Journal of Forest Research

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/tjfr20

Effects of fire on tree species composition and carbon stocks of a peat swamp forest in Central Kalimantan, Indonesia

Laode Alhamd, Siti Sundari, Francis Q. Brearley & Joeni Setijo Rahajoe

To cite this article: Laode Alhamd, Siti Sundari, Francis Q. Brearley & Joeni Setijo Rahajoe (2025) Effects of fire on tree species composition and carbon stocks of a peat swamp forest in Central Kalimantan, Indonesia, Journal of Forest Research, 30:1, 42-48, DOI: 10.1080/13416979.2024.2389990

To link to this article: https://doi.org/10.1080/13416979.2024.2389990

JOURNAL OF FOREST RESEARCH
2025, VOL. 30, NO. 1, 42–48
https://doi.org/10.1080/13416979.2024.2389990

ORIGINAL ARTICLE

OPEN ACCESS Check for updates

Effects of fire on tree species composition and carbon stocks of a peat swamp forest in Central Kalimantan, Indonesia

Laode Alhamd [a], Siti Sundari [a], Francis Q. Brearley [b] and Joeni Setijo Rahajoe [a]

[a]Research Center for Ecology and Ethnobiology, National Research and Innovation Agency (BRIN), Jalan Raya Jakarta Bogor Km. 46, Cibinong, Indonesia; [b]Department of Natural Sciences, Manchester Metropolitan University, Manchester, UK

ABSTRACT

Peat swamp forests are important in the global carbon (C) budget because of the huge amount of C stored in these ecosystems, particularly in below-ground components. Indonesia has some of the greatest extent of peat swamp forests globally, yet many of them are being disturbed by fires that are becoming increasingly frequent. In Kalampangan, Central Kalimantan, the tree species (≥4.8 cm diameter) composition, aboveground biomass (AGB) and litter standing crop of peat swamp forests were sampled, and the overall ecosystem C stock estimated, within two 1-ha sampling plots, one of which was undisturbed (natural) and the other previously burned. The AGB and litter standing crop found in the natural forest totaled 341 and 6.77 Mg ha^{-1}, respectively. The AGB declined more than six-fold to 53.2 Mg ha^{-1}, and the litter standing crop declined by about half to 3.30 Mg ha^{-1} in the disturbed forest; the total number of tree species declined from 114 to 80 per hectare. The disturbed peat swamp lost just over 200 Mg C ha^{-1} to the atmosphere due to the combustion of tree biomass and the upper layer of the peat, but C stocks still remained very high overall (c. 1100 Mg ha^{-1}) due to the thick layer of peat (>2 m) making peat swamp forest conservation imperative due to their huge carbon stocks.

ARTICLE HISTORY
Received 15 September 2023
Accepted 5 August 2024

KEYWORDS
Aboveground biomass; carbon; Central Kalimantan; litter; peat swamp forest

Introduction

Tropical peat swamp forests are unique ecosystems that play a crucial role in carbon (C) storage and water regulation, but they are fragile and vulnerable to disturbance, particularly fires. Indonesia has approximately 13.4 million ha of peat swamp forest, with Sumatra (5.85 million ha), Kalimantan (4.54 million ha) and Papua (3.01 million ha) hosting the majority of these forests (Anda et al. 2021). Indonesian peat C stocks were approximately 57.4 Gt, equating to about three-quarters of the total soil C pool of the country (Page et al. 2011). Since the 1960s, illegal logging, drainage, changing land uses such as plantation development, and fires have all contributed to the degradation of tropical peatlands releasing large amounts of carbon dioxide (CO_2) to the atmosphere (Page et al. 2002). More recently, since the 1990s, peat swamp forests in Kalimantan have undergone rapid and extensive deforestation (Page et al. 2009; Murdiyarso et al. 2010; Posa et al. 2011; Miettinen et al. 2012). Now, the increasingly frequent fires, including in 1997, 2002, 2006, 2015, and 2019 related to the El Niño-Southern Oscillation (Nurdiati et al. 2022), are majorly disrupting the dynamics and recovery of peat swamp forests. This is because fires lead to extensive changes in the forest habitats, microclimate, soil properties, biogeochemical cycling, and the presence of wildlife (Kinnaird and O'Brien 1998; Yeager et al. 2003; Simbolon 2004; Simbolon et al. 2004; Slik and van Balen 2006; Sazawa et al. 2018), in addition to human health (Hein et al. 2022) with forests that have burned being more susceptible to burning in the future. Forest structure (i.e. number of trees and their size distribution) is also altered by forest fires in peat swamp forests and, as a result, this will have an impact on their capacity to store C.

One of the mitigation strategies for increasing global CO_2 emissions is to reduce tropical forest degradation and deforestation, with the Indonesian government promising to cut CO_2 emissions by up to 41% by 2030 in support of the Paris Agreement (Ministry of Environment and Forestry 2022). Non-sustainable drainage-based peatland management accounts for the majority of CO_2 emissions. As a result, paludiculture programs (swamp cultivation) have been proposed to mitigate the problem by planting beneficial peat swamp forest species that do not require drainage and may offer a sustainable and economically viable alternative (Giesen 2015, 2021). Either way, more sustainable use of peat swamp areas is urgently required if these key ecosystems are to remain as essential C stocks into the future (Wijedasa et al. 2016).

Above-ground biomass (AGB), litter (and deadwood), and soil organic matter are the three main pools of stored C in peat swamp forests. Organic matter includes litter, which is the remains of dead vegetation or dead materials such as wood, on the soil surface. The production of vegetation biomass requires the nutrients from the dead organic matter that are released during the decomposition process (Proctor et al. 1983; Aerts and Chapin 2000). However, there are few reports of litter production, or litter standing crop, in the peat swamp forest despite these being important for nutrient cycling (Rahajoe and Kohyama 2003; Basuki et al. 2019).

CONTACT Laode Alhamd laod003@brin.go.id Research Center for Ecology and Ethnobiology, National Research and Innovation Agency (BRIN), Jalan Raya Jakarta Bogor Km. 46, Cibinong, Indonesia
Supplemental data for this article can be accessed online at https://doi.org/10.1080/13416979.2024.2389990

There have been a numerous studies done in the peat swamp forest of Kalimantan, yet comparative ecological studies that examine species diversity, AGB, litter, and their C stocks are still few as most studies focus on only one of these aspects. The majority of these previous studies focused on forest structure and floristics, species distribution in relation to peat depth, and changes in species composition after degradation (Simbolon 2008; Mirmanto 2010; Astiani 2016; Freund et al. 2018; Volkova et al. 2023). In the peat swamp forest of Kalampangan in Central Kalimantan, the objectives of this current study are to extend earlier studies by focusing on the change in tree species composition following fires, and to link this with AGB and litter production, using a permanent sampling plot methodology combined with estimate of the whole ecosystem C stocks, to determine how fires affect forest ecosystem diversity and functioning.

Methods

Study site

The study was carried out using two 1-ha sampling plots at Kalampangan in Central Kalimantan's peat swamp forest. One plot was considered "natural" as, to the best of our knowledge, it had not been altered by logging or fire, and the other was a disturbed forest that had burned in 2015 and was 4 years post-fire at the time of the study in 2019. The plots were separated by about 1 km and centered on 114° 2′ E and 2° 21′ S (Figure 1). Histosols were the major soil group (Taufik et al. 2019). Mean annual precipitation ranged between 2750 and 3610 mm per year (2015–2020; Meteorology & Climatology Station of Tjilik Riwut, Central Kalimantan) with the drier season lasting from June to October.

Field sampling

Based on a survey of the uniformity of the vegetation, two representative plots of peat swamp forest were enumerated using sampling plots of 1 ha (100 m × 100 m) in natural forest near Sebangau National Park and in an adjacent disturbed forest. Each plot was subdivided into 100 subplots measuring 10 m × 10 m. The height and diameter at breast height (1.3 m; DBH) of all trees ≥4.8 cm DBH were measured (or above buttresses as appropriate), they were numbered, and their coordinates were recorded. From the base to the top of the trunk, a telescopic pole was used to measure each tree's height. The Herbarium Bogoriense, Research Center for Ecology and Ethnobiology, BRIN, identified species as needed; with only 0.6% of stems remaining unidentified to a morphospecies.

By removing only the organic portion of the material and the soil that was attached to the organic matter, litter was collected from 10 replicate quadrats of 50 cm × 50 cm in each plot. Leaves, twigs (small branches of diameter ≤2 cm), and branches (>2 cm diameter) were separated from the field-collected samples. After that, the samples were oven-dried for 2 days at 70°C, and weighed. A C-N analyzer (Yanako

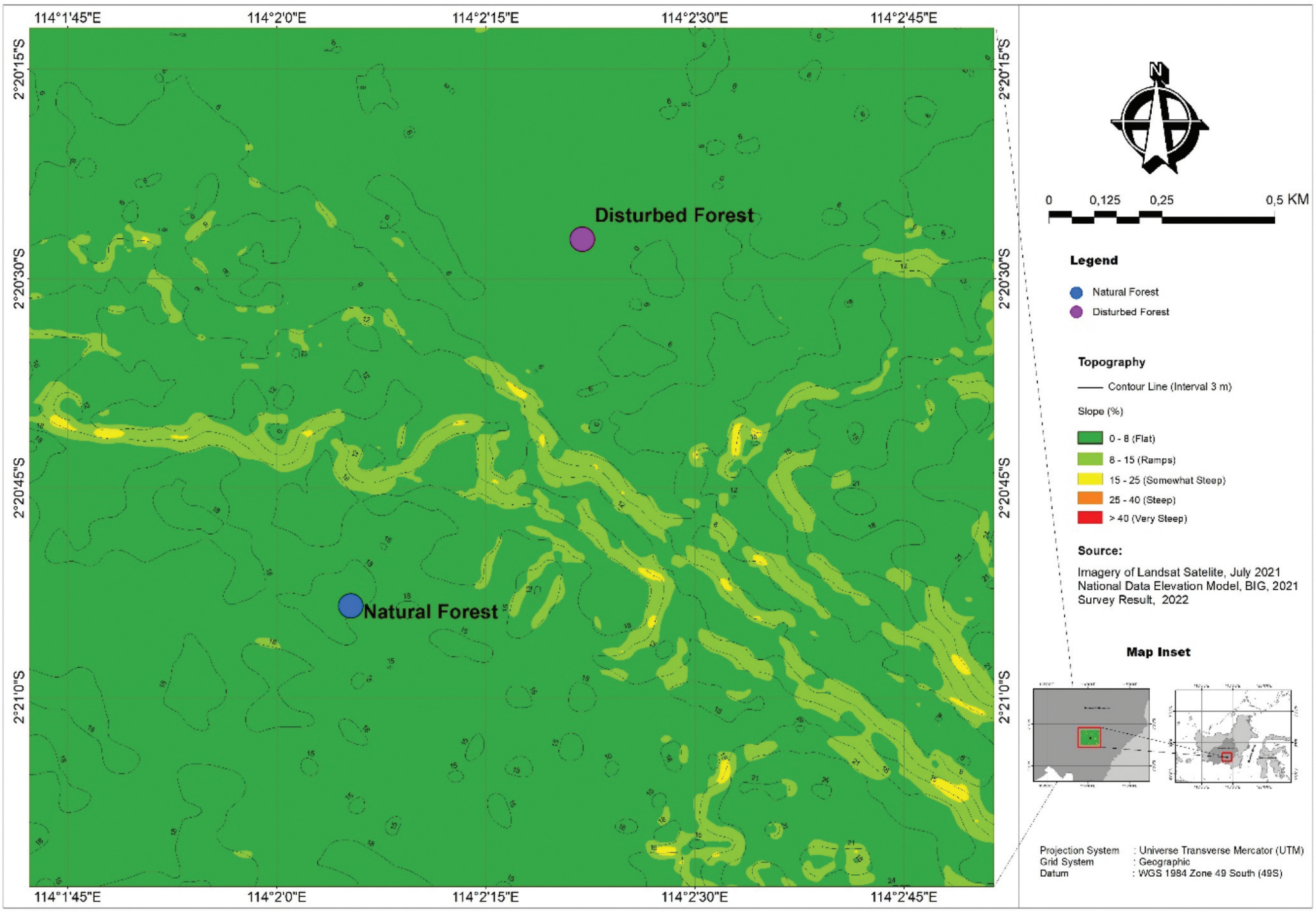

Figure 1. Locations of the natural and disturbed peat swamp forests in Central Kalimantan, Indonesia, based on local topography.

Macro corder JM1000CN) was used to estimate the C content of the litter using 10 mg of ground sample from each category.

Data analysis

Basal area, relative density, relative dominance, and relative frequency were used to describe the structure and composition of the forest vegetation on a per species basis.

$$\text{Basal area(BA)} = \pi r^2, \text{where r is stem radius} \quad (1)$$

$$\text{Relative density(RD)} = \frac{\text{Density of a tree species}}{\text{Total density of all individuals}} \times 100 \quad (2)$$

$$\text{Relative dominance(Rdo)} = \frac{\text{Basal area of a tree species}}{\text{Basal area of all individuals}} \times 100 \quad (3)$$

$$\text{Relative frequency(RF)} = \frac{\text{Number of subplots a tree species occurs in}}{\text{Total nuber of subplots}} \times 100 \quad (4)$$

The Importance Value Index (IVI) for each species was calculated by summing the last three parameters (Mueller-Dombois and Ellenberg 1974).

$$\text{Importance Value Index(IVI)} = \text{RD} + \text{RDo} + \text{RF} \quad (5)$$

Species diversity was determined using the Shannon-Wiener diversity index.

$$\text{Shannon Wiener diversity index}(H') = -\sum\left[\frac{ni}{N}\ln\frac{ni}{N}\right] \quad (6)$$

where ni is the number of individuals of species i and N is total number of all individuals.

An equation designed specifically for mixed-species peat swamp forests was used to estimate the above-ground biomass (AGB) of individual trees (Manuri et al. 2014) viz:

$$\text{AGB} = 0.15 \times \text{DBH}^{2.095} \times \text{WD}^{0.664} \times \text{H}^{0.552} \quad (7)$$

where AGB is above-ground biomass (Mg), DBH is diameter at breast height at 1.3 m above the soil surface (cm), WD is wood density (g cm^{-3}) taken from Soewarsono (1990), and H is tree height (m). To determine the AGB of each plot, the sum of all trees within the plot was calculated. To determine above-ground C, AGB values were multiplied by 0.456 which was the mean value of C concentrations (45.6%) of tropical tree wood (Martin et al. 2018). Belowground root biomass was calculated using the equation of Niiyama et al. (2010) and multiplied by 0.456 as above to give the C stocks (Martin et al. 2018).

Results

Forest structure and species composition

Within the natural forest, there were a total of 2,851 stems (DBH ≥4.8 cm) within 114 species, 60 genera, and 41 families; the total basal area (BA) was 41.2 m^2 ha^{-1} (Table 1). In contrast, a total of 926 individual trees were recorded in the disturbed forest. There were 80 species, 47 genera, and 32 families and a total BA of 6.09 m^2 ha^{-1} (Table 1). All of these values declined when stems ≥10 cm, and particularly stems ≥30cm were considered. Both forests were dominated by smaller-stemmed individuals (Figure 2a); 61% of stems in the natural forest were less than 10 cm DBH with that number increasing to 88% in the disturbed forest. In terms of larger stems, only 1.8% and 1.0% of them were 30 cm DBH or greater in the natural forest and disturbed forest, respectively. In the natural forest, the species with the greatest IVIs were *Cratoxylum glaucum* (Hypericaceae), *Calophyllum canum* (Calophyllaceae), *Madhuca* sp. (Sapotaceae), *Ctenolophon parvifolius* (Ctenolophonaceae) and *Combretocarpus rotundatus* (Rhizophoraceae), whereas *Cratoxylum arborescens* (Hypericaceae), *Combretocarpus rotundatus* and *Rubroshorea teysmanniana* (Dipterocarpaceae) were the most important species (i.e. greatest IVI) in the disturbed forest (Supplementary Table S1), with the first two species continuing to sprout from the burned trunks that were still present. Species diversity (*H*') was 3.62 in the natural forest compared with 3.22 in the disturbed forest (Table 1), indicating the area's generally high diversity. Fifty-one species were shared between the two plots; 63 were only found in the natural forest with about half that number (29) only found in the disturbed forest (Supplementary Table S1).

Aboveground biomass

The total standing AGB in the natural forest was 341 Mg ha^{-1}, with *Co. rotundatus*, *Cr. glaucum* and *Madhuca* sp. accounting for 18.6%, 12.0% and 9.0%, of the total AGB, respectively (Figure 2b). The canopy height was about 18 m with only four trees (two each of *Co. rotundatus* and *Cr. glaucum*) taller than 25 m. Among the trees greater than 50 cm DBH (11 stems), there were eight individuals of *Co. rotundatus* and one each of *Calophyllum biflorum* (Calophyllaceae), *Drepananthus havilandii* (Annonaceae) and *Lithocarpus leptogyne* (Fagacaee). In the disturbed forest, the total standing AGB was about one-sixth of the natural forest at 53.2 Mg ha^{-1}, of which *C. rotundatus* accounted for 36.8% of the total. *Cratoxylum arborescens* and *R. teysmanniana* contributed 8.2% and 6.3% of total AGB, respectively (Figure 2b). Although the largest trees may reach 20 m in height, the

Table 1. Forest structural and diversity parameters in natural and disturbed peat swamp forests, Central Kalimantan, Indonesia.

	DBH ≥4.8 cm		DBH ≥10 cm		DBH ≥30 cm	
	Natural	Disturbed	Natural	Disturbed	Natural	Disturbed
Stem density (no. ha^{-1})	2851	926	1110	111	52	9
Basal area (m^2 ha^{-1})	41.2	6.09	34.1	3.54	13.8	1.69
No. families	41	32	33	20	12	4
No. genera	60	47	48	26	14	4
No. species	114	80	72	33	17	4
H'	3.62	3.22	3.44	3.11	2.11	1.00
No. species shared	51		22		4	

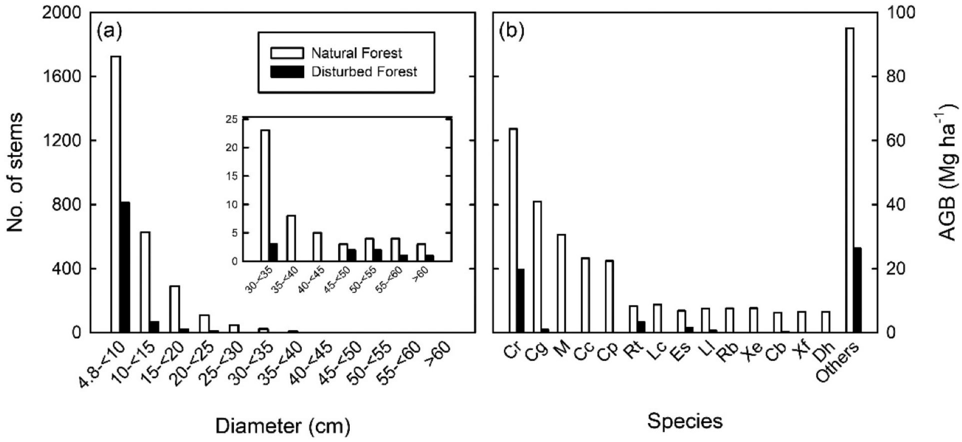

Figure 2. (a) Diameter distribution of trees and (b) above-ground biomass (AGB) in major tree species in natural and disturbed peat swamp forests, Central Kalimantan, Indonesia. The inset in (a) shows the number of stems of the larger diameter trees which cannot be seen clearly in the main panel due to their low abundance. Abbreviations: CR = *Combretocarpus rotundatus*; CG = *Cratoxylum glaucum*; M = *Madhuca* sp.; CC = *Calophyllum canum*; CP = *Ctenolophon parvifolius*; RT = *Rubroshorea teysmanniana*; LC = *Litsea coriacea*; ES = *Elaeocarpus stipularis*; LL = *Lithocarpus leptogyne*; RB = *Rubroshorea balangeran*; XE = *Xylopia elliptica*; CB = *Calophyllum biflorum*; XF = *Xylopia fusca*; DH = *Drepananthus havilandii.*

majority of trees were between 5 and 10 m tall. Six trees of *Co. rotundatus* were greater than 45 cm DBH but no other species had stems greater than 35 cm DBH.

Litter standing crop

Mass of each of the three litter standing crop categories in the natural forest was about double that in the disturbed forest, as was the total litter mass (6.77 ± s.e. 0.50 Mg ha^{-1} vs. 3.30 ± 0.44 Mg ha^{-1}). Leaves contributed about 60% of the total litter mass, whereas twigs and branches contributed about 20% each to the total mass (Figure 3).

Ecosystem carbon stock

Standing trees in the natural and disturbed forests contributed 155.6 and 24.2 Mg ha^{-1} of C, respectively (Figure 4). In terms of the total ecosystem C stock, we used the values from this study for AGB and litter mass. The peat deposit C stock for the natural forest was estimated for a depth of 3.5 m, whereas for the disturbed forest we estimated C for a depth of 2.5 m; these depth measurements were based on Hirano et al. (2012). For the peat C stock estimation we used a bulk density of 0.09 g cm^{-3} and C content of 56% (Page et al.

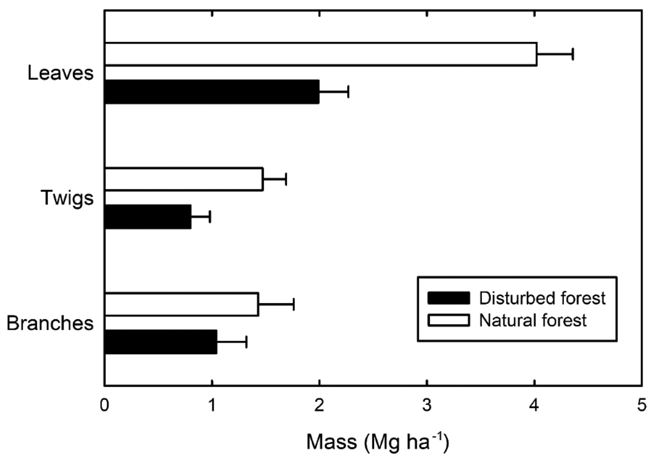

Figure 3. Litter standing crop in three categories, viz leaves, twigs (≤2 cm diameter) and branches (>2 cm diameter) in natural and disturbed peat swamp forests, Central Kalimantan, Indonesia. Values are mean ± standard error.

2011). In terms of C loss, we assumed that both forests had the same AGB, belowground biomass and litter mass prior to the fire(s) and therefore calculated the loss from each component as the difference between the natural and disturbed forest. We used a combustion factor of 0.5 for wood (Toriyama et al. 2014) with half of the wood considered to remain in the ecosystem as deadwood or pyrogenic C after the fire. We further assumed that the fires burned to a depth of 25 cm as a typical depth shown in other studies (Ballhorn et al. 2009; Volkova et al. 2021) and calculated C loss accordingly. Overall, burned forests lost just over 200 Mg C ha^{-1} (Figure 4). The estimated total C stock for the natural forest was 1,945 Mg C ha^{-1}, while that of the disturbed forest was 1,105 Mg C ha^{-1}, of which over 90% remained in the peat itself (Figure 4).

Discussion

The natural peat swamp forest in our study was dominated by tree species such as *Calophyllum canum* and *Cratoxylum glaucum* that are typical of other peat swamp forest locations in Kalimantan (Simbolon 2008; Mirmanto 2010; Volkova et al. 2021, 2023). Other species, such as *Ctenolophon parvifolius* and *Madhuca* sp., which are typical of natural peat swamp forests, were also abundant, as well as *Elaeocarpus petiolatus* (Elaeocarpaceae) and a few species belonging to the Dipterocarpaceae; the total number species recorded was 114. In contrast, burning of the now disturbed tropical peat swamp forest lead to a clear decline in the number of species to 80, and *Cratoxylum arborescens*, *Combretocarpus rotundatus* and *Rubroshorea teysmanniana* were the species that were found most abundantly in the disturbed forest. Important biological features of late successional forests include habitats for large tree species-associated flora and fauna as well as a greater variety of stand structures (Brockerhoff et al. 2017). Other studies have shown a similar decline in tree species diversity following tropical peat fires, with areas that are repeatedly burned losing additional species (Astiani 2016; Volkova et al. 2023).

Since 1997, there has been a large fire almost every year in the peat swamp forests of Kalimantan. Fires in these forests not only remove much of the upper layer of the peat substrate but also result in the loss of vegetation above the peat

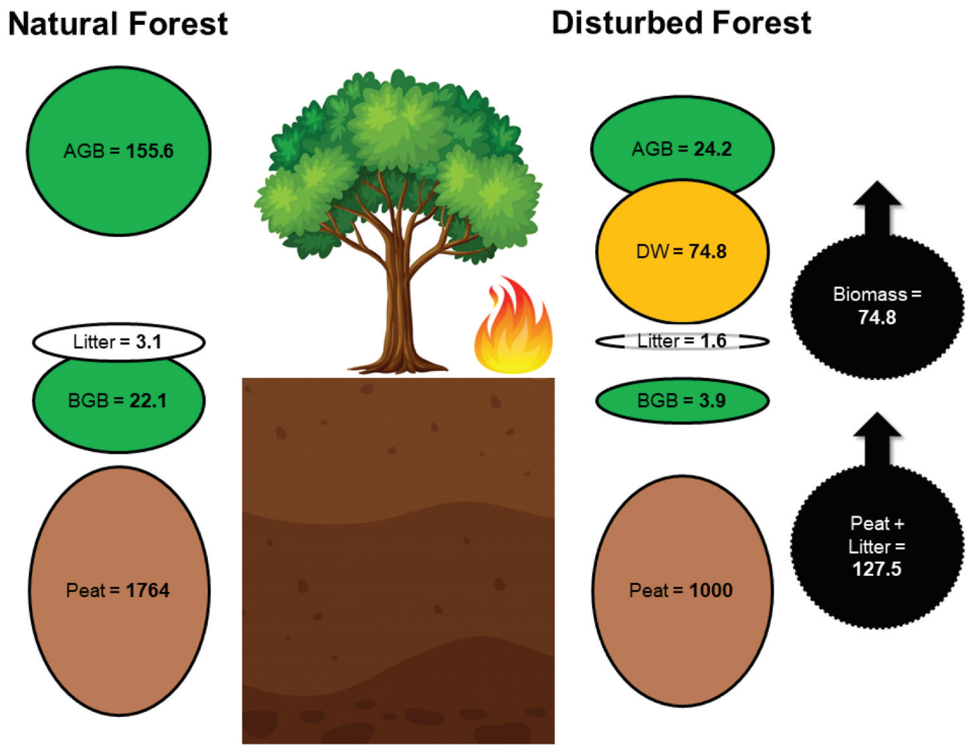

Figure 4. Carbon stocks (filled ovals) and fluxes (dotted ovals and black arrows) in natural and disturbed peat swamp forests, Central Kalimantan, Indonesia. All values are Mg ha^{-1} with the size of the ovals (logarithmically) proportional to their value. AGB = above-ground biomass, DW = deadwood, BGB = below-ground biomass.

surface and slow the process of succession. The burned trees may recover through resprouting if fires are not too severe. For example, *Co. rotundatus* was found in both forest types, but the disturbed forest had proportionally more trees with large diameters (>30 cm) because this species was able to survive under an open canopy where it grew well. This species is also important during regeneration in logged-over forests or after fires because the fallen *Co. rotundatus* stems can grow back and develop shoots that grow into larger trees (Blackham et al. 2014). Even though the disturbed forest has begun to recover, fires that occur during the dry season prevent some of the smaller trees – those with a DBH of less than 5 cm – from growing back, leading to reduced vegetation biomass. In addition, open areas are often dominated by ferns and grasses and are accompanied by periodic flooding, particularly during the rainy season, which impairs the regeneration of peat swamp forest trees (Page et al. 2009).

Crown area and density are a major factor in forest litter production. Because of their low density, the smaller trees in the disturbed forest this will result in less litter production. There are few estimates of litter standing crop in peat swamp forests, but our results agree well with those of Volkova et al. (2021) who also found around 3.99 Mg ha^{-1} in a disturbed forest at another study site in Central Kalimantan. In natural forests, the litter typically comes from trees closest to the collection site, whereas in disturbed forests the leaf fall was dominated by pioneer plants, particularly ferns like *Stenochlaena palustris* (Aspleniaceae) and *Nephrolepis falcata* (Polypodiaceae). The two predominant tree species, *Co. rotundatus* and *Cr. arborescens*, which have large leaf areas and thick leaves, also contributed substantially to the leaf litter production and, hence, standing crop.

The C stock of AGB in natural forests were comparable to than the average value for other Indonesian peat swamp forests, although at the lower end of the range (Darmawan et al. 2013; Hergoualc'h and Verchot 2011), and the low AGB of the disturbed forests suggested that this forest had actually burned previously (Hoscilo et al. 2011; Shiodera et al. 2016). The much reduced AGB in the disturbed forest can be attributable to the past land use history, with longer and more severe disturbances resulting in a longer period of time before a given biomass is recovered, if at all in the case of severe and repeated disturbances (Page et al. 2009). Large trees play an important role in forest C storage (Bastin et al. 2018) as evidenced by the high C stocks found in the natural forests compared to disturbed forests in our study area. Our findings indicate that when the forest is disturbed, the C stock of AGB, or standing trees, and litter production will change, and it will take some time for the forest to return to its natural state. The summation of AGB and litter in our study indicates that disturbed forest above-ground C stocks are about six times lower than those of natural forests. However, one important C stock that we did not measure directly was that of deadwood which is important as charred wood can be a long-term store of C. We used a basic estimate of the combustion factor, i.e. the amount of living biomass converted to deadwood rather than being combusted, but these need more study (Krisnawati et al. 2023).

We provided an estimate of the changes in the C stock following disturbance although this is based on a number of assumptions, including that AGB in both plots was equal prior to the fire, which may not be the case as the disturbed forest was on shallower peat which is known to host shorter trees (Mirmanto 2010). Additionally, our estimate of below-ground biomass was based on data from a lowland evergreen forests on more common mineral soils where root biomass may be different. We note the shortcomings with the estimation of deadwood above. Finally, we assume that our natural forest had not been disturbed by fire although the relatively low stature and presence of some secondary forest species (*Co. rotundatus* and *Cr. glaucum*) suggests it might have been burned in the past. Further degradation of the disturbed forest may lead to additional C loss through peat subsidence and subsequent oxidation.

Conclusions

The findings of this study demonstrate the significance of the natural peat swamp forest in maintaining tree diversity and contributing to local, and indeed, global C cycles. The finding that the natural peat swamp forest contains more C than disturbed forests indicates how disturbance may reduce forest C stocks in this region. Whilst around half of the above-ground C stock of peat swamp forests would be released as a result of fire damage to the forest, below-ground C stocks remain high and need conserving *in situ*. There are many areas of Indonesia with peat swamp forests and further studies in Sumatra and Papua, for example, would give us improved information on the role these forests play in biogeochemical cycles and how disturbances affect this.

Acknowledgements

We would like to express our gratitude to the Head of the Research Center for Ecology and Ethnobiology at the National Research and Innovation Agency (BRIN) for locating the study and providing support for it. The authors are grateful to the Palangkaraya University staff at CIMTROP for their assistance during the fieldwork. A special thanks goes to Prof. Herwint Simbolon, who passed away recently, for supporting this study and to Dr Thomas Smith for useful discussions. Additionally, we appreciate the anonymous reviewers' comments and suggestions for improving this paper.

Disclosure statement

No potential conflict of interest was reported by the author(s).

ORCID

Laode Alhamd http://orcid.org/0000-0002-2574-5952
Siti Sundari http://orcid.org/0000-0002-5982-8983
Francis Q. Brearley http://orcid.org/0000-0001-5053-5693
Joeni Setijo Rahajoe http://orcid.org/0000-0002-5581-4058

Authors' contributions

LA, SS & JSR designed the study, LA & SS collected data, LA & FQB analysed the data, LA & FQB wrote the manuscript.

Data availability statement

Forest plot data will be uploaded to ForestPlots.net; Leaf litter data is available on request from the authors.

References

Aerts R, Chapin FS III. 2000. The mineral nutrition of wild plants revisited: a reevaluation of processes and patterns. Adv Ecol Res. 30:1–67. doi: 10.1016/S0065-2504(08)60016-1.

Anda M, Ritung S, Suryani E, Hikmat M, Yatno E, Mulyani A, Subandiono RE, Suratman H. 2021. Revisiting tropical peatlands in Indonesia: semi-detailed mapping, extent and depth distribution assessment. Geoderma. 402:115235. doi: 10.1016/j.geoderma.2021.115235.

Astiani D. 2016. Tropical peatland tree-species diversity altered by forest degradation. Biodiversitas. 17(1):102–109. doi: 10.13057/biodiv/d170115.

Ballhorn U, Siegert F, Mason M, Limin SH. 2009. Derivation of burn scar depths and estimation of carbon emissions with LIDAR in Indonesian peatlands. Proc Natl Acad Sci USA. 106 (50):21213–21218. doi: 10.1073/pnas.0906457106.

Bastin J-F, Rutishauser E, Kellner JR, Saatchi S, Pélissier R, Hérault B, Slik F, Bogaert J, De Cannière C, Marshall AR, et al. 2018. Pan-tropical prediction of forest structure from the largest trees. Glob Ecol Biogeog. 27(11):1366–1383. doi: 10.1111/geb.12803.

Basuki I, Kauffman JB, Peterson J, Anshari GZ, Murdiyarso D. 2019. Land cover changes reduce net primary production in tropical coastal peatlands of West Kalimantan, Indonesia. Mitig Adapt Strateg Glob Chang. 24(4):57–573. doi: 10.1007/s11027-018-9811-2.

Blackham GV, Webb EL, Corlett RT. 2014. Natural regeneration in degraded tropical peatland, Central Kalimantan, Indonesia: implications for forest restoration. For Ecol Manag. 324:8–15. doi: 10.1016/j.foreco.2014.03.041.

Brockerhoff EG, Barbaro L, Castagneyrol B, Forrester DI, Gardiner B, González-Olabarria JR, Po'b L, Meurisse N, Oxbrough A, Taki H, et al. 2017. Forest biodiversity, ecosystem functioning and the provision of ecosystem services. Biodivers Conserv. 26(13):3005–3035. doi: 10.1007/s10531-017-1453-2.

Dharmawan IWS, Saharjo BH, Supriyanto S, Arifin HS, Siregar CA 2013. Persamaan Alometrik dan Cadangan Karbon Vegetasi pada Hutan Gambut Primer dan Bekas Terbakar. J Penelitian Sosial dan Ekonomi Kehutanan. 10(2):175–191. doi: 10.20886/jphka.2013.10.2.175-191.

Freund CA, Harsanto FA, Purwanto A, Takahashi H, Harrison ME. 2018. Microtopographic specialization and flexibility in tropical peat swamp forest tree species. Biotropica. 50(2):208–214. doi: 10.1111/btp.12512.

Giesen W. 2015. Utilizing non-timber forest products to conserve Indonesia's peat swamp forests and reduce carbon emissions. J Indones Nat Hist. 3:10–19.

Giesen W. 2021. Tropical peatland restoration in Indonesia by replanting with useful indigenous peat swamp species. paludiculture. In: Osaki M, Tsuji N, Foead N Rieley J, editors. Tropical peatland eco-management. Singapore: Springer; p. 411–441. 10.1007/978-981-33-4654-3_14.

Hein L, Spadaro JV, Ostro B, Hammer M, Sumarga E, Salmayenti R, Boer R, Tata HL, Atmoko D, Castañeda J-P. 2022. The health impacts of Indonesian peatland fires. Environ Health. 21(1):62. doi: 10.1186/s12940-022-00872-w.

Hergoualc'h K, Verchot LV. 2011. Stocks and fluxes of carbon associated with land use change in Southeast Asian tropical peatland: a review. Glob Biogeochem Cycles. 25:GB2001. (2). doi: 10.1029/2009GB003718.

Hirano T, Segah H, Kusin K, Limin SH, Takahashi H, Osaki M. 2012. Effect of disturbances on the carbon balance of tropical peat swamp forests. Glob Chang Biol. 18(11):3410–3422. doi: 10.1111/j.1365-2486.2012.02793.x.

Hoscilo A, Page SE, Tansey KJ, Rieley JO. 2011. Effect of repeated fires on land-cover change on peatland in southern Central Kalimantan, Indonesia, from 1973 to 2005. Int J Wildland Fire. 20(4):578–588. doi: 10.1071/WF10029.

Kinnaird MF, O'Brien TG. 1998. Ecological effects of wildfire on lowland rainforest in Sumatra. Conserv Biol. 12(5):954–956. doi: 10.1046/j.1523-1739.1998.012005954.x.

Krisnawati H, Budiharto B, Zamzani F, Adinugroho WC, Qirom MA, Weston CJ, Volkova L. 2023. Building capacity for estimating fire emissions from tropical peatlands; a worked example from Indonesia. Sci Rep. 13(1):14355. doi: 10.1038/s41598-023-40894-z.

Manuri S, Brack C, Nugroho NP, Hergoualc'h K, Novita N, Dotzauer H, Verchot L, Putra CAS, Widyasari E. 2014. Tree biomass equations for tropical peat swamp forest ecosystems in Indonesia. For Ecol Manag. 334:241–253. doi: 10.1016/j.foreco.2014.08.031.

Martin AR, Doraisami M, Thomas SC. 2018. Global patterns in wood carbon concentration across the world's trees and forests. Nat Geosci. 11(12):915–920. doi: 10.1038/s41561-018-0246-x.

Miettinen J, Shi C, Liew SC. 2012. Two decades of destruction in Southeast Asia's peat swamp forests. Front Ecol Environ. 10:124–128. doi: 10.1890/100236.

Ministry of Environment and Forestry. 2022. Operational plan Indonesia's FOLU Net Sink 2023. [accessed 2023 July 12]. https://www.menlhk.go.id/uploads/site/post/1647334063.pdf.

Mirmanto E. 2010. Vegetation analyses of sebangau peat swamp forest, Central Kalimantan. Biodiversitas. 11(2):82–88. doi: 10.13057/biodiv/d110206.

Mueller-Dombois D, Ellenberg H. 1974. Aims and methods of vegetation ecology. New York (USA): John Wiley & Sons.

Murdiyarso D, Hergoualc'h K, Verchot LV. 2010. Opportunities for reducing greenhouse gas emissions in tropical peatlands. Proc Natl Acad Sci USA. 107(46):19655–19660. doi: 10.1073/pnas.0911966107.

Niiyama K, Kajimoto T, Matsuura Y, Yamashita T, Matsuo N, Yashiro Y, Ripin A, Kassim AR, Noor NS. 2010. Estimation of root biomass based on excavation of individual root systems in a primary dipterocarp forest in Pasoh forest Reserve, Peninsular Malaysia. J Trop Ecol. 26(3):271–284. doi: 10.1017/S0266467410000040.

Nurdiati S, Bukhari F, Julianto MT, Sopaheluwakan A, Aprilia M, Fajar I, Septiawan P, Najib MK. 2022. The impact of El Niño southern oscillation and Indian Ocean Dipole on the burned area in Indonesia. Terr Atmos Ocean Sci. 33:16. doi: 10.1007/s44195-022-00016-0.

Page SE, Hoscilo A, Langner A, Tansey KJ, Siegert F, Limin SH, Rieley JO. 2009. Tropical peatland fires in Southeast Asia. In: Cochrane M, editor. Tropical fire ecology: climate change, land use and ecosystem dynamics. Berlin, Germany: Springer Praxis; p. 263–287. 10.1007/978-3-540-77381-8_9.

Page SE, Rieley JO, Banks CJ. 2011. Global and regional importance of the tropical peatland carbon pool. Glob Chang Biol. 17(2):798–818. doi: 10.1111/j.1365-2486.2010.02279.x.

Page SE, Siegert F, Rieley JO, Boehm H-D, Jaya A, Limin SH. 2002. The amount of carbon released from peat and forest fires in Indonesia during 1997. Nature. 420(6911):61–65. doi: 10.1038/nature01131.

Posa MRC, Wijedasa LS, Corlett RT. 2011. Biodiversity and conservation of tropical peat swamp forests. BioScience. 61(1):49–57. doi: 10.1525/bio.2011.61.1.10.

Proctor J, Anderson JM, Fogden SCL, Vallack HW. 1983. Ecological studies in four contrasting lowland rain forest in Gunung Mulu National Park, Sarawak. II. Litterfall, litter standing crop and preliminary observation on herbivory. J Ecol. 71(1):261–283. doi: 10.2307/2259976.

Rahajoe JS, Kohyama T. 2003. The relationship between N, P retuned via litter production and nutrient use efficiency of heath and peat swamp forests in Central Kalimantan. Tropics. 13(1):1–8. doi: 10.3759/tropics.13.1.

Sazawa K, Wakimoto T, Fukushima M, Yustiawati Y, Syawal MS, Hata N, Taguchi S, Tanaka S, Tanaka D, Kuramitz H. 2018. Impact of peat fire on the soil and export of dissolved organic carbon in tropical peat soil, Central Kalimantan, Indonesia. ACS Earth Space Chem. 2(7):692–701. doi: 10.1021/acsearthspacechem.8b00018.

Shiodera S, Atikah TD, Apandi I, Seino T, Haraguchi A, Rahajoe JS, Kohyama TS. 2016. Peat-fire impact on forest structure in peatland of Central Kalimantan. In: Osaki M Tsuji N, editors. Tropical peatland ecosystems. Tokyo, Japan: Springer; p. 197–212. 10.1007/978-4-431-55681-7_12.

Simbolon H. 2004. Dinamika hutan dipterocarp campuran Wanariset Semboja, Kalimantan Timur setelah tiga kali kebakaran tahun 1980-2003. Biodiversitas. 6:133–137. doi: 10.13057/biodiv/d060213.

Simbolon H. 2008. Local distribution and coexistence of prevalent tree species in peat swamp forests of Central Kalimantan. Reinwardtia. 12:373–382. doi: 10.14203/reinwardtia.v12i5.83.

Simbolon H, Siregar M, Wakiyama S, Sukigara N, Abe Y, Shimizu H. 2004. Impacts of forest fires on tree diversity in tropical rain forest of East Kalimantan, Indonesia. Phyton. 45:551–559.

Slik JWF, van Balen S. 2006. Bird community changes in response to single and repeated fires in a lowland tropical rainforest of eastern Borneo. Biodivers Conserv. 15(14):4425–4451. doi: 10.1007/s10531-005-4385-1.

Soewarsono PH. 1990. Specific gravity of Indonesian Woods and its significance for practical use. Bogor, Indonesia: Pusat Penelitian Dan Pengembangan Hasil Hutan.

Taufik M, Veldhuizen AA, Wösten JMH, van Lanen Haj. 2019. Exploration of the importance of physical properties of Indonesian peatlands to assess critical groundwater table depths, associated drought and fire hazard. Geoderma. 347:160–169. doi: 10.1016/j.geoderma.2019.04.001.

Toriyama J, Takahashi T, Nishimura S, Sato T, Monda Y, Saito H, Awaya Y, Limin SH, Susanto AR, Darma F, et al. 2014. Estimation of fuel mass and its loss during a forest fire in peat swamp forests of Central Kalimantan, Indonesia. For Ecol Manag. 314:1–8. doi: 10.1016/j.foreco.2013.11.034.

Volkova L, Adinugroho WC, Krisnawati H, Imanuddin R, Weston CJ. 2021. Loss and recovery of carbon in repeatedly burned degraded peatlands of Kalimantan, Indonesia. Fire. 4(4):64. doi: 10.3390/fire4040064.

Volkova L, Krisnawati H, Qirom MA, Adinugroho WC, Imanuddin R, Hutapea FJ, Ma M, Di Stefano J, Weston CJ. 2023. Fire and tree species diversity in tropical peat swamp forest. For Ecol Manage. 529:120704. doi: 10.1016/j.foreco.2022.120704.

Wijedasa L, Jauhiainen J, Könönen M, Lampela M, Vasander H, Leblanc M-C, Evers S, Smith TEL, Yule CM, Varkkey H, et al. 2016. Denial of long-term issues with agriculture on tropical peatlands will have devastating consequences. Glob Chang Biol. 23:977–982. doi: 10.1111/gcb.13516.

Yeager C, Marshall AJ, Stickler CM, Chapman CA. 2003. Effect of fire on peat swamp and lowland dipterocarp forest in Kalimantan, Indonesia. Trop Biodivers. 8:121–138.