Peat fires in Central Kalimantan, Indonesia: Fire impacts and carbon release

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Abstract

During 1997 and 1998 intensive land irrigation and clearance activities in Indonesia, combined with a greatly extended ENSO-related dry season, created conditions for several months of forest fires. Fires were particularly intense in the lowland peatlands of Kalimantan and Sumatra where both forest and peat fires occurred. Impacts of fire on peat swamp forests were investigated in a 25,000 km^2 (2.5 MHa) study area in Central Kalimantan using LANDSAT TM/ETM and ERS-2 radar satellite images. By combining data from remote sensed images with field measurements, it has been possible to determine fire impact, carbon storage in the peatlands and carbon emission by fire. Results indicate that 32 % of the study area has been fire affected (796,906 ha); the largest scars are in areas impacted by logging, forest clearance and peatland drainage. Systematic peat drillings showed that huge amounts of carbon are stored in this tropical peatland suggesting that the contribution of tropical peat to the global resource is much greater than thought previously and could be as much as 20-30% of the total. Carbon emissions from peat and forest combustion have been also significant on a global scale. A conservative estimate suggests that the thickness of peat lost by combustion during the fires averaged 0.40 m over the study site n resulting in approx. 3 Billion m^3 of burned peat. Total carbon losses from the 1997 peatland fires in the study area are estimated to be in the range 0.218 to 0.491 Gt C, with the greatest contribution of atmospheric CO_2 derived from peat rather than forest combustion.

Introduction

Central Kalimantan has one of the largest areas of tropical peat swamp forest (PSF) world-wide (Rieley et al., 1996). Up to the beginning of the 90ies large areas of pristine PSF remained. In 1996 a giant land-use conversion project was initiated by the Indonesian government in order to develop 1 Million ha of wetlands (mostly PSF) into fields for rice cultivation and transmigration (Mega Rice-Project, MRP) (Notohadiprawiro, 1998). Between January 1996 and July 1998 more than 4400km of irrigation channels were laid out in the peat swamp (**Fig. 1**). Because topography and hydrology of the peatland were not sufficiently considered beforehand and sluices not properly planned, the peatland was severely drained by these channels (**Fig. 2**).. This situation was aggravated by the 1997 El Nino. Central Kalimantan was the major region in Indonesia where peatlands were on fire. The dry season spanned six months from mid May to end of October 1997 during which there was hardly any rainfall. Hundreds of fires were started in order to clear deforested land of vegetation. After removal of the commercial timber, the remaining tree debris was removed by means of fire as the cheapest, most readily available land clearance tool. Many of these fires spread into forest areas where they burned with greater intensity and both the surface vegetation and underlying peat were ignited.

Several assessments have been made of the amount of land in Indonesia that was damaged by the 1997 fires (Barber & Schweithelm, 2000). Initial estimates indicated that approximately 3.06 Mha were affected (Liew et al., 1998), but this was increased subsequently to 6.5 Mha (BAPPENAS, 1998) and 13.18 Mha (Fuller & Fulk 2001). Of this latter area, at least 1.4 Mha was peatland that was either in a natural condition supporting peat swamp forest, degraded peatland with secondary vegetation, or agricultural land of farms and plantations on drained peatland. Two of the most intensive sources of smoke and particulate matter reaching the atmosphere were the fires centred on the peatlands of Central Kalimantan and South Sumatra (Ref.). In both of these areas vegetation and underlying peat caught fire, contributing greatly to the so-called haze (particulate-laden smog) that drifted across SE-Asia. It is estimated that the fires resulted in over US$ 9 billion in damage from losses in agriculture, timber, non-timber forest products, hydrological and soil conservation services, and biodiversity benefits, whilst the haze cost an additional US$ 300 million, most of which was borne by Indonesians for health treatment and lost tourism revenues (BAPPENAS, 1998).

The objectives of this investigation were to provide more accurate estimates of the area and fire impact on the vegetation of fire affected peatland within Central Kalimantan, encompassing near-pristine, forested peatland and degraded and drained peatland, to quantify carbon emissions by this fire disaster and to elucidate some of the environmental consequences of the fires. A combination of remote sensing, GIS and field checking and field measurements was employed. The pre-fire land cover and burned area was derived from a Landsat TM images. The burned area was also assessed from images acquired by the European ERS SAR radar satellite. Information from radar was necessary to reliably assess the burned area, because active microwave systems are able to penetrate haze and clouds which hamper optical satellite systems. Field measurements included peat drillings to determine peat depth and the thickness of the burned peat layer. Some of the environmental impacts of the fires are discussed and predictions are made concerning the future sustainability of tropical peatland in Kalimantan.

Methods

The pre-fire vegetation cover was derived from a Landsat TM image acquired in May 1997 (Landsat TM 5, 118-62, 29.5.1997), the burned area from the first relatively cloud free Landsat TM image acquired after the end of the fires (Landsat TM 5, 118-62, 29.3.1998, **Fig 2A**). Standard methodologies were employed for Landsat TM image processing, geometric correction, signature analysis and change detection. Interpretation of Landsat TM images (canals 1-5) was done by visual on-screen digitising at scale 1:100,000 (minimal mapping unit 50 ha). The interpretation key for land cover and burned surfaces was established from GPS recorded ground observations. The pre-fire land cover assessment was adapted to the TREES classification scheme (Stiebig et al., 2000) Fire scars were also mapped in a multittemporal image product in which ERS-1/2 SAR images acquired before and after the fire were combined into a single colour image suitable for visual interpretation (**Fig 2B**). When fire affects vegetation during dry weather conditions there is a significant decrease in ERS radar backscattering depending on the type of vegetation and the fire damage (Siegert & Ruecker, 2000). The ERS AMI instrument detects structural features of the earth's surface (volume scattering) and the moisture content of the vegetation (dielectric properties) (Ulaby et al., 1986). Fire decreases both. Volume scattering decreases, because fire consumes vegetation and moisture content decreases because fire damaged plants lose their foliage. Furthermore, the opened canopy and the reduced leaf biomass allow more backscatter from the exposed ground surface. A mosaic of 6 ERS images was made out of 12 ERS-1/2 images (frames no. 3645,3663; orbits 07873, 11652,12110, 12883, 13112, 32828 (ERS-1)) acquired before the fires (beginning of July 1997) and towards the end of the fire season (October 1997). Images acquired after rains had started again (November 1997) were not suitable because surface water in swamps disturbed burnt scar detection.. The bi-temporal ERS SAR mosaic was visually interpreted at scale 1:200,000 (minimal mapping unit 100 ha). Two damage classes were defined based on the estimated percentage of dead trees: 1.) 50-80% trees dead and 2.) > 80% trees dead. All satellite images were integrated into a Geographical Information System for further quantitative analysis. The area was confined to the overlapping region in all RS data sets (25,000 km^2). NOAA AVHRR (Advanced Very High Resolution Radiometer, 1km spatial resolution) hotspot data was used to discriminate fire and drought effects in radar images (siegert & Hoffmann, 2000). An area was scored as burned only when there was 1.) a clear decrease in backscatter or 2.) a weak decrease in backscatter in conjunction with NOAA-AVHRR hotspots. Extensive ground-truthing had been carried out prior to the fires in order to check image classification of land-use and vegetation. Post-fire ground-truthing within the study area was carried out both on foot or boat and by low level aerial reconnaissance to verify the existence and magnitude of burn scars. All ground and aerial survey routes were recorded by GPS in continuous track mode and stored in the GIS (**Fig 1**). In the field a laptop computer and a software was used which allowed to visualize the current position as determined by the GPS on the laptop screen superimposed onto the satellite images and interpretation results.

The depth of the peat layer was assessed on more than 100 locations in Block C of the MRP area (**Fig 4B, left**). All drillings were made along the new canals (the only way to access the heavily burned peat swamp forest) at regular intervals of 500m. Both, peat depth and surface level were measured. This data was used to calculate peat volume and carbon storage. The thickness of the peat layer destroyed by the fires was estimated on the basis of tree trunks and their remaining root system (**Fig 4A**). Measurements of CO2 emissions in exposed, deforested peatland were done over two years. An infrared gas analyser based method was used for in situ determination of CO_2 emissions on 20 cm diameter study plots, cleared from green vegetation (Vasander & Jauhiainen, 2001). A cylindrical aluminium chamber with a flexible synthetic-rubber sealing was placed over a selected study plot and air from the chamber-covered area circulated between the CO_2 analyser (PP Systems, model EGM-2) and the chamber. A battery-powered fan mixed sample air and prevented formation of concentration gradient inside the chamber. Carbon dioxide flux rate is detected as a linear increase in chamber CO_2 concentration during measuring period of 4 minutes, and in calculus it is proportioned to area and time.

Results

The first relatively cloud free post-fire Landsat TM image from the study site was available only 6 months after the fires. It shows that the MRP area was most severely affected by fire **(red colors, Fig 3A)**. **Figure 3B** shows the corresponding area in the

ERS SAR change detection mosaic: burned areas appear in yellow, orange and brown colours, depending on fire impact and time period of burning. There is a good agreement in burnt scars detected by Landsat TM and ERS SAR (**Fig 3A,B**). However, some areas identified as being burned in the ERS SAR mosaic appear unburned in the Landsat TM image (lower right in **Fig 3A,B**) or are covered by clouds and haze. Comparison with NOAA AVHRR hotspots indicated that in these areas fire actually occurred. The pre-fire land cover classification indicated that these areas were mainly agricultural areas, fallow land and not forests. We conclude that sparse vegetation (grass and bush lands) escaped detection by Landsat TM due to fast regrowth of vegetation within the six month period. On the other hand, some fire scars escaped detection by ERS SAR, because they were afire after the ERS imagery has been acquired.

The total burned area as derived from the combined evaluation of Landsat TM and ERS-2.was calculated to be 796,906 hectares (32 % of the total study area, **Fig 3C**). Of these 82% had total damage (>80% trees dead). Figure 2D shows the Landsat TM derived land cover map. !6 different land cover classes were discriminated (**Fig 3D**). Peat swamp forests were classified into four different groups depending on the degree of canopy closure (**Table 1**). A canopy closure >70% indicates undisturbed pristine peat swamp forests, a canopy closure of < 70% indicates that these forests have been disturbed by previous logging operation or small scale land clearing activities. The intersection of the burnt scar map with the pre-fire land cover classification showed that almost half of the burned area was peat swamp forest (closed, open, fragmented: 47,4%, **Table 1**). Other vegetation types strongly affected by fire included forest mosaics, fallow land and bush land. If one considers the burned area per land cover as percentage of the total area covered by this land cover (**Table 1**, column 4) it becomes evident that previous disturbance of the forests by logging increased fire impact. 70% of the fragmented and 58,6% of the open peat swamp forests have been destroyed by the fires, while closed (pristine, type A) peat swamp forest had only 4,5% damage. Periodically inundated freshwater swamp forests near rivers were hardly affected. Severe damage occurred also in forest mosaics (54%) and bush land (45.2%). The spatial pattern of fire occurrence shows that largest fire scars are located in areas drained by the recently established irrigation canals. The large block of undisturbed forest of the Sungai Sebangau catchment.(left in **Fig 3A,B**) shows only some scattered fire scars in areas where intense logging occurred previously.

Field surveys of burned areas in Block C revealed a loss of surface peat from a minimum of 0.20 m to a maximum of 1.50 m (**Fig. 4A**). A conservative overall estimate suggests that the thickness of peat lost by combustion during the fires averaged 0.40 m over the extensive peatland areas of the study site. In some locations the intensity and duration of the fires, as a result of both surface and sub-surface fires, was such that a much greater thickness of peat, from 1.0 m to 1.5 m, was removed. By applying two estimates for the thickness of peat burned away (0.40 m and 1.00 m) lower and upper limits to the total volume of peat lost from the fire damaged areas (**Table 2**) have been calculated. The range of total carbon lost from combusted peat within the study area is obtained by combining these data with an average value of 57% for peat carbon content and 0.10 g cm^{-3} for peat bulk density (Neuzil, 1997).

Assuming that all of the peatland areas that burned also supported peat swamp forest the amount of carbon lost to the atmosphere in the combustion of above-ground biomass could have amounted to between +50 to 100 t C ha-1. These values are derived from the assumptions that (1) pristine peat swamp forest vegetation has an above ground biomass carbon content of 200 t C ha-1 (Diemont et al., 1997) and no more than 50% of the above-ground biomass was consumed by fire, (2) in degraded swamp forest logging has already removed half of the biomass and fire consumed 50% of the remaining biomass. These broad-brush estimates of the amount of timber remaining undamaged by fire are based on field observations but require more detailed investigation before accurate data can be produced. It was notable that in burnt areas many of the fallen trees showed little trunk damage but had been destabilised by the peat fires, which destroyed the root systems. The loss of carbon from combustion of above-ground forest biomass is estimated to be 0.038 Gt C. Total carbon losses from the 1997 peatland fires in the study area are estimated to be in the range 0.218 to 0.491 Gt C (**Table 2**), with the greatest contribution to emissions of atmospheric CO2 derived from peat rather than forest combustion.

To estimate the total carbon storage of the peat layer and potential future emissions by recurrent fires and peat decomposition we surveyed Block C of the MRP area and performed peat drillings in regular intervals of 500m (**Figs. 3B, 3C**). The left panel of **Fig. 3C** shows the GPS recorded location of peat drillings, the middle the surface profile and the right peat depth. Up to 12m of peat have been measured in Block C. We calculated peat volume of Block C to surpass 8 Billion m^3 of peat. Assuming a similar composition of the deposit in the whole study area the peat volume totals to 64 Billion m^3 with an average depth of 2 m to 3 m (Ref.). Measurments of CO2 emission on previously burned peatlands showed that rates varied between 216 and 404 mg m-2 h-1 depending on water level, while the average emission rate was approx. 300 mg m-2 h-1. To estimate the contribution of peat decomposition on carbon losses from the whole fire damaged area we used the average emission rate: during a one year period decomposing peat would increase the amount of carbon emissions by 4.16 Mt which equals to a total loss of peat of 1.1 – 2.5%.

Discussion and conclusions

Mapping of burn scars indicates that fire damage is proportional to the level of prior human activity and forest disturbance, with logged over and developed areas having the greatest amount of burned land. This concurs with the results of research carried out in East Kalimantan following the 1982/83 fires when heavily disturbed forest burned away almost completely, leaving very few live trees (Siegert & Hoffmann, 2000). Pristine forest, in comparison, was much less affected and, even if it did go on fire, usually only the ground vegetation was consumed leaving the middle and upper tree layers intact (Schindele et al., 1989). The problem with peatland, however, is that once fire becomes established within the peat it destroys tree root systems. As a result, most of the trees become unstable and topple over even though they may experience minimal damage to their trunks and canopies. Many of the fire scar areas detected in the remote sensed images were found to have a large amount of fallen timber scattered over the burned peat surface.

Two linked factors have, therefore, played key roles in determining the distribution of fire scars: degree of forest disturbance and lack of peatland hydrological integrity. Areas of degraded peatland experienced excessive water-table drawdown during the ENSO drought whilst, in contrast, large areas of pristine peat swamp forest, despite experiencing a significant drop in water table, were relatively unaffected by fire. The greatly reduced rainfall during the 1997 ENSO event led to a very marked drop in the level of the peat water table. At a peat water table monitoring station in peat swamp forest in the upper catchment of Sungai Sebangau, the water table fell to 98 cm below the surface in mid-November, 1997. Even so, this area was unaffected by forest fires. In comparison, the water table at this location in 1995 and 1996 remained close to the peat surface throughout the dry season with a maximum drawdown of only 20 cm. After the drought ended in December 1997 the peat water table responded very rapidly to rainfall events and returned to its normal wet season level within one month. (H. Takahashi, pers. comm.). Data on the peat water table in the drained and degraded peatlands of the mega-rice project are not available, but reports from local people suggest that the peat water table was at an extremely low level, up to 1.5 m or more below the peat surface, at the height of the ENSO-related drought (S. Limin, pers. comm.). This allowed some sub-surface peat fires to destroy a considerable thickness of peat.

In the study area, the MRP was a major location for fires because: 1.) the area was criss-crossed by an extensive system of wide and deep channels that facilitated excessive drainage of the peatland landscape (**Fig. 2**), 2.) most of the peat swamp forests had been disturbed by logging, 3.) land was cleared of residual trees and wood debris with fire as the only economic method by which to achieve this, and 4.) many people were able to access the previously inaccessible interior of this peatland landscape to exploit the residual timber resources, mostly using fire in the process.

The combustion of vegetation and surface peat resulted in a significant loss of carbon to the atmosphere of between 0.218 and 0.491 Gt C. If this figure is applied proportionately to the total area of peatland in Indonesia that was damaged during the 1997/98 fires (i.e. 1.45 Mha, this figure is probably significantly higher because 0.8Mha have been burned in our study site alone) the total emissions could have been in the region of 0.40 and 0.90 Gt C. This compares with an estimated net annual fixation in temperate peatlands of 0.10 Gt C yr-1 and for tropical peatlands of only 0.06 Gt C yr-1. These values also compare with a global annual emission from the burning of fossil fuels of 5.4 Gt C yr-1. By any level of comparison, therefore, the 1997/98 peatland fires in Indonesia were significant on both a regional and a global scale.

The peat drillings showed that huge amounts of carbon are stored in tropical peatlands. This provides a projected tropical peat carbon store of 191 Gt, which added to the boreal/temperate peat carbon store of 390 Gt, gives a revised estimate of the global peat carbon store of 581 Gt. On this basis the contribution of tropical peat to the global resource is much greater than thought previously and could be as much as 33% of the total. This is very significant because tropical peat comprises of only about 10 per cent of the global peatland area (Immirzi & Maltby, 1992; Lappalainen, 1996). Since estimates of the global soil carbon pool range from 1,000-2,000 Gt (Bohn, 1976; Schlesinger, 1984; Woodwell *et al.*, 1978) the amount of carbon in peatlands globally is a major proportion of this, possibly as much as 50%. The fires in 1997 exposed large areas of peat, which will be affected by recurrent fires and decompose by oxidation and thus will significantly contribute to global carbon emissions (Ref.).

Peat combustion also resulted in a significant loss of nutrients (lost in smoke and ash) from what is already a nutrient-deficient ecosystem. Studies of the geochemistry of tropical peat have shown that the surface 1.0 to 1.5 m have an enhanced level of several important plant nutrient elements as a result of bioaccumulation. Most of this nutrient pool has been removed as a result of the fires and this will have serious consequences for vegetation re-establishment, especially attempts at agricultural conversion programmes.

Extensive fire damage to the peat soils of Central Kalimantan will accelerate the changes brought about by drainage works. One of the most important natural resource functions of tropical peatlands at the regional scale is their role in regulating water in the landscape (Page & Rieley, 1998). The 1997 ENSO-related drought was followed by a period of above average rainfall, called La Niña. In Central Kalimantan, 1998 was an exceptionally wet year in which there was widespread flooding, particularly in and around the MRP area. These floods were worse than in previous prolonged wet seasons because removal of the forest and peatland drainage, combined with the consequences of the fires, impaired the hydrological functions of degraded peatland areas.

The prognosis for the future sustainability of the peatlands of Central Kalimantan is bleak. When the next prolonged dry season occurs, there will be a high likelihood of further fires. Since it is clear from the results presented above that fire damage increases in proportion to the level of human disturbance, and the rate of disturbance is increasing throughout the entire peatland area of Indonesia (20 Mha), the effects of future droughts and fires will be cumulative. Long-term prospects for this area are not promising even though the MRP projects has been stopped in 1998. Evidence form ground surveys and satellite imagery (own unpublished work) suggests that illegal logging has increased tremendously since 1999 thus disturbing the remaining pristine peat swamp forests.. The MRP area will experience a greatly heightened risk of fire damage during future dry seasons and flooding during rainy seasons. The question that remains to be answered is how long will it take for repeated fires on a large scale to upset the stability of the peat swamp forest ecosystem beyond the point of recovery? In its natural state, tropical peat swamp forest is in a dynamic relationship with its environment and any persistent change, particularly in climatic wetness, will have implications for its long-term stability (Page et al., 1999). In a degraded state, tropical peatlands become an increasingly fragile natural resource and highly susceptible to fire (Cochrane et al., 1999). In recognition of this, one report on fire prevention planning (BAPPENAS, 1998) suggests that all peat soils in Indonesia should be subject to special regulations on land clearance, especially that burning of any kind, including managed burning, should be strictly prohibited. The results of this study indicate that in order to prevent a recurrence of the 1997 peatland fires much more attention needs to be paid to the natural resource functions performed by large peatland landscapes.

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Table 1: Percentage of burned land covers as derived from the combined evaluation of of pre- and post-fire Landsat TM and ERS SAR images. Closed forest (type A): >70% forest cover, > 70% canopy cover; Closed forest (type B): >70% forest cover, 70% - > 40% canopy cover; open forest: >70% forest cover, 40% - > 10% canopy cover; fragmented forest: >40-70% forest cover, > 10% canopy cover; Forest mosaics: >10 – 40% forest cover, >10% canopy cover.

Land cover	**Damage [ha]**	**Total Area [ha]**	**% of land cover**	**% of burned area**
Closed, periodically inundated forest (type A)	1.196	16.821	7,1%	0,2%
Fragmented, periodically inundated forest	20.460	130.446	15,7%	2,6%
Closed peat swamp forest (type A)	9.809	217.069	4,5%	1,2%
Closed peat swamp forest (type B)	288.832	1.030.010	28,0%	36,2%
Open peat swamp forest	23.876	40.719	58,6%	3,0%
Fragmented peat swamp forest	55.297	78.955	70,0%	6,9%
Forest Mosaics, Other Vegetation & Forest	139.313	257.713	54,1%	17,5%
Swamp grassland	31.073	75.822	41,0%	3,9%
Agriculture, fallow land	109.869	302.555	36,3%	13,8%
Bush land	93.969	207.884	45,2%	11,8%
Other land cover	23.212	133.624	17,4%	2,9%
Total	**796.906**	**2.491.619**	**-**	**100,0%**

Table 2: Estimated emissions of carbon to the atmosphere from peat and vegetation combustion.

Vegetation/ land-use class	**Fire damaged area (ha)**	**Volume of combusted peat (m^3) assuming depth lost**		**Loss of C (Gt) from combusted peat* at depths of**		**Loss of C (Gt) from biomass**	**Total loss of C (Gt) - biomass + peat at depths**	
		0.40 m	**1.00 m**	**0.40 m**	**1.00 m**		**0.40 m**	**1.00 m**
Peat swamp forest	298641	1.2 x 10^9	2.99 x 10^9	0.068	0.170	0.029**	0.097	0.199
Peat swamp forest (disturbed)	218486	0.87 x 10^9	2.18 x 10^9	0.049	0.124	0.009***	0.058	0.133
Other land use classes	279779	1.1 x 10^9	2.8 x 10^9	0.063	0.159	n/a	0.063	0.159
TOTAL	**796906**	**3.19 x 10^9**	**7.97 x 10^9**	**0.181**	**0.453**	**0.038**	**0.218**	**0.491**

* calculated by applying values of 57% for peat carbon content and 0.10 g cm^{-3} for peat bulk density (Neuzil, 1997)
** calculated on the basis of 50% timber left standing and assuming a biomass carbon content of 200 t C ha^{-1} for peat swamp forest (Diemont *et al.*, 1997)
*** calculated on the basis of 25% timber left standing (same basis as above)
**** calculated on the basis of 50% timber left standing and assuming a biomass carbon content similar to that of peat swamp forest

Figures

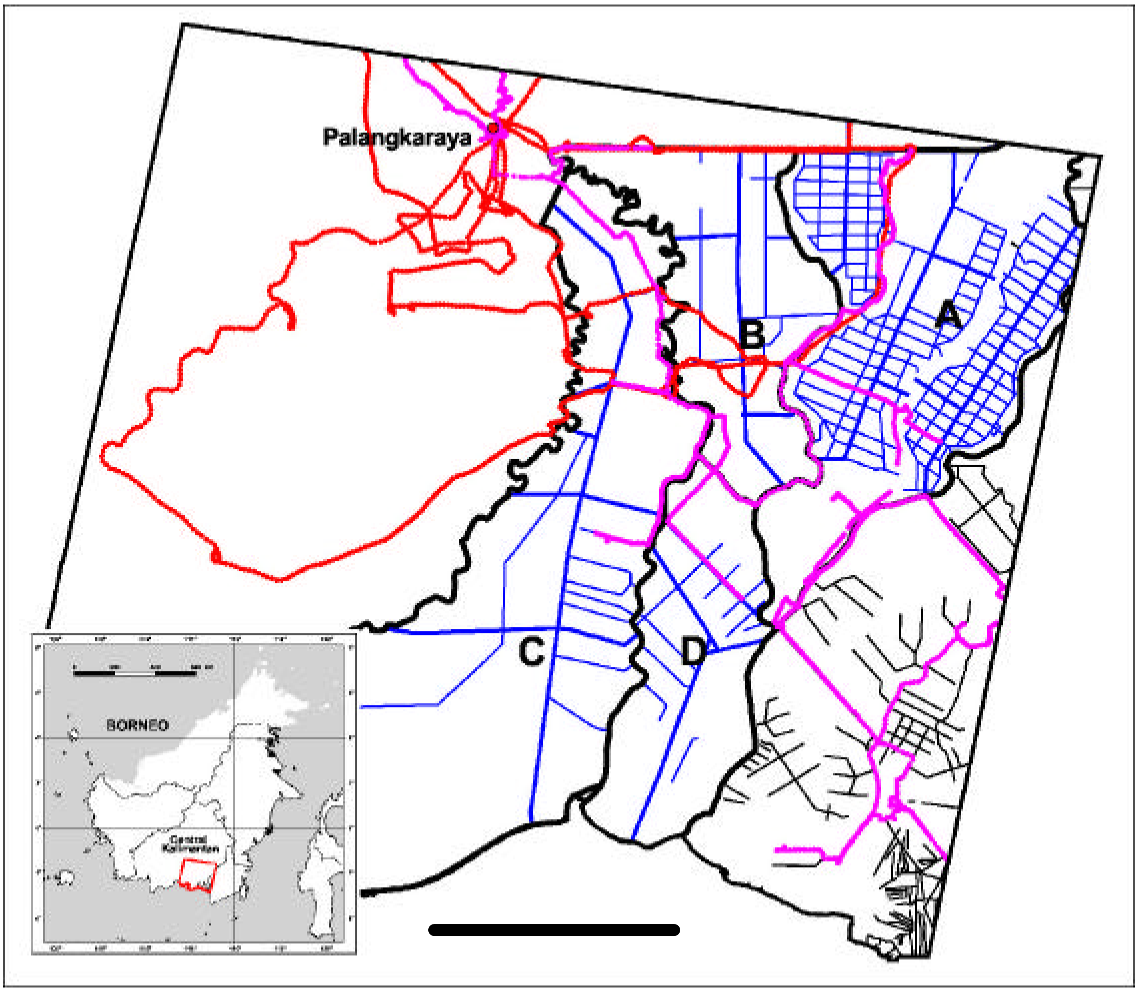

Fig. 1. Study site in Central Kalimantan, Indonesia, on the island of Borneo (insert). Thick black outlines: Blocks A, B, C, and D of the MRP area. Blue: irrigation channels made between 1996 and 1997, black: old irrigation channels. Superimposed: GPS tracks of ground surveys (purple) and aerial surveys (red). Bar: 50 km.

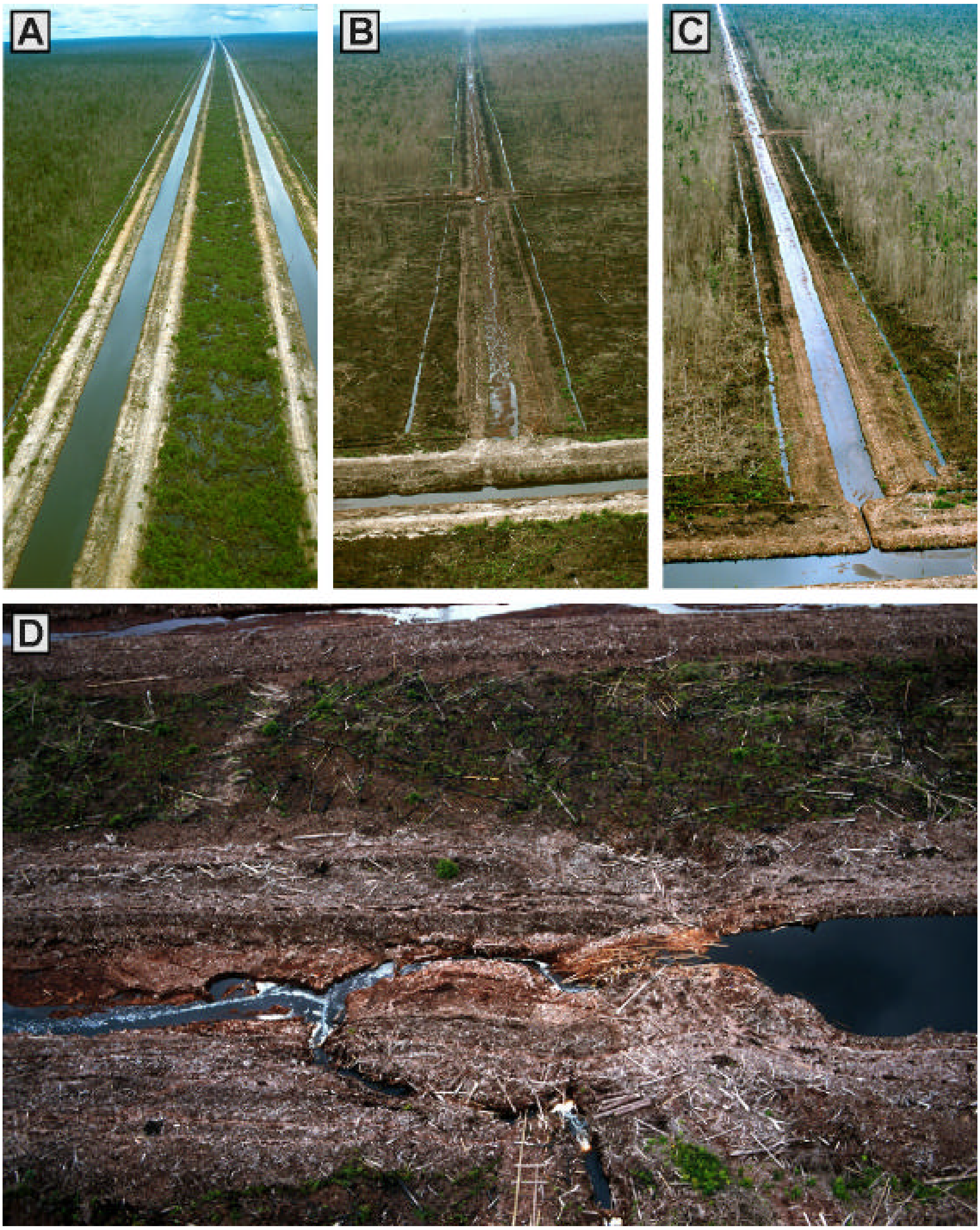

Figure 2. Aerial photographs of the MRP irrigation channels. **A.** Main channel 110 km long and 2 x 15meters wide. **B**. Drained side channel and **C**. side channel filled with water. The total length of the side channels exceeds 4200km. **D.** A dam made of peat opened by locals to extract timber from the MRP area. Proper sluices never have been built.

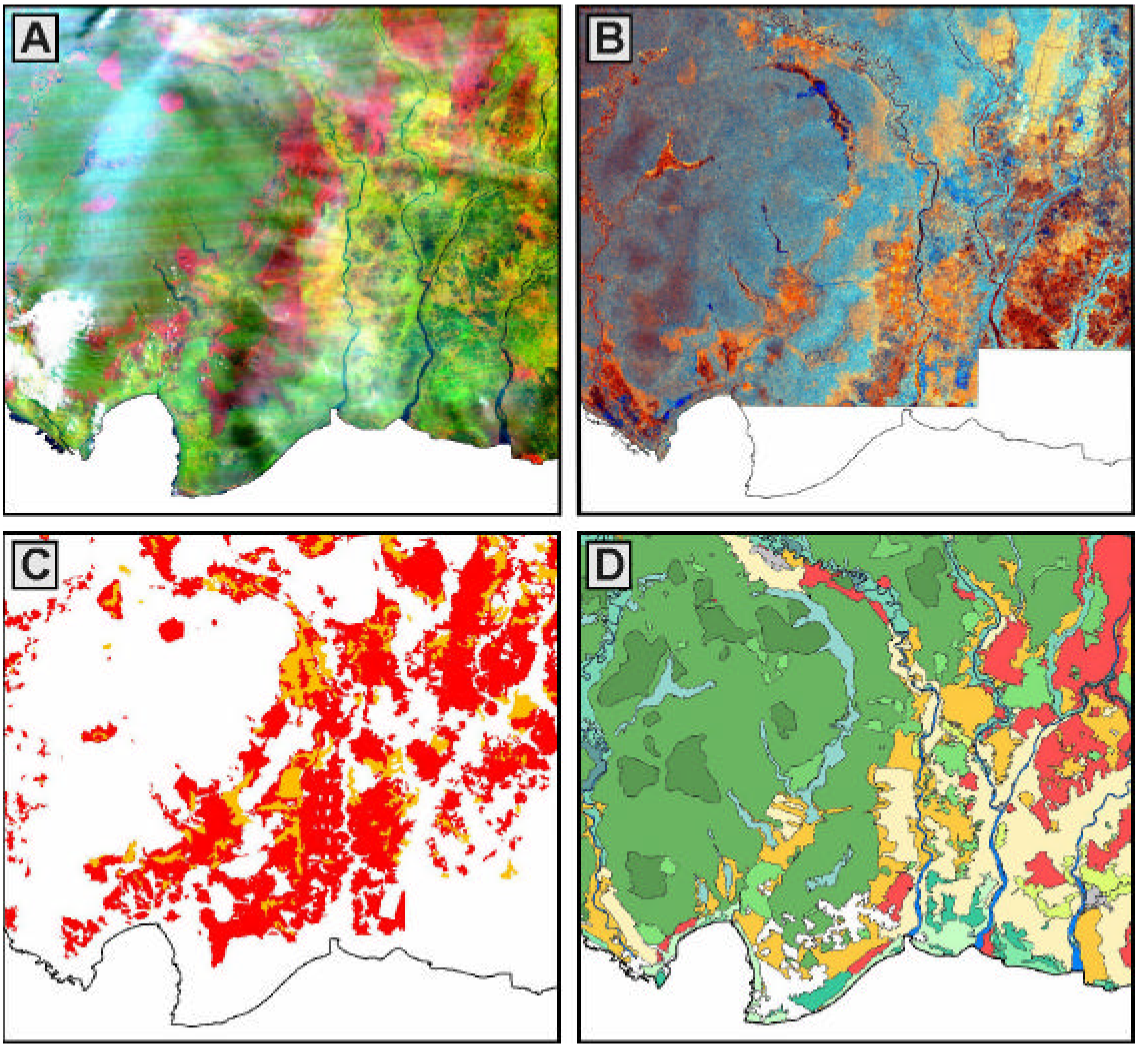

Figure 3. Burned area assessment in Central Kalimantan peatlands based on satellite imagery. A: Landsat TM image acquired 6 Month after the fire. Green: unburned forest, red: burned forest (>80% trees dead). **B.** Mulitemporal ERS-mosaic made from radar images acquired before fire and after the fires in 1997. Yellow and orange colors: burned forest **C.** Mapped fire scars. Red: total damage (>80% trees dead), orange: severe damage (50-80% trees dead) **D.** Pre-fire land-cover map: green shades: peat swamp forest, orange colors: severely disturbed peat swamp forest, red: forest mosaics, bush and grass lands, beige: agriculture and fallow land.

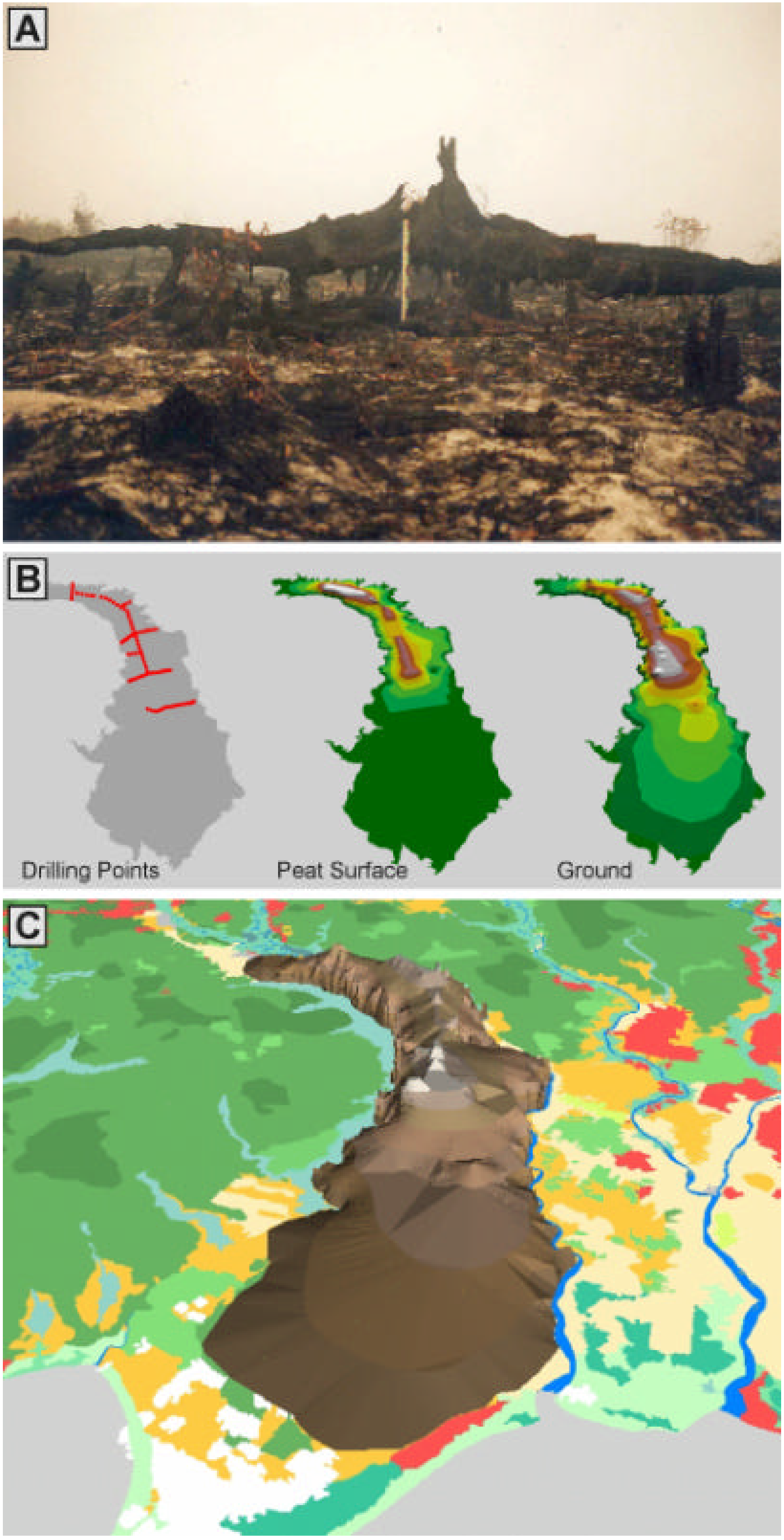

Figure 4. Assessment of peat depth and volume in block C of the MRP area. A. Burnt peat swamp forest. 70cm of peat have been consumed by the fire, as can be seen from the uncovered root system. **B.** GPS measured location of peat drillings (left), surface profile (green: 0.5 – 1m, white 7-8m, middle) and peat dep (right). **C.** Three-dimensional representation of peat volume and surrounding vegetation cover.

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