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# EFFECTS OF FIRES ON PEAT SWAMP AND LOWLAND DIPTEROCARP FORESTS IN KALIMANTAN, INDONESIA

Carey P. Yeager[1,4], Andrew J. Marshall[2], Claudia M. Stickler[3,4], and Colin A. Chapman[4,5]

[1]. WWF Indonesia, P.O. Box 5020, JKTM 12700, Jakarta, Indonesia
[2]. Department of Anthropology, Harvard University, Cambridge, MA 02138, USA
[3]. College of Natural Resources and the Environment, Box 116455, 103 Black Hall, University of Florida, Gainesville, FL 32611-6455, USA
[4]. Department of Zoology, University of Florida, Gainesville, Florida 32611, USA
[5]. Wildlife Conservation Society, 2300 Southern Boulevard, Bronx, NY 10460, USA

## ABSTRACT

The effects of the fires that burned over 4.7 million ha of Indonesia's tropical forests during 1997 and 1998 are largely unknown. We assess the immediate impacts of these fires on five forest areas representing several different habitats in Kalimantan 1-2 months after the fires went out. Comparisons of transects in burned and unburned forest areas were conducted at three sites: Tanjung Puting National Park, Kutai National Park, and Sungai Wain Nature Reserve. In general, burned forests had reduced canopy and ground cover, lower tree species richness and diversity, and higher canopy tree, seedling, and sapling mortality than unburned forests. Species richness in peat swamp forests at Tanjung Puting was reduced by 59% by the fires, and in two lowland dipterocarp forests by 24% (Sungai Wain) and 57% (Kutai). Resurveying of transects at Tanjung Puting 8 months after the first survey showed that burned forests suffer higher tree mortality and further species loss in the months following fires. In addition, species richness was lower in forests that had been logged prior to burning than in forests that had been undisturbed before the fires. The long-term ecological effects of burning on forest diversity, structure, and species composition are discussed, and the conservation implications of the high fire hazard in Indonesia are considered.

Key words: Fire, Tropical forests, Selective logging, Peat forests, Kalimantan

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## INTRODUCTION

In 1997 and 1998, fires burned approximately 9.7 million ha in Indonesia and at least 9.2 million ha throughout tropical Latin America (Barber and Schweithelm, 2000; Cochrane, 2002). Although fires have always occurred in these areas (Saldarriaga and West, 1986; Haberle and Ledru, 2001), human population growth, changes in land-use practices, and climate change are interacting to increase fire frequency and intensity. Previously, fires in 1982 and 1983 burned 3.6 million ha of forest in East Kalimantan alone (Leighton and Wirawan, 1986). Rijksen and Meijaard (1999) reported that by the end of 1997, fires had significantly affected 36 of the 45 major forest blocks remaining in Kalimantan. High rates of commercial exploitation of forests, regularly reoccurring droughts associated with El Niño climatic oscillations, and continued widespread use of fire for clearing land, virtually guarantee that the fire threat in Indonesia will remain high.

The majority of the 1997/1998 fires were set by plantation companies and small scale farmers to clear land. In some areas with land tenure conflicts, arson occurred. Fires quickly raged out of control due to poor logging practices, which had resulted in increased fuel loads, and drought conditions exacerbated by the 1997 El Niño climatic oscillation (Meijaard and Dennis, 1997; Dauvergne, 1998; EEP, 1998; Schweithelm and Glover, 1999). These fires and the resulting haze, imposed immense economic, public health, and ecological costs across Southeast Asia. Economic estimates suggest that the cumulative costs were US$ 9.2 billion (Barber and Schweithelm, 2000). This figure includes firefighting costs, losses of agricultural and plantation crops, short-term health damages, losses in tourism and transportation revenues, and losses in the forestry sector. It does not include long-term health costs, reduction in ecological services, or biodiversity losses.

In contrast to the relatively large amount of information available to estimate economic costs, few data exist on direct ecological effects of these fires. This lack of data is due to a paucity of field surveys, a limited understanding of the functioning of rainforest and peat-swamp ecosystems, and the difficulty of parsing out the independent effects of drought and land-use practices (Dudley and Jeanrenaud, 1997; Barber and Schweithelm, 2000). Although specific quantitative data are limited, matched comparisons of burned and unburned forest have demonstrated that fire has severe impacts on tree mortality and forest structure. Kinnaird and O'Brien (1998) reported that the 1997 fires that burned in the Bukit Barisan Selatan National Park in southwest Sumatra killed 2.4% of trees outright and injured a further 16.3% of trees. This forest was a mosaic of primary forest (50%), lightly disturbed forest (27%), and previously burned forest (23%). Tree mortality was elevated in the 6 months after the fires, with tree mortality rates of 24.6% being recorded in burned plots, versus 9.8% in unburned plots. Seedling mortality in burned plots ranged from 70% to 100%, and sapling mortality from 25% to 70% (Kinnaird and O'Brien, 1998). Previously, Woods (1989) reported that the Bornean fires of 1982-1983 led to tree mortality rates of 38% to 94% in logged forests and 19% to 71% in unlogged forests. In both forest types sapling mortality rates exceeded 78% (Woods, 1989). Such changes are likely to result in a loss of biodiversity and perturbation of ecosystem function.

Few data are available on the effects of fire on tropical forests in Kalimantan, an area encompassing approximately one third of Indonesia's remaining tropical rainforest (Bappenas, 1993). Two recent studies indicate that the effects of fires on lowland dipterocarp forests are compounded where selective logging has taken place and burned areas continue to deteriorate long after the fires are extinguished (van Nieuwstadt, 2001; Slik *et al.*, 2002). However, more information about how fire affects different Indonesian forest habitats is needed to formulate conservation and management plans.

In this study we assess the effects of the 1997-1998 fires on five forests in Kalimantan. One-two months after the fires went out, data were collected at the following sites: Tanjung Puting National Park (peat swamp forest flooded by fresh water), Kutai National Park (lowland dipterocarp forest), Sungai Wain Nature Reserve (lowland dipterocarp forest), Muara Kaman Nature Reserve (freshwater swamp and peat swamp forest), and Muarabu/Mapulu/

Liang Belana (forest on limestone karst). Additional data were collected at Lempake, an unburned limestone plateau forest to allow comparisons to Muarabu/Mapulu/Liang Belana. Direct comparisons of matched burned and unburned transects were possible at Tanjung Puting, Kutai, and Sungai Wain. Vegetation at Tanjung Puting was resurveyed 8 months after the initial survey to assess longer-term effects of burning. We provide an assessment of the effects of burning on the abundance and species composition of various forest types, and basic descriptions of the effects of fire on soil quality.

## METHODS

### Study Sites

The study was conducted in six different areas of Kalimantan (Figure 1), representing lowland dipterocarp forest, limestone, and swamp habitats. Most of the areas were somewhat degraded by logging or other activities and had burned previously, generally, during the 1982/1983 ENSO-related fires (Table 1).

*Tanjung Puting National Park*: Surveys were carried out at Natai Lengkuas Station, Tanjung Puting National Park, and outside the park on the north bank of the Sekonyer Kiri River. Peat swamp, heath (kerangas), and lowland dipterocarp are the major forest types in this park; however, the fires occurred primarily in the peat swamp forest. Transects were placed in the peat swamp perpendicular to the river's edge. Large open areas (hundreds of meters in breadth and width) where hundreds of trees had fallen were observed; many trees still had live foliage although their roots were burned. Fire and haze have only recently become a problem for the park, although settlers in the area have for decades used fire to clear land, and to improve fishing and hunting efficiency. There were major fires in the park in 1991, 1994, and 1997. All fires in the park followed prolonged droughts. Illegal logging and mining activities degraded parts of the park prior to the fires.

*Kutai National Park*: Surveys were carried out in lowland dipterocarp forest at the Mentoko and Prefab locations in June 1998. Major fires occurred here in 1982/1983, 1987, and 1998. In addition to previous fires, illegal logging, farming, and mining activities have degraded large portions of the park. Transects were placed near the Sangatta River on the northern border.

*Sungai Wain Nature Reserve*: This small reserve of lowland dipterocarp forest (secondary growth) is located near Balikpapan. Parts of the reserve burned in 1982/1983, but many parts of the reserve are still in relatively good condition compared to Kutai.

*Muarabu/Mapulu/Liang Belana*: This area is limestone forest (karst) and has no protected area status. The forest appears to have been relatively undisturbed prior to the fires, most likely due to the inaccessibility of the terrain (steep jagged slopes). Prior fires in 1982/1983 were reported to have been less intense than the 1998 fires.

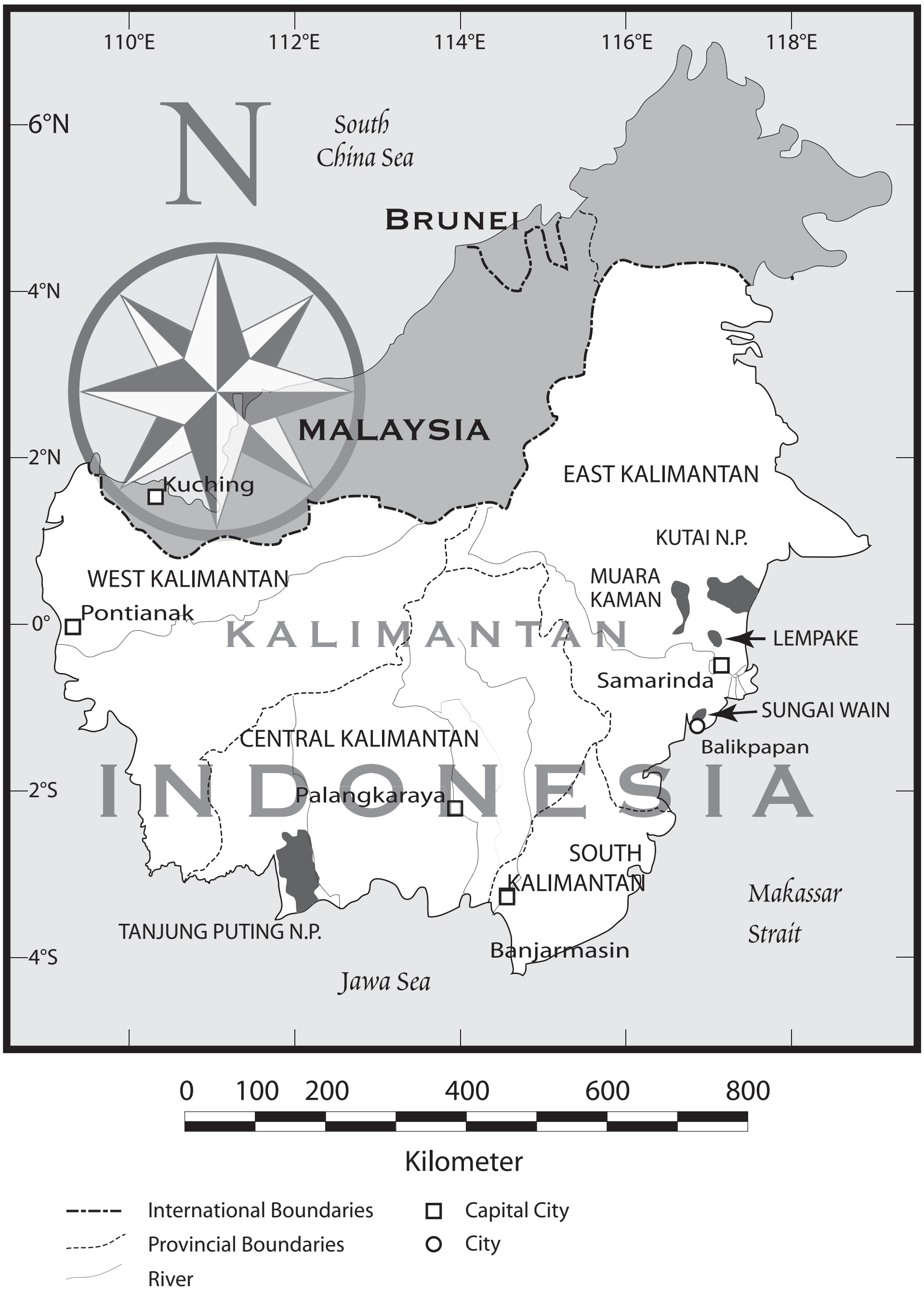


Figure 1. The Location of Each of the Sites Used to Assess the Impact of Fire on Forest Structure in Kalimantan, Indonesia.

Table 1. Descriptions of Transect Sites Used to Assess the Impact of Fire on Forest Structure in Kalimantan, Indonesia (FW = freshwater, [1] this is in West Sugai at Kedang Kepala).

| Site | Location | Habitat type | Fire History | Degradation | # Transects |
|---|---|---|---|---|---|
| Kutai | Prefab | Lowland Dipterocarp | 82/83, 97/98 | some logging | 3 |
| Kutai | Prefab | Lowland Dipterocarp | 82/83 | some logging | 2 |
| Kutai | Mentoko | Lowland Dipterocarp | 82/83, 97/98 | some logging | 2 |
| Sungai Wain | Sungai Wain | Lowland Dipterocarp | 82/83, 97/98 | some logging | 5 |
| Sungai Wain | Sungai Wain | Lowland Dipterocarp | 82/83 | some logging | 5 |
| Muarabu | Muarabu | Limestone karst | 82/83, 97/98 | very little | 5 |
| Lempake | Lempake | Limestone plateau | None | very little | 5 |
| Tanjung Puting | Natai Lengkuas | FW Peat Swamp | 94 partial, 97/98 | very little | 5 |
| Tanjung Puting | Natai Lengkuas | FW Peat Swamp | multiple, 97/98 | some logging | 5 |
| Tanjung Puting | Natai Lengkuas | FW Peat Swamp | None | very little | 5 |
| Muara Kaman | Kedang Kepala[1] | FW Peat Swamp | 82/83?, 97/98 | some logging | 5 |
| Muara Kaman | Cagar Alam | FW Swamp | 82/83, 97/98 | some logging | 5 |

*Lempake*: Lempake is a limestone plateau forest maintained for watershed protection. There is no history of burning and the forest is in very good condition. The local community regularly hunts in the area.

## Vegetation Transects

A total of 52 transects (400 x 5m) were randomly placed within burned and non-burned areas in the three habitat types (Table 1). We placed 17 transects in lowland dipterocarp forest, 10 transects in limestone, and 25 transects in swamp habitats. We attempted to place transects in burned and unburned areas adjacent to each other in each habitat type. However, this was not always possible, because in some areas, the extent of the burned area was so great that it was impossible to find unburned areas or unburned areas were so remote that it was not feasible to reach them on foot. The minimum burned area in which transects were placed was 50 ha. Some transects placed in known burned areas contained small unburned patches (indicated by a lack of charcoal traces and little mortality). These unburned patches were excluded from analyses of tree density and diversity.

All trees >10 cm DBH (diameter at breast height) within each transect that were still alive (based on presence of young leaves or sap flow from a small bark slash) were identified by local name by a resident of the area. Where possible, scientific names were added. It was generally not possible to collect fertile voucher specimens, since trees were generally not fruiting or flowering. The term species is used for convenience, but technically these are morphospecies. The Shannon-Weaver Index of diversity (H') was calculated using the morphotypes. We measured the height of the fire scar on all live trees. Litter depth was measured every 20 meters along each transect, by placing a straight edge ruler into the litter approximately 1 m to the side of the transect. Canopy cover was assessed using a GRS densitometer with 1/0 point sampling every 20 m along the transect. The GRS densitometer is a T shaped tube with an angled sighting mirror and offset level that allows one to vertically sample forest canopy or understory coverage. At these same locations, ground cover (<30 cm tall) was sampled with a GRS densitometer in the same fashion, but simply turning the densitometer towards the ground. Trees were rechecked in July 1998 at Tanjung Puting to determine longer term survival and mortality.

Soil samples were collected every 100 m along transects, except at Tanjung Puting which was flooded. These were analyzed by the Pusat Penelitian Tanah dan Agroklimat Laboratory in Bogor, Indonesia, for organic carbon and nitrogen.

We noted the presence / absence of simple indicators of environmental quality for each 20 x 5 m segment of each transect. These included humidity (moss or lichen, epiphytes, hanging or bole vines) and direct human disturbance indicators (cut trees, machete marks, trash, or other anthropogenic traces).

## Data Analysis

Data for species richness in vegetation transects were weighted by the amount of transect area that was burned. In a few transects, small areas appeared unburned. To prevent an artificial inflation of species richness, only the burned areas of the transects were included. Because this reduced the transect area, the transects were weighted as follows. First, the number of tree species was divided by the transect area burned. Second, the average number of species per transect meter was multiplied by the number of meters not burned. These two figures were added together to obtain the weighted species number. Example: Transect 6 had 340 meters burned and 60 meters unburned. There were 4 species in the 340 burned meters, so 4/340 = 0.011765. This figure was multiplied by 60 (the number of unburned meters), 0.011765 x 60 = 0.71. This number was added to the number of species, 4 + 0.71 = 4.71, to obtain the corrected value.

Two-Factor Analysis of Variance, using each transect as an independent data point, was used to analyze the data. Only transects in the Sungai Wain and Kutai lowland dipterocarp forests (n = 17) and the Tanjung Puting peat swamp (n = 15) were used because no unburned control transects existed from the other sites. The two factors examined were burn status (burned or unburned area) and location (inside or outside the park). All tests were two-tailed. Only descriptive statistics are provided for freshwater swamp at Muara Kaman, as there was no control available in the area. Burned versus unburned limestone forest transects were placed on different geologic and soil substrates, and thus are not directly comparable with each other; therefore only descriptive statistics are provided.

# RESULTS

## Canopy Cover and Ground Cover

Canopy cover was lower in the burned versus unburned transects (peat swamp: $F = 469.57$, $df = 1,13$, $p < 0.001$; lowland dipterocarp: $F = 37.44$, $df = 1,15$, $p < 0.001$; Figure 2). Similarly, ground cover was lower in the burned versus unburned transects in lowland dipterocarp ($F = 30.38$, $df = 1,15$, $p < 0.0001$; Figure 2). Flooding prevented assessment of ground cover in the peat swamp.

## Tree Species Richness and Diversity

Tree species richness was lower in burned transects in lowland dipterocarp ($F = 6.50$, $df = 1,15$, $p < 0.0001$) and peat swamp ($F = 34.88$, $df = 1,13$, $p < 0.0001$; Table 2) compared to the unburned forests of similar type. Burned peat swamp at Tanjung Puting had 13.1% fewer species (nondegraded area inside park) to 68.9% fewer species (previously degraded area outside park) than the unburned forest inside the park. Lowland dipterocarp forest had 7.3% (Sungai Wain) to 31.0% (Kutai) fewer species. The Sungai Wain lowland dipterocarp site had significantly higher species richness than the Kutai National Park lowland dipterocarp site ($F = 19.56$, $df = 1,15$, $p < 0.0001$).

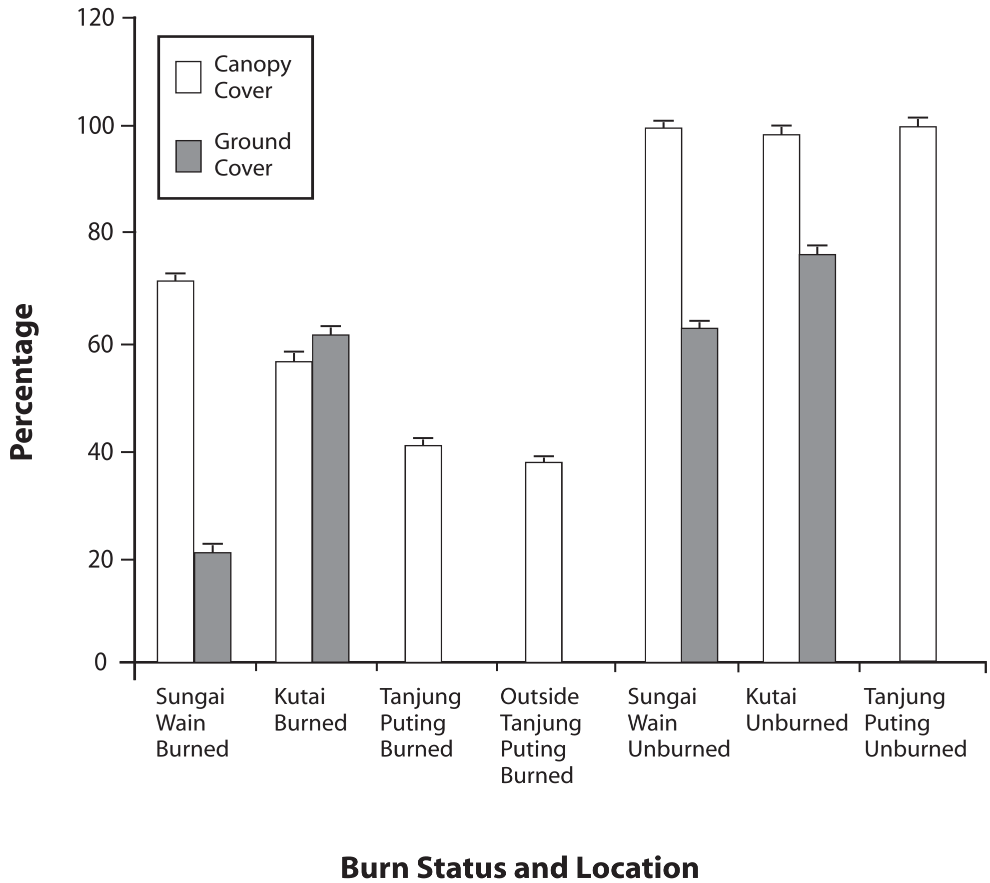


Figure 2. The percentage ground cover and canopy cover at burned and unburned locations in lowland dipterocarp (Sungai Wain and Kutai) and peat swamp (Tanjung Puting) in Kalimantan, Indonesia.

Table 2. The total number of different species per site (all transects combined), and the average number and range for species, DBH, burn scar height, and number of trees/ha for the transects at each site in Kalimantan, Indonesia (live trees > 10 cm DBH; FW = Freshwater, PS = Peat Swamp).

| Site | Total species | Average # species (range) | Average Diversity H′ (range) | Average DBH (cm) (range) | Average burn scar ht (range) | Average # trees/ha (range) |
|---|---|---|---|---|---|---|
| **Burned Lowland Forest** | | | | | | |
| Kutai* | 35 | 16.2 (9-32) | 2.4 (1.7-3.4) | 33.2 (24.5-47.5) | 1.3 (.7-2.1) | 122.0 (80-245) |
| Sungai Wain | 139 | 40.4 (32-54) | 3.5 (3.1-3.8) | 23.4 (19.7-27.2) | 0.6 (.4-.8) | 295.0 (270-320) |
| *Grand Average (SD)* | | 28.3 (15.7) | 2.9 (0.7) | 28.3 (8.7) | 0.9 (0.6) | 208.5 (103.3) |
| **Unburned Lowland Forest** | | | | | | |
| Kutai | 51 | 30.5 (30-31) | 2.9 (2.8-3.0) | 20.3 (19.7-20.8) | | 410.0 (370-450) |
| Sungai Wain | 150 | 53.2 (38-69) | 3.7 (3.3-4.0) | 20.4 (18.9-22.4) | | 481.0 (385-620) |
| *Grand Average (SD)* | | 46.7 (14.8) | 3.5 (0.4) | 20.4 (1.2) | | 460.7 (84.5) |
| **Burned Limestone Forest** | | | | | | |
| Muarabu | 49 | 15.8 (10-27) | 2.4 (2.1-3.1) | 23.8 (19.4-30.9) | 0.3 (.2-.5) | 157.0 (115-225) |
| *Standard Deviation* | | 7.1 | 0.4 | 4.5 | 0.1 | 48.8 |
| **Unburned Limestone Forest** | | | | | | |
| Lempake | 154 | 53.2 (47-63) | 3.7 (3.5-4.0) | 23.0 (21.8-25.8) | | 490.0 (410-550) |
| *Standard Deviation* | | 6.6 | 0.2 | 1.6 | | 56.7 |
| **Burned Swamp Forest** | | | | | | |
| Tanjung Puting - Peat Swamp | 53 | 18.4 (12-26) | 2.3 (1.7-3.1) | 21.5 (17.9-24.3) | 1.1 (.7-1.7) | 248.0 (200-290) |
| Tanjung Puting - Degraded PS | 19 | 10.1 (5-15) | 1.4 (1.2-1.7) | 24.5 (21.8-26.4) | 0.9 (0-1.6) | 244.0 (76-378) |
| Muara Kaman - Degraded PS | 37 | 12.6 (8-16) | 1.8 (1.1-2.1) | 20.2 (17.9-25.5) | 0.9 (.4-2.4) | 454.0 (140-660) |
| Muara Kaman - Degraded FW | 21 | 10.4 (7-15) | 1.3 (.9-2.3) | 36.0 (22.6-45.2) | 0.4 (.1-1.1) | 325.3 (165-463) |
| *Grand Average (SD)* | | 12.9 (5.1) | 1.7 (0.6) | 25.5 (7.9) | 0.8 (0.6) | 317.8 (142.8) |
| **Unburned Swamp Forest** | | | | | | |
| Tanjung Puting | 61 | 34.4 (31-35) | 2.9 (2.8-3.1) | 22.0 (20.8-23.0) | | 975.0 (855-1150) |
| *Standard Deviation* | | 3.2 | 0.1 | 0.9 | | 107.5 |

* The burned and unburned sites at Prefab were compared, as we could not find an unburned place at Mentoko in which to place transects.

If the Mentoko site is added, then the total number of species in the burned transects is 63.

In peat swamp, species diversity (H') was lower in burned transects than in unburned areas ($F = 5.96$, df = 1,13, $p = 0.031$). Areas heavily degraded prior to the fires of 1997/1998 had significantly lower diversity than areas that were not previously degraded (dipterocarp: $F = 14.5$, df = 1,15, $p < 0.002$, peat swamp: $F = 15.75$, df = 1,13, $p = 0.002$).

## Average Tree Density

Tree density was lower in the burned transects compared to the unburned transects (dipterocarp: $F = 46.75$, df = 1,15, $p < 0.0001$, peat swamp: $F = 188.69$, df = 1,13, $p < 0.0001$; Table 2). Burned peat swamp at Tanjung Puting had 74.8% fewer tree stems / ha than the unburned areas of the same habitat (Table 2). Burned lowland dipterocarp forest at Kutai and Sungai Wain had 70.2% and 38.7% fewer stems / ha respectively as compared to unburned areas in the same locations. There were significantly fewer stems at Kutai as compared to Sungai Wain for all transects ($F = 12.39$, df = 1,15, $p = 0.004$).

In peat swamp areas in Tanjung Puting that were known to have burned more than twice, there were almost no live trees (3 trees/ha), and almost all vegetation had been reduced to charcoal. Some ferns and grasses were present. Generally, in peat swamp areas that have burned twice, the stem density was 53.8 trees/ha, whereas in areas burned only once the stem density was 358.3 trees/ha.

## Average DBH

The average DBH of trees >10 cm DBH in dipterocarp forest was higher in burned transects than in unburned transects (Table 2; $F = 6.63$, df = 1,15, $p = 0.023$). In peat swamp, there was no difference between burned and unburned transects, but there was a significant difference between sites based on degradation levels previous to the 1997 fires. The average DBH at the heavily degraded peat swamp site in Tanjung Puting National Park was significantly higher than the sites originally in good condition ($F = 5.47$, df = 1,13, $p = 0.038$).

## Seedling and Sapling Density

Seedling and sapling densities were lower (seedling: $F = 56.77$, df = 1,13, $p < 0.0001$; sapling: $F = 31.94$, df = 1,13, $p < 0.0001$) in burned peat swamp (mean seedlings = $1.29/m^2$; mean saplings = $0.08/m^2$) than in unburned transects (mean seedlings = $4.48/m^2$; mean saplings = $0.77/m^2$) at Tanjung Puting. In lowland dipterocarp forest, there were no differences between burned (mean seedlings = $6.54/m^2$) and unburned transects (mean seedlings = 3.94 per $m^2$) with respect to seedling density ($F = 0.72$, df = 1,15, $p = 0.413$). Sapling density, however, was significantly lower ($F = 12.45$, df = 1,15, $p = 0.004$) in burned transects (mean saplings = $0.16 / m^2$, SD = 0.27) than unburned transects (mean saplings = $0.95 / m^2$).

## Fire Scars

Fire scars on living tree stems typically reached only 1 m above the ground; however, occasionally they reached up to 2 m or more at Kutai and in the Muara Kaman peat swamp (Table 2). They averaged 0.9 m (± 0.6 m) in burned lowland forest; Kutai (1.3 m) had a higher average burn scar than Sungai Wain (0.6 m). Fire scar height in the swamp areas averaged 0.8 m (± 0.6 m). Ground fires appeared to be predominant, with fire only rarely reaching the canopy by traveling up vines.

## Leaf Litter

Leaf litter was deeper in unburned transects for both dipterocarp ($F = 10.21$, $df = 1,15$, $p = 0.007$) and peat swamp ($F = 17.92$, $df = 1,15$, $p < 0.001$) than in the burned transects. It was also deeper at Sungai Wain than Kutai ($F = 13.21$, $df = 1,15$, $p = 0.003$).

## Soil Quality—Lowland Dipterocarp Sites

In lowland dipterocarp forests, carbon did not vary significantly between burned and unburned ($F = 0.56$, $df = 1,15$, $p = 0.458$) transects or between sites ($F = 1.54$, $df = 1,15$, $p = 0.218$; Table 3). Nitrogen ($F = 14.10$, $df = 1,15$, $p < 0.0001$) was higher at burned and unburned sites at Kutai than in Sungai Wain. There was no difference in nitrogen levels between burned and unburned areas at either site ($F = 1.72$, $df = 1,15$, $p = 0.194$). The carbon to nitrogen ratio ($F = 69.01$, $df = 1,15$, $p < 0.0001$) was higher at burned and unburned sites in Sungai Wain than at Kutai. However, the ratio did not vary between burned and unburned transects at either site ($F = 1.71$, $df = 1,15$, $p = 0.195$).

## Environmental Quality Indicators

Human disturbance was present in all sites, including National Parks, and included machete slashes, cut trees (for fuelwood or logging), tapped trees, and trash (Table 4). There were no differences between burned and unburned sites in anthropogenic disturbance level in dipterocarp forest or peat swamp.

Epiphytes ($F = 25.71$, $df = 1,15$, $p < 0.0001$), bole vines ($F = 74.76$, $df = 1,15$, $p < 0.0001$), and hanging vines ($F = 122.04$, $df = 1,15$, $p < 0.0001$) were less common in burned dipterocarp transects than in unburned dipterocarp transects (Table 4). Sungai Wain contained more epiphytes ($F = 50.83$, $df = 1,15$, $p < 0.0001$), moss ($F = 13.1$, $df = 1,15$, $p = 0.003$), and bole vines ($F = 5.48$, $df = 1,15$, $p = 0.036$) than Kutai. In peat swamp, epiphytes ($F = 67.12$, $df = 1,13$, $p < 0.0001$), moss ($F = 101.16$, $df = 1,13$, $p < 0.0001$), bole vines ($F = 45.19$, $df = 1,13$, $p < 0.0001$), and hanging vines ($F = 120.87$, $df = 1,13$, $p < 0.0001$) were all less common in burned transects than unburned transects. Epiphytes ($F = 10.61$, $df = 1,13$, $p = 0.007$) and moss ($F = 15.08$, $df = 1,13$, $p = 0.002$) were more common in the degraded burned peat swamp than in the less degraded burned peat swamp at Tanjung Puting.

## Recensus of Post-burn Transects at Tanjung Puting National Park

The same transects at Tanjung Puting were revisited approximately 8 months after the first survey (nine months following the fire), in July 1998. There was a further large decline in both number of tree stems (> 10 cm DBH) and number of tree species in both burned and unburned sites (Figure 3). The number of stems decreased by 34.7% between surveys in burned transects within the park. Outside the park, in areas burned and logged, the number of stems remaining decreased by 38.4%. In contrast, stem number declined by only 4.9% in unburned areas during the same time. In the first survey, average number of stems in the unburned areas was more than 3 times that of the burned and the logged and burned areas.

Tree species richness was reduced by 35.2% in burned areas, but only by 15.8% in the logged and burned areas. Unburned areas had a 3.3% reduction in number of species. Whereas burned areas had 54 species in the first survey, burned and logged areas had only 19 species. This compares with 61 species in the unburned areas. At each site, the most abundant species was *Ganua motleyana* (Sapotaceae). Only two other species, *Mangifera* sp. (Anacardiaceae) and *Lophopetalum javanicum* (Celastraceae), were common to all three sites, but they varied in their position among the 10 most abundant species at each site.

Table 3. Soil Quality Characteristics Used to Assess the Impact of Fire At Each of the Sites in Kalimantan, Indonesia.

| Site | Burn status | # samples | C (mg/kg) | N (mg/kg) | C/N |
|---|---|---|---|---|---|
| Kutai - Prefab | burned | 15 | 1.7 | 0.2 | 11.2 |
| Kutai – Mentoko | burned | 10 | 1.7 | 0.2 | 9.6 |
| Sungai Wain | burned | 23 | 1.9 | 0.1 | 15.1 |
| Muarabu | burned | 23 | 6.6 | 0.5 | 12.0 |
| Muara Kaman- Kedang Kepala | burned | 3 | 41.9 | 2.1 | 19.7 |
| Muara Kaman – Cagar Alam | burned | 17 | 4.3 | 0.4 | 10.1 |
| **Average** | | | **9.7** | **0.6** | **12.9** |
| Kutai - Prefab | unburned | 10 | 1.8 | 0.2 | 9.8 |
| Sungai Wain | unburned | 25 | 2.0 | 0.1 | 14.4 |
| Lempake | unburned | 24 | 7.4 | 0.8 | 9.5 |
| **Average** | | | **3.7** | **0.4** | **11.3** |

Table 4. Average Environmental Quality Indicators for Each of the Sites. The Percentage of the Segments (n = 20/transect) on Transects That Showed Evidence of Each Parameter. The Number of Trees Cut and Tapped is the Average Number of Trees Affected.

| Locale | Fire | Human Disturb. | Epiphyte | Moss/ Lichen | Bole Vine | Hanging Vine | # Trees cut | # Trees tapped |
|---|---|---|---|---|---|---|---|---|
| **Burned Lowland Forest** | | | | | | | | |
| Kutai | 100 | 20 | 0 | 46 | 11 | 15 | 1.2 | 0.0 |
| Sungai Wain | 99 | 22 | 21 | 100 | 12 | 19 | 1.4 | 0.0 |
| **Unburned Lowland Forest** | | | | | | | | |
| Kutai | 0 | 55 | 8 | 40 | 63 | 85 | 0.0 | 0.0 |
| Sungai Wain | 0 | 21 | 80 | 100 | 99 | 98 | 0.6 | 0.0 |
| **Burned Limestone Forest** | | | | | | | | |
| Muarabu | 100 | 14 | 51 | 99 | 30 | 31 | 0.0 | 0.0 |
| **Unburned Limestone Forest** | | | | | | | | |
| Lempake | 0 | 27 | 93 | 100 | 96 | 95 | 0.8 | 1.6 |
| **Burned Swamp Forest** | | | | | | | | |
| Tanjung Puting - Peat Swamp | 96 | 2 | 25 | 23 | 30 | 15 | 5.2 | 0.0 |
| Tanjung Puting - Degraded PS | 80 | 40 | 54 | 53 | 20 | 27 | 8.8 | 0.0 |
| Muara Kaman - Degraded PS | 99 | 24 | 12 | 90 | 18 | 17 | 0.6 | 0.0 |
| Muara Kaman - Degraded FW | 76 | 16 | 6 | 26 | 16 | 48 | 0.0 | 0.0 |
| **Unburned Swamp Forest** | | | | | | | | |
| Tanjung Puting | 0 | 15 | 97 | 100 | 91 | 93 | 3.6 | 0.0 |

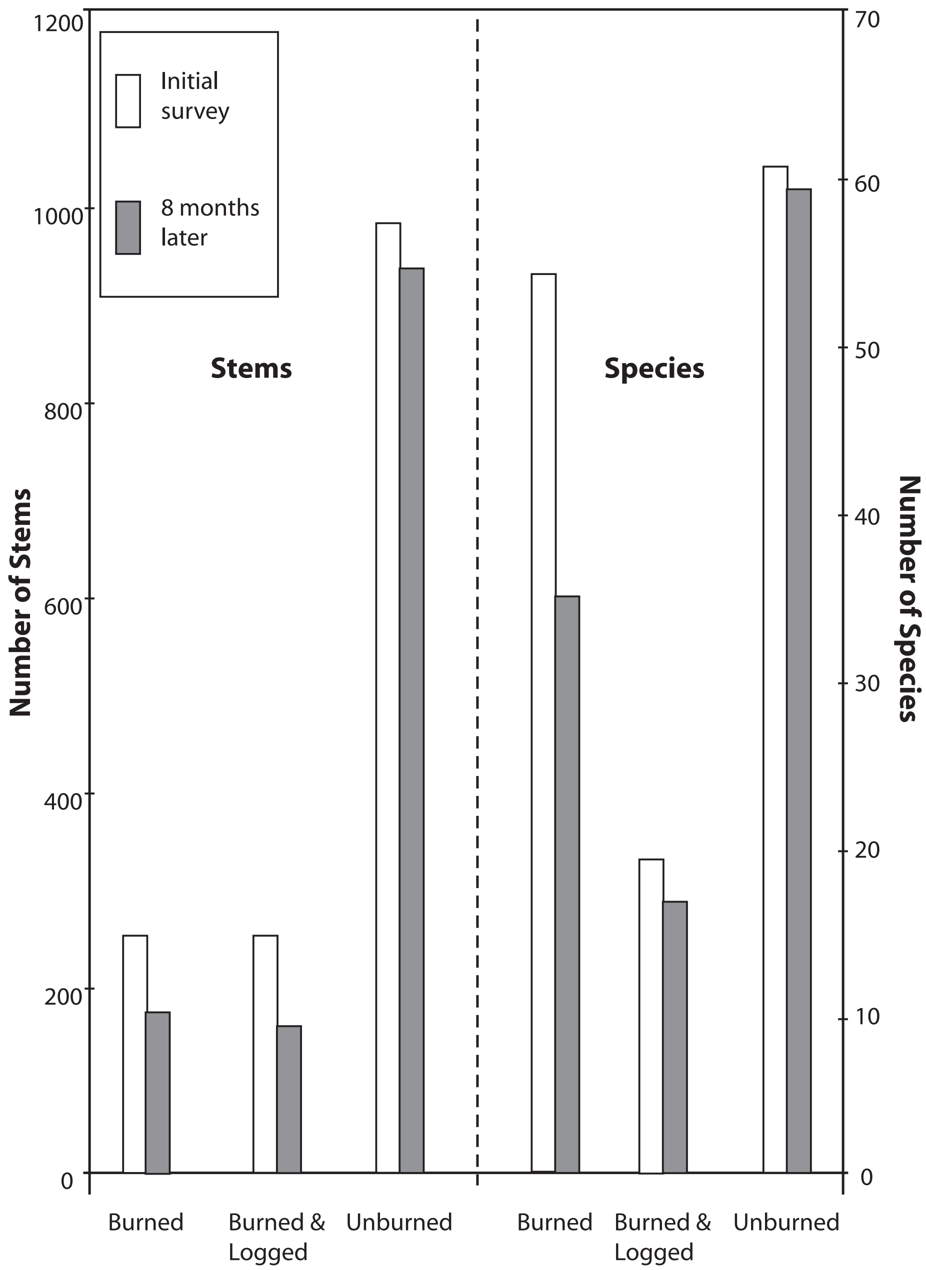


Figure 3. The Decrease in the Number of Trees and Number of Tree Species at Tanjung Puting National Park, Indonesia Over an Eight Month Period Following the 1997/1998 Fires.

## DISCUSSION

Although fires were once thought to rarely affect undisturbed tropical forests because of fuel characteristics and predominantly moist conditions (Richards, 1966; Whitmore, 1985; Goldammer and Seibert, 1990), they are becoming an increasingly common threat to tropical forests (Woods, 1989; Goldammer, 1993; Kinnaird and O'Brien, 1998; Nepstad *et al.*, 1999; Cochrane, 2002). It is now recognized that one low-intensity burn can reduce an intact rainforest canopy by an average of 40% within one year of the fire (Cochrane *et al.*, 1999; Cochrane and Schulze, 1999). This reduces humidity levels in the forest, increasing the rate and amount of drying of biomass, increasing fuel load and making the forest far more fire-susceptible than it was in its pre-fire condition (Holdsworth and Uhl, 1997; Cochrane *et al.*, 1999; Cochrane and Schulze, 1999). The forest also becomes more vulnerable to invasion by weedy vines and grasses because the natural forest seed bank is dramatically reduced and because light and humidity conditions favor the establishment of these species (Goldammer, 1999; Cochrane and Schulze, 1999; Cochrane, 2001b; van Nieuwstadt *et al.*, 2001).

We examined several burned sites in Kalimantan to provide preliminary quantitative data on the direct ecological effects of fires. The specific effects of fire varied with disturbance history and habitat type, but clear patterns emerged. At all sites, burned forest had lower canopy cover, decreased species richness, and reduced tree and sapling density than unburned forests.

### Effects of forest type and disturbance history on severity of burn damage

While fire was clearly detrimental to the diversity and structure of the forests, the severity of the impact varied depending on forest type and history of degradation. Peat forests were affected more seriously by fire than other lowland forests. Peat swamps are composed of high volume, low density layers of decomposing plant material and sediment (Ellery *et al.*, 1988). They can be several meters thick and thus provide a continuous fuel source with few barriers to fire. Because of the conditions in peat swamps, the rates of combustion and fire spread are slow. For this reason, peat swamp fires can burn for long periods; in some cases, decades. In addition, the low density of peat leads to low density ash, which can easily be lifted into the air producing large volumes of smoke (Ellery *et al.*, 1988). Peat fires can also burn both above and below the surface and thereby eliminate both above- and below-ground vegetative structures and destroy the seed bank (Ellery *et al.*, 1988).

Seed banks may partially counteract the loss of tree abundance and species over the longterm, but van Nieuwstadt *et al.* (2001) documented that the 1997/1998 fire at Sungai Wain killed 85% of the dormant seeds in the litter layer and over 60% of the seeds in the upper 1.5 cm of soil. They conclude that those seeds that were not killed immediately germinated, contributing to high seedling density 4 months after the fire. The number of seedlings present in lowland dipterocarp forests after burning suggests that seed banks may help to restore local biodiversity in this habitat, although the density of viable seeds remaining in the soil is greatly reduced. However, because seed banks are often destroyed in subterranean peat fires they are unlikely to provide a buffer in this habitat.

Although seedling and sapling densities in burned peat swamp areas were lower than in unburned areas, no significant difference in seedling density was found between burned and unburned lowland dipterocarp forest; however, there may have been large differences in the composition of the seedling community. Kennard and Gholz (2001) attributed seedling success following high-intensity burns to increased concentrations of soil nutrients. Our results show no significant differences in soil nutrients between burned and unburned areas, which may be due to rapid declines in nutrient concentration levels after the initial period of increase (Kennard and Gholz, 2001). Given past findings documenting increases in soil nutrients after fires (Riswan and Hartanti, 1995), this finding should be viewed with caution. Sapling density in burned lowland dipterocarp areas was lower than in unburned areas. Thus, the seedling density in burned areas of lowland dipterocarp forests may be a result of seed germination from the remaining seed bank, as well as reduced competition.

Degradation history of a forest also determines the severity of the effects of fire (Woods, 1989; Slik *et al.*, 2002). In peat swamp, areas that had burned only once retained over a third of their stems, and therefore had reasonable potential for recovery. Areas that burned twice had only approximately 5% of their tree stems remaining, and areas burned more frequently had almost no trees remaining. These results indicate that areas that burn only once may be able to largely recover forest structure within a few decades, provided there is no further degradation. Areas that burn two or more times may not recover their original structure and may be degraded into grassland or shrub habitats (Goldammer, 1999). The number of times an area burned may have been influenced by the history of logging and other activities. Peat swamp areas that burned multiple times had also been logged. These areas showed dramatically lower stem density and diversity relative to areas that had only burned once and had very little or no logging history.

The degradation history of a forest also affects the impact of fire on lowland dipterocarp forest. The impact of fire seems to have been greater at Kutai than at Sungai Wain. Both sites burned in 1982/1983 and were somewhat degraded through logging. In both areas, transects were located inside the park. However, in addition to previous fires, illegal logging, farming, and mining activities have degraded large portions of Kutai. Our results show that whereas anthropogenic disturbance was fairly even in the burned areas in both parks, it was nearly 3 times more prevalent in the unburned area of Kutai than the unburned area at Sungai Wain. Kutai may have already been more degraded and thus more vulnerable fire.

## Longer-term effects of fire

A re-survey of the burned transects at Tanjung Puting showed that approximately an additional third of the trees that burned in the peat swamp died during the eight months following the fires. This highlights the importance of repeated assessments of mortality, and suggests that the mortality values recorded after the fires in the other locations may substantially underestimate the true impacts of fires (Holdsworth and Uhl, 1997, Kinnaird and O'Brien, 1998, Cochrane *et al*., 1999). It should be noted, however, that mortality during this period was unusually high in all parts of the forest. Approximately 5% of the trees in the non-burned control transects also died during these eight months, compared to normal mortality rates for the area of approximately 1% per year (Yeager, unpublished data). We assume that the general increase in tree mortality was due to the drought stress associated with the 1997 El Niño climatic oscillation event.

## Implications for Indonesia/Conservation Recommendations

Approximately 10% of the world's remaining tropical forests are found in Indonesia (FAO, 2001). These forests are home to some of the world's richest biodiversity (MacKinnon *et al.*, 1996). Despite their global importance, these forests are disappearing at an alarming rate. Official estimates from the early 1990s indicate that there were approximately 92 to 113 million ha of forested land in Indonesia (GOI, 1991); however, in 1997 the World Resources Institute reported that only 53 million ha of forest that had not been recently disturbed remained (Bryant *et al.*, 1997). Indonesia's forests are currently disappearing at a rate of 1.5 to 2 million ha annually (Bryant *et al.*, 1997; Barber and Schweithelm, 2000). Fire often plays a critical role in forest loss. Areas often experience a chain of events (e.g., intensive logging, inequitable land allocation, population migrations) of which fire is one of the last that leads to forest conversion. Fire also plays a central role in inhibiting forest regeneration. Thus, it is crucial that the long-term implications of forest fires be considered.

Large scale fires are likely to be a serious threat to Indonesia's forests over the next decade because of the positive feedback loops associated with forest fires (Cochrane *et al.*, 1999, Laurance and Williamson, 2001; Nepstad *et al.*, 2001). Fires encourage drought by releasing smoke into the atmosphere, reducing rainfall, and increasing fire risk (Cochrane *et al.*, 1999; Nepstad *et al.*, 2001). In addition, repeated fires have been shown to convert forest to grassland (Cochrane *et al*., 1999; Goldammer, 1999). This increases albedo, thereby decreasing water vapor flux to the atmosphere, which results in lower rainfall (Nepstad *et al.*, 1999). This effect may be amplified in Indonesia, where large expanses of peat forest in Central Kalimantan have been drained for rice agriculture. Fire also increases the fuel load and dries the forest floor, increasing fire susceptibility (Holdworth and Uhl, 1997; Cochrane et al., 1999; Cochrane, 2001). Previously burned or logged areas have large amounts of dead, dry wood. There is also evidence that the frequency of El Niño southern oscillations is increasing (Goldammer and Price, 1998).

Both the economic and ecological costs of future fires in Indonesia will be enormous. Many of the most severe ecological costs of this destruction, such as the loss of biodiversity, loss of a large portion of Indonesia's remaining population of wild orangutans, and the long-term health costs are impossible to adequately valuate (Barber and Schweithelm, 2000). Indonesia has more than 53% of the world's remaining tropical peatland (Radjagukguk, 1997), and over 99% of these peat forests are in Sumatra, Kalimatan, and West Papua. Our results show that they may also be the most vulnerable to destruction by fire.

Special care should be taken to protect or rehabilitate areas that have burned once. After one fire, forests still have fairly high tree density and potential for forest regeneration, but a second burning can degrade them further, potentially irreversibly. Peat swamps appear to be particularly damaged by repeat burns. These forests may warrant special protection since rehabilitation of peat swamps is likely to be extremely difficult, and may not be even be possible in some areas, given that peat can only develop over extremely long periods of time.

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