Peat swamp forest types and their regeneration in Giam Siak Kecil-Bukit Batu Biosphere Reserve, Riau, East Sumatra, Indonesia

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SUMMARY

Although the ecology of tropical peat swamp forests is only now becoming understood, they are already under severe threat of conversion and degradation. Based on studies of the peat swamp forest of the Giam Siak Kecil–Bukit Batu Biosphere Reserve carried out between 2009 and 2010, this paper discusses forest types and regeneration processes in terms of promoting biodiversity conservation and sustainable management of the remaining peat swamp forest. Permanent plots covering a total area of three hectares were established in natural and disturbed forest areas. Within these plots, 135 tree species belonging to 34 families were identified. Mixed peat swamp forest and bintangur forest, which have different dominant species, were identified as the main forest types. The greatest species richness was in logged-over forest, with 82 species and a density of 2,492 stems ha^{-1}. The success of regeneration varied between typical main species in the logged-over forest and in forest disturbed by wind and fire. All of the forest stands had high densities of trees with diameters at breast height (DBH) of 3–10 cm, which are a potential source of recruitment to ensure the sustained regeneration of the forest remaining in the Biosphere Reserve. Regeneration is very important for improving the condition of disturbed peat swamp forest areas in the reserve, but natural regeneration will not be sufficient to restore the forest vegetation and conserve the associated biodiversity. Some form of human-assisted accelerated regeneration will be needed, such as enrichment planting of typical canopy species that have problems with establishment. It is important for the remaining natural peat swamp forests to be conserved because of their unique forest-type formations which have distinct dominant species, floristic composition, diversity and local environment characteristics. Improved management of secondary forest must be achieved through rehabilitation, halted forest conversion, and reducing the impact of disturbance by wind and fire.

KEY WORDS: forest degradation; south-east Asia, trees; tropical peatland; vegetation regeneration

INTRODUCTION

Peat has accumulated in the coastal lowlands of south-east Asia and supports peat swamp forest vegetation dominated by trees (Furukawa 1994, Rieley & Ahmad-Shah 1996, Page *et al*. 1999, Page *et al*. 2006). Indonesia has the largest area of peat swamp forest in the tropics, covering an estimated 20.7 Mha (range 16–27 Mha) (Sorensen 1993, Rieley *et al*. 1996a, Rieley *et al.* 1996b, Page *et al*. 2011) and distributed mainly across Sumatra (4.7–9.7 Mha), Kalimantan (3.1–6.3 Mha) and Irian Jaya (8.9 Mha) (Silvius 1989, Rieley *et al*. 1996a). In Sumatra, 4.04 Mha of peatland is located in Riau Province within the Sumatran peat swamp forest ecoregion (WWF 2008).

Indonesian tropical peat swamp forest is a unique wetland ecosystem and an important natural resource with considerable environmental and economic value (Rieley & Page 1997). It is a major carbon sink, mitigating the effects of global warming (Sorensen 1993, Maltby 1997, Sugandhy 1997, Page & Rieley 1998, Rieley & Page 2005, Jaenicke *et al*. 2008). In its natural state, tropical peat swamp forest contributes to biodiversity; as well as to landscape functions including water storage and supply, coastal protection, erosion prevention and flood mitigation (Rieley & Page 2005). The ground vegetation is sparse, consisting mostly of saplings with some sedges and pandans (Rieley & Ahmad-Shah 1996). In terms of tree species, heights and girths, the vegetation of peat swamp forest is a changing continuum from periphery to centre, reflecting increasing waterlogging and decreasing mineral nutrient availability in the surface peat. Thus, there are numerous sub-types of peat swamp forest depending upon environmental factors and plant competition (Sieffermann *et al*. 1988, Rieley & Ahmad-Shah, 1996, Page *et al*. 1999, Page *et al*. 2006).

Six phasic communities have been described for the peatlands of Sarawak and Brunei (Anderson 1961, 1963, 1964, Kobayashi 1998), ranging from a structurally complex species-rich community around the edge of the peat dome to a species-poor 'padang' community on deep peat. The intermediate communities are dominated by the dipterocarp tree *Shorea albida*. This species is absent from the peat swamp forests of Central Kalimantan, where only five phasic communities have been described (Anderson 1976, Shepherd *et al*. 1997, Page *et al*. 1999). The peatlands of the Malay Peninsula and Sumatra appear to have only two main forest types, namely mixed peat swamp forest (MPSF) and pole forest (Anderson 1976, Morley 1981, Morley 2000).

Anderson (1976) listed some of the structural characteristics of the peat swamp forests of Sumatra and Kalimantan where, in moving from marginal MPSF to central padang forest, tree density increased from 722.5 to 1,012.5 ha^{-1}, mean basal area per tree decreased from approximately 0.05 to 0.03 m^2, and canopy height dropped from 20 m to 10 m. Although tree species diversity may be relatively low compared to lowland dipterocarp forest (Furukawa 1994), peat swamp forest still exhibits high biodiversity including many species of animals and plants whose survival is threatened (Giesen 2004). The trees *Dactylocladus stenostachys*, *Gonystylus bancanus*, *Horsfieldia crassifolia*, *Shorea balangeran* and *Shorea teysmanniana* are almost exclusive to peat swamp forest in south-east Asia (Rieley & Ahmad-Shah 1996, Page *et al*. 2006).

An investigation of the peat swamp forests along the east coast of Sumatra revealed distinct compositional differences between forests on deep and medium-depth peat (Brady 1997a, Rieley & Ahmad-Shah 1996). Trees that were common to all forest types included *Garcinia* spp., *Shorea* spp., *Palaquium* spp., *Campnosperma auriculatum*, and *Eugenia* spp. Common species in the "pole forests" that occur towards the centres of these peat swamps include *Eugenia* spp., *Calophyllum costulatum*, *Shorea* spp., *Pandanus atrocarpus* and other *Pandanus* species. In the rarely accessed central "low pole forest" on Padang Island, Riau, where the canopy height is only 10–18 m, the principal tree species are *Eugenia* spp. and *Tristania obovata*, with lesser numbers of *Calophyllum sundaicum* and *Pandanus atrocarpus*. In medium-height pole forest with a canopy of up to 25 m, *Calophyllum costulatum* and *C. sundaicum* are abundant. The tall pole forest contains abundant *Calophyllum costulatum*, *C. sundaicum* and *C. ferrugineum* with a maximum canopy height of 32 m and diameters at breast height (DBH) of 30–40 cm (Rieley & Ahmad-Shah 1996). Soewandono (1937, cited in Giesen 2004) noted that the central areas of the island of Bengkalis (Riau) were characterised by an abundance of *Eugenia* spp., *Tristania* spp., *Calophyllum* spp., *Tetramerista glabra*, *Campnosperma* spp. and *Shorea* spp. In the Kerumutan Wildlife Reserve (Sumatra), the dominant species changed along the interior river. Near the river, *Koompassia malaccensis* and *Durio lowianus* were dominant among the canopy trees; whereas towards the interior of the peat swamp forest, the dominant species was *Shorea teysmanniana*, followed by *Palaquium burckii* and *Swintonia glauca* (Momose & Shimamura 2002).

The Sumatran peat swamp forest ecosystem remains in five large blocks in Riau. One of them is Giam Siak Kecil-Bukit Batu, which was declared a biosphere reserve in 2009. The uniqueness of this biosphere reserve is that it is a vast landscape consisting of a hydrological network of small lakes and streams and peat swamp forest. The dominant natural ecosystems are peat swamp forests which are surrounded by land under different types of use such as production forests, degraded/abandoned lands, industrial plantations (timber and oil palm), agricultural lands and settlements (Jarvie *et al*. 2003, MAB Indonesia 2008). This biosphere reserve will be managed using a zoned approach. Three zones have been identified to promote the sustainable management of the peat swamp forest ecosystem; namely a core area (178,722 ha), a buffer zone (222,426 ha) and a transition zone (304,123 ha). The natural peat swamp forest remnant, located in the core area, consists of 84,967 ha in the Giam Siak Kecil Wildlife Reserve, 21,500 ha in the Bukit Batu Wildlife Reserve and 72,255 ha in production forest allocated to forest conservation by the Sinar Mas Company. The function of the core area is to conserve biodiversity, the buffer zone functions to protect the core area, and the transition area functions as the outer and largest area of the biosphere reserve (MAB Indonesia 2008). Owing to the massive areas of degraded peat swamp forest in the biosphere reserve, preserving the forest remnants is important, especially in conservation and core areas. Consequently, it is necessary to study the vegetation in order to elucidate the characteristics and regeneration processes of the remaining peat swamp forest. In this article we mainly discuss the forest types, structure, regeneration processes and tree species diversity of peat swamp forest within the Giam Siak Kecil–Bukit Batu Biosphere Reserve.

METHODS

Study sites

The Giam Siak Kecil–Bukit Batu Biosphere Reserve is located between 0°44'–1°11' N and 0°11'–102°10' E in two districts (Bengkalis and Siak) and one city (Dumai), in Riau Province, Sumatra Island, Indonesia (Figure 1). Its total area in 2009 was 705,271 ha, but by 2011 this had been reduced to 698,663 ha, of which 75 % is covered by peatland. Topographically, most of the terrain is at altitudes of 0–50 m a.s.l. The climate is tropical and is influenced by the ocean; the average annual temperature is 28 °C (range 26–32 °C). Rainfall varies from 1,349 to 4,078 mm y^{-1}; the rainy season is usually from September to January and the dry season from February to August (MAB Indonesia 2008, BPS 2008).

The ongoing development of large areas of peatland as timber estates and oil palm plantations on a landscape scale constitutes a serious threat to peat swamp forest ecosystems in Indonesia and, recently, the peat swamp forest of the Giam Siak Kecil–Bukit Batu Biosphere Reserve has been degrading at an alarming rate. A large part of the buffer zone has been developed as an industrial timber estate (195,259 ha or 88 %) and production forest (27,167 ha or 12 %), while the peatland in the transition zone has been converted to oil palm plantations, agriculture and housing (304,123 ha) and industrial timber estate (5,665 ha) (MAB Indonesia 2008). From 1999 to 2009, the remaining peat swamp forest was subjected to illegal logging of high-quality timber trees such as *Shorea* spp., *Tetramerista glabra*, *Gonystylus bancanus*, *Palaquium sumatranum*, *Palaquium burckii*, *Durio acutifolius* and *Koompassia malaccensis*. The logging activities decreased after 2005 and had stopped completely by the beginning of 2010.

Natural forest still remains along the upper reaches of the Bukit Batu River because this part of the river is too narrow to be used as a log removal route. The natural forest is characterised by two types. The first type has much surface water, dense growth of *Pandanus* spp. and a low tree density; and the second type has little surface water, relatively flat microtopography, asam paya (*Salacca conferta*), and a dense tree stand. The logged-over forest located in the Bukit Batu River Basin has been classified into three types with, respectively, dense upper-storey trees, less dense upper-storey trees, and no upper-storey trees.

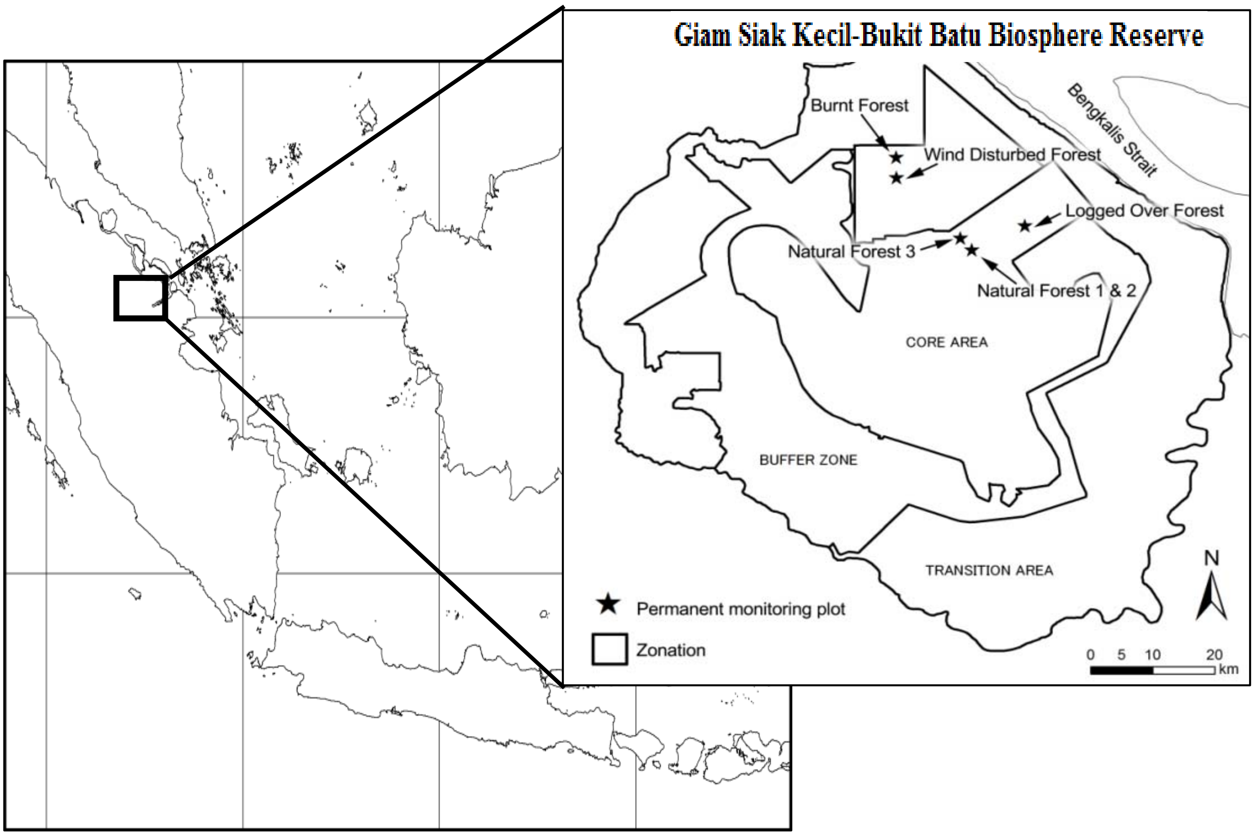

Figure 1. The study area and locations of permanent monitoring plots.

A large area of around 47,200 ha in the buffer zone of the biosphere reserve has been impacted severely by illegal logging and fire following its settlement by transmigrants since the early 2000s. Much of it was burned in 2005 after which it was colonised by ferns and *Melastoma* spp. The openness of this area exposed the remaining trees to wind damage and many trees have toppled over. Currently, this area is easily accessible and the migrant population of the village has increased dramatically since 2008. The wind-disturbed and burnt forest were classified into two types with, respectively, dense upper-storey trees and dense *Melastoma* species and ferns.

Vegetation surveys and study plots

In 2009–10, we carried out a survey of six 0.5 ha permanent monitoring plots in natural and disturbed forest that were also intended for ecological studies. The total area of the plots was three hectares. Three plots were located in natural peat swamp forest at 01° 21' 12.7" N, 101°47'22.7" E and 01° 22' 16.2" N, 101° 46' 23.1" E; and the remaining three plots were in logged-over peat swamp forest at 01° 23' 24.4" N, 101° 51' 59.1" E, wind-disturbed forest at 01° 27' 56.7" N, 101° 40' 49.8" E, and burnt forest at 01° 27' 46.6" N, 101° 40' 50.1" E (Figure 1).

We divided each of the 0.5 ha monitoring plots into six 25×25 m sub-plots in which the DBH of all trees ≥3 cm was recorded. To study natural regeneration, we laid out 144 2×2 m quadrats inside ten of the 25×25 m sub-plots in the three disturbed plots. Within the quadrats, saplings of DBH≤10 cm were counted. Voucher specimens of plants were sent to the Ecology Laboratory of Riau University for identification and verified at the Herbarium Bogoriense in LIPI, Cibinong, Indonesia.

Data analysis

Forest types and structure were analysed using the Importance Value (IV) index (Curtis & McIntosh 1951), the average sum of relative dominance (total basal area of a species ÷ total basal area of all species), relative frequency (number of plots in which a species occurs ÷ total number of plots sampled), and relative density (total individuals of a species ÷ total number of individuals of all species). The species with the highest IV index was considered to be the most “important” in a plot. Sorensen’s coefficient (*Ss*) was used to measure the similarity of species composition (Magurran 1988, Krebs 1994) and to generate a dendrogram comparing floristic similarities between the forest-type communities.

Species composition was analysed mainly by determining the number of species and families with percentage representation greater than 5 % (Tran *et al*. 2005). Diversity was quantified using species richness (*S*) and the Shannon–Wiener index (H') (Krebs 1994). *S* is the number of species recorded in the sampled area (Magurran 1988). We also calculated the evenness or equitability index (*E*), using the equation

$$E = \frac{H'}{\ln(S)} \qquad [1]$$

The value of H' is high if the numbers of species and individuals, and the distribution of individuals of each species, are high; and if the distributions of individuals for each species are almost even. Typically, the value of the index ranges from 1.5 (low species richness and evenness) to 3.5 (high species evenness and richness) (McDonald 2003).

Basal area of all the trees of a given species or of all trees in the sample plots can be estimated using the DBH values as follows: Basal area (m^2 ha^{-1}) = $\sum \pi\,(DBH)/2)^2$ (Ravindranath & Ostwald 2008).

RESULTS

Forest types and structure

The main criterion for determining forest types and structure is the IV. The five species with the highest IV values are listed for each habitat type in Table 1. From this, we identified two forest types based on the dominant species: Mixed Peat Swamp Forest (MPSF) and Bintangur Forest (BF). In MPSF, particular species (e.g. *Shorea* spp., *Shorea teysmanniana*, *Durio acutifolius*, *Calophyllum lowii*, *Madhuca motleyana*, *Palaquium sumatranum* and *Xylopia havilandii*) may be present in one sub-plot and not in another, but the IVs and basal areas of the five main species are similar; therefore, each makes an equal contribution to the forest community. In BF, *Calophyllum lowii* (local name bintangur) consistently makes the greatest contribution to basal area, and the densities and basal areas of the five dominant species differ markedly. Local people call this forest *hutan dare* or young forest, because the canopy is low and relatively closed and the tree diameter is small compared to mixed peat swamp forest.

The dendrogram (Figure 2) shows that *Ss* ranges from 71.6 % to 39.8 % between the forest type communities. Some plots of different forest types are identical floristically, especially Plots 1, 2 and 3. In contrast, the similarity between Plots 5 and 6 and Plots 1–3 was lower, indicating that the two forest communities represented by these plots differed in species composition.

Table 1. Importance Value index (IV) of five tree species in each type of land cover.

Sampling plot	Species	Basal Area (m^2 ha^{-1})	Mean IV (%)	Forest type
Plot 1	*Diospyros hermaphroditica*	1.70	21.84	MPSF
	Calophyllum lowii	2.38	18.02	
	Eugenia paludosa	2.18	17.44	
	Shorea spp.	1.80	17.30	
	Durio acutifolius	2.18	17.19	
		Total: 18.83		
Plot 2	*Eugenia paludosa*	0.82	20.78	MPSF
	Shorea teysmanniana	2.66	20.13	
	Diospyros hermaphroditica	1.70	19.70	
	Calophyllum lowii	1.87	16.67	
	Durio acutifolius	1.87	15.94	
		Total: 18.49		
Plot 3	*Palaquium sumatranum*	4.57	36.53	MPSF
	Diospyros hermaphroditica	1.17	16.72	
	Mezzetia parvifolia	2.14	15.16	
	Shorea teysmanniana	2.87	14.86	
	Mangifera longipetiolata	0.48	12.26	
		Total: 25.61		
Plot 4	*Eugenia paludosa*	1.72	23.64	MPSF
	Madhuca motleyana	1.55	19.60	
	Diospyros hermaphroditica	1.69	18.03	
	Xylopia havilandii	1.27	14.61	
	Palaquium sumatranum	1.45	13.67	
		Total: 19.61		
Plot 5	*Calophyllum lowii*	6.81	79.24	BF
	Shorea teysmanniana	1.35	21.73	
	Eugenia paludosa	0.26	14.30	
	Tetractomia tetrandum	0.40	12.69	
	Mangifera longipetiolata	0.14	12.68	
		Total: 11.57		
Plot 6	*Calophyllum lowii*	3.58	79.42	BF
	Shorea teysmanniana	1.73	35.40	
	Plantonela obovata	0.15	25.66	
	Mangifera griffithii	0.06	17.01	
	Eugenia paludosa	0.20	16.15	
		Total: 6.68		

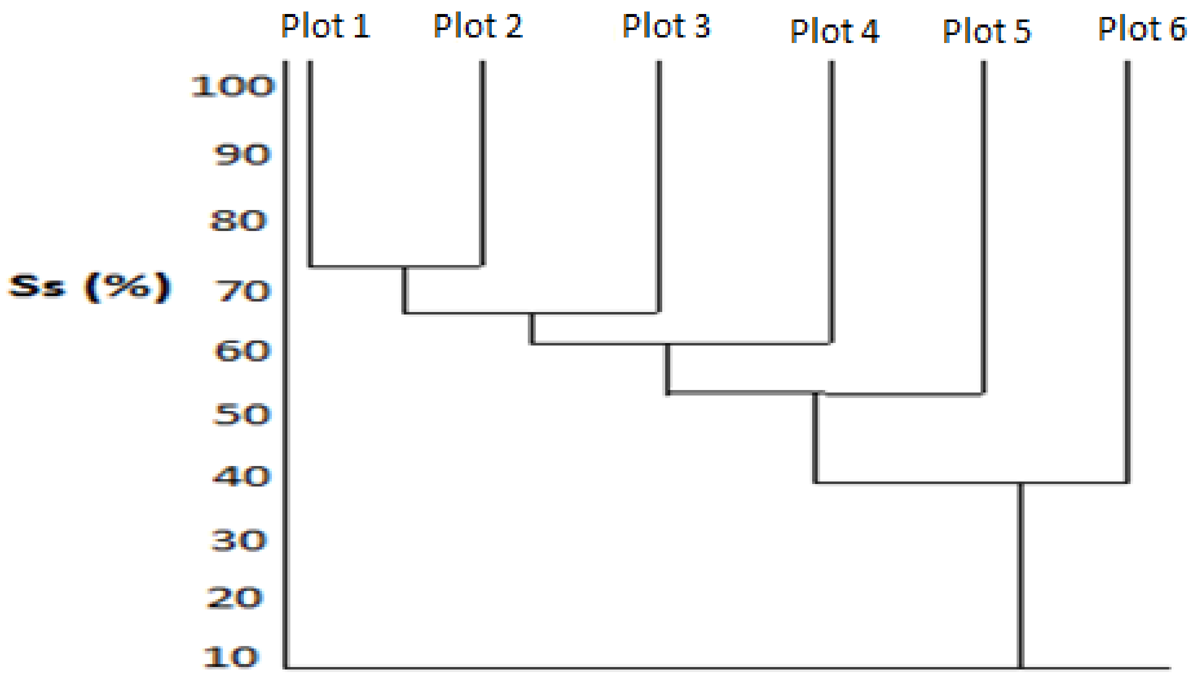

Figure 2. Dendrogram constructed using Sorensen's similarity index (*Ss*).

There are two principal forest types depending on the environmental conditions (Table 2), namely: forest located near to the river, characterised by above-ground water; and forest far (approximately 23 km) from the river, characterised by dry surface peat, where fires occur annually and some of the trees have been blown over. Comparing the study plots, tree density is greatest (2,492 stems ha^{-1}) in Plot 4, followed by Plots 1–3 and Plot 5 which have similar stand densities. Plot 6 has the lowest density (662 stems ha^{-1}), while Plot 3 has the largest basal area (25.61 m^2 ha^{-1}) (Table 2). This forest is still in good condition, as shown by the number of trees with DBH >30 cm (Figure 3).

The diameter distribution pattern of all species is similar among forest stands, showing a reverse J-shaped curve (Figure 3). There are most individuals in small-diameter classes, and numbers decrease with increasing diameter. We found no differences between any of the plots in the density of small-diameter trees owing to the impact of logging activities and wind disturbance. All of the forest stands have a high density of stems with a DBH of 3–10 cm, which is the potential source of recruitment to larger diameter classes, ensuring sustained forest regeneration if there is no further disturbance.

Composition, species richness, and diversity

The total numbers of families and species were determined for each forest plot, grouped, and ranked for families contributing a percentage composition greater than 5 % (Table 3). Overall, 135 tree species belonging to 34 families were identified. Myrtaceae and Ebenaceae are the most abundant families overall, followed by Clusiaceae, Sapotaceae and Dipterocarpaceae. Based on the number of species in each family, Sapotaceae is the dominant family (eleven species); followed by Lauraceae (ten species); Dipterocarpaceae, Myrtaceae and Burseraceae (nine species each); and Annonaceae (eight species). In the Dipterocarpaceae, *Shorea* is the most common genus (eight species), followed by Ebenaceae with five species of *Diospyros* and Sapotaceae with five species of *Palaquium*.

Twenty-three families were observed in Plot 1, represented by 55 species. Eight of these families each contribute >5 % of the individuals in the plot. In Plot 2, 73 species in 28 families were identified. Six families each contribute >5% of the individuals in this plot. In Plot 3, 74 species in 29 families were detected. Of the 28 families and 82 species in Plot 4, five families each contribute >5 % of all individuals. Plot 5 has 30 families and 64 species. Five of these families each contribute >5 % of the individuals in

Table 2. Tree density and basal area in each type of forest stand.

Sampling plot	Characteristics of forests	Density (stems ha^{-1})	Basal area (m^2 ha^{-1})
Plot 1	Much water on the forest floor, 50–100 m from river, peat depth >6 m, *Pandanus* spp. present.	1,228	18.33
Plot 2	100–150 m from the river, peat depth >6 m, dense *Pandanus* spp.	1,274	18.49
Plot 3	Little or no surface water, relatively flat micro-topography, 50–100 m from the river, peat depth >6 m, asam paya (*Salacca conferta*) present.	1,406	25.61
Plot 4	Ten years after selective logging, 150–1000 m from the river, peat depth >6.5 m. In the rainy season, water present 150 m from the river, asam paya (*Salacca conferta*) present.	2,492	19.61
Plot 5	Wind and indirect fire disturbance, surrounded by drainage canals and pulpwood plantation, approximately 23 km from the river, peat depth >10 m, *Calophyllum lowii* the dominant species.	1,280	11.57
Plot 6	Wind and indirect fire disturbance, surrounded by drainage canals and pulpwood plantations, peat depth >10 m.	662	6.68

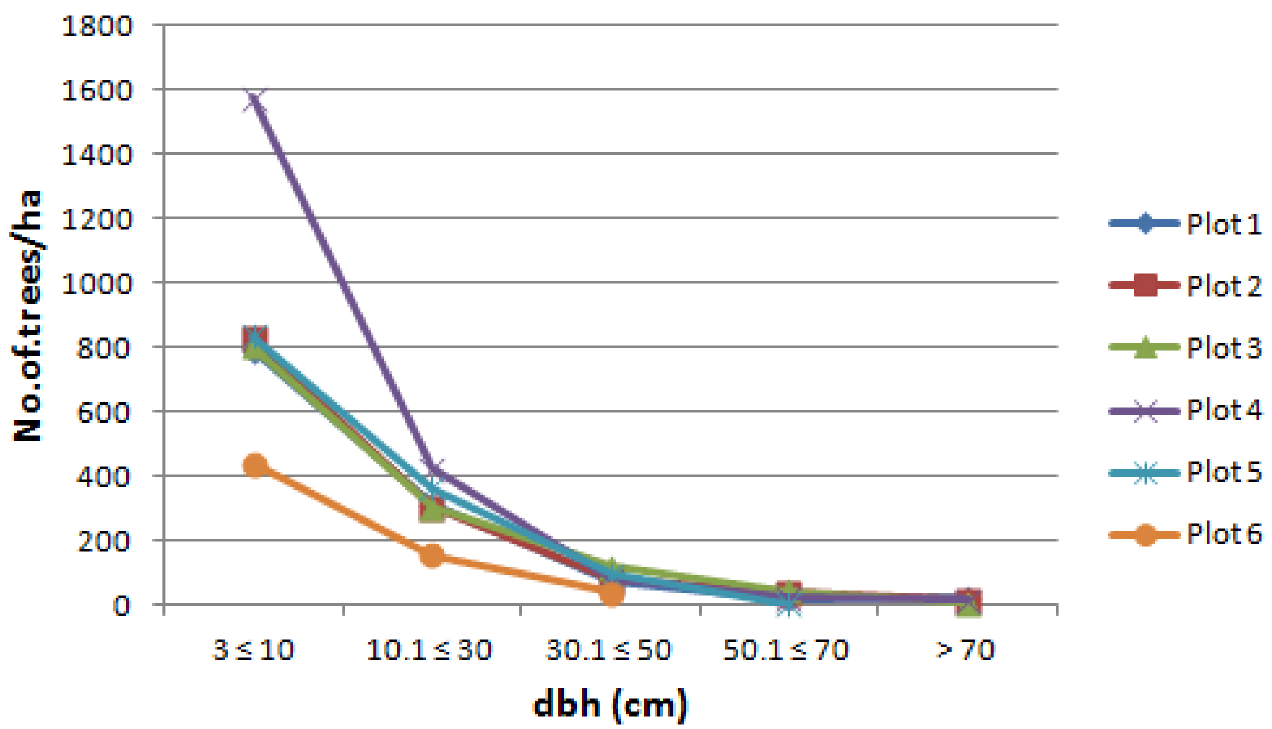

Figure 3. Diameter class distribution of all trees recorded in the study plots.

Table 3. Families with percentage composition greater than 5 % in the different forest plots.

Sampling plots	Total species	Total families	Family	Composition (%)	No. of species in each family
Plot 1	55	23	Myrtaceae	22.79	7
			Ebenaceae	14.49	4
			Chrysobalanaceae	8.14	2
			Clusiaceae	7.65	4
			Rutaceae	6.67	2
			Polygalaceae	6.03	2
			Annonaceae	6.02	4
			Dipterocarpaceae	5.37	5
			Total	77.16*	
Plot 2	73	28	Myrtaceae	24.96	6
			Sapotaceae	13.19	5
			Ebenaceae	7.37	3
			Clusiaceae	7.07	4
			Anacardiaceae	5.97	5
			Dipterocarpaceae	5.19	8
			Total	63.75*	
Plot 3	74	29	Sapotaceae	21.34	9
			Ebenaceae	13.09	2
			Aquifoliaceae	8.53	5
			Anacardiaceae	7.82	2
			Myristicaceae	7.68	5
			Myrtaceae	7.25	5
			Total	65.71*	
Plot 4	82	29	Sapotaceae	16.69	6
			Myrtaceae	15.89	5
			Ebenaceae	9.71	4
			Annonaceae	9.23	4
			Rutaceae	7.38	2
			Total	58.9*	
Plot5	64	30	Anacardiaceae	18.84	4
			Myrtaceae	17.03	5
			Clusiaceae	16.26	3
			Ebenaceae	7.81	3
			Dipterocarpaceae	7.35	5
			Total	67.29*	
Plot 6	36	22	Clusiaceae	30.81	4
			Elaeocarpaceae	16.72	1
			Myrtaceae	10.05	3
			Anacardiaceae	9.97	1
			Ebenaceae	5.57	1
			Total	73.12*	

* As a percentage of all families combined.

the plot. Plot 6 has 22 families and 36 species. The family composition is similar in Plots 5 and 6, and five families each contribute >5% of the individuals in these plots.

Plot 1 has the greatest number of families with percentage composition >5 % (77.16 % of the species); the main families are Myrtaceae (seven species, 22.79 %) and Ebenaceae (four species, 14.49 %). In Plot 6 (73.12 %), the main family is Clusiaceae (four species, 30.81 %). The fewest families are in Plot 4 (58.9 %), with six species in the Sapotaceae (16.69 %) and five species in the Myrtaceae (15.89 %).

Three common measures of species diversity are shown in Table 4. The simplest measure of diversity in the six study plots is species richness, *i.e.* the total number of species. A community dominated by one or two species is considered to be less diverse than one in which several different species have similar abundances. Diversity increases with species richness and evenness, and the greatest species richness is in Plot 4 (82 species), followed by Plot 3 (74 species) and Plot 2 (73 species). The Shannon–Wiener diversity index is highest in Plots 2 and 4 (H' = 3.6) and lowest in Plot 6 (H' = 2.7) (Table 4). The evenness index is closest to unity (0.84) in Plots 1 and 2 and indicates increasing single species dominance through Plots 3–5 to the highest single-species dominance in Plot 6 (evenness index 0.77).

Regeneration processes

The regeneration performance of trees (DBH < 10 cm) is summarised in Table 5. The H' is usually high (H' = 3.0) or fairly high (H' = 2.1), although it is low in Sub-plot 9 of the burnt forest (H' = 1.2).

The number of species is similar in each of the forest plots apart from Sub-plot 9 (11 spp.). Sub-plot 2 of the logged-over forest has the greatest number of families (22) and Sub-plot 9 the fewest (10 families). The number of stems ha^{-1} is high in most of the forest plots, but low in Plots 9 and 10 of the burnt forest (12,344 and 19,531 stems ha^{-1}, respectively). The IV indicates that some of the main upper-storey species do not regenerate in the initial stage of succession after disturbance. The colonisers are pioneer species (*i.e. Eugenia cerina* and *Melastoma* sp.) in all of the wind-disturbed and burnt forest plots, although *Palaquium sumatranum* has started to regenerate and is the dominant species in Plots 2 and 3 of the logged-over forest.

The regeneration performance of six main upper-storey tree species was examined (Table 6). *Calophyllum lowii* has the highest regeneration performance in the wind-disturbed forest plots, but performs less well in the logged-over and burnt forest plots, with no regeneration in Sub-plots 2 and 3 in the logged-over forest and Sub-plot 9 of the burnt forest.

The best regeneration performance is by *Palaquium sumatranum* in Sub-plots 2 and 3 of the logged-over forest, but this species is rare in the other forest plots. This shows that distinct forest formation types occur in logged-over, wind-disturbed and burnt forests, as Plot 4 was logged-over forest classified as MPSF and Plots 5 and 6 were in wind-disturbed forest classified as BF. The other upper-storey tree species show limited or no regeneration.

A difference is seen for some typical understorey trees (Table 7). *Eugenia paludosa* and *Eugenia setosa* show vigorous regeneration in almost all of the plots, followed by *Ilex macrophylla*, *Diospyros hermaphroditica* and *Mangifera longipetiolata*. The number of stems is greatest in the Myrtaceae, implying that plants of this family regenerate readily after disturbance. *Eugenia paludosa* and *Eugenia setosa* (Myrtaceae) and *Diopyros hermaphroditica* (Ebenaceae) are the most promising nurse species in efforts to restore degraded peat swamp forest in Giam Siak Kecil–Bukit Batu Biosphere Reserve.

Table 4. Diversity index values for trees in each type of forest plot.

Measures of diversity	Sampling plot					
	Plot 1	Plot 2	Plot 3	Plot 4	Plot 5	Plot 6
Species richness	55	73	74	82	64	36
Shannon–Wiener diversity (*H*’)	3.37	3.60	3.56	3.60	3.31	2.70
Evenness index (*E*)	0.84	0.84	0.83	0.82	0.80	0.77

Table 5. Regeneration performance of tree species (DBH < 10 cm) in each disturbed forest plot.

Plot	Sub-plot	No. species	No. families	No. stems ha^{-1}	H'	Dominant species	IV
Plot 4*	Sub-plot 1	36	18	35781	2.9	*Dialum indum*	25.0
	Sub-plot 2	38	22	37656	2.8	*Palaquium sumatranum*	27.9
	Sub-plot 3	36	19	31250	3.0	*Stemonorus scorpioides*	27.7
Plot 5†	Sub-plot 4	37	19	57813	2.6	*Eugenia cerina*	42.6
	Sub-plot 5	36	20	39531	2.9	*Eugenia cerina*	28.9
	Sub-plot 6	29	19	49688	2.3	*Eugenia cerina*	39.7
	Sub-plot 7	24	15	40156	2.2	*Eugenia cerina*	45.7
	Sub-plot 8	26	16	42969	2.1	*Eugenia cerina*	55.8
Plot 6‡	Sub-plot 9	11	10	12344	1.2	*Melastoma* sp.	117
	Sub-plot 10	32	20	19531	3.0	*Melastoma* sp.	24.7

* logged-over forest, † wind-disturbed forest, ‡ burnt forest

Table 6. Regeneration performance of six main upper-story peat swamp forest trees in disturbed plots.

Species	Family	Number of stems (DBH < 10 cm)									
		Plot 4*			Plot 5†					Plot 6‡	
		Sub-plot			Sub-plot					Sub-plot	
		1	2	3	4	5	6	7	8	9	10
Calophyllum lowii	Clusiaceae	3	0	0	50	14	51	16	24	0	1
Shorea teysmanniana	Dipterocarpaceae	1	1	0	1	0	1	2	0	0	0
Palaquium sumatranum	Sapotaceae	0	54	24	0	0	0	0	0	0	2
Shorea uliginosa	Dipterocarpaceae	0	0	0	0	3	0	0	0	0	0
Tetramerista glabra	Theaceae	0	0	0	6	0	7	0	0	0	0
Gonystylus bancanus	Thymelaeaceae	0	1	5	0	0	6	0	0	0	0

* logged-over forest, † wind-disturbed forest, ‡ burnt forest

Table 7. Regeneration performance of some typical peat swamp forest understorey trees in disturbed plots.

Species	Family	Number of stems (DBH < 10 cm)									
		Plot 4*			Plot 5†					Plot 6‡	
		Sub-plot			Sub-plot					Sub-plot	
		1	2	3	4	5	6	7	8	9	10
Diospyros hermaphroditica	Ebenaceae	11	2	3	19	2	3	0	2	0	7
Eugenia paludosa	Myrtaceae	13	10	13	15	18	11	17	7	0	9
Ilex macrophylla	Aquifoliaceae	0	5	11	4	0	6	20	20	0	1
Eugenia setosa	Myrtaceae	24	23	7	14	17	2	3	2	0	3
Mangifera longipetiolata	Anacardiaceae	0	3	4	6	16	17	58	33	1	4

* logged-over forest, * wind-disturbed forest, ‡ burnt forest

DISCUSSION

Forest types and structure

Evaluation of the Importance Value (IV) Index identified two types of forest, namely MPSF and BF. Similar results were reported by Anderson (1961) and Shepherd *et al*. (1997), who identified a MPSF in Borneo with dominant species *Gonystylus bancanus*, *Calophyllum* spp., *Dactylocladus* spp., *Neoscrotechinia* spp., *Cratoxylum* spp., *Shorea balangeran* and *Shorea teysmanniana*, although *Shorea albida* was absent. Studies of the MPSF examined here and another Sumatran peat swamp forest identified dominant species including *Gonystylus bancanus* and *Shorea* spp., although *Shorea albida* and *Shorea balangeran* were absent (Table 8). Sumatran peat swamp forest included BF and pole forest with the same dominant *Calophyllum* spp. Shepherd *et al*. (1997) identified this forest type in the peat swamp forest of the Sebangau River, Central Kalimantan, but reported different species of *Calophyllum* from those recorded on Sumatra. Similar results were obtained by Mogea & Mansur (1999) and Haryanto (1989). Therefore, further taxonomic and ecological studies of *Calophyllum* spp. are needed. Brady (1997b) identified two types of peat swamp forest in the Bengkalis (Sumatra) peat swamp forest, namely MPSF and pole forest. The pole forest was dominated by *Calophyllum* spp. This result is quite different from that of Momose & Shimamura (2002), who studied the peat swamp forest of the Kerumutan forest block in Riau. In the biosphere reserve examined in the present study, *Swintonia* species were absent. Therefore, some differences exist between Sumatran peat swamp forest types based on their dominant species (Table 8).

The natural and logged-over forests are classified as MPSF because the IVs of the dominant species are almost equal. In contrast, the wind-disturbed forest is classified as BF in which the IVs of the other dominant species differ. *Calophyllum* is the main species forming the forest community in wind-disturbed forest plots.

Composition, species richness, and diversity

Species diversity is one of the basic concepts of ecology used to characterise communities and ecosystems (Whitmore 1984). One indicator for assessing plant diversity is H' (Ludwig & Reynolds 1988). We examined this index and also *Ss*. Compared to other studies (Table 9), the H' and species richness were higher in the lowland peat swamp forest of the biosphere reserve examined in this study. Different Sumatran peat swamp forests have between 25 and 142 tree species in common with other peat swamp forests in south-east Asia, but fewer species than dryland rain forests in the same region, which have 100–290 species (Posa *et al*. 2011). The extreme chemical and hydrological conditions of peat swamp forests may impose constraints on local and regional tree diversity (Philips 1998, Posa *et al*. 2011).

Slight differences were observed in the species compositions of the forest plots studied. Fewer families and species were found in the logged-over forest compared to the five other types, perhaps because of recent selective logging activities. Moreover, *Ss* ranged from 31.5 to 70.58 %, reflecting the difference in species composition between pairs of plots; the lowest similarity was between the natural MPSF and wind-disturbed BF. All of the natural MPSF plot pairs had a *Ss* >50 %, indicating that most of the peat swamp forest species had recovered naturally after five years of logging disturbance in the logged-over MPSF.

The most abundant families were Myrtaceae and Ebenaceae. Brady (1997a) found that *Eugenia* spp. (family Myrtaceae) had the highest cover abundance in each Sumatran peat swamp forest community. Our results revealed that the Myrtaceae family was present in all of the plots. Moreover, most of the tree families in our study were found in other lowland peat swamp forests in south-east Asia, including members of the Anacardiaceae, Annonaceae, Burseraceae, Clusiaceae, Dipterocarpaceae, Euphorbiaceae, Lauraceae, Leguminaceae, Myristicaceae, Myrtaceae and Rubiaceae (Bruenig & Droste 1995, Shepherd *et al*. 1997).

Stand structure and the diameter distribution of stands and species is an important variable that needs to be considered as a basis for monitoring stand development after disturbance. The diameter class distribution of trees can be used to indicate the relative age structure and state of a forest (Odum 1971) and as an indicator of a natural or human-induced history (Lorimer 1980). Two main diameter classes were found: reserve stock (DBH < 3 cm) and mature stock (DBH > 70 cm). The diameter class distribution for all forest types shows a negative exponential or reverse J-shaped curve, suggesting mature forests (Rollet 1978, Blance *et al*. 2000). Logged-over forest has the greatest density of stems with DBH 3–10 cm. These are the source of recruitment to larger-diameter classes, which ensures the sustained regeneration of the forest, assuming no further disturbance. Different factors causing forest disturbance affect stand density differently. In selectively logged-over forest, the forest canopy is opened gradually, while natural disturbance can open the forest canopy drastically. Compared to natural forest, stand density was higher in logged-over forest and lower in wind-disturbed forest. Illegal logging enables light-demanding tree species to grow more quickly, leading to dominance of understorey species with diameters of 3–10 cm. Conversely, tree densities in the natural MPSF (Plots 1 and 2) and wind-disturbed BF (Plot 5) are similar, indicating that the forest here is mature compared to the logged-over MPSF.

Regeneration processes

Regeneration is key to the existence of species in a community. It is also a critical component of forest management because regeneration maintains the desired species composition and stocking after biotic and abiotic disturbances (Khumbongmayum *et al*. 2005). The natural regeneration of the peat swamp forest ecosystem is influenced by the interrelationships between peat subsidence, surface flooding during the wet season, and vegetation succession (Page *et al*. 2008). In the wind-disturbed and burnt forests, the dominant regenerating species after any disturbance are the pioneer species

Table 8. Comparison of forest types and dominant genera of Sumatran peat swamp forest.

Forest types	Dominant genera	Location	References
MPSF	*Koompassia*, *Durio*	Kerumutan	Momose & Shimamura 2002
	Parastemon, *Tetramerista*	Bengkalis	Haryanto1989
	Shorea, *Gonystylus*	Bengkalis	
	Tetramerista, *Shorea*	Bengkalis	
	Diospyros, *Calophyllum*	Bukit Batu	This study
	Eugenia, *Shorea*	Bukit Batu	
	Palaquium, *Diospyros*	Bukit Batu	
	Eugenia, *Madhuca*	Bukit Batu	
MPF	*Shorea*, *Swintonia*	Kerumutan	Momose & Shimamura 2002
PSF	*Palaquium*, *Swintonia*	Kerumutan	
BF	*Calophyllum*, *Tetramerista*	Bengkalis	Haryanto 1989
	Calophyllum, *Shorea*	Bukit Batu	This study
	Calophyllum	Bengkalis	Brady 1997b

MPSF = mixed peat swamp forest, MPF = meranti paya forest, PSF = padang suntai forest, BF = bintangur forest, PF = pole forest

Table 9. Number of species (NS) and diversity (H') in peat swamp forests of Sumatra.

Site Locality	Plot (ha)	DBH (cm)	NS	H'	References
Bukit Batu	3	>3	135	3.3	This study
Giam Siak Kecil–Bukit Batu	2.4	>10	125	2.9	LIPI 2007, unpublished.
Bengkalis	14.0	>0.1	131	-	Mogea & Mansur 1999
Kampar Peninsula	1.0	>10	27	2.7	Gunawan *et al*. 2007
Senepis Peninsula	0.2	>10	25	2.7	Istomo *et al*. 2009
Berbak National Park, Jambi	-	-	142	-	Giesen 2004
Aceh	1.6	>10	44	-	Purwaningsih & Yusuf 2000

Eugenia cerina and *Melastoma* spp. In burnt forest, the fern *Nephrolepis biserrata* quickly colonises the open land. Such species are competitors and facilitators in secondary succession (Kobayashi 1998). Gunawan *et al*. (2007) found that regeneration processes are influenced by disturbed reproductive trees in degraded greenbelt peat swamp forests where some secondary species showed vigorous regeneration, whilst most of the typical canopy species (*e.g. Shorea teysmaniana, Shorea uliginosa* and *Calophylum grandiflorum*) had limited or no regeneration.

Kobayashi (1998) classified the initial vegetation recovery into shrub, herb, fern and climber types. Shrubs and herbs are considered facilitators, while ferns and climbers are competitors during secondary succession. The upper-storey species *Palaquium sumatranum* regenerates well in logged-over forest, while *Calophylum lowii* starts to regenerate in wind-disturbed forest. *Palaquium sumatranum* and *Calophylum lowii* are both important upper-storey species in the Sumatran peat swamp forest vegetation community. Therefore, the regeneration of these species should promote similar species dominance in disturbed forest areas in the future. Comparison of the logged-over and natural forest plots indicates that *Palaquium sumatranum* is a dominant species for re-establishing a MPSF while *Calophylum lowii* started to regenerate in the wind-disturbed forest. The BF should persist in the biosphere reserve in the absence of further disturbance. In contrast, the pioneer *Melastoma* sp. colonised the burnt forest quickly after fire and *Calophylum lowii* was absent. Regeneration of *Calophylum lowii* after burning may be easier since the burnt forest is close to the wind-disturbed forest, a source of *Calophylum lowii* seeds. Nevertheless, most of the upper-storey species have problems regenerating. Kobayashi (1998) found that the natural regeneration of dipterocarp species and ramin (*Gonystylus bancanus*) is very poor. Therefore, some form of human-assisted regeneration is needed to promote biodiversity in disturbed peat swamp forest, such as enrichment planting and accelerated regeneration (Kobayashi 1998).

Conservation of the remaining peat swamp forest in the Biosphere Reserve depends upon, firstly, improved protection of the remaining natural forest and, secondly, improved management for rehabilitation of degraded secondary forest.

Remaining natural forests

We already know that tropical peat swamp forests are very important natural resources because of their functions as habitats for various kinds of flora adapted to survive in the very extreme environment, and their role in reducing the impact of global warming through carbon storage. This role is influenced by three factors: water, peat soil and vegetation. Change in one factor can cause damage to the whole ecosystem (Parish *et al*. 2008, GEC 2012). Peat swamp forests are also one of the last refuges for critically endangered animals, for example tiger, rhino and orangutan amongst many others.

This study has revealed that natural peat swamp forest in Sumatra can be classified into two main forest types, namely mixed peat swamp forest (MPSF) and bintangur forest (BF), which are distinguished by dominant tree species that form vegetation communities with unique floristic composition and basal areas. They have high species richness, tree diversity and unique environmental characteristics. For the MPSF at upstream locations within Bukit Batu forest block, differences in environmental factors associated with the water situation (proximity to river) are reflected by variations in floristic composition, basal area and density of the forest. BF, on the other hand, is located far away from the river, and is consistently dominated by *Callophylum lowii* (local name bintangur). This is a unique vegetation formation existing on very deep (> 10 m) peat.

Conservation of natural forests preserves important ecosystem services (e.g. biodiversity maintenance and carbon storage) amidst the increasing rates of land use change and forestry (LULUCF) in the biosphere reserve. Because it consists of three interconnected and interdependent components (forest, water and peat), peat swamp forest is a fragile ecosystem. In order to conserve the peat swamp forest that remains, improved management at the landscape scale is necessary.

Almost all of the remaining natural peat swamp forest in the Biosphere Reserve is located in the core area, which is surrounded by peatland under intensive development for industrial pulp tree plantations, oil palm plantations and settlements. Drainage canals cause peat soils to become drier. Hence, improving water management in the buffer and transition zones is one of the measures that must be considered in order to achieve conservation of peat swamp forest within the biosphere reserve.

Degraded secondary forests

We classified degraded secondary forest into logged-over forest and wind-and-fire-disturbed forest. There are two differences between logged-over forest and wind-and-fire-disturbed forest; firstly, the regeneration performance of the upper-storey tree species and, secondly, vigorous regeneration of *Palaquium sumatranum* and *Callophylum lowii*. *Palaquium sumatranum* dominates in logged-over forest while *Callophylum lowii* is most successful in wind-and-fire-disturbed forest, even though most of the typical upper storey trees are absent owing to limited or no regeneration. At this point improved management through rehabilitation should be implemented, in order to re-establish principal tree species characteristic of the natural vegetation communities of the peat swamp forest ecosystem.

The main causes of degradation in logged-over forest were logging and forest conversion. Illegal logging has been a major problem in this area since the early 2000s, causing degradation of the forest for a distance of approximately three kilometres on both sides of Bukit Batu River. The damage done ranges from moderate (through heavy) to severe. Severely degraded areas are mostly colonised by grasses and ferns. Heavily degraded areas are dominated by *Macaranga* sp. or woody pioneer species. Moderately degraded areas are undergoing regeneration by trees characteristic of peat swamp forest. Another factor that causes degradation is forest conversion to various land uses. Malay people have converted forest into jungle rubber gardens, and in some of the older villages rubber cultivation has been undertaken since the 1970s. Nowadays, villagers face problems relating to the status of their land rights because, in 1999, the Government of the Republic of Indonesia declared the conservation area. As a consequence, villagers now have only restricted access to the forest to undertake their traditional activities, and Central Government prohibits forest conversion. In this case, improved management should promote rehabilitation using multi-purpose tree species that have both economic and conservation values, such as *Dyera lowii, Shorea spp, Tetramerista glabra* and *Palaquium sumatranum*. The villagers could still harvest rubber latex and, at the same time, derive benefit from other forest trees that are planted.

Additional factors promoting further degradation of secondary forest are wind, fire and conversion to plantations. In the transition zone, large areas of peatland have been deforested and planted with fast-growing *Acacia* trees for which large drainage canals must be excavated. Wind-and-fire-disturbed forests support a unique vegetation formation under extreme environmental conditions. This forest is dominated by *Calophylum lowii*, which can grow in peat of all depths up to 10 m. This species can be damaged, however, because its trunks break easily and it can be blown over by strong wind. Improved management should be promoted in order to conserve the remaining fragile bintangur forest.

We believe the remaining natural peat swamp forest is important to conserve owing to its unique habitat types, biodiversity and environmental characteristics. Rehabilitation of degraded secondary forest must be achieved through improved and appropriate management and stopping any further forest conversion and disturbance. In achieving this, natural regeneration is very important in order bring back the original peat swamp forest vegetation and its associated biodiversity, but some form of human-assisted regeneration is needed.

CONCLUSIONS

- The main forest types in Giam Siak Kecil – Bukit Batu Biosphere Reserve are mixed peat swamp forest (MPSF) and bintangur forest (BF), which have different dominant species.
- Natural regeneration is very important for improving the condition of degraded peat swamp forest in the bosphere reserve, even though this will not be sufficient to bring back the forest vegetation and its associated biodiversity for a long time.
- Some form of human-assisted regeneration is needed now to speed up re-establishment of the range of tree species characteristic of natural peat swamp forest.
- Most of the sub-storey tree species and some canopy trees such as *Palaquium sumatranum* and *Calophylum lowii* regenerate quickly.
- This study confirms the uniqueness of this biosphere reserve and its remaining peat swamp forest with its different forest types, (animal and plant) species composition and environmental conditions, as well as the need for improved management of secondary forest by rehabilitation and arresting forest conversion, wind and fire.

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