. 5) in the unlogged forest were dominated by *Vatica rassak* Blume (IVI = 36.10%) and *Syzygium anomalum* Lauterb. (IVI=18.15 %), *Planchonella anteridifera* (C.T.White & W.D.Francis ex Lane-Poole) H.J.Lam (IVI=16.62 %), *Hopea iriana* Slooten (IVI=14.70 %) and *Hopea celtidifolia* Kosterm. (IVI=14.69 %). After one year of logging, species like *Vatica rassak* Blume (IVI=33.64%) and *Syzygium branderhorstii* Lauterb. (IVI=30.65 %), *Hopea celtidifolia* Kosterm. (IVI=19.78%), *Gymnacranthera farquhariana* (Hook.f. & Thomson) Warb. (IVI=18.86 %) and *Rhodomyrtus* sp. (IVI=15.51 %) were the most dominant. In the five-year logged forest, *Vatica rassak* Blume (IVI=38.68 %), *Syzygium acutangulum* Nied. (IVI=24.96 %), *Hopea celtidifolia* Kosterm. (IVI=19.55 %), *Canarium asperum* Benth. (IVI=14.97 %) and *Hopea iriana* Slooten (IVI=14.83 %) grew plentifully. Species such as *Vatica rassak* Blume (IVI=29.82 %), *Syzygium anomalum* Lauterb. (IVI=25.79 %), *Lithocarpus rufovillosus* (Markgr.) Rehder (IVI=19.58 %), *Gironniera subaequalis* Planch. (IVI=13.08 %) and *Melicope elleryana* (F. Muell.) T.G. Hartley (IVI=13.00 %) were the five-densest species growing in ten-year logged forest. The species of *Vatica rassak* Blume (IVI=73.00 %), *Canarium asperum* Benth. (IVI=22.54 %), *Lithocarpus rufovillosus* (Markgr.) Rehder (IVI=15.07 %), *Syzygium anomalum* Lauterb. (IVI=15.05 %) and *Rhodamnia cinerea* Jack (IVI = 12.86%) were the dominant species after 15 years of logging.

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[here Fig 2]

[here Fig 3]

[here Fig 4]

[here Fig 5]

Distribution of Individuals Based on Tree Diameter

[here Tab 3]

The result of the Kolmogorov-Smirnov test for DBH distribution showed that the observed value of d is less than the critical value ($d < _{0.05}$). Therefore, the DBH distribution followed DBH classes as presented in Table 3. The number of individuals in both unlogged and logged forests decreased negatively exponentially with increasing diameter. The general pattern of the DBH distribution was an inverted J shape.

Edaphic Factors in Unlogged and Logged Forest

[here Tab 4]

The SOM showed a significant difference in forest conditions (Tab. 4, F test, $P<0.05$). The lowest content of SOM was in a one-year and a one-year logged forest, while the highest content of SOM was in a five-year logged forest. The SOM in the unlogged forest, the ten-year logged forest, and the fifteenth year after logging showed significant differences compared to other forests. In general, SOM in logged forests was not significantly different from that in unlogged forests. Moreover, C organic (%) and dried weight (g) of litterfall were significantly different among forest conditions (Tab. 4, F test, $P>0.05$). In brief, litterfall conditions were similar between unlogged and logged forests.

Discussion

The Compositional and Structural Alteration of Dominant Tree Species after Logging Conditions in the Forest

The dominant tree species were dynamically recorded in both the understory and upperstory layers of the forest during the research. Different logging conditions led to changes in the dominant tree species. In the understory, 12 tree species were identified, with the top five most dominant in both unlogged and logged forests. The saplings also comprised 12 different tree species that occurred in both unlogged and logged forests. Furthermore, in upperstory fourteen and fifteen, various tree species were dominant in both unlogged and logged forests, serving as poles and trees, respectively.

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The seedlings of *Hopea celtidifolia* and *Vatica rassak* were the dominant species in unlogged and logged forests, except one year after logging, while *Syzygium anomalum* became the dominant species in the forest one and ten years after logging. Most of the twelve dominant species were present in both unlogged and logged forests. The interesting point in the compositional change in species was that *Macaranga bifoveata* became the dominant species in the first year after logging. The seedlings of *M. bifoveata* were present in about 43% of this one-year-old logged forest, and the density of this species was 4,167 individuals per hectare. In saplings, the tree species *Syzygium anomalum* and *Vatica rassak* were dominant in both unlogged and logged forests. The logging did not impact the density of the *S. anomalum* and *V. rassak* species.Those species are polycarpic plants, and the seeds appear to have high germination viability (Herrera and Jovani 2010, Peh et al. 2011, Rasingam and Parthasarathy 2009). Therefore, seedlings of both species were able to survive under higher light levels, and these species are not favourable as animal food (Murdjoko et al. 2016b). A similar phenomenon was that *M. bifoveata* grew abundantly not only in forests that were the first year after logging, but also in the most unlogged forests. This species was a pioneer species that responded positively to the gap opening resulting from logging (Gutiérrez-Granados et al. 2011, Gourlet-Fleury et al. 2013, Arbainsyah et al. 2014, Saiful and Latiff 2014). The presence of *M. bifoveata* indicated that an invasive species had just entered the logged forest. Hence, it is clear that only a short time after the canopy gap was created by logging, pioneer plants such as *M. bifoveata* began colonising the forest (Asase et al. 2014, Oke 2012, Schnitzer and Carson 2001).

In the upper story, the dynamics of tree species composition also occur in logged forests. Different species dominated the poles and trees at various times after logging. In poles, *G. farquhariana* was the most dominant tree species in unlogged and logged forests. The alteration of forest conditions did not influence this species. Similarly, other species, such as *B. tokbrai* and *H. celidifolia*, could survive and grow after logging. It seems that the logging did not affect the density of those species. Surprisingly, *M. bifoveata* was still present up to the pole phase. In the tree phase, *V. rassak* was the most dominant species in both unlogged and logged forests, followed by *H. celtidifolia* and *S. anomalum*. Those species are well adapted to different forest conditions. Although the species *V. rassak*, *S. anomalum*, *H. celtidifolia*, and *G. farquhariana* are target species during logging, they remain dominant in the upper story. Moreover, the presence of *M. bifoveata* in the tree phase was less dominant, suggesting that remnant trees reached the upperstory. This tendency was also observed in compositional changes in logged forests (Osazuwa-Peters et al. 2015, Whitfeld et al. 2014).

Forest structure, in general, did not differ between unlogged and logged forests, in which the number of small individuals (seedlings and saplings) was denser than the number of large individuals (poles and trees), regardless of species. Species such as *S. anomalum* and *V. rassak* showed that both small and large individuals were present in both unlogged and logged forests. In contrast, other species like

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Lithocarpus rufovillosus, Melicope elleryana, Pimelodendron amboinicum, Rhodamnia cinerea, Rhodomyrtus sp., and *S. acutangulum* were only found in large individuals growing in logged forest. Moreover, species of *Canarium hirsutum* and *Goniothalamus* sp. tended to grow dominantly as small individuals after logging. It seems that those species were favoured in forests with more open canopy gaps, as logging ecologically altered light penetration and density (Murdjoko et al. 2022, Rumayomi et al. 2024). Another species, such as *M. bifoveata*, could grow into both small and large individuals after logging. The ecological conditions in the logged forest were more favourable to this pioneer species (Zimmerman and Kormos 2012). However, this species would be outcompeted when the canopy of other trees was denser, resulting in no gap and reduced light availability (Kuswandi and Murdjoko 2015). Fifteen years after logging, *M. bifoveata* was not found in large trees. It indicates that the canopy in this forest was dense, allowing less light to penetrate the layers beneath.

Dynamics of Soil Condition after Logging

Edaphic factors between logged and unlogged forests were statistically similar (F test, $P > 0.05$). The logging did not alter SOM and litterfall conditions. Since logging activity damaged the forest floor vegetation, recovery took approximately one year to be covered by vegetation, particularly liana (Murdjoko et al. 2017). The pioneer plants and other seedlings could also grow to cover the forest floor. Hence, nutrient loss could be prevented, and soil organic matter remained in the logged forest. Additionally, remnant trees and logging-related wood debris would contribute to litterfall (Chiti et al. 2016). Presumably, the microclimatic condition did not change dramatically. Thus, natural processes such as decomposition still take place, as the logging condition (C/N) between unlogged and logged forests was not significantly different ($P>0.05$). Therefore, the content of SOM (%) and C organic (%) was not significantly different between unlogged and logged forests. Soil properties change as vegetation density, including tree cutting, increases (Murdjoko et al. 2022). Our study demonstrates that tropical forest soils are not static post-disturbance but undergo a complex successional process. The peak in SOM at year five represents a vital phase of nutrient flux that bridges the gap between the loss of primary biomass and the establishment of a functional secondary forest. For policymakers and foresters in tropical rainforests, including Papua region, these results underscore the importance of long-term monitoring. Sustainable management must look beyond timber volume to the invisible recovery of the soil, ensuring that the foundational edaphic factors—the true "capital" of the forest—are maintained for future generations.

Conclusions

In this forest, seedlings were the most abundant in both unlogged and logged forests compared to other phases. However, the number of individuals decreased after logging. In terms of species dominance, most of the forest was dominated by the genera of *Hopea, Vatica,* and *Syzygium.* Those species were already

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present before logging, but after logging, pioneer species such as *M. bifoveata* appeared. This can be an indicator that the forest is under the successional process. Furthermore, soil conditions, including soil organic matter, C/N, C content in litterfall, and dried weight, were not significantly different between unlogged and logged forests, indicating that ecological conditions are generally similar in both types of forests. Hence, the logged forest could reach the same condition as an unlogged forest. However, studies of forest dynamics should be conducted to understand better understand the forest recovery process following logging as an artificial disturbance.

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For Review Only

References

Asase A., Asiatokor B. K., Ofori-Frimpong K. 2014 - *Effects of selective logging on tree diversity and some soil characteristics in a tropical forest in southwest Ghana.* Journal of Forestry Research *25* (1): 171–76. doi:10.1007/s11676-014-0443-4

Bohlman S., Pacala S. 2012 - *A forest structure model that determines crown layers and partitions growth and mortality rates for landscape-scale applications of tropical forests.* Journal of Ecology 100 (2): 508–18. doi:10.1111/j.1365-2745.2011.01935.x

Brown H. C. A., Appiah M., Berninger F. A. 2022 - *Old timber plantations and secondary forests attain levels of plant diversity and structure similar to primary forests in the West African humid tropics.* Forest Ecology and Management 518 (January). doi:10.1016/j.foreco.2022.120271

Chazdon R. L., Finegan B., Capers R. S., Salgado-Negret B., Casanoves F., Boukili V., Norden N. 2010 - *Composition and dynamics of functional groups of trees during tropical forest succession in northeastern Costa Rica.* Biotropica 42 (1): 31–40. doi:10.1111/j.1744-7429.2009.00566.x

Chiti T., Perugini L., Vespertino D., Valentini R. 2016 - *Effect of selective logging on soil organic carbon dynamics in tropical forests in central and western Africa.* Plant and Soil 399 (1–2): 283–94. doi:10.1007/s11104-015-2697-9

Crausbay S. D., Martin P. H. 2016 - *Natural disturbance, vegetation patterns and ecological dynamics in tropical montane forests.* Journal of Tropical Ecology 32 (5): 384–403. doi:10.1017/S0266467416000328

Curtis J., McIntosh R. 1950 - *The Interrelations of Certain Analytic and Synthetic Phytosociological Characters.* Ecology 31 (3): 434–55.

de Avila A. L., Ruschel A. R., de Carvalho J. O. P., Mazzei L., Silva J. N. M., Lopes J. do C., Araujo M. M., Dormann C. F., Bauhus J. 2015 - *Medium-term dynamics of tree species composition in response to silvicultural intervention intensities in a tropical rain forest.* Biological Conservation 191: 577–86. doi:10.1016/j.biocon.2015.08.004

Duah-Gyamfi A., Swaine E. K., Adam K. A., Pinard M. A., Swaine M. D. 2014 - *Can harvesting for timber in tropical forest enhance timber tree regeneration?* Forest Ecology and Management 314: 26–37. doi:10.1016/j.foreco.2013.11.025

Durbin J. 1975 - *Kolmogorov-smirnov tests when parameters are estimated with applications to tests of exponentiality and tests on spacings.* Biometrika 62 (1): 5–22. doi:10.1093/biomet/62.1.5

Edwards D. P., Tobias J. A., Sheil D., Meijaard E., Laurance W. F. 2014 - *Maintaining ecosystem function and services in logged tropical forests.* Trends in Ecology and Evolution 29 (9): 511–520. doi:10.1016/j.tree.2014.07.003

Gandhi Y., Mitlöhner R. 2014 - *Tree Species Composition, Diversity and Structure in Tunas Logging*

For Review Only

Concession Area of Papua-Indonesia. Tree 66: 47.

Hattori D., Kenzo T., Irino K. O., Kendawang J. J., Ninomiya I., Sakurai K. 2013 - *Effects of soil compaction on the growth and mortality of planted dipterocarp seedlings in a logged-over tropical rainforest in Sarawak, Malaysia.* Forest Ecology and Management 310: 770–776. doi:10.1016/j.foreco.2013.09.023

Herrera C. M., Jovani R. 2010 - *Lognormal distribution of individual lifetime fecundity: Insights from a 23-year study.* Ecology 91 (2): 422–430. doi:10.1890/09-0849.1

Huth A., Drechsler M., Köhler P. 2004 - *Multicriteria evaluation of simulated logging scenarios in a tropical rain forest.* Journal of Environmental Management 71 (4): 321–333. doi:10.1016/j.jenvman.2004.03.008

Kuswandi R., Murdjoko A. 2015 - *Population Structures of Four Tree Species in Loggpopulation Structures of Four Tree Species in Logged-Over Tropical Forest in South Papua, Indonesia: an Integral Projection Model Approach.* Indonesian Journal of Forestry Research 2 (2): 93–101. doi:10.20886/ijfr.2015.2.2.93-101

Kuswandi R., Sadono R., Supriyatno N., Marsono D. 2015 - *Keanekaragaman Struktur Tegakan Hutan Alam Bekas Tebangan Berdasarkan Biogeografi di Papua.* Jurnal Manusia dan Lingkungan 22 (2): 151–159.

Lozada J., Arends E., Sánchez D., Villarreal A., Soriano P., Costa M. 2012 - *Vegetation Succession of Logged Forest in the Western Alluvial Plains of Vegetation Succession of Logged Forest in the Western Alluvial Plains of Venezuela.* Journal of Tropical Forest Science 24 (3): 300–311.

Murdjoko A. 2013 - *Recuperation of Non-commercial Trees in Logged Forest in Southern Papua, Indonesia.* Jurnal Manajemen Hutan Tropika 19 (2): 94–102. doi:10.7226/jmht.19.2.94

Murdjoko A., Brearley F. Q., Ungirwalu A., Djitmau D. A., Benu N. M. H. 2022 - *Secondary Succession after Slash-and-Burn Cultivation in Papuan Lowland Forest, Indonesia.* Forests 13 (3): 1–14.

Murdjoko A., Marsono D., Sadono R., Hadisusanto S. 2016a - *Tree Association with Pometia and its Structure in Logging Concession of South Papua Forest.* Jurnal Manajemen Hutan Tropika (Journal of Tropical Forest Management) 22 (3): 180–191. doi:10.7226/jtfm.22.3.180

Murdjoko A., Marsono D., Sadono R., Hadisusanto S. 2016b - *Plant Species Composition and Their Conspecific Association in Natural Tropical Rainforest, South Papua.* Biosaintifika: Journal of Biology & Biology Education 8 (1): 33. doi:10.15294/biosaintifika.v8i1.5217

Murdjoko A., Marsono D., Sadono R., Hadisusanto S. 2017 - *Recovery of residual forest ecosystem as an impact of selective logging in South Papua: An ecological approach.* Biotropia 24 (3): 230–245. doi:10.11598/btb.2017.24.3.732

Nascimento R. G. M., Machado S. do A., Figueiredo Filho A., Higuchi N. 2014 - *A growth and yield*

For Review Only

projection system for a tropical rainforest in the Central Amazon, Brazil. Forest Ecology and Management 327: 201–208. doi:10.1016/j.foreco.2014.05.007

Oke D. O. 2012 - *Effects of short rotation natural fallow on diversity of plant species and population of soil microbes in Aponmu, Ondo State, Nigeria.* Journal of Tropical Forest Science 24 (1): 18–26.

Osazuwa-Peters O. L., Chapman C. A., Zanne A. E. 2015 - *Selective logging: Does the imprint remain on tree structure and composition after 45 years?* Conservation Physiology 3 (1): cov012. doi:10.1093/conphys/cov012

Peh K. S. H., Lewis S. L., Lloyd J. 2011 - *Mechanisms of monodominance in diverse tropical tree-dominated systems.* Journal of Ecology 99 (4): 891–898. doi:10.1111/j.1365-2745.2011.01827.x

Pielou E. C. 1966 - *The measurement of diversity in different types of biological collections.* Journal of Theoretical Biology 13 (C): 131–144. doi:10.1016/0022-5193(66)90013-0

Putz F. E., Zuidema P. A., Synnott T., Peña-Claros M., Pinard M. A., Sheil D., Vanclay J. K., Sist P., Gourlet-Fleury S., Griscom B., Palmer J., Zagt R. 2012 - *Sustaining conservation values in selectively logged tropical forests: The attained and the attainable.* Conservation Letters 5 (4): 296–303. doi:10.1111/j.1755-263X.2012.00242.x

R Core Team 2025 -R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Rasingam L., Parthasarathy N. 2009 - *Diversity of understory plants in undisturbed and disturbed tropical lowland forests of Little Andaman Island, India.* Biodiversity and Conservation 18 (4): 1045–1065. doi:10.1007/s10531-008-9496-z

Relawan R. 2014 - *the Effect of Silvicultural Treatment on Stand Growth of Logged-Over Forest in South Papua.* Indonesian Journal of Forestry Research 1 (2): 117–126. doi:10.20886/ijfr.2014.1.2.568.117-126

Rumayomi N. A. A., Murdjoko A., Mulyadi A. U. M., Benu N. M. H. 2024 - *Species richness and diversity in secondary lowland forest, Bintuni, Bird's Head Peninsula, West Papua, Indonesia.* Jurnal Manajemen Hutan Tropika (Journal of Tropical Forest Management) 30 (2): 295–304. doi:10.7226/jtfm.30.2.295

Schnitzer S. A., Carson W. P. 2001 - *Treefall gaps and the maintenance of species diversity in a tropical forest.* Ecology 82 (4): 913–919. doi:10.1890/0012-9658(2001)082[0913:TGATMO]2.0.CO;2

Shannon C. E. 1948 - *A Mathematical Theory of Communication.* The Bell System Technical Journal *27* (4): 623–656. doi:10.1145/584091.584093

Spellerberg I. F., Fedor P. J. 2003 - *A tribute to Claude-Shannon (1916-2001) and a plea for more rigorous use of species richness, species diversity and the "Shannon-Wiener" Index.* Global Ecology and Biogeography 12 (3): 177–179. doi:10.1046/j.1466-822X.2003.00015.x

For Review Only

Steur G., Verburg R. W., Wassen M. J., Teunissen P. A., Verweij P. A. 2021 - *Exploring relationships between abundance of non-timber forest product species and tropical forest plant diversity.* Ecological Indicators 121 (April 2020): 107202. doi:10.1016/j.ecolind.2020.107202

Whitfeld T. J. S., Lasky J. R., Damas K., Sosanika G., Molem K., Montgomery R. A. 2014 - *Species richness, forest structure, and functional diversity during succession in the New Guinea Lowlands.* Biotropica 46 (5): 538–548. doi:10.1111/btp.12136

Yamada T., Hosaka T., Okuda T., Kassim A. R. 2013 - *Effects of 50 years of selective logging on demography of trees in a Malaysian lowland forest.* Forest Ecology and Management 310: 531–538. doi:10.1016/j.foreco.2013.08.057

Yamada T., Yoshioka A., Hashim M., Liang N., Okuda T. 2014 - *Spatial and temporal variations in the light environment in a primary and selectively logged forest long after logging in Peninsular Malaysia.* Trees - Structure and Function 28 (5): 1355–1365. doi:10.1007/s00468-014-1040-z

Zimmerman B. L., Kormos C. F. 2012 - *Prospects for Sustainable Logging in Tropical Forests.* BioScience 62 (5): 479–487. doi:10.1525/bio.2012.62.5.9

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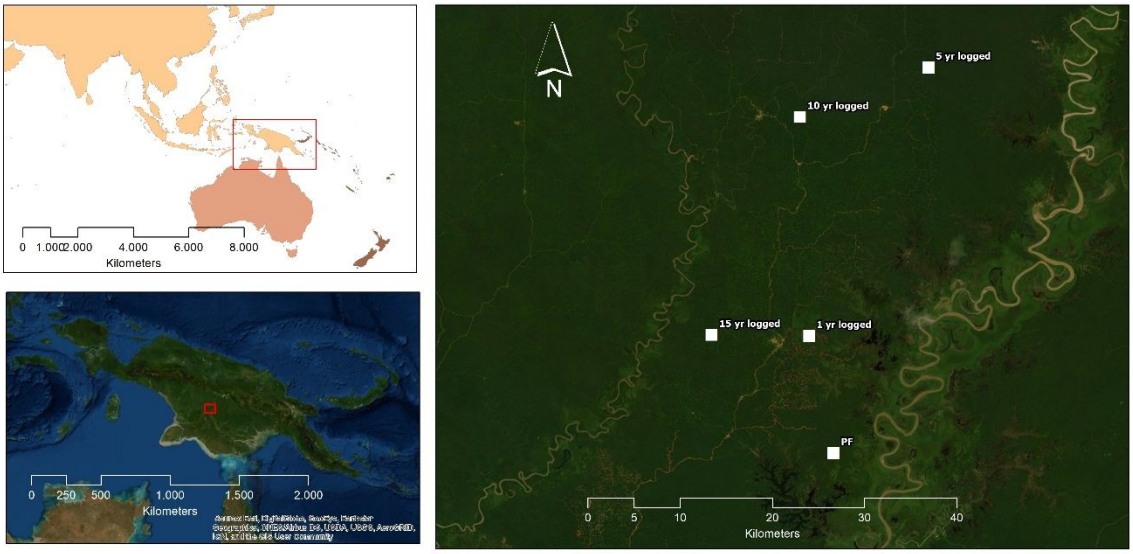

Figure 1 Study area of research. (PF=unlogged forest, I yr logged=one year after logging, 5 yr logged=five years after logging, 10 yr logged=ten years after logging, and 15 yr logged=fifteen years after logging)

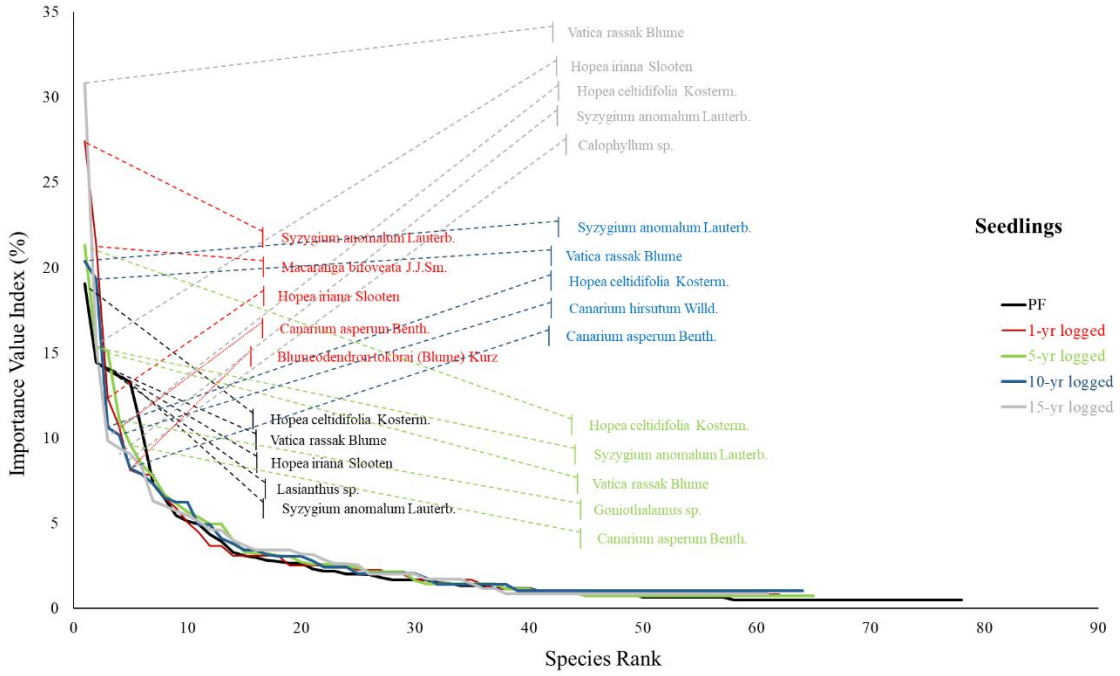

Figure 2 The five most dominant species of seedlings. PF=unlogged forest, 1-yr logged=one year after logging, 5-yr logged=five years after logging, 10-yr logged=ten years after logging, and 15-yr logged=fifteen years after logging.

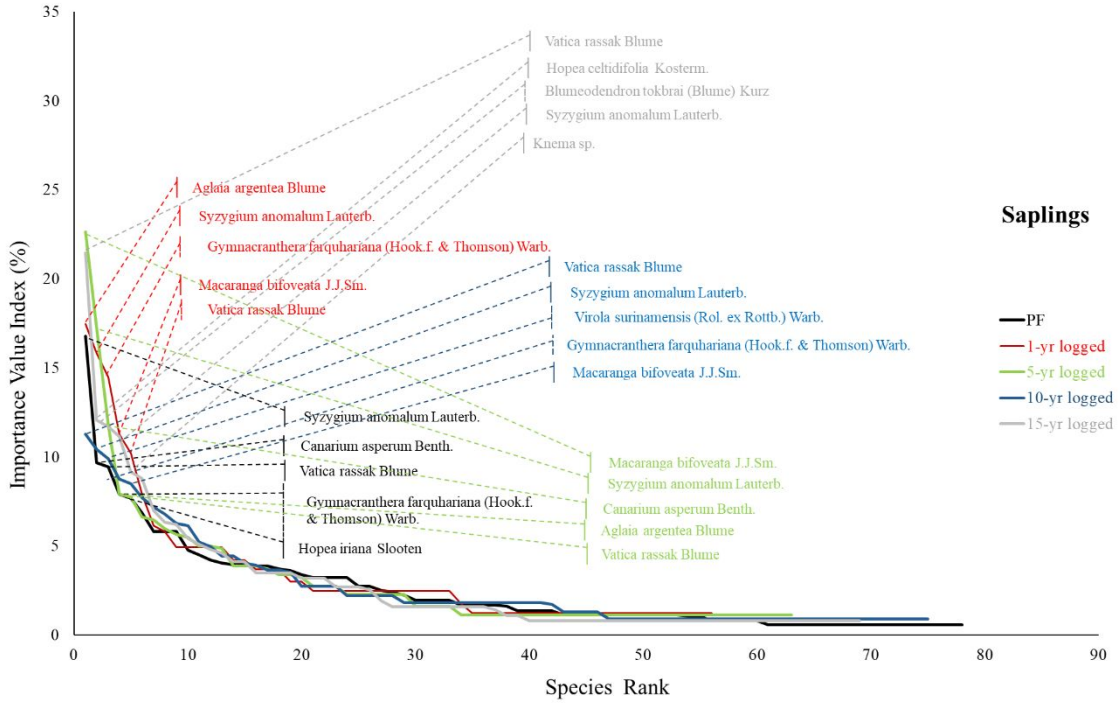

Figure 3 The five most dominant species of saplings. PF=unlogged forest, 1-yr logged=one year after logging, 5-yr logged=five years after logging, 10-yr logged=ten years after logging, and 15-yr logged=fifteen years after logging.

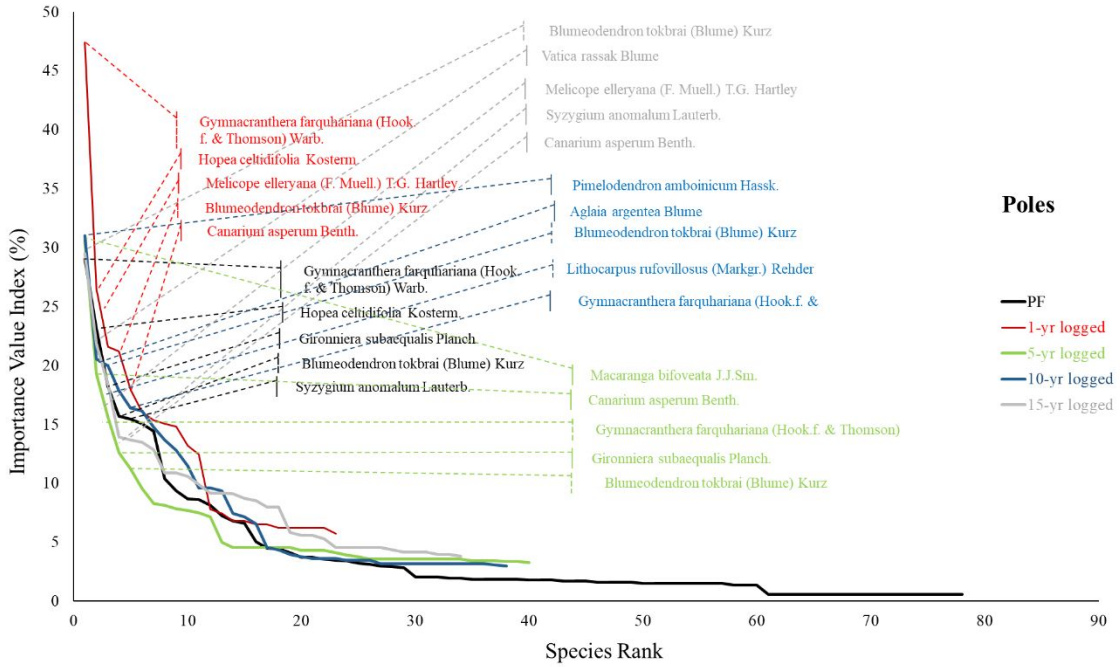

Figure 4 The five most dominant species of poles. PF=unlogged forest, 1-yr logged=one year after logging, 5-yr logged=five years after logging, 10-yr logged=ten years after logging, and 15-yr logged=fifteen years after logging.

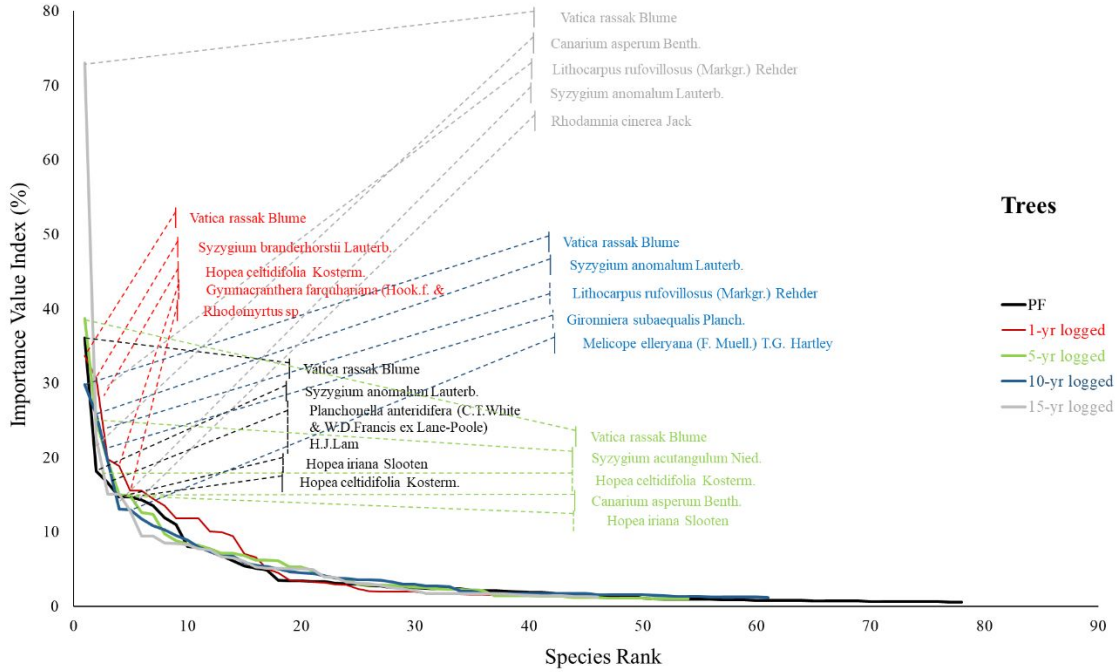

Figure 5 The five most dominant species of trees. PF=unlogged forest, 1-yr logged=one year after logging, 5-yr logged=five years after logging, 10-yr logged=ten years after logging, and 15-yr logged=fifteen years after logging.

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Table 1 Average and standard deviation of tree species diversity between unlogged and logged forest based on Shannon-Weiner (H') and evenness (E). "ns" denotes non-significant significance; F is value of analysis of variance and P is the probability value.

Indices	F	P		unlogged forest	1- year logged	5 -year logged	10 -year logged	15 -year logged
H'	3.19	0.15^{ns}	Average	2.61	2.37	2.48	2.58	2.39
			Stdev	0.26	0.36	0.46	0.32	0.39
E	0.674	0.611^{ns}	Average	0.91	0.90	0.89	0.93	0.89
			Stdev	0.08	0.11	0.11	0.06	0.10

Table 2 Number of stem per hectare per phase for unlogged and logged forest

Phase	Number of stems per hectare (individuals. ha^{-1})				
	unlogged forest	1 year -logged	5 year- logged	10- year logged	15- year logged
Seedlings	34728	29833	39333	22667	28000
Saplings	3583	2493	2747	3360	4280
Poles	396	143	253	273	220
Trees	194	140	188	158	147

Table 3 Number of stems per hectare per diameter at breast height (DBH) for unlogged and logged forest

DBH classes (cm)	Number of stems per hectare (individuals. ha^{-1})				
	unlogged forest	1-year logged	5-year logged	10-year logged	15-year logged
<20	38715	32477	42337	26290	32505
20-39.9	151	110	157	141	112
40-59.9	32	19	27	26	26
60-79.9	2	3	1	2	3
80-99.9	0	1	1	0	2

Table 4 Soil characteristics of unlogged and logged forest. The statistical differences were symbolized as the asterisk (**) while "ns" denotes non-significant significance. Letters among five types of forest indicate the post hoc test of Tukey in which the same letters express a non-significant difference and different letters show a significant difference. F is value of analysis of variance and P is probability value.

Edaphic factors	F	P		unlogged forest	1-year logged	5-year logged	10-yr logged	15-yr logged
Soil								
SOM (%)	4.58	0.003**	Average	10.24	8.47	16.73	10.96	10.95
			Stdev	2.43	2.99	6.60	2.05	8.90
				ab	a	b	ab	ab
Litterfall								
C organic (%)	0.641	0.674^{ns}	Average	35.85	33.33	33.24	33.94	34.82
			Stdev	0.89	3.76	2.41	2.28	0.77
Dried weight (g.m^{-2})	1.392	0.3^{ns}	Average	27.09	21.90	16.91	15.01	19.55
			Stdev	15.46	3.33	4.78	1.17	1.68
N Total (%)	0.423	0.824^{ns}	Average	0.86	0.98	1.07	1.04	0.92
			Stdev	0.08	0.17	0.10	0.14	0.03
C/N	0.811	0.566^{ns}	Average	41.10	34.60	31.03	33.04	37.76
			Stdev	3.02	7.02	1.30	4.83	2.01

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