

Historical data guides restoration of degraded peat swamp forests in Southeast Asia

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Abstract. Peat swamp forests in Southeast Asia are under heavy pressure. Deforestation, forest degradation, wildfires, and drainage have damaged or destroyed substantial areas of the once extensive peat swamp forest formations. Several efforts are underway to rehabilitate degraded peat forests areas in order to restore some of the valuable ecosystem services these forested areas once provided. However, these efforts often result in (mixed)-plantations that only partly resemble the original peat forests. Information about these peat swamp forests' complex origin and ecology is needed to improve restoration outcomes further. Our paper analyses historical data from coastal peat swamp forests in Sarawak and Brunei and discusses the potential to use this as the reference value for intact peat forests. We describe the observed stand structure and species composition for pristine peat swamp forest, and we analyze the population structure of three dominant peat swamp forest species: *Gonystylus bancanus* (*ramin*), *Dactylocladus stenostachys* (*jongkong*) and *Shorea albida* (*alan batu*). We compare the historical data with data from recently measured, degraded peat swamp forests. We discuss our results in relation to processes of peat dome formation, nutrient availability and hydrology, and give recommendations for peat swamp forest management and restoration.

1. Introduction

Peat swamp forests (PSF) are tropical moist forests grown on waterlogged, acid soils that prevent dead leaves and wood decomposing completely. This results in the formation of a thick layer of acidic peat over time. Tropical PSF is a relatively rare ecosystem found in large areas of Southeast Asia where it is vital not only for biodiversity but also for mitigating floods and droughts. As the organic material accumulates over time, it retains even more water through capillary action, up to 13 times its weight. Peat swamps eventually form a dome of wet organic material that can rise above the surrounding flood levels, acting as a giant sponge that holds in moisture [1, 2]. Peat swamp forests possess characteristics that no other type of forest possesses. Waterlogged conditions, high acidity and organic matter levels, low nutrient input, and a lack of soil or firm ground within peat swamp forests have resulted in diverse forest structures. Although this habitat has lower biodiversity than neighboring mineral soil forests, unique and endangered species live and rely on peat forests throughout the year [3]. In Sarawak and Brunei's PSF, zoning is perhaps the most prominent feature [4]. [1] and [5] identified six concentrically



zoned phasic communities in these PSFs using the topographic/edaphic factors and successional stages to classify the plants.

The exploitation of peat swamp forests started in the 1950s when industrial-scale logging of the typical peat swamp species *ramin* (*Gonystylus bancanus*) commenced. This has resulted in a dramatic loss of PSF and associated population decline of *ramin* and other PSF timber species across its geographic range [6, 7]. *Ramin* has been observed to flower sporadically and regenerate poorly in both natural forests and logged-over forests [8-10]. Global concerns on the status of natural *ramin* populations have led to the listing of *ramin* on Appendix II of the Convention on International Trade of Endangered Species of wild flora and fauna (CITES) in 2005. A recent IUCN Red List assessment stated a 90% reduction of *ramin* timber stock in Indonesia between 1991 and 2000. It is thought that around 11% of intact PSF present in five Indonesian provinces in 1983 remain [7]. Therefore, the species is listed as 'critically endangered'.

While PSF has long been considered an impediment to economic growth and development, peat swamp forests in Southeast Asia are now being cleared, drained, and burned to make way for plantations, constructions, and other developments. Invasions of pristine peat swamp forests by humans have a significant negative impact on the natural ecosystem. The deep peat layers that accumulated over the years store immense amounts of carbon released into the atmosphere if peatlands are drained, cleared, and burned [11-13]. As of today, tropical peat swamp ecosystems are in various states of degradation [14, 15], and emphasis will have to be placed on restoration in order to conserve this unique habitat.

In this article, we used historical plot data measured in the 1950s and recently collected data to (i) describe the ecology, distribution, and exploitation history, as well as the historical distribution as measured by Anderson in the 1950s, (ii) analyze the population structure of three dominant PSF species: *G. bancanus* (*ramin*), *Dactylocladus stenostachys* (*jongkong*) and *Shorea albida* (*Alan batu*), and (iii) compare this with the current stand structure and the population structure of the three selected species in recently monitored, disturbed plots. We restrict our review to the biogeographical region of Southeast Asia. We aim to galvanize research and emphasize the urgent need for management and restoration, emphasizing the silvicultural aspects of the three species.

2. Materials and Method

Anderson conducted one of the first comprehensive inventories of peat swamp forest in Southeast Asia between 1954 and 1961 in Sarawak and Brunei, prior to commercial exploitation [1]. The historical data collected by Anderson were analyzed prior to data recently collected at Maludam National Park in 2020 and the Everherald concession area near Betong in 2010 (see Figure 1). The forest in both Maludam NP and Ever Herald are logged-over PSF located in Sarawak, Malaysia, and have peat depths ranging between 2-10 m.

2.1. Anderson's surveys

Anderson started his ecological surveys of the peat swamp forests of Sarawak and Brunei in 1954. Measurements sites were selected using aerial photographs, after which transects were established from the perimeter of peat domes into the center. A half-acre (2000 m²) plots were established along these transects at half-mile (800 m) intervals. In total, 53 plots were measured, covering 10.6 ha at 5 locations in Sarawak and one in Brunei [5].

Measurements were taken using the imperial system, and therefore, we converted all measurements to metric values. Anderson used girth classes (inch) which do not relate to regularly used 10 cm diameter of breast height (DBH) classes. Therefore, we grouped Anderson's girth classes into 10 cm DBH classes to equate to the recent data for convenience purposes. The methodology used is comparable to that used in [16, 17].

2.2. Data from Maludam National Park

The Maludam peninsula is the largest single peat-dome covered by peat swamp forest remaining in Sarawak and Brunei, with peat depth ranging between 0-12 m [18]. The Maludam National Park of Sarawak was established in 2000 within the Maludam peninsula and covers some 40,000 ha. However,

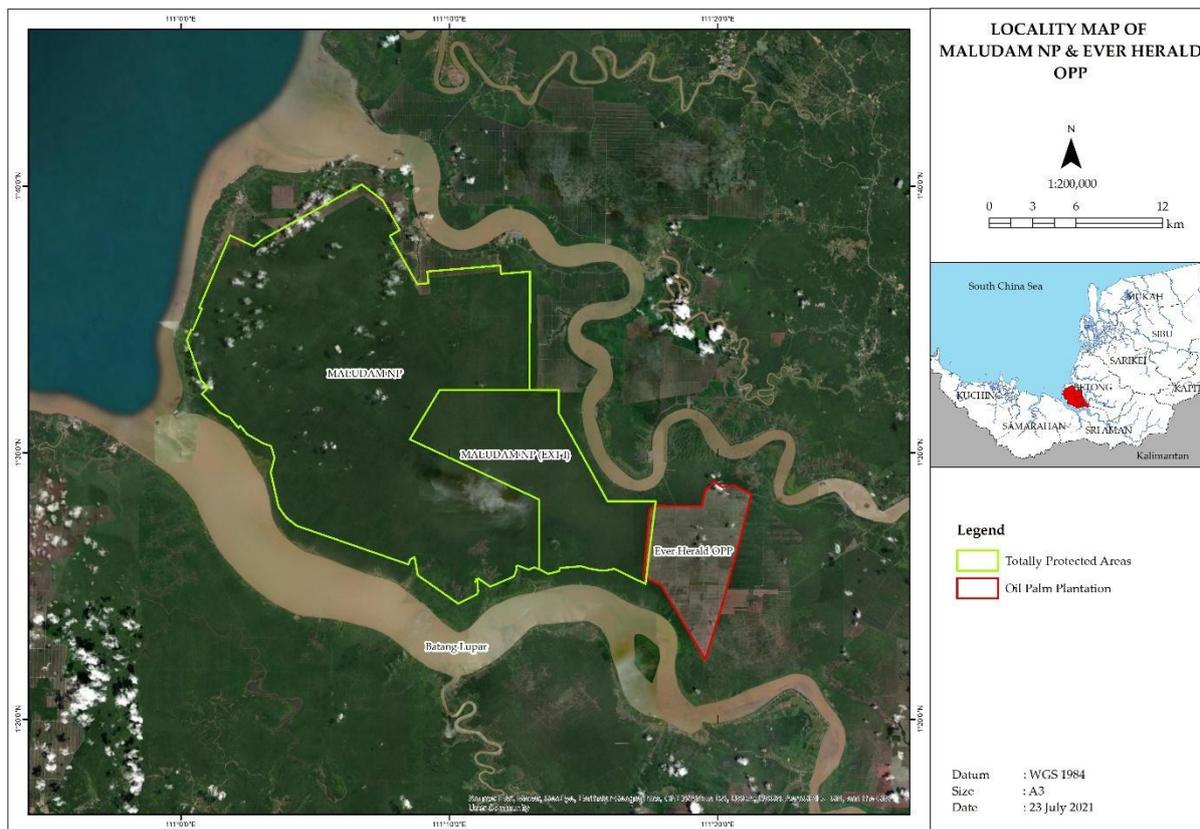
the forest inside Maludam National Park was extensively logged until 1999 and, as a result, is a severely disturbed forest.

In 2020, five plots were established north of Maludam NP as part of a larger forest survey. The main plot (A) covers 20 by 50 meters (1000 m²) and contains four sub-plots for measuring various diameter classes as indicated below:

- Main plot trees (A) : 20x50 m Trees with DBH ≥ 30 cm
- Subplot trees (B) : 2x 10x20 m Trees with DBH ≥ 10 cm and < 30 cm
- Saplings (C) : 2x 5x5 m Trees with DBH ≥ 2 cm and < 10 cm

2.3 Data from Ever Herald (Betong)

In 2010, two 50 x 50 m (2500 m²) plots were established within the Ever Herald concession area near Betong in the southeast of the Maludam peninsula. Both plots were located in *Shorea albida*-dominated forest types with peat depth ranging between 7-10 m. The forest was logged over from the 1970s into the late 1990s. All stems ≥ 5 cm DBH were recorded in the plots, and nested subplots were used to measure regeneration. Here we are using data for all stems ≥ 10 cm DBH in order to compare with Anderson's data.



Source: Forest Department Sarawak & Sarawak Forestry Corporation

Figure 1. Location of Maludam National Park and Everherald concession area in Sarawak, Malaysia.

3. Results and Discussion

Based on Anderson's data, we first describe the phasic communities and the diameter distribution of primary peat swamp forest and the three studied species. We then discuss the distribution as found in the Maludam and Ever Herald plots, and we compare this with Anderson's data.

3.1. Phasic communities

Anderson (1961) uses the term 'phasic community' (PC) to classify the peat swamp forest types of Sarawak and Brunei. A PC can be described as a stage in the development of coastal peat domes. Peat formation is thought to have started about 6000 years BP when global sea levels stabilized. Sediment deposited in tidal mangrove forests in river deltas caused a progression of mangroves towards the sea. In the older inland mangroves, tidal influence faded, and peat formation started to take place. With the peat layer thickening, conditions became ombrotrophic. New peat formation on the edges continued and caused the peat structure to be dome-shaped with the phasic communities lying in rings around the center; hence these are called peat domes [19-21]. In Table 1, an overview of the phasic communities is given, including relation with peat depth; it should be noted, however, that this is a rough estimate, and there is a high variation in peat depth amongst each PC [22, 23]

Table 1. Overview of Anderson's phasic communities (PC) of concentric forest associations within coastal basin peat swamp of Borneo. Peat depth range after [22, 23].

Phasic community	No. of species	Stems ha ⁻¹	Canopy height (m)	Peat Depth (main range, in m)	Description
PC1 - <i>Gonystylus-Dactylocladus-Neoscortechina</i> Association (Mixed swamp forest)	129	630	30-43	0-5 (but also found at > 10 m)	Found at peat swamp margins, structure and physiognomy are similar to lowland dipterocarp evergreen rain forest on mineral soils; uneven canopy with dominants reaching 40-45 m; 120-150 tree species ha ⁻¹ ; epiphytes and climbers abundant; <i>Shorea albida</i> is not present
PC2 – <i>Shorea albida-Gonystylus-Stemonurus</i> Association (Alan Batu forest)	136	642	30-46	5-8	Similar to PC1, but with large (>3.5 m girth) trees of <i>Shorea albida (alan)</i> scattered throughout; <i>Stenomurus umbellatus</i> indicator species
PC3 – <i>Shorea albida</i> Consociation (Alan Bunga forest)	41	506	46-58	8-10	Even upper canopy between 50-60 m in height; dominated by <i>Shorea albida</i> with 70-100 trees ha ⁻¹ ; middle storey commonly absent; moderately dense understory; <i>Pandanus andersonii</i> forms dense thickets in the shrub layer; climbers and epiphytes are uncommon
PC4 – <i>Shorea albida-Litsea-Parastemon</i> Association (Padang Alan forest)	45	711	30-37	10-12	Dense, even canopy at 30-40 m; composed of relatively small (<1.8 m DBH), pole-like trees with a xerophytic appearance; <i>Shorea albida</i> density > 400 trees ha ⁻¹ ; indicator species include small prostrate shrubs (<i>Euthemis minor</i> and <i>Ficus deltoiea</i> var. <i>motleyana</i>); herbs, ferns, epiphytes, and climbers are rare or absent
PC5 – <i>Tristania-Parastemon-Palaquium</i> Association	19	1280	15-22	12-14	Typically found in peat swamps' central dome; narrow transitional fore; the layer between PC4 and PC6 is rare; dense, even, closed canopy at 15-20 m with a high density (850-1,250 stems ha ⁻¹) of small-sized trees
PC6 – <i>Combretocarpus-Dactylocladus</i> Association (Padang Paya forest)	6	-	2-12	>14	Found in peat swamps' central dome; resembles open savannah woodland with stunted, xeromorphic trees; patchy shrub layer present; pitcher plants (<i>Nepenthes</i> spp.) and epiphytes; ant-plants (<i>Myrmecodia tuberosa</i> and <i>Lecanopteris sinuosa</i>) serve as indicator species

Remarks: this includes only trees ≥9.7 cm DBH (12 inches girth). Source: [1].

3.2. General forest structure as measured by Anderson

The first two phasic communities (PC1 and PC2) have a structure comparable to dryland tropical forests, but PC2 has a distinctive high density of giant *Shorea albida* trees (>100 cm DBH). PC3 and PC4 are *S. albida*-dominated forest types and show a DBH distribution that is quite atypical compared to other tropical forest formations (Figure 2). A large part of the population is distributed in the 30-70 cm range (PC3) and the 20-50 cm range (PC4), with comparatively few trees in the 10-20 cm class. The forest in PC5 has almost no trees >50 cm, and 85% of the population is in the 10-20 cm DBH class.

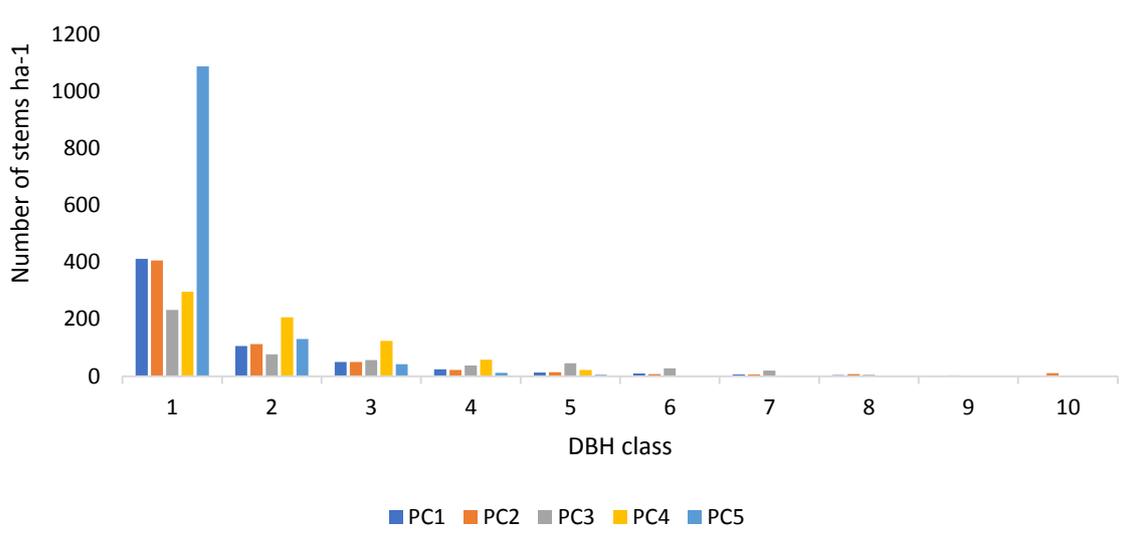


Figure 2. Diameter frequency distribution of all trees in 5 Phasic Communities (PC) as observed by Anderson in undisturbed, pristine PSF.

3.3. *Ramin* (*Gonystylus bancanus*)

Ramin is a tree species in the Thymelaeaceae family, growing in peat swamp forests in Southeast Asia. *Ramin* is a medium to large tree with recorded maxima of 45 m in height and 120 cm in diameter at breast height (DBH) [6, 24]. It has been described as a slow-growing species that prefers partial shade to regenerate [25, 26] and is often a dominant canopy species in primary forests [27, 28]. *Ramin* naturally occurs in high densities on the perimeter of peat domes [1], [29], with up to 20 large individuals (>50 cm DBH) per hectare. In several locations, *ramin* has been observed to be the single dominant tree species, with more than half of the total number of large trees in the peat swamp forest of Kalimantan [6].

It is evident that *ramin* attains its greatest size in PC 1, as this is the only community that has trees ≥ 70 cm DBH (Figure 3). *Ramin* is well distributed in PC 1 but robust in the 40-90 cm size classes. In PC 2, *ramin* does not reach the same size as in PC 1 but is nonetheless fairly common in the mid-size classes (30-60 cm). The species attains its most robust presence in PC 3, in which it is very common in the 10-40 cm size classes. The distribution of *ramin* in PC 4 is similar to that of PC 3, but it is less common. *Ramin* is only present as a small tree (10-30 cm) in PC 5 and absent in PC6.

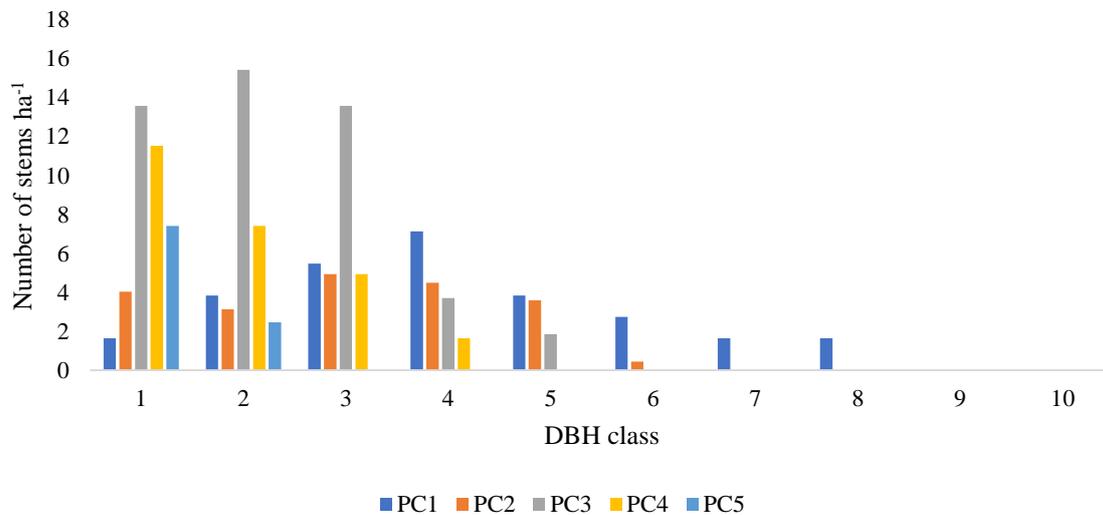


Figure 3. Diameter frequency distribution of *ramin* (*G. bancanus*) in 5 Phasic Communities (PC) as observed by Anderson in undisturbed, pristine PSF.

3.4. Jongkong (*Dactylocladus stenostachys*)

Jongkong is the only species in the monotypic genus *Dactylocladus*, in the family Crypteroniaceae. The species is endemic to Borneo and occurs in peat swamps and occasionally in *kerangas* [30, 31]. In Sarawak, *jongkong* was formerly one of the principal timber species from peat swamp forest. *Jongkong* is a light-demanding species that regenerates in canopy gaps if enough seed trees are present [32]. *Jongkong* is a canopy species in mixed swamp forest, often alongside *G. bancanus* (*ramin*), *Copaifera palustris* (Sepetir) and several *Shorea* spp. [5, 6]. In this forest type, *jongkong* reaches 40 meters in height and 150 cm in DBH [30, 33]. It becomes very common towards the center of peat domes and can be the dominant species, although size is significantly reduced. Here, *jongkong* rarely exceeds 20 cm DBH and/or 12 m in height [1, 32].

Jongkong is the only species that were recorded in all phasic communities (Figure 4). It is, however, noted that *jongkong* has an irregular distribution in mixed swamp forests and is not always a common species [34]. In Sebangau national park in Central Kalimantan, [11] describe a similar peat dome gradient as Anderson did for Sarawak. *Jongkong* was found to be common in mixed swamp forests, low pole forests and very low canopy forests. It was also commonly recorded in tall interior forests, a forest type that cannot directly be explained by peat dome zonation.

In PC 1, *jongkong* occurs as a canopy species but is not common in the lower storeys. In PC 2, it is common in the canopy alongside *Shorea albida*, but also occurs frequently in the middle storey. The canopies of PC 3 and 4 are completely dominated by *S. albida*, and here *jongkong* occurs only in the middle- and understorey. In PC 5 it is the most common species in the pole stage (mainly in the 10-20 cm DBH class), but no trees of >30 cm DBH are recorded. In the final phasic community 6, *jongkong* is very abundant (although *Combretocarpus rotundatus* is dominant) but only occurs as a very much stunted shrub, rarely exceeding 5 meters in height. It is evident that *jongkong* progressively decreases in size, starting in PC 2 and eventually reducing to a small shrub in PC 6.

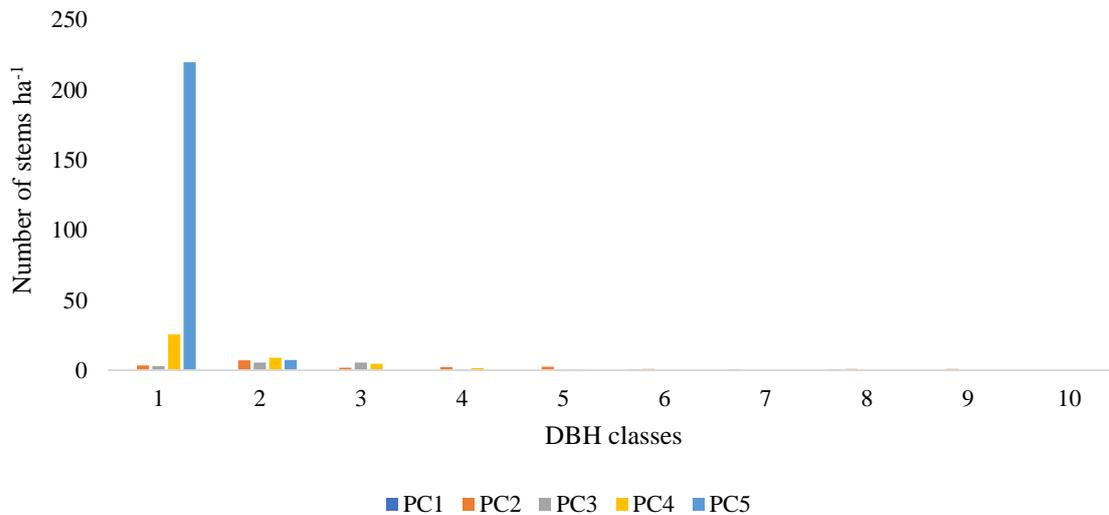


Figure 4. Diameter frequency distribution of *jongkong* (*D. stenostachys*) in 5 Phasic Communities (PC) as observed by Anderson in undisturbed, pristine PSF.

3.5. *Alan* (*Shorea albida*)

Alan is a dipterocarp tree species endemic to north-western Borneo. It occurs in peat swamp forests and occasionally in kerangas. In Sarawak and Brunei peat swamp forests, *Alan* is a very common species, extending into West Kalimantan [6, 35]. The species is apparently absent from (north) eastern and southern Borneo. *Alan* is a canopy and emergent species in several peat swamp phasic communities. Although rare in mixed swamp forests (PC1), it is widespread in all other phasic communities except PC6. *Alan* forms uniform stands and completely dominates the canopy in PC3 and PC4 [1].

Alan can grow to over 70 m in height and 200 cm in DBH, often with large buttresses [6]. Although the trees grow very large and tall, they are often hollow and have broken crowns that regrow after damage [36]. In the interior of peat domes, the species has a strongly reduced size and often has a pole-like appearance. In a primary forest, climatic damage is the main successional process, with windfall and lightning strikes frequently occurring in pure *alan* stands [37, 38]. Also, insect damage was observed to cause widespread death of pure *alan* stands [39].

The timber of *alan* is highly variable in density and is described as both a medium and a light hardwood [33]. The species were logged in Sarawak, although it was not as important as *ramin*. *Alan* timber is usually traded as dark red or light red meranti, and its timber is thus mixed with other *Shorea* spp. [6]. Due to logging and large-scale PSF conversion, the *alan* population has been significantly reduced. It is currently listed as 'vulnerable' on the IUCN red list [40].

The dominance of *alan* in phasic communities 3 and 4 can clearly be identified when looking at its size class distribution (Figure 5). *Alan* was recorded in PC1 but is uncommon. PC2 is the principal dominant in the canopy and is mainly found as a large tree (>70 cm DBH), but the species does occur in all size classes. In PC3, *alan* is very common and has a near-normal distribution. Large trees are still present, but the bulk of the population is in the 40-80 cm size classes. The average tree size is much smaller in PC4, where *alan* is again very common. Here the population is concentrated in the 20-50 cm size classes. In PC5, most of the *alan* population can be found in the lower (10-30 cm) size classes, and the species is no longer dominant but still fairly common. *Alan* is absent from PC6.

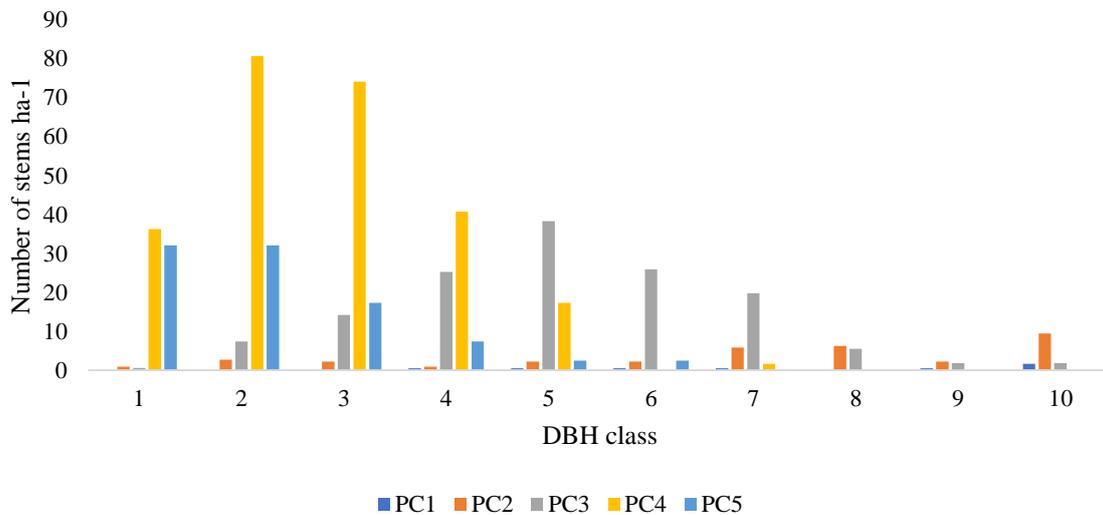


Figure 5. Diameter frequency distribution of *alan* (*S. albida*) in 5 Phasic Communities (PC) as observed by Anderson in undisturbed, pristine PSF.

3.6. Maludam NP data

The data collected in Maludam NP in 2020 was from 5 plots located in PC 1. Comparing the diameter frequency distribution of all trees observed in PC 1 with data based on the historical records of Anderson shows a highly disturbed diameter distribution, with almost no large trees (Figure 6). Only one tree ≥ 50 cm was found (*D. stenostachys*). *Ilex cymosa* is the most common species and is dominant in the 10-20 cm DBH class. The forest appears to be in a state of regeneration.

Further analysis of the three species showed that *alan* is not present in the Maludam plots, which might not be surprising because the plots were established in PC1. *G. bancanus* (in 40-50 cm DBH class) and *D. stenostachys* (in 50-60 cm DBH class) were both recorded only once as mature trees. No regeneration of the three species was found. Overall species diversity was low for mixed swamp forests, with only 27 species recorded (including regeneration) in the five plots. This is very low in comparison to the 129 species in PC1 observed by Anderson.

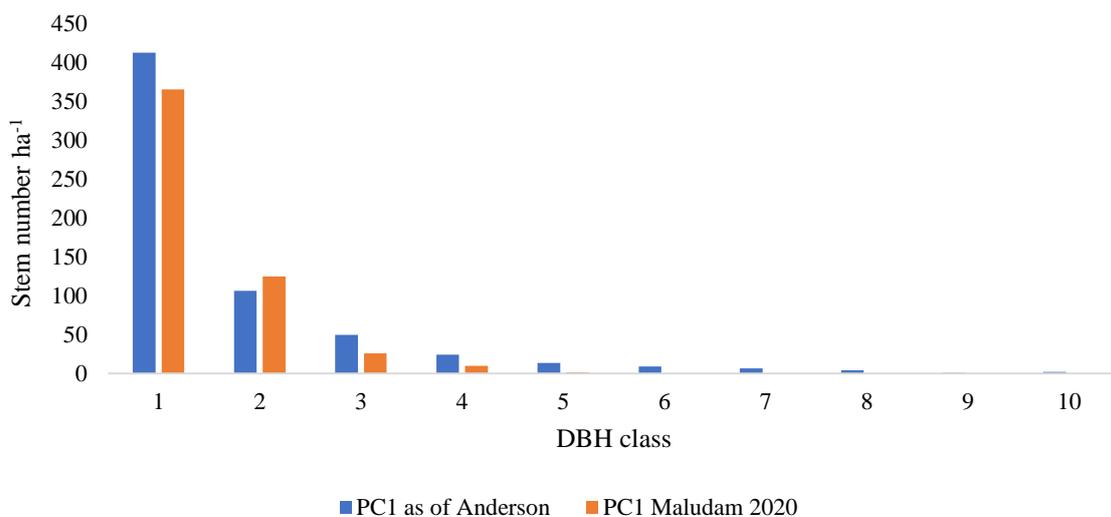


Figure 6. Diameter frequency distribution of all trees observed in PC 1 in Anderson's plots (blue) and the Maludam 2020 plots (orange).

3.7. Ever Herald data

Significant differences can be noted when comparing the DBH distribution of the PC3 *Alan Bunga* forest in the Ever Herald concession with Anderson's data. Tree abundance in the 10-20 cm DBH class is nearly twice as high in the Ever Herald plots, whereas all other DBH classes have a much lower stocking compared to Anderson's data. The same pattern can be seen in the *Padang Alan* (PC4) forest, but more extreme. Both forest types are strongly disturbed and have lost nearly all large trees. Although densities in the 10-20 cm DBH class are very high, both plots are in a regenerative state.

Compared to the recently measured Maludam plots, regeneration appears to have been successful. *S. albida* and *D. stenostachys* have a high stem number in both PC's (Table 2). The successful regeneration of *S. albida* is an interesting fact, as the regeneration of the species can be problematic [1, 10, 39]. *G. bancanus* is absent from PC3 and rare in PC4, and stem numbers are far below average. See [appendix 1](#) for an overview of stem numbers per DBH class.

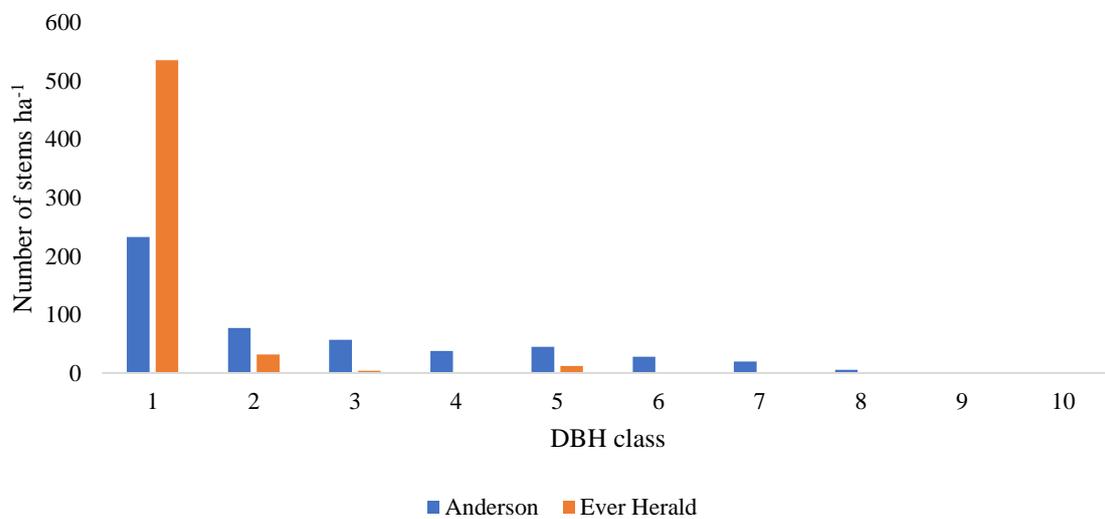


Figure 7. Diameter frequency distribution of all trees observed in PC3 in Anderson's plots (blue) and 2010 Ever Herald plots (orange).

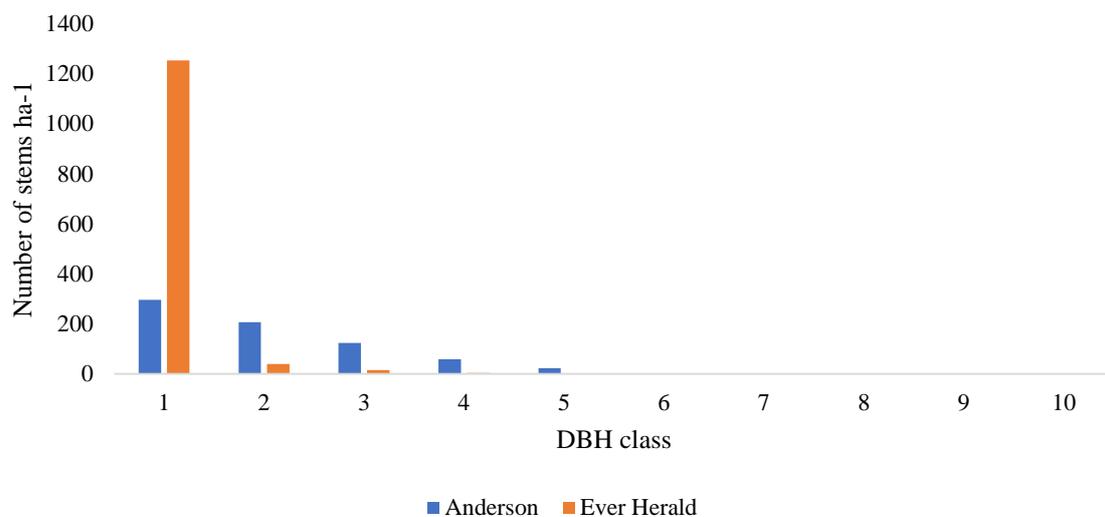


Figure 8. Diameter frequency distribution of all trees observed in PC4 in Anderson's plots (blue) and 2010 Ever Herald plots (orange).

Table 2. Comparison of stem number ha⁻¹ between Andersons’ data and the Ever Herald plot data for PC3 and PC4.

Species	PC3		PC4	
	Anderson	Ever Herald	Anderson	Ever Herald
All species	506.0	584	711.0	1312
<i>D. stenostachys</i>	15.4	68	41.6	52
<i>G. bancanus</i>	48.2	0	25.5	4
<i>S. albida</i>	140.8	188	250.7	876

3.8. Discussion

According to Anderson (1963) [5], Sarawak's pristine natural PSF was rich in plant diversity, including several endemic species from six distinct communities. He identified 1528 dicotyledons, 106 monocotyledons, six gymnosperms, and 66 pteridophyte species that inhabit PSF. The forest has long been recognized as critical habitat for several of Borneo's endemic plants, including *Copaifera palustris*, *D. stenostachys (jongkong)*, *Dryobalanops rappa*, *S. albida (alan)*, *Shorea inaequilateris*, and *Shorea uliginosa* [41]. These are large timber trees that contribute significantly to the PSF's structure and biomass. A little study was conducted on *S. albida* and *D. stenostachys*, but *ramin* has conceived quite some interest. Below we discuss the three species in relation to their rehabilitation.

3.8.1. *Ramin*. *G. bancanus (ramin)* is a highly prized tropical timber found exclusively in this type of forest. Its population was once dominant in its natural habitat but has since dwindled significantly. Additionally, this species has been reported to have a low rate of regeneration [42]. This has led to *ramin's* listing in CITES' appendix II.

Drainage infrastructure poses a significant obstacle for the restoration of degraded peatlands and *ramin* in particular. Strong growth of *ramin* has been noted on sites with high water tables and/or high soil moisture content. This is likely because fast-growing competitors cannot establish under such circumstances [25, 26, 43].

Partial shade has been noted to favor growth [25, 26]. This suggests that *ramin* is most suitable for enrichment plantings in existing, logged-over forests since light conditions are generally favorable. In clear-cut areas, *ramin* will likely not thrive, and other species are needed to achieve forest cover. Trials with line-planting methods yielded high survival percentages (70-80%), whereas plantings in open areas gave much lower survival rates (20-40%) [44]. Thus, line-planting can be seen as a promising method of *ramin* restoration in degraded peatland. There has been much interest in *ramin* as a reforestation species, but large-scale plantings have not yet been implemented. For now, the species remains highly endangered.

3.8.2. *Jongkong*. In Sarawak, *jongkong* was a major timber species [32], and as one of the 'desirable' MSF species, silvicultural treatment was applied to favor this species [45]. Elimination of competing vegetation was found to affect *jongkong* growth positively [10, 46].

Currently, *D. stenostachys* is not used for peatland restoration. However, its pioneer characteristics could become an important reforestation species throughout its native range. *Jongkong* has properties that potentially make it an interesting species: regeneration occurs under high light circumstances, is fast-growth when young, can compete with other pioneers, is tolerant of high acidity and high water tables, and has high-value timber. In contrast to later successional species like *ramin*, *jongkong* could be planted on highly degraded sites, both in shallow and deep peat areas. Furthermore, the species can be used to establish tree cover in open sites, which then can be enriched with later successional shade-bearing species. However, further research and planting trials are essential to understand the reforestation potential of *D. stenostachys* fully.

3.8.3. *Alan*. Most *alan batu*, *alan bunga* and *padang alan* forests have been cleared for agricultural plantations. The largest extent of intact *alan* forest can now be found in Brunei [47], in protected areas

of Sarawak (including Loagan Bunut NP) [48], and possibly in West Kalimantan. Large areas of strongly disturbed *alan* forest are present in Sarawak (e.g., on the Maludam peninsula) and could be a target for rehabilitation measures. However, it must be considered that *alan*-dominated forest types (PC2-4) naturally covered a much smaller extend (17% of Sarawak PSF) than mixed swamp forest (80% of Sarawak PSF) [1, 10], so *alan* planting can only be justified on specific sites.

Alan appears to regenerate with mixed results. [1] observed a general low sapling abundance but high seedling densities in mast years. However, these seedlings did not progress into the sapling or tree stage because light conditions were not sufficient. Only in canopy gaps created by windfall or lightning damage did *alan* regeneration progress and was often successful and fast-growing [1, 37]. [10] reported that, after logging, *alan* regeneration was often outcompeted by many other species, including *jongkong* in PC2. Even in logged-over pure *alan bunga* stands in PC3, *alan* regeneration was not always successful and was outcompeted by other species [10]. The Ever Herald plots seem to have had very successful *alan* regeneration, showing that producing a new generation is possible. *Alan* line planting has been suggested as a rehabilitation option, but this needs more research [49].

3.8.4. Prospects for restoration of degraded PSF. Enrichment planting of *ramin*, *alan* and *jongkong* can be undertaken in areas where more intensive logging has taken place, parent trees are scarce, and canopy cover has been reduced. For each of these species, we recommend the following:

- *Ramin* (*G. bancanus*) regeneration is problematic, and mature trees are absent from many PSF ecosystems. Enrichment plantings could be used to restore *ramin* densities. However, caution must be exercised when planting *ramin*, as it requires partial shade and is not an 'easy' species. Due to *ramin*'s slow growth rate, it will take a long time to reach natural densities. Therefore, it is critical to tailor restoration goals to the needs of phasic communities and local conditions.
- *Jongkong* (*D. stenostachys*) has disappeared mainly because of logging and forest clearance. However, the light-requiring species can successfully regenerate in logged-over forests and canopy gaps, provided sufficient mature seed trees are present. In contrast to *ramin* and *alan*, the species has not been listed on the IUCN Red List, even though *jongkong* has also experienced dramatic population decline. *Jongkong* may be an interesting planting option in cleared peat swamps, as the species is tolerant of full light conditions, provided the water table has been restored. It is therefore strongly recommended to start trial plantings using *jongkong*.
- *Alan* (*S. albida*) has a more restricted natural distribution than *ramin* and *jongkong*, but it was/is an invaluable species within its natural range. While natural regeneration may be sufficient in some locations, the species has been known to be outcompeted by species with a faster growth rate. *Alan* is an intriguing species for enrichment planting because pure stands may be ecologically justified when planted in the appropriate phasic community (PC3 or PC4).

4. Conclusions

PSF rehabilitation measures must be based on the original composition of the vegetation. Natural regeneration may be possible in areas where mother trees remain and hydrological conditions remain relatively stable. However, human intervention is required when the disturbance is severe, and seedlings and seed sources are scarce or absent. Light to moderately heavy degraded PSF is best restored using local successional species from the original Phasic Community. For example, *Jongkong* is suitable as pioneer species in open areas in a wide range of PC's (PC 1-5), whereas *ramin* is best planted in PC 1 and 2 under a bit more shade. *Alan* is very suitable as successional species in PC 2-4 but may need some protection from competitors in order to establish successfully.

It is critical to monitor all rehabilitation efforts in order to maximize their potential and learn from their mistakes. Rehabilitation has shown great promise thus far, and it is expected that restoring hydrological conditions and establishing a dense forest canopy will restore ecosystem function on mildly degraded sites. The degree of disturbance (particularly hydrological disturbance), the depth of peat, seed availability, seed and seedling predation, and competition with other plant species all limit tree regeneration.

We believe that conserving the remaining natural peat swamp forest is critical due to its unique habitat types, biodiversity, and ecological characteristics. Rehabilitation of degraded secondary forest requires enhanced management effectiveness and a halt to further forest conversion and disturbance. While natural regeneration is critical for re-establishing the original peat swamp forest vegetation and biodiversity, human-assisted regeneration is also frequently required.

References

- [1] Anderson J A R 1961 The Ecology and Forest Types of the Peat Swamp Forests of Sarawak and Brunei in relation to their Silviculture
- [2] Phillips V D 1998 Peatswamp ecology and sustainable development in Borneo *Biodivers. Conserv.* **7(5)** 651-71
- [3] Page S E, Rieley J O, Shotykh O W and Weiss D 1999 Interdependence of peat and vegetation in a tropical peat swamp forest *Philos. Trans. R. Soc. B Biol. Sci.* **354(1391)** 1885-87
- [4] Whitmore T C 1984 Tropical Rainforests of the Far East. 2nd edition Oxford Oxford University Press
- [5] Anderson J A R 1963 The Flora of the Peat Swamp Forest of Sarawak and Brunei, including a catalogue of all recorded species of flowering plants, ferns, and fern allies *Singapore Gardens Bulletin* **20** 131-228
- [6] Soerianegara I and Lemmens R H M J 1993 Plant Resources of South-East Asia No 5: Timber trees: Major commercial timbers Wageningen Pudoc Scientific Publishers
- [7] Barstow M 2018 *Gonystylus bancanus*. The IUCN Red List of Threatened Species
- [8] Ismail P, Nizam M S, Latiff A, Hanum I F and Shamsudin I 2011 Phenology of *Gonystylus bancanus* in pahang, peninsular Malaysia *J. Trop. For. Sci.* **23(2)** 143-51
- [9] Shamsudin I 1996 *Gonystylus bancanus*: some observations on its flowering, fruiting, seed predation and germination *J. Trop. For. Sci.* **8(3)** 424-26
- [10] Lee H S 1979 Natural regeneration and reforestation in the peat swamp forests of Sarawak *Tropical Agricultural Research Centre* **12** 51-60
- [11] Page S, Rieley J O and Banks C J 2011 Global and regional importance of the tropical peatland carbon pool *Glob. Chang. Biol.* **17(2)** 798-818
- [12] Page S and Hoscilo A 2016 Fire in Borneo Peatlands The Wetland Book Springer Science+Business Media
- [13] Couwenberg J, Dommain R and Joosten H 2010 Greenhouse gas fluxes from tropical peatlands in south-east Asia *Glob. Chang. Biol.* **16(6)** 1715-32
- [14] Yule C M 2010 Loss of biodiversity and ecosystem functioning in Indo-Malayan peat swamp forests *Biodivers. Conserv.* **19(2)** 393-409
- [15] Page S, Hoscilo A, Wösten H, Jauhiainen J, Silvius M, Rieley J, Ritzema H, Tansey K, Graham L, Vasander H and Limin S 2009 Restoration ecology of lowland tropical peatlands in Southeast Asia: Current knowledge and future research directions *Ecosystems* **12(6)** 888-905
- [16] van der Meer P J and Verwer C C 2011 Towards a reference carbon value for peat swamp forest in Southeast Asia based on historical inventory data In *Workshop on tropical wetland ecosystems of Indonesia: science needs to address climate change adaptation and mitigation – Bali, April 11-14 2011*
- [17] Verwer C and van der Meer P 2010 Carbon pools in tropical peat forest: Towards a reference value for forest biomass carbon in relatively undisturbed peat swamp forests in Southeast Asia Wageningen UR
- [18] van der Meer P J, Demies M A, Shabudin M S, Verwer C, Beintema A, Hilligers P J M and Teo S P 2013 Tropical peat swamp forests of Sarawak. Sustainable Use and biodiversity conservation in a changing environment. Alterra, Wageningen UR, Netherlands
- [19] Dommain R, Cobb A R, Joosten H, Glaser P H, Chua A F L, Gandois L, Kai F, Noren A, Salim K A, Su'ut N S H and Harvey C F 2015 Forest dynamics and tip-up pools drive pulses of high

- carbon accumulation rates in a tropical peat dome in Borneo (Southeast Asia) *J. Geophys. Res. Biogeosciences* **120** 617-40
- [20] Esterle J S and Ferm J C 1994 Spatial variability in modern tropical peat deposits from Sarawak, Malaysia and Sumatra, Indonesia: analogues for coal *Int. J. Coal Geol.* **26** 1-41
- [21] Morley R J 2013 Cenozoic ecological history of South East Asian peat mires based on the comparison of coals with present day and late quaternary peats *J. Limnol.* **72(2)** 36-59
- [22] Anderson J A R 1984 The tropical peat swamps of western Malesia. *Ecosystems of the world - Mires: Swamp, Bog, Fenn and Moor* **4b** 181-199
- [23] Melling L 2017 Chapter 4 Peatlands in Malaysia. *Tropical Peatland Ecosystems* 59-73
- [24] Kartiko H D P 2002 *Gonystylus bancanus* Seed Leaflet **58**
- [25] Lee D W, Krishnapillay B, Haris M, Marzalina M and Yap S K 1996 Seedling development of *Gonystylus bancanus* (ramin melawis) in response to light intensity and spectral quality *J. Trop. For. Sci.* **8(4)** 520-31
- [26] Jans W W P, Dibor L, Verwer C, Kruijt B, Tan S and van der Meer P J 2012 Effects of light and soil flooding on the growth and photosynthesis of ramin (*Gonystylus bancanus*) seedlings in Malaysia *J. Trop. For. Sci.* **24(1)** 54-63
- [27] Khali Aziz H, Ismail P, Ani S, Mohd Azahari F, Yong H and Ihsan S K 2010 *Gonystylus bancanus* jewel of the peat swamp forest Forest Research Institute Malaysia. Sungai Buloh, Selangor: Gemilang Press
- [28] Chua L S 2008 Ramin (*Gonystylus bancanus*) in Malaysia *NDF Workshop Case Studies WG 1 – Trees, Case Study* **1** 1-21
- [29] Pribadi D O and Kusuma Y W C 2015 Microhabitat influence on growth distribution pattern of ramin (*Gonystylus bancanus*) in Siak, Riau Province *Biotropia* **22(1)** 1-10
- [30] Soepadmo E, Wong K M and Saw L G (eds.) 1996 Tree Flora of Sabah and Sarawak Volume 2 Kuala Lumpur: Forest Research Institute Malaysia
- [31] Kartawinata K 1980 A note on Kerangas (heath) forest at Sebulu, East Kalimantan *Reinwardtia* **9(4)** 429-47
- [32] Sosef M S M, Hong L T and Prawirohatmodjo S (eds.) 1998 Plant Resources of South-East Asia No. 5 Timber trees: Lesser-known timbers PROSEA/ITTO Leiden Backhuys Publishers
- [33] Wong T M, Lim S C and Chung R C K 2002 A Dictionary of Malaysian Timbers 2nd edition *Malayan Forest Records No. 30* Kuala Lumpur Forest Research Institute Malaysia
- [34] Truong P 2004 Regeneration of Mixed Swamp Forest of Sarawak (Malaysia): Study Based on Six Typical Mixed Swamp Forest Species. *JWG Malaysia-The Netherlands Sustainable Management of Peat Swamp Forests of Sarawak with Special Reference to Ramin* JWG/RAM/05
- [35] Soepadmo E, Saw L G and Chung R C K (eds.) 2004 The Tree Flora of Sabah and Sarawak Volume 5 Kuala Lumpur: Forest Research Institute Malaysia
- [36] Monda Y, Kiyono Y, Chaddy A, Damian C and Melling L 2018 Association of growth and hollow stem development in *Shorea albida* trees in a tropical peat swamp forest in Sarawak, Malaysia *Trees* **32(5)** 1357-64
- [37] Anderson J A R 1964 Observations on climatic damage in peat swamp forest in Sarawak *Commonw. For. Rev.* **43(116)** 145-58
- [38] Brünig E F 1964 A study of damage attributed to lightning in two areas of *Shorea albida* forest in Sarawak *Commonw. For. Rev.* **43(116)** 134-44
- [39] Anderson J A R 1961 The destruction of *Shorea albida* forest by an unidentified insect *Emp. For. Rev.* **40(103)** 19-29
- [40] Randi A, Julia S, Ling C Y, Linsky J, Oldfield S and Tsen S 2019 *Shorea albida* The IUCN Red List of Threatened Species
- [41] Tawan C S 2006 Plant diversity and commercial timbers In: The Biodiversity of a Peat Swamp Forest in Sarawak 29-60 Kota Samarahan University Malaysia Sarawak Publication

- [42] Tawan C S and Ipor I B 2007 *Gonystylus bancanus* (Miq.) Kurz. (Ramin): A potential species for rehabilitation of the peat swamp forest in Sarawak *Proceedings of the Conference on Natural Resources in the Tropics: Development and Commercialization of the Tropical Natural Resources* 391-394
- [43] van der Meer P J, Tan S, Chai F Y C and Dibor L 2004 Ramin (*Gonystylus bancanus*) regeneration and growth in Sarawak's peat swamp forests *JWG Malaysia-The Netherlands Sustainable Management of Peat Swamp Forests of Sarawak with Special Reference to Ramin* JWG/RAM/15
- [44] Ismail P, Khali Aziz H and Grippin A 2007 Restoring the wetland ecosystem: experience in peat swamp forest restoration trials in Peninsular Malaysia *Conference on Forestry & Forest Products Research* 233-42
- [45] Chai F Y C 1991 Diameter increment models for the mixed swamp forests of Serawak Master Thesis, University of British Columbia
- [46] Sia P C 2004 Growth and yield of logged-over peat swamp forests of Sarawak *JWG Malaysia-The Netherlands Sustainable Management of Peat Swamp Forests of Sarawak with Special Reference to Ramin* JWG/RAM/14
- [47] Nor Zamzam H 2016 Modelling and Communicating the Ecological Characteristics of Peat Swamp Forest Communities in Brunei Master Thesis, University of Leicester
- [48] Tawan C S, Ipor I B and Wan Sulaiman W H 2008 Floral diversity of the peat swamp forests of Sarawak *Trop. Peatlands* 39-44
- [49] Kitaoka A, Uchimura I and Asaishi H 2000 Planting of *Shorea albida* Sym. on peat swamp land in Sarawak, Malaysia *Proceedings of the 8th International Workshop on Bio-technology Applications for Reforestation and Biodiversity Conservation* Kathmandu, Nepal

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Appendix

Table A1. Comparison forest structure Ever Herald-Anderson.

PC3 DBH class	<i>S. albida</i>		<i>D. stenostachys</i>		<i>G. bancanus</i>		All species	
	Ever Herald	Anderson	Ever Herald	Anderson	Ever Herald	Anderson	Ever Herald	Anderson
1	176	0.6	48	3.1	0	13.6	536	232.8
2	0	7.4	20	5.5	0	15.4	32	77.2
3	0	14.2	0	0.6	0	13.6	4	56.8
4	0	25.3	0	0.6	0	3.7	0	37.7
5	12	38.3	0	0.0	0	1.9	12	45.1
6	0	25.9	0	0.0	0	0.0	0	27.8
7	0	19.8	0	0.0	0	0.0	0	19.8
8	0	5.6	0	0.0	0	0.0	0	5.6
9	0	1.9	0	0.0	0	0.0	0	1.9
10	0	1.9	0	0.0	0	0.0	0	1.9
Total	188	140.8	68	9.8	0	48.2	584	506

PC4 DBH class	<i>S. albida</i>		<i>D. stenostachys</i>		<i>G. bancanus</i>		All species	
	Ever Herald	Anderson	Ever Herald	Anderson	Ever Herald	Anderson	Ever Herald	Anderson
1	836	36.2	36	25.5	4	11.5	1252	296.0
2	28	80.7	8	9.1	0	7.4	40	207.1
3	12	74.1	4	4.5	0	4.9	16	124.3
4	0	40.8	4	1.6	0	1.6	4	58.5
5	0	17.3	0	0.8	0	0.0	0	22.6
6	0	0.0	0	0.0	0	0.0	0	0.8
7	0	1.6	0	0.0	0	0.0	0	1.6
8	0	0.0	0	0.0	0	0.0	0	0.0
9	0	0.0	0	0.0	0	0.0	0	0.0
10	0	0.0	0	0.0	0	0.0	0	0.0
Total	876	250.7	52	41.5	4	25.5	1312	711