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Asia-Pacific Network for Sustainable Forest Management and Rehabilitation

COMPLETION REPORT

Improving capacities towards reducing greenhouse gas emissions from peat swamp forest fires in Indonesia (2018P5-IND)

01 January 2019 – 31 March 2022

Ministry of Environment and Forestry

Forest Research and Development Center, Forestry and Environment Research Development and Innovation Agency

21 April 2022

BASIC INFORMATION

Project Title (ID)	Improving capacities towards reducing greenhouse gas emissions from peat swamp forest fires in Indonesia (Project ID 2018P5-IND)
Supervisory Agency	Ministry of Environment and Forestry, Indonesia
Executing Agency	Forest Research and Development Center, Forestry and Environment Research Development and Innovation Agency
Implementing Agency	The University of Melbourne
Date of Project Agreement: 14/12/18	
Duration of implementation: 01/19-12/21, 36 months (extended by 3 months to 03/22)	

Total project budget (in USD)	**498,170**	APFNet assured Grant (in USD)	**199,990**
Actual project cost (in USD)	776,990	APFNet disbursed Grant (in USD)	179,991

Disbursement Status	Date of disbursement	Amount (in USD)
Initial disbursement	01/19	85,108.50
Disbursement Y2	03/20	54,112.50
Disbursement Y3	12/21	40,770.00
Balance to be disbursed		19,999.00
Reporting Status	Schedule [1]implementation	Project progress status[2]
First reporting (period covered: 01/19-12/19)	on track	satisfactory
Second reporting (period covered: 01/20-12/20)	on track	satisfactory
Third reporting (period covered: 01/21-03/22)	on track	satisfactory

[1] Schedule [1]implementation status could be on track/behind/ahead of schedule
[2] Project progress status could be ranked as satisfactory, dissatisfactory, moderately satisfactory, moderately dissatisfactory

List of Project Team

Dr Haruni Krisnawati is the Project Coordinator. Dr Haruni is a Professor at the Forest Research and Development Center, Indonesian Ministry of Environment and Forestry. She leads the research group on forest assessment and biometrics within the center. She is also leading the technical development of the Indonesian National Carbon Accounting System (INCAS) – a system for accounting GHG emissions and removals to support GHG Inventory and Measurement, Reporting and Verification (MRV) requirements for the forest sector in Indonesia.
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Dr Liubov Volkova is an international expert from the Implementing Agency. Dr. Volkova is a Senior Research Fellow at the University of Melbourne (UoM) and has strong expertise in forest inventory, bushfire fuels, forest fire emissions and carbon accounting.

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Dr Chris Weston is an international expert and a member of the steering committee. Dr Weston is an Associate Professor at the UoM and has expertise in forest soils, greenhouse gas emissions and biomass sampling. He has over two decades of experience leading and delivering on research projects funded by a range of national and international mechanisms. Dr Weston has close links with several forestry schools throughout the region and will draw on this network for the extension of results to a broader area within the region.

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Mr Wahyu Catur Adinugroho is the project PhD student from the Executing Agency. Mr Adinugroho oversees project data, sample preparation, sample analysis, methodology development. His expertise is in the area of forest ecology and carbon accounting.

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Mr Rinaldi Imanuddin is the project team member from the Executing Agency. Mr Imanuddin has expertise in forest assessment and biometrics and is involved in developing project spatial data.

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List of the Project Steering Committee

Dr Haruni Krisnawati;

Dr Liubov Volkova;

Dr Chris Weston, informal Chair

Dr Kirsfianti Ginoga is the member of the steering committee. She is the former Director at the Forest Research and Development Center, Indonesian Ministry of Environment and Forestry. Prior to this position, she acted as the Director of Research and Development Center for Climate

Change and Policy and the Director of GHG Inventory and MRV within the Directorate General of the Climate Change.

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Ms Nikki Fitzgerald is a member of the Project Steering Committee. Ms Fitzgerald is an Active Director for the International Relation, Markers and Partnerships at the Australian Government, Department of Industry, Science, Environment and Research (DISER). Ms Fitzgerald has several decades of experience in international policy related to MRV, emissions and GHG inventory.

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Executive Summary

Indonesia has the largest share of the tropical peat forest carbon pool (estimated at 57 Gt or 65% of the total), yet it also experiences the most rapid degradation of its peat swamp forests (PSFs) due to strong economic and social pressures for timber and land for agriculture and plantations. Clearance and drainage of PSFs over recent decades has resulted in an unprecedented increase in peat fires, with smoke and pollution affecting not only Indonesia but all south-eastern Asia. Before this project, Indonesia didn't report emissions from PSF fires due to high levels of uncertainty and low quality of the data. Being a Tier 1 economy for biomass burning emission reporting it's assumed that all carbon stocks will be emitted, making emissions estimated from PSF fires unrealistically high. Recent research indicates that a proportion of carbon stocks that is otherwise assumed to be released into the atmosphere is transferred from biomass to residue pools. In addition, previous emission estimates from fires reported only CO_2. The contribution of the high global warming potential methane (CH_4) and nitrous oxide (N_2O) also need to be accounted for developing a reliable baseline of PSF emissions.

The main goal of this project was to improve the capacity of forest managers, local communities and policy makers in Indonesia to develop robust strategies to reduce GHG emissions from fires in peat swamp forests. With the more specific objectives including: Improve the knowledge base of fuel loads (fine and heavy) and their characteristics in peat swamp forests at different stages of degradation; further develop the knowledge base of peat soil carbon and char production during fires; develop parameters for better and more accurate estimates of GHG emissions (CO_2 and non-CO_2) from peat-fires for inclusion in Indonesia's reporting of Forest Reference Emission Level (FREL) to the United Nations Framework Convention on Climate Change (UNFCCC); build and extend the scientific basis for developing adaptive management options and enhance the capacity in decision making for GHG emission reduction from peat-fires; expand network and capacity building through workshops, communications and policy notes to further enhance the information sharing and technology transfer.

These objectives have been accomplished over the lifetime of the project.
During the first year of the project, we have reviewed potential sources of information related to biomass and carbon from peat swamp forests. These findings have been published in a peer reviewed scientific journal, *Science of the Total Environment*, 'Identifying and addressing knowledge gaps for improving greenhouse gas emissions estimates from tropical peat forest fires', Volkova et al 2021. Key fundings of our first publication were lack of data for parameters to estimate emissions from peat fires in literature; pointing out that contribution of deadwood to peatfire emissions is not properly accounted for; and that pyrogenic carbon accounts for 12% of aboveground carbon (AGC) in repeatedly burnt peat forests yet it is excluded from the AGC balance and peat fire emissions. During first and second year of the project we conducted a number of field trips in PSF: primary, secondary long unburnt and repeatably burnt and degraded peatlands. Because there were no standard operational procedures developed to address the research questions of this project, we have developed a unique comprehensive sampling protocol to capture variability and challenges of measuring biomass in forests of contrasting stages of recovery after peat fires. This protocol is published in our first publication Volkova et al 2021 mentioned above.

The developed sampling protocol has been translated into Indonesian and made as a pocket size booklet for the convenience and easier referral by the field crew. We continued ongoing communication with the Government of Indonesia and have helped with the revision of the parameters used in GHG emissions estimates. Specifically, in our second publication in the *Science of the Total Environment*, 'Carbon balance of tropical peat forests at different fire history and implications for carbon emissions', Krisnawati *et al* 2021, we have revised peat combustion factor that varies with the depth of peat burnt and pointed out that current assumption of complete combustion of peat in fires is an oversimplification leading to greater uncertainties in the peat fire emissions estimates. Other updated parameters included varying peat bulk density and peat carbon content with fire frequency and inclusion in fire estimates AGC. The findings of this project have contributed to reducing uncertainties in peat fire emissions estimates and provided Indonesian Government with confidence to report emissions from peat fires. These fundings were key for the revision of the Indonesia's FREL which has been recently submitted to the UNFCCC.

Capacity building was an essential part of this project, the researchers from the Forestry and Environment Research Development and Innovation Agency, in both Bogor and Banjarbaru locations, have learned new skills in data analysis as well as data management and processing, and manuscript submission process. In addition, forestry staff and local people have improved their capacity in forest inventory skills and in knowledge of the sources of GHG emissions.

Findings of this project have been presented at numerous seminars, international conferences, and workshops promoting both new approaches and novel data for improving GHG emission estimates and the role of the sponsors in supporting this project.

In March 2022 we held a *Key Findings and Result Integration Workshop* that attracted more than 40 participants from diverse background, with keynote speakers from the Ministry of Environment and Forestry and from the University of Melbourne.

CONTENTS

1. BACKGROUND AND INTRODUCTION

1.1 Project context

Indonesia has the largest share of the tropical peat forest carbon pool (estimated at 57 Gt or 65% of the total), yet it also experiences the most rapid degradation of its peat swamp forests (PSFs) due to strong economic and social pressures for timber and land for agriculture and plantations. Clearance and drainage of PSFs over recent decades has resulted in an unprecedented increase in peat fires, with smoke and pollution affecting not only Indonesia but all south-eastern Asia. In 2016 Indonesia has developed a National Carbon Accounting System (INCAS) for estimating GHG emissions from forests and peatlands, including peat swamp forest fires. A particular challenge with PSFs is determining fuel loads and fuel type (coarse and fine) available for combustion. To make progress with emissions estimates the INCAS has adopted fuel load estimates that are calculated from peat bulk density and peat depth. This method does not allow for the presence of heavy fuels in the calculation of emissions. Heavy fuels, such as woody debris and uplifted tree roots are left on the ground after clearance of PSFs. These heavy fuels are critical in the development of deeper peat fires that smolder for weeks or months; they also release more potent gases than fine fuels and produce heavy smoke. Field data of heavy fuel loads in PSFs in Indonesia is limited to a few studies with only the small diameter heavy fuel category (<4 cm diameter) accounted, or with estimates only of volumes of heavy fuels. The combustion of heavy fuels directly relates to fire severity such that lower intensity fires will combust a smaller proportion of heavy fuels and will create greater loads of pyrogenic carbon (char) that will remain in the peat soil for many years. Understanding how fire intensity affects combustion of heavy fuels and production of char will help to develop policy incentives for more appropriate burning regimes to reduce emissions.

Emissions from biomass burning are calculated as the product of area burnt (Area), fuel load (Fuel Load), a combustion factor (CF) and the emission factor specific for each gas (EF): *Emission i = Area x Fuel Load x CF x EFi (Eq.1).*

Fuel Load and ***CF*** remain highly uncertain for Indonesian PSFs and directly influence emission estimates. By addressing this knowledge gap this project helps to improve our understanding of GHG emission from peat swamp forests and the actions needed to reduce GHG emissions and smoke haze.

Kalimantan on the island of Borneo, with about 4.78 million ha (32%) of Indonesian peatlands area, was selected for study sites (Fig 1). Currently, emissions from drained and burnt peatlands contribute 2 x 10^9 t CO_2 per year and account for 5% of global carbon budget. Understanding what parameters contribute the most to the emissions and developing methodologies for reducing GHG emission from peatland fires will have a strong impact on human health and on regional economies.

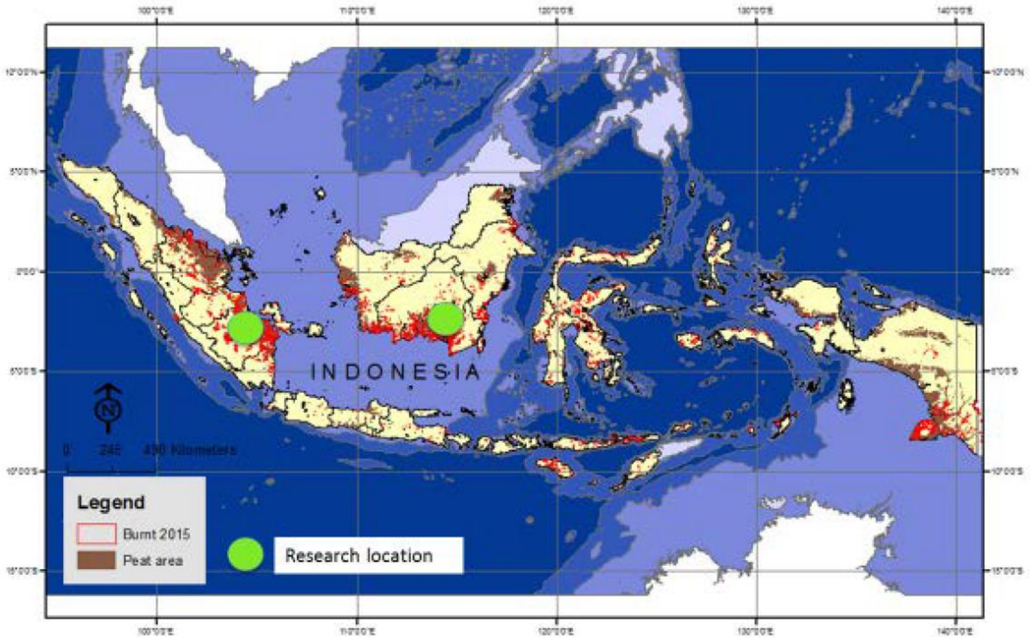

Figure 1. Study sites research area in Indonesia

At the beginning of the project, Indonesia didn't report emissions from PSF fires due to high levels of uncertainty and low quality of the data. Being a Tier 1 economy for biomass burning emission reporting it was assumed that all carbon stocks would be emitted, making emissions estimated from PSF fires unrealistically high. Recent research indicates that a proportion of carbon stock that is otherwise assumed to be released into the atmosphere is transferred from biomass to residue pools. In addition, current emission estimates from fires report only CO_2. The contribution of the high global warming potential methane (CH_4) and nitrous oxide (N_2O) also need to be accounted for developing a reliable baseline of PSF emissions.

The project addresses the significant problem of smoke and GHG emissions from fires in degraded PSFs and aimed at developing robust methodologies for estimating GHG emissions and improved and more realistic emissions estimates that would then improve policy for reduction of emissions from PSF fires. The project builds the capacity of forest managers, local communities, and policy makers to understand the drivers of GHG emissions that is crucial for developing best practices and policies for emission reduction.

This project addresses the APFNet priority and objective "to promote sustainable forest management to enhance ecological functions and ecosystem security of forests". The clearing, draining, and burning of peat swamp forests is a major form of forest degradation and contributor to GHG emissions to the atmosphere. There are serious gaps in knowledge of fire impacts on peat swamp forest carbon pools so that emission estimates are highly uncertain and as such are not included in Indonesian reporting to UNFCCC. This project measures and describes PSF above-ground and below-ground carbon pools in accordance with the IPCC recommendations. Peat swamp forests that are intact, degraded and burnt once, and degraded and burnt several times are assessed for above-ground and below-ground fuels according to size class including heavy or coarse (logs left after clearing), fine (litter) and soil peat. The project estimates forest and peat-fire emissions of CO_2 and the non-CO_2 gases methane and nitrous oxide, providing more accurate emission estimates for these forests than have been attempted to date. By better describing the risks of GHG emissions associated with the burning applied at different stages of forest conversion and fire intensities, forestry policies and management actions can be targeted to reduce carbon losses.

The project is a natural evolution in the development of more accurate reporting under Indonesian's international requirements and in the development of policies to reduce GHG emissions from peat forest fires, thus providing a basis for interventions to improve air quality at local and regional scales.

1.2 Project goal(s) and objectives

The main goal of this project is to improve the capacity of forest managers, local communities, and policy makers in Indonesia to develop robust strategies to reduce GHG emissions from fires in peat swamp forests.

Specific objectives of this project include:

- Improve the knowledge base of fuel loads (fine and heavy) and their characteristics in peat swamp forests at different stages of degradation.
- Further develop the knowledge base of peat soil carbon and char production during fires.
- Develop parameters for better and more accurate estimates of GHG emissions (CO_2 and non-CO_2) from peat-fires for inclusion in Indonesia's reporting of Forest Reference Emission Level (FREL) to the UNFCCC.
- Build and extend the scientific basis for developing adaptive management options and enhance the capacity in decision making for GHG emission reduction from peat-fires.
- Expanding network and capacity building through workshops, communications, and policy notes to further enhance the information sharing and technology transfer.

1.3 Project outputs and outcomes

The Project outputs and outcomes include but not limited to a number of publications which improve knowledge base of peat fire emission parameters, and peat swamp forests carbon recovery. As mentioned above, the revised parameters of peat combustion factor have contributed to the updates in the Indonesian peat fire emissions estimates and built a knowledge base for more accurate reporting of future peat fire emissions.

In our first publication, published in *Science of the Total Environment*, 'Identifying and addressing knowledge gaps for improving greenhouse gas emissions estimates from tropical peat forest fires', Volkova et al 2021, we not only identified knowledge gaps in peat fire emissions parameters and developed a unique sampling protocol tailored to different forest recovery stages, but also have provided a power analysis on a number of field sites required to achieve a desired outcome.

In our second publication, published in in the *Science of the Total Environment*, 'Carbon balance of tropical peat forests at different fire history and implications for carbon emissions', Krisnawati *et al* 2021, we have revised peat combustion factor that varies with the depth of peat burnt and pointed out that current assumption of complete combustion of peat in fires is an oversimplification leading to greater uncertainties in the peat fire emissions estimates. Other updated parameters included varying peat bulk density and peat carbon content with fire frequency and inclusion in fire estimates AGC. We identified that about 17 years is required for AGC of peat swamp forests to recover to pre-fire level. These fundings were key for the revision of the Indonesia's FREL which has been recently submitted to the UNFCCC.

In our third manuscript, published in *Fire*, 'Loss and Recovery of Carbon in Repeatedly Burned Degraded Peatlands of Kalimantan, Indonesia', Volkova, Adinugroho *et al* 2021 we identified that in degraded peatlands only 4-5 years is required for carbon to recover to pre-fire levels. We also pointed out that in degraded peatlands, major carbon pools contributing to fires are not a peat layer but a combination of grass roots, shrubs layer and peat. We have shown that because of it, using the default IPCC method (Eq 1) to estimate emissions from degraded peatlands would lead to overestimation of emissions.

Our ongoing communication with the Government of Indonesia meant that we continued to build capacities in both parameters required to estimate emissions and methodologies used to estimate emissions. As was discussed during our *Key Findings and Result Integration Workshop* we showed that using a simplified methodology for reporting emissions (as was done in FREL1) would lead to overestimation of emissions and restricting the reporting to only CO_2 emissions ignoring other greenhouse gases. In Second FREL, emission from CH4 is now reported – a significant step forward for the Indonesian Government.

In our workshop we also discussed major sources of emissions from peat fires and have shown that AGC is a rather minor source of peat fire emissions when compared with emissions from peat layer. Because AGC has a shorter recovery time than peat layer it is important to protect long unburnt peat swamp forests from fires for both carbon benefits and biodiversity outcomes (see our presentations in the attached folder).

Our major policy recommendation was to review existing reporting methodology from a simplified Tier 1 (FREL1) to a method proposed by IPCC (FREL2) and include other greenhouse gases and AGC layer in emission estimates.

Capacity building was an important component of this project. For field measurement and data analysis we extended our collaboration beyond the project team and included researchers from the Ministry of Environment and Forestry, Sebangau National Park and Banjarbaru Environmental and Forestry Research and Development Institute. The contribution of these researchers has been recognized in a co-authorship in our publications and leading roles in data analysis.

The fundings of this project were widely disseminated as flies and presented at a number of international meetings and conferences (Peat Fire Congress, COP 26, INAFOR 2021) as well as at a number of seminars and workshops held by our respectful agencies (both in University of Melbourne, FORDA and APFNet workshop).

2. PROJECT IMPLEMENTATION

2.1 Project schedule and implementation arrangements

Project activities schedule is presented in Annex A. There were no major changes in project activities that have impacted on the project scope. Project was low to medium risk as the major objective of this project was to develop a robust dataset of fuel loads for the inclusion of GHG emissions from peat-fires into Indonesia's FREL. We managed to conduct several in person meetings, staff exchange to Australia and Indonesia, participate in field campaigns and secure foreign research permits before COVID 19 outbreak and international border closure. We accessed and summarized previously collected data from the unpublished sources and managed to collect our data during dry season.

We managed to sample data from burning degraded peatlands during fires in 2019. While this activity was planned for the second year of the project, we opportunistically sampled sites when it was possible rather than when it was planned in our activities.

During the third year of the project, we continued working remotely and communicated via zoom, emails and WhatsApp. Due to delay in receiving funds for the third year of the project and busy schedule of the Government of Indonesia representatives to participate in the project final workshop we extended our project by three months. Funds allocated to staff exchange to Australia were redirected to the attendance at COP26 in Glasgow by the Project Coordinator so that project findings could be presented at the highest possible level to influence international policies.

2.2 Project resources and costs

Project financial resources (finances and in-kind) were directed towards project implementation. Both Executing Agency and Implementation Agency have supplied the APFNet with the audit reports.

The total budget for this project was USD 498,170 including cash contribution from APFNet of USD 199,990; and additional cash USD 70,000 from the Australian government and in kind contribution from the University of Melbourne and FORDA. The Executing Agency, FORDA received (inc 10% of funds to be dispersed at the completion of this report) USD 109,965 and Implementing Agency, UoM - USD 90,025. Our actual expenditures are matching the funds received and the financial and audit reports for each year were provided to the APFNet.

The audit report for year 3 of the projects are provided directly to the APFNet by independent audit companies/auditors. There was no major relocation of funds (but a relocation of traveling budget to attend COP26 in lieu of staff exchange program due to closed Australian border). Project funds were managed to achieve the milestones of the project and expenses were audited by external independent companies/auditors.

2.3 Procurement and consultant recruitment

The purchased goods and services under approved work plan were only used by the Project and have contributed to the achievement of project goals and objectives. Those services included day to day running of the project such as a dedicated office space, project administration, phone, and internet services. Resources were used for delivering samples from field location in Kalimantan for processing and analyses at Bogor Research Laboratories. Project used laboratory ovens, a weighing room, and contracted a dedicated laboratory technician for sample analysis. Project funds were used for travelling to the field sites (inc. air fare, car rent, accommodation and per diem), hire of local support crew, hire of boats and motorcycles to reach forests and a hire of a crew with augers to measure peat depth and to collect peat samples up to 6 m depth.

Project funds were also used for consumables such as paper and plastic zip bags to collect and transport samples, purchase of diameter at breast height (DBH) tapes for measuring trees, a caliper for measuring coarse woody debris, metal ropes for measuring depth of peat burnt and production of aluminum frames to collect elevated and litter fuels. There were no fixed assets purchased under this project

Project involved international consultants Dr Volkova and Dr Weston from the Implementation Agency to fulfill specific tasks such as project design, sampling protocol development, data analysis, power analysis, editing and writing and editing of the manuscripts. The contribution of the consultants and project team is clearly stated in the manuscripts in authors contribution.

2.4 Monitoring & evaluation and reporting

Regular monitoring and evaluation (internal and external led by APFNet) were conducted to make sure project implementation is on track and in the direction of achieving project objectives. Covid 19 caused disruption for both Executing and Implementing Agencies and that, among others, led to the delay in producing audit reports. As such we were not able to receive funds for Year 3 activities till December 2021 and requested an extension so that a proper final workshop can be conducted. The workshop involved representatives from the Supervisory Agency, the Ministry of Environment and Forestry that were also committed with their time in December 2021.

Project progress has been regularly shared among project team and stakeholders by emails and zoom meetings. High quality reports, concept notes and accepted manuscripts have been submitted to the APFNet.

2.5 Dissemination and knowledge sharing

Project findings have been presented at numerous seminars, webinars, and workshops, both national and international meetings. We participated in the 5th International Conference of Indonesia Forestry Researchers (INAFOR) 2019, Asia -Pacific Forestry Week 2019, the 6th INAFOR 2021, International Peatland Congress 2021, COP 26 UN Climate Change Conference 2021, and APFNet workshop on Carbon accounting 2021. We produced several fliers and two YouTube videos promoting the outcomes of this project. Our talks had great interest from the scientific and general auditory and produced vivid discussions. Participation in these international and national evens further promoted the Project findings and resulted in greater awareness of the project impact and outcomes.

Project outcomes were published in 3 peer-reviewed publications mentioned above with copies provided to the APFNet, 3 flyers and a number of presentations given in the attachments

The list of the conferences and meeting is below:

1) INAFOR 2019 – 28 August 2019, Bogor, Indonesia, the plenary session - Climate resilience and the effective use of natural resources. Asia-Pacific Forestry Week 2019 – 17-21 June 2019, Incheon, Korea, Forests for Peace and Well-Being session
2) International Peatland Congress- 4 May 2021 – online, improving knowledge in the parameters for estimating GHG emissions from peat swamp forests fires in Indonesia. Stream III: Regulating services.
3) COP26 UN Climate Change Conference – 31 October -13 November 2021, Managing C-rich Peatlands: from Research to Policy and Action under the theme: "Peatland Science and Technology" at the Peatland Pavilion.
4) APFNet workshop – 8 December 2021, virtual meeting, Holding Forests Accountable

- APFNet Forest Carbon Accounting Zoom Webinar

5) INAFOR 2021 - 8 September 2021, virtual meeting, plenary session - Managing Forest and Natural Resources, -Session - Sustainable and Friendly Use

The project developed two video clips for project dissemination, which could be found on YouTube through these links:

1) Improving peat fire emission factor: https://www.youtube.com/watch?v=5UQmbEhVZ24
2) How depth were peat would be burnt? https://www.youtube.com/watch?v=OZseHuzFdMA

3. PROJECT PARTNERES' PERFORMANCE

3.1 Performance of Supervisory Agency

The supervisory Agency, the MoEF, has been supportive of the project. The supervisory Agency was involved in regular meeting with the project team and provided clarifications for estimating and reporting GHG at the Government level and sharing internal policy documents that were valuable for the Project team to fully understand approaches and challenges for the Indonesian Government in its emissions reporting to the UNFCCC.

3.2 Performance of Executing Agency

The Executing Agency, FORDA has fulfilled its responsibilities and tasks in full. The EA was responsible for project implementation, development of the project plan and project activities, looked after technical implementation, data collection and analysis, sample processing and labor support. The EA was responsible for project results dissemination, flyers preparation and organization of the workshops.

3.3 Performance of Implementing Agency

The Implementing Agency, University of Melbourne has fulfilled its responsibilities and tasks in full. The IA was instrumental in supporting the EA in developing project plan, project sampling design and sampling intensity. The IA guided the EA with data analysis, capacity building for data analysis and results presentation, writing for the scientific audience and support with everyday activities of the project. The IA was involved in project results dissemination, flyers preparation and organization of the workshops.

3.4 Performance of APFNet

APFNet has provided timely support and clear guidance to the project planning, implementation, and management. APFNet disbursed project grant in a timely manner (except for funds for Y3 of the project due to delay with receiving the audit report). APFNet provided prompt feedback on all project activities and shown flexibility with the project implementation.

4. PROJECT PERFORMANCE

4.1 Project achievements

The project activities are met in full and project results, outputs and outcomes have been presented to the APFNet during a lifetime of the project as publications, fliers, and presentations.

Activity 1.1: Comprehensive literature review

Scientific publications and gray literature, such as industry and research project reports, related to fire emission measurements from PSF fires were reviewed to establish knowledge gaps. A literature review paper entitled 'Identifying and addressing knowledge gaps for improving greenhouse gas emissions estimates from tropical peat forest fires' has been published in *Science of the Total Environment*. A standard operating procedure (SOP) for measuring fuel loads in peat swamp forests and first preliminary results was developed by the project and has been translated into Indonesian for easy use and guidance by local field team during the field measurement.

Activity 1.2: Establishment of field sites and data processing

Plots representing four treatments (intact, degraded-not burnt, degraded-burnt once and degraded and burnt multiple times) with 3 blocks and 6 plots each were established for field activities in Kalimantan after consultation with the local representatives. Fire and site history data were accessed using governmental resources and remote sensing information (MODIS, Landsat).

A sampling design was developed. Peat soils, fine and heavy fuels and tree core samples were processed in the laboratory for estimation of fuel dry mass, carbon content, peat bulk density, mass of char and tree density.

Activity 1.3: Developing the baseline of emissions from PSFs fires

Stock difference between fuels (fine and heavy) were used to estimate burning efficiency of fuels at different forest degradation stages. Major GHG emissions including CO_2 and non-CO_2 gases were estimated.

Output 2: Understanding the main sources of GHG emissions from PSFs fires

Activity 2.1: Analysis of the sources of GHG emissions by fuel type and forest degradation stage

Findings from the field measurements and different treatments were assessed for the sources of GHG emissions in PSFs fires. Emission from AGC and peat layer at different forest degradation stages were analyzed

Activity 2.2: Identification of possible strategies for emission reduction

Findings were presented and discussed with the relevant stakeholders (MoEF, local government) for capacity building and to develop strategies to reduce GHG emissions.

Output 3: Analysis of the proposed changes and development of policy recommendations

One of the ultimate objectives of this project was to facilitate the scientifically credible evaluation of change in management strategies for reducing GHG emission from PSFs fires. This was achieved by comparing the impact of changes to reporting emission using different methods and publishing our fundings in peer-reviewed publications.

Activity 3.1: Assessing the impact of changes

Changes in emission estimates were assessed by comparing various scenarios of peatland emissions (emissions from long unburnt forests, emission from repeatedly burnt forests and emission from degraded peatlands, with and without AGC). Findings were presented and discussed with the MoEF and local government for capacity building in understanding the results and steps to implementation of changes in forest management.

Activity 3.2: Developing policy recommendations

Based on the outcomes of the discussions with relevant stakeholders, most appropriate and practically feasible recommendations for emission reduction reporting from PSF fires were developed. This work allowed MoEF staff to understand the consequences of moving to a higher Tier in reporting emissions from peat fires (before Indonesia used Tier 1, the IPCC default parameters, for reporting GHG emissions from forest fires, while the data from this project allowed Indonesia to move to a higher Tier in reporting emissions using economy-specific data, [i.e. Tier 2]).

Output 4: Capacity building

A comprehensive network involving scientists, policymakers and stakeholders was developed and the capacity of government officials and local forest managers was enhanced in policy making related to emission reduction using the methods described below.

Discussions with local government and forestry representatives were included in our field trips and workshops. Employing and training local people for field measurements provided them with general forest inventory skills and improved local community knowledge and capacity for understanding sources of GHG emissions. The project also included laboratory analysis and sample preparation which were carried out by local staff and were included in the budget as "cost per sample".

Activity 4.1: Workshops

An inception workshop was held at the beginning of the project. Two training workshops were held for government officials during project. Local forestry workers were involved in the project from the initiation stage. A series of meetings and briefings including the development of manuals for applying field sampling methodologies were held.

Activity 4.2: Research Higher degree students training

This activity was designed to train next generation foresters who would be able to apply

SFM knowledge to forest management practices. This project supported 1 PhD student to work on the project. The PhD student has now completed his studies.

Activity 4.3: Conferences and publications

The project achievements were presented at regional and international conferences. Fundings were published in peer-reviewed journals to facilitate reporting and verification process for Indonesia reporting its GHG emissions from PSF fires under the international requirements.

Activity 4.4: Staff exchange

Staff from the Indonesian MoEF were hosted at the UoM facilities for capacity building, data analysis and publication writing during Y1 of the project. Due to COVID and closed borders the staff exchange for Y3 of the project did not go ahead and was substituted with Executing Agency presenting fundings of this project at COP26.

4.2 Project Impacts

The project had a scientific, capacity building, social and environmental impacts. New revised parameters of peat emission factors have been developed and are shaking old grounds of oversimplified emissions estimates coming from Indonesian peatlands. We also developed new functions to estimate the recovery of peat swamp forests carbon and tree diversity after fires. Our findings indicate that aboveground carbon will be about 80% recovered within 10 years after fire, and species richness and diversity will recover to about 80% within 16-22 years after fires. In degraded peatlands, subjected to frequent and repeated burns recovery of carbon is anticipated within 3 years after peat fire.

Our joint publications led to career advancement of the Executing and Supervising Agencies colleagues and their greater international recognition. Inclusiveness of Indonesian colleagues into manuscript preparation, submission to the journal, revision and addressing reviewer's comments have shown Indonesian colleagues how to deal with sometimes very difficult and challenging criticism.

The project coordinator, Dr Haruni Krisnawati has been promoted to the position of Professor becoming one of a few female professors in the MoEF of the Government of Indonesia. Because of her leading role in the peat combustion factor publication, she received several invitations to the round tables and seminar presentations at COP26 in Glasgow. Dr Volkova, the project leader from the IA has received numerous acknowledgements about capacity building component of the project. Over the lifetime of this project, we have conducted a series of training workshops on data analysis, R-coding, results integration, and one to one training sessions in writing scientific publications.

4.3 Sustainability

The work on improved emission estimates and more realistic parameters used in the emission estimates will have long lasting positive consequences on Indonesian environmental policies and highlights the need for targeted recovery actions (such as with peat species diversity) or increasing water table to reduce peat carbon oxidation. The follow up activities include continued collaboration between IA and EA, and finalizing the project publications, overseen the project PhD student to completion, development of new proposals to further improve emission reporting and emission reduction actions.

5. CONCLUSION, LESSONS LEARNED AND RECOMMENDATIONS

5.1 Conclusion

The success of this project is that Indonesia is currently revising its FREL using new updated data derived from our activities. The dataset amassed in this project also allowed for investigation of the recovery of species diversity of peat swamp forests following repeated fires. We observed that the richness and diversity of tree species recovers to about 80% of relatively undisturbed forests about 16-22 years after peat fires, as does the aboveground biomass. Management interventions, such as enrichment planting, will be required to increase the number and diversity of species which are not able to naturally recover over the first three decades after fires.

The capacity building aspect of this project resulted in new skills acquired by both Indonesian and Australian researchers – we worked effectively as a team, producing several peer-reviewed publications with the prospect of more to follow. COVID travelling restrictions and closed border at the beginning of the year 2 of Project meant that we had to convert all our planned face to face and field activities to online which in some cases was disadvantageous for our Indonesian colleagues especially in training sessions such as R. Rising costs of the project activities and personal, hidden and unanticipated costs such as foreign research permits fees or hiring of boats to reach field sites meant that we had to look for fundings elsewhere to be able to successfully finish project and on time. Our objective self-assessment is that project team worked well and achieved the outcomes despite sometimes difficult and challenging circumstances.

5.2 Lessons learned and recommendations

We learnt that without building capacity and close and trusted relationship this project would not get off the ground. Building good relationship from the start is the secret for success for any project.

We advocate for ongoing capacity building at the highest Governmental and research levels of all parties involved, as not only our Indonesian partners improved their capacities but also researchers from Australia and Project managers from APFNet learnt a few new things.

Another lesson from this project is to be flexible and adjust activities based on the circumstances. For example, we planned to conduct fire study during the second year of the project, yet a peat fire ignited near our research sites during Y1 of the project and we relocated our activities, contacted local communities for permission to carry out field measurements and have conducted our sampling of burning peat opportunistically during Y1 of the project. As it happened, Y2 was a wet year and no fires were ignited near study area – thus we would have missed our unique opportunity.

The logical continuation of this project would be extending this project to other peat domes in Sumatra and Papua to support national reporting (C loss and recovery, biodiversity and forest structural recovery).
Linking recovery of carbon and ecosystem services (such as biodiversity) with livelihood development via REDD+ and voluntary carbon credits is also an important area for future directions

Our main recommendation to APFNet is to significantly reduce administration burden of the project implementation: please remove the need for mid-year reports, cost by activity is redundant as it is very difficult to separate cost by category and activity. This was our first APFNet project and similar project such as granted by the Australian Research Council (ARC) or other Australian Government Agencies do not require mid-year project reports, or cost by activity separation. Project outputs can be submitted as publications rather than repeated in the project tables. These unnecessary reports require a significant time commitment and deprive resources from project implementation.

Annexes

A. Project Implementation status
B. Financial statement
C. Project audit reports
D. Project outputs, such as technical reports, key project documents
   D-1 Publications
   d) Identifying and addressing knowledge gaps for improving greenhouse gas emissions estimates from tropical peat forest fires
   e) Carbon balance of tropical peat forests at different fire history and implications for carbon emissions
   f) Loss and Recovery of Carbon in Repeatedly Burned Degraded Peatlands of Kalimantan, Indonesia
   D-2 Standard Operating Procedure ---Measuring Fuels Peat swamp Forest
   D-3 Project Poster/ flyers
   D-4 Project presentations
E. Photos, media clips and other materials used/available for project outreach

Annex A. Implementation status (scheduled versus actual)

Project Objective/Outputs /Activities (in line with PD/AWPs)	**Indicators** (in line with PD/AWPs)	**Baseline of activities**	**Progress made (%completion of activities and degree of output/objective achievement)**	**Appraisal time**	**Actual time**
Objective • Improve knowledge base of fuel loads (fine and heavy) and their characteristics in peat swamp forests at different stages of forest degradation; • Further develop the knowledge base of peat soil carbon and char production during fires; • Develop parameters for accurate estimate of GHG emission (CO2 and non-CO2) from peat fires	1. Developed baseline of GHG emissions from fires in PSF at various stages of forest degradation; 2. Identified drivers of emissions from PSF fires; 3. Updated methodology for reducing GHG emissions	Publications, submitted FREL#2 to the UNFCCC; workshops and surveys	100%	3 years	3.5 years

• Build and extend a scientific basis and adaptive management options to enhance capacity in decision making for GHG emission reduction from peat fires • Expanding network and capacity building through workshops, communications and policy notes to further enhance the information sharing and technology transfer					
Output 1: Developing the baseline of GHG emission from PSF fires					
Activity 1.1	Review of grey and published literature on GHG emissions from peat fires.	Publication to STOTEN	100%	9 months	16 months
Activity 1.2	Establishment of field sites and data processing	A map of study sites, data analyzed are given in the publication #2	100%	20 months	20 months

Activity 1.3	Review of fuels and burning efficiencies of those fuels for peat swamp forests across a range of intact and degraded states	Publication #2	100%	11 months	11 months
Output2 Understanding the drivers of GHG emissions from PSFs fires					
Activity 2.1	Evaluation of GHG emissions based on input variables measured under activity 1.3	Presentation to the MoEF (submitted to APFNet during annual reviews)	100%	12 months	12 months
Activity 2.2	Sensitivity analysis of the key biophysical drivers of GHG emissions with matrix of actions to mitigate or reduce each driver	Presentation at the final workshop (available in the Annex)	100%	13 months	13 months
Output 3 Analysis of the proposed changes and development of policy recommendations					
Activity 3.1	Analysis of the impact of changes using trade off analysis and sophisticated	Presentation to the MoEF (submitted to APFNet during annual reviews)	100%	13 months	15 months

	statistical techniques				
Activity 3.2	A developed set of policy changes based on principles of trade-off and cost-benefit that address emission reduction in a quantifiable way	Publication in submission based on feedback from the workshop participants	Due to delay with the final workshop publication is 90% completed (under interval review	10 months	12 months
Output 4 Capacity building					
Activity 4.1	A PhD student working on the project	PhD student is near completion	90% (outside our control)	3 years	4 years
Activity 4.2	Attendance at the conferences, presentation of the project results	Attended 4 international conferences and several webinars and seminars	100%	9 months	10 months
Activity 4.3	Staff exchange, Staff Travel to COP 26	Staff travel to Australia in 2018, Staff Presented at COP 26	100%	3 months	3 months
Activity 4.4	Workshops, Extension notes, conferences, and publications	Workshop notes, conference presentations and publications	100%	6 months	12 months

Annex B Details of project cost by category

-	APFNet Grant				Counterpart Fund			
	Anticipated A_1	**Actual B_1**	**Variance $C_1(A_1-B_1)$**	**Variance rate $D_1(C_1/A_1*100\%)$**	**Anticipated A_2**	**Actual B_2**	**Variance $C_2(A_2-B_2)$**	**Variance rate $D_2(C_2/A_2*100\%)$**
Project staff cost (Salary and allowance for project staff and management personnel)	9,000	7,425	**1,575**	**17,5**	57,000			
Consultancy cost (Local and international consultants' cost)	64,000	68,305.94	(4,306)	(6.7)	120,500	247,598.9	-127,099	-105.5
Travel and other related cost consultancy (Air fare, local travel, per-diem and etc)	28,025	27,717.92	307	1.1	6,880	10,000	-3,120	-45.3
Travel and related cost Project staff (Air fare, local travel, per-diem and etc)	22,440	21,562	878	3,9				
Meeting and training cost (Venue, facility, hospitality, speakers/experts' fees, participants accommodation, meeting material, etc)	17,100	16,405	**695**	4,1	1,800			
Field activities cost	28,000	31,475	**(3,475)**	(12,4)	-			
Publication &Dissemination cost (Formulation, editing, publishing of articles, reports, books and information products and organization of outreach activities, media activities)	6,000	4,219	**1,781**	29,7	9,000			

Office Operation cost (Project administrative management fee and administrative staff cost, lease/rental of office premises, office and facility maintenance, etc)	4,800	3,725	**1,075**	22,4	-			
Procurement (Purchase of vehicles, equipment, facilities etc)	9,125	7,812	**1,313**	14,4	30,000			
Monitoring, evaluation, and audit cost	3,000	3,760	**(760)**	(25,3)	3,000			
Miscellaneous	8,500	6,454	**2,046**	24,1	-			
TOTAL	199,990	198,861	**1,129**		228,180			

THE UNIVERSITY OF MELBOURNE

AUDIT REPORT

TO ASIA-PACIFIC NETWORK FOR SUSTAINABLE FOREST MANAGEMENT AND REHABILITATION (APFNET) – IMPROVING CAPACITIES TOWARDS REDUCING GREENHOUSE GAS EMISSIONS FROM PEAT SWAMP AND FOREST FIRES IN INDONESIA

I advise that an audit has been conducted of the Financial Statement of Income and Expenditure for Asia-Pacific Network for Sustainable Forest Management and Rehabilitation (APFNET) – Improving Capacities Towards Reducing Greenhouse Gas Emissions From Peat Swamp Forest Fires in Indonesia for the period **1 January 2019 – 31 March 2022**.

AUDIT OBJECTIVE

The audit was conducted in accordance with Commonwealth Standard Grant Agreement. Specifically, this includes forming an opinion on whether the Financial Statement is true and fair, and The University of Melbourne has complied with its obligations to expend grant payments in accordance with the Agreement.

AUDIT SCOPE

The University of Melbourne is responsible for the preparation of the information provided in the Financial Statement. We have conducted an audit of the Financial Statement in order to express an opinion in accordance with the Project Agreement.

The Financial Statement has been prepared to satisfy the requirements of Project Agreement. The prevention and detection of fraudulent activity is the responsibility of The University of Melbourne. We disclaim any assumption of responsibility for any reliance on this audit report to any person other than the parties to the Project Agreement, or for any purpose other than that for which it was prepared.

Our audit was conducted in accordance with Australian Auditing Standards. The audit procedures included an examination, on a test basis, of evidence supporting the Financial Statement. Our audit procedures have been undertaken to form an opinion whether, in all material respects, the grant funds have been used in accordance with their intended purpose. We did not examine all transactions over the defined review period, as a consequence, we do not provide a guarantee that all errors or omissions, whether intentional or otherwise were detected.

The audit opinion expressed in this report has been formed on the above basis.

AUDIT OPINION

I confirm that in my opinion:

- the Financial Statement presents fairly, in all material respects, the grant income and expenditure on the Project; and
- the contribution of The University of Melbourne is **USD335,399.13** in-kind in accordance with the terms of the Project Agreement.

The Financial Statement signed by the Senior Research Accountant of Research Accounting Services and UOM In-Kind Contributions Statement signed by the Chief Investigator in accordance with the Project Agreement are attached.

Amely Li

Digitally signed by Amely Lim
Date: 2022.05.25 18:18:38 +10'00'

25 May 2022
____
Date

Amely Lim Sor K, CPA CIA CISA
Auditor – Data Analytic
Risk and Assurance
Legal and Risk, COO Portfolio
Level 4, Alan Gilbert Building (Building 104), 161 Barry Street
The University of Melbourne, Victoria 3010 Australia
T: +61 3 834 49386; Email: sorl@unimelb.edu.au

Financial Statement of Income and Expenditure
for the period from 01 January 2019 to 31 March 2022

Project Title:	Improving Capacities Towards Reducing Greenhouse Gas Emissions From Peat Swamp Forest Fires in Indonesia		
Grantor:	Asia Pacific Network for Sustainable Forest Management and Rehabilitation (APFNet)		
Grantor Reference:	2018P5-IND		
Chief Investigator:	Dr Liubov Volkova		
UOM Reference:	094633 & 094643		
Start Date:	01-Jan-19	End Date:	31-Mar-22

	Budget Excl GST		DoEE Actuals (Excl GST)				APFNet Actuals (Excl GST)				
	DoEE Budget USD	APFNet Budget USD	Nov-Dec 2018 USD	2019 USD	2020 USD	Cumulative USD	2019 USD	2020 USD	2021 USD	Mar-22 USD	Cumulative USD
INCOME											
Grant income	78,839.99	92,025.00	39,419.99	39,419.99	0.00	78,839.99	40,172.00	22,797.81	19,818.00	0.00	82,787.81
Total Income for the reporting period	**78,839.99**	**92,025.00**	**39,419.99**	**39,419.99**	**0.00**	**78,839.99**	**40,172.00**	**22,797.81**	**19,818.00**	**0.00**	**82,787.81**
EXPENDITURE											
Salary & Oncosts	41,062.43	64,000.00	0.00	23,864.56	21,183.15	45,047.71	31,531.78	17,887.94	0.00	16,683.18	66,102.90
Travel and Fieldwork	9,033.96	19,125.00	2,667.08	1,972.27	403.92	5,043.27	9,649.75	4,105.27	279.09	1,172.27	15,206.38
Other Expenses											
Indirect Costs	28,743.60	8,900.00	14,374.50	14,374.50	0.00	28,749.00	5,533.58	2,476.42	0.00	2,705.71	10,715.71
Total Expenditure for the reporting period	**78,839.99**	**92,025.00**	**17,041.58**	**40,211.34**	**21,587.07**	**78,839.99**	**46,715.11**	**24,469.63**	**279.09**	**20,561.16**	**92,025.00**
Net Surplus/(Deficit)	**0.00**	**0.00**	**22,378.41**	**-791.34**	**-21,587.07**	**0.00**	**-6,543.11**	**-1,671.82**	**19,538.91**	**-20,561.16**	**-9,237.19**

I certify that:

a) income and expenditure as shown above is true and correct as reflected in the University's accounting system; and

b) salaries paid under the grant accord with the general rates in force at the University.

Digitally signed by Santi Tran
Date: 2022.05.25 10:36:36 +10'00'

Santi Tran
Research Accountant,
Research Accounting Services

Research, Innovation and Commercialisation

The University of Melbourne

In-Kind Contributions Statement

Project Period from 01-Jan-2019 to 31-March -2022

Project Title:	Improving Capacities Towards Reducing Greenhouse Gas Emissions From Peat Swamp Forest Fires in Ir
Grantor:	Asia Pacific Network for Sustainable Forest Management and Rehabilitation (APFNet)
Grantor Reference:	2018P5-IND
Chief Investigator:	Dr Liubov Volkova
UOM Reference:	094643
Project Period:	

	USD
Salary & Oncosts	134,159.65
Infrastructure	
Overhead (all associated costs, e.g. office space rents, etc. not charge to grant funds)	201,239.48
Total In-Kind Contribution	**335,399.13**

Certification

I hereby certify that the In-Kind contributions have been provided in accordance with the agreement between the *Asia Pacific Network for Sustainable Forest Management and Rehabilitation (APFNet)* and The University of Melbourne.

Dr Liubov Volkova
Chief Investigator

19/05/22
Date

LAPORAN AUDITOR INDEPENDEN (INDEPENDENT AUDIT REPORT)

TO ASIA-PACIFIC NETWORK FOR SUSTAINABLE FOREST MANAGEMENT AND REHABILITATION (APFNET) – IMPROVING CAPACITIES TOWARDS REDUCING GREENHOUSE GAS EMISSIONS FROM PEAT SWAMP FOREST FIRES IN INDONESIA

I advise that an audit has been conducted of the Financial Statement of Income and Expenditure for Asia-Pacific Network for Sustainable Forest Management and Rehabilitation (APFNET) – Improving Capacities Towards Reducing Greenhouse Gas Emissions from Peat Swamp Forest Fires in Indonesia for the period 1 January 2021 – 31 March 2022.

AUDIT OBJECTIVE

The audit was conducted in accordance with Grant Agreement. Specifically, this includes forming an opinion on whether the Financial Statement is true and fair, and the Forest Research and Development Center has complied with its obligations to expend grant payments in accordance with the Agreement.

AUDIT SCOPE

Forest Research and Development Center is responsible for the preparation of the information provided in the Financial Statement. We have conducted an audit of the Financial Statement in order to express an opinion in accordance with the Project Agreement.

The Financial Statement has been prepared to satisfy the requirements of Project Agreement. We disclaim any assumption of responsibility for any reliance on this audit report to any person other than the parties to the Project Agreement, or for any purpose other than that for which it was prepared.

Our audit procedures have been undertaken to form an opinion whether, in all material respects, the grant funds have been used in accordance with their intended purpose. We did not examine all transactions over the defined review period, as a consequence, we do not provide a guarantee that all errors or omissions, whether intentional or otherwise were detected.

The audit opinion expressed in this report has been formed on the above basis.

AUDIT OPINION

I confirm that in my opinion: the Financial Statement presents fairly, in all material respects, the grant income and expenditure on the Project.

PT. Tia Tuana Jaya

PT. Tia Tuana Jaya

Wanti Setianingsih, S.Kom., M.Ak.
Director
Date: July 06, 2022

Financial Statement of Income and Expenditure
for the period of 01 January 2021 - 31 March 2022

Project Title	:	Improving capacities towards reducing greenhouse gas emissions from peat swamp forest fires in Indonesia
Awarding Agency	:	Asia Pacific Network for Sustainable Forest Management and Rehabilitation (APFNet)
Project ID	:	2018P5-IND
Principal Investigator	:	Dr. Haruni Krisnawati
Project Period	:	01 January 2021 – 31 March 2022

	Project Budget (1 Jan 2021 – 31 Mar 2022) (USD)	Actual (1 Jan 2021 – 31 Mar 2022) (USD)
INCOME		
Grant income	23,280.00	20,952.00
Total income for the reporting period	**23,280.50**	**20,952.00**
EXPENDITURE		
Project staff	3,000.00	3,450.00
National staff travel for fieldwork	0	0
National staff exchange/international travel	5,380.00	6,519.00
Capacity building meetings	5,800.00	6,350.00
Field activities	0	0
Publication & dissemination	2,000.00	2,460.00
Office operation	1,600.00	1,744.00
Procurement	0	0
Monitoring and evaluation	3,000.00	2,450.00
Miscellaneous	2,500.00	3,587.00
Total expenditure for the reporting period	**23,280.00**	**26,560.00**
Carryforward from previous period		(60,50)
Project balance at year ended 31 Mar 2022		**(5.668,50)**

I certify that the income and expenditure as shown above is true and correct as reflected in the project's accounting system and all the rates follow actual rates.

PT. Tia Tuana Jaya

PT. Tia Tuana Jaya

Wanti Setianingsih, S.Kom., M.Ak.

Director

Date: July 06, 2022

21 July 2022

Dr Lu De
Executive Director
APFNet

Re: Budget spent, Project 2018P5-IND

Dear Dr Lu,

We would like to clarify regarding the budget spent, that overall the expenditures did not exceed the project budget allocated for all years.

For Y3, the major overspending category was from national staff exchange for international travel, including return flight and accomodation. This is because we underestimated the costs which were based on the lowest costs at the time of writing the project workplan, but the reality was almost double at the time of activity implementation. Although there are some overspending categories, we could manage the overall budget within activities with overall variance of less than 10%.

The project balance as shown in the audit report cover the actual expenses during the project duration.

The surplus amount ($5,128.50) will be used for scientific paper publications. We are currently preparing draft manuscripts for publications: (1) Post fire recovery of tree species diversity in tropical peat swamp forest (proposed journal: Science of the Total Environment, charge: $3,500); (2) Developing allometric equations for small trees in mixed-species forests of tropical rainforest ecozone (proposed journal: Forest Ecology and Management, charge: $3,460); (3) Building capacities to address climate change in tropical peat swamp forest (proposed journal: Forests, charge: $2,106). The estimated charges are based on journal's article processing charge applies to papers accepted after peer review. Pending acceptance of the paper, we will also look for a waivers or a discount from the journal, if possible.

Thank you for your support and opportunity.

Yours sincerely,

Dr. Haruni Krisnawati
Project Coordinator,
Forest Research & Development Cente
Jl. Gunung Batu No 5 Bogor, INDONESIA

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Identifying and addressing knowledge gaps for improving greenhouse gas emissions estimates from tropical peat forest fires

Liubov Volkova [a,*], Haruni Krisnawati [b], Wahyu C. Adinugroho [b], Rinaldi Imanuddin [b], Muhammad A. Qirom [c], Purwanto B. Santosa [c], Wawan Halwany [c], Christopher J. Weston [a]

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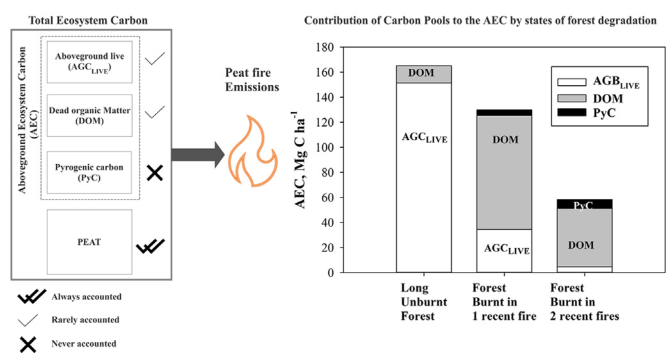
HIGHLIGHTS

- Lack of data for the parameters to estimate emissions from peat fires in the literature
- Contribution of deadwood to peatfire emissions is not properly accounted.
- Deadwood accounts for 50–60% of aboveground carbon in recently burnt peat forests
- PyC accounts for 12% of aboveground carbon in repeatedly burnt peat forests

GRAPHICAL ABSTRACT



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Pyrogenic carbon
Deadwood
Power analysis

ABSTRACT

Tropical peatlands are areas of high carbon density that are important in biosphere-atmosphere interactions. Drainage and burning of tropical peatlands releases about 5% of global greenhouse gas (GHG) emissions, yet there is great uncertainty in these estimates. Our comprehensive literature review of parameters required to calculate GHG emissions from burnt peat forests, following the international guidelines, revealed many gaps in knowledge of carbon pools and few recent supporting studies. To improve future estimates of the total ecosystem carbon balance and peatfire emissions this study aimed to account for all carbon pools: aboveground, deadwood, pyrogenic carbon (PyC) and peat of single and repeatedly burnt peat forests. A further aim was to identify the minimum sampling intensity required to detect with 80% power significant differences in these carbon pools among long unburnt, recently burnt and repeatedly burnt peat swamp forests.

About 90 Mg C ha^{-1} remains aboveground as deadwood after a single fire and half of this remains after a second fire. One fire produces 4.5 ± 0.6 Mg C ha^{-1} of PyC, with a second fire increasing this to 7.1 ± 0.8 Mg C ha^{-1}. For peat swamp forests these aboveground carbon pools are rarely accounted in estimates of emissions following multiple fires, while PyC has not been included in the total peat carbon mass balance. Peat bulk density and peat carbon content change with fire frequency, yet these parameters often remain constant in the published emission estimates following a single and multiple fires. Our power analysis indicated that as few as 12 plots are required to detect meaningful differences between fire treatments for the major carbon pools. Further field studies directed at improving the parameters for calculating carbon balance of disturbed peat forest ecosystems are required to better constrain peatfire GHG emission estimates.

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0048-9697/

1. Introduction

Tropical peatlands are areas of high carbon density that play an important role in biosphere-atmosphere interactions (Canadell et al., 2004). They cover about 182 million ha across South America, Africa and Asia; the latter accounts for about 20.3% (36.9 million ha) of the total area (Leng et al., 2019). Within Asia, Indonesia has the largest area (20.7 million ha) and the largest share of tropical peat carbon (57.4 Gt, 65%) of the global total for peatlands (Page et al., 2011). Rapid degradation of peatlands continues around the globe, including in Indonesia, where they are converted to agriculture and plantations for palm oil and wood pulp, and subject to timber extraction (Koh et al., 2009). Drainage of peatlands for agriculture and plantations dries out surface peat over extensive areas, making them susceptible to recurring fires, especially during recent extended dry spells associated with global warming. Repeated and extensive fires, following drainage and selective logging, played an important role in peat forest loss in Indonesia over 1973–2005 (Hoscilo et al., 2011). Regional droughts in 1997–98, 2005, 2015–16, and 2019 resulted in an unprecedented increase in peat fires in Indonesia, affecting both natural forests and those subjected to conversion to plantations. Smoke and air pollution from those fires affected not only Indonesia but all countries in Southeast Asia (Hayasaka et al., 2014; Marlier et al., 2015; Tham et al., 2019; Wiggins et al., 2018). Reducing smoke and emissions from peat fires is important for health and air quality, it is also gaining national and international significance as a mechanism for addressing climate change (UNFCCC, 2015). For these reasons the Food and Agriculture Organisation (FAO) of the United Nations (UN) has recently declared that improving the assessment of greenhouse gas emissions (GHG) from peatland is a global strategic priority (FAO and Wetlands International, 2012).

Following the Intergovernmental Panel on Climate Change (IPCC) guidelines, GHG emissions from peat fires are estimated as the sum of emissions from burning of aboveground (AG) carbon stocks and combustion of peat, using Equation 2.27 of the IPCC (2006b) and Eq. 2.8 of the IPCC (2014), (Eq. (1)):

$$E_i = A \cdot [(M_{AG} \cdot C_{AG} \cdot CF_{AG} \cdot Gef_{i\_AG}) + (M_{PEAT} \cdot C_{PEAT} \cdot CF_{PEAT} \cdot Gef_{i\_PEAT})] \cdot 10^{-3} \quad (1)$$

where: E_i is emission for the i^{th} direct or indirect GHG; the i^{th} direct GHGs are CO_2, CH_4, N_2O, and indirect GHGs are CO, NO_x and VOC (volatile organic compounds), Gg; A is the peat burnt area, ha; M_{AG} is mass of aboveground fuel (live biomass, litter and deadwood) available for combustion, Mg ha^{-1}; C_{AG} is a carbon mass fraction in aboveground fuels which is required for all carbon and nitrogen emissions estimates. CF_{AG} is the combustion factor of aboveground fuels (AG) estimated as the difference in the aboveground fuel before and after fire, unitless; and, Gef_{i_AG} is a gas-specific emission factor or the amount of the i^{th} GHG released per kg of dry AG matter burnt, g kg^{-1}.

M_{PEAT} is the mass of dry peat, Mg ha^{-1}. M_{PEAT} is calculated from peat bulk density (BD), g cm^{-3} multiplied by peat depth loss h, cm. C_{PEAT} is peat carbon concentration, required for all carbon and nitrogen emissions estimates. CF_{PEAT} is peat combustion factor; and, Gef_{i_PEAT} is gas-specific emission factor or the amount of the i^{th} GHG released per kg of dry peat burnt, g kg^{-1}.

If there is a lack of country-specific data to estimate peat fire emissions, the IPCC provides default parameters for M, C, CF and Gef_i based on a limited number of studies; these are shown in Tables 2.4–2.6 of IPCC (2006b), and in Tables 2.6–2.7 of IPCC (2014). For tropical peatland the default CF_{AG} is 0.50 (based on one study of Levine, 2000) and CF_{PEAT} is 1.0 (or 100% combustion).

With this background in mind our study firstly reviews the supporting data in the literature to identify knowledge gaps for improving GHG emissions estimates. Secondly, with a view to improve emission parameters, a field study is then applied to determine the sampling intensity to identify differences in emission parameters among a range of peat forests burnt at different fire frequencies.

2. Knowledge gaps in the emissions estimates

2.1. Knowledge gaps in the emissions parameters

Although emissions from tropical peat forest fires have been the subject of hundreds of publications[1], most studies do not improve knowledge of parameters required for the IPCC emissions equations. Current emissions from drained or burnt Indonesian peatlands are claimed to be in the range of 2 Billion t CO_2 per year, accounting for about 5% of the global carbon budget (UN, 2017), yet there is limited transparency in these estimates. Because there are very few studies to support country-specific conditions, the IPCC default parameters are often used. The IPCC default parameters for such a significant carbon pool as M_{PEAT} are derived from just three studies (Ballhorn et al., 2009; Page et al., 2002; Usup et al., 2004). Emissions from aboveground fuels are often excluded; for example, among published estimates of Indonesian peat fire emissions, we found only a few original studies that measured (and included) losses from aboveground dead biomass (e.g. Siahaan et al., 2020; Toriyama et al., 2014). Furthermore, emission estimates derived from complex biogeochemical models lack empirical data to reduce uncertainty in predictions. For example, the recently released Global Carbon Budget (Friedlingstein et al., 2019) estimates peat fire emissions using a complex model (the Global Fire Emission Database, GFED4s), yet it provides similar estimates for Indonesian peat fire emissions to estimates made with default parameters of the IPCC (Prosperi et al., 2020; Rossi et al., 2016).

In its first Nationally Determined Contribution (NDC), Indonesia committed to reduce its GHG emissions by 26% relative to a business as usual scenario by 2020, and by 41% with international support. For the period from 2020 to 2030 these reduction targets are 29% (unconditional) and 41% (conditional) (Republic of Indonesia, 2016). Due to a high level of uncertainty in peat fire emissions parameters, the Indonesian Government excluded emissions from peat fires in its first Forest Reference Emission Level (FREL) submitted to the UNFCCC (MoEF, 2016), preventing it from subsequently claiming emission reduction from reduced peat fires.

There are not many studies which support fire emission parameters of Eq. (1) in a comprehensive way. Moreover, the majority of studies report field data collected at least ten or more years ago (Table 1). With few recent empirical studies on which to improve emission estimates the IPCC was unable to update emissions parameters in the 2006 Guidelines for the 2019 refinement (IPCC, 2019).

In recognizing the general lack of new or recent literature to support emission estimates, we provide here a detailed overview of the parameters required to estimate peat fire emissions as a commentary to information presented in Table 1:

$M_{AG} \cdot CF_{AG}$ – the mass of aboveground fuel and its combustion factor are covered by fewer than 10 studies, where only three cover all aboveground fuels, and a further two studies that measured CF_{AG} as pre- to post-fire mass difference. Fewer than five studies report losses of aboveground fuels resulting from multiple fires. There seems to be no common or standardised approach for measuring and reporting all aboveground fuels in peat forests.

M_{PEAT} – there are fewer than ten studies providing information on the critical peat loss (burn depth) parameter. Only Usup et al. (2004) reports on belowground fuels such as grass roots and submerged woody debris. While there is a reasonable coverage in the literature on peat BD (Table 1), and also see the often referenced studies (e.g. Neuzil, 1997; Supardi et al., 1993); only a few studies report changes in peat

[1] Above 500,000 results from Google search for 'Peat fire emissions AND Indonesia' and around a thousand from the Web of Science using a combination of words' peat fire, carbon loss, tropical' at 20 April of 2020.

Table 1
Review of the parameters contributing to tropical peat fire emissions estimates as per IPCC Guidelines, for the detail of studies refer to Supplementary Table S1.

Study	M_{AG}	CF_{AG}	M_{PEAT}		C_{PEAT}	CF_{PEAT}	Gef_{i_PEAT}	Date collected
			h	BD				
1					x			2013–2014
2				x	x			2007–2010
3	x	*	x	x				2014-2015
4			x					2007
5			x					1997
6							x	n/g
7	1	*						2014
8	2							2011
9			x	x				2011
10							x	2009
11			x	x	x			2010–2013
12							x	2015
13							x	2003
14	x	*			x			2005
15							x	2015
16			x	x	x			2010–2011
17				x				2000
18	1	*						2007-2008
19	x	*						2001
20							x	2009
21				x	x			1969–2012
22			x	x	x			1999/2000
23				x	x			1995
24	x	*		x	x			2009
25				x	x		x	2016
26	3	x						2001–2002
27	1			x	x			2015
28				x	x			1997–1999
29	x	*						2015
30			x					2015
31				x				2013
32				x	x		x	2016
33							x	n/g
34			x				x	2015
35	x	*						2009
36	x	x	x			x		2002
37				x	x			n/g
38				x	x		x	2015

* Can be extrapolated from the data; n/g – not given; 1– trees only; 2 – only volume of CWD; 3 – litter and branches only.

BD following one or more fires (e.g. Konecny et al., 2016; Sinclair et al., 2020). Although there are numerous studies of C_{PEAT}, none report the impact of fire or frequent fires on this parameter. Given strong evidence for the fire-modification of soil organic carbon, this is a major knowledge gap given the extent of frequently burnt peatlands.

CF_{PEAT} – a value of 1 is universally applied and assumes complete combustion of peat (Usup et al., 2004); it is acknowledged in the literature as an oversimplification (Hooijer et al., 2014; Konecny et al., 2016).

Gef_{iAG} parameter, not specific to peat swamp forests, has a good coverage in the literature from studies for other forests types (Andreae, 2019). Gef_{iPEAT} is a reasonably well-studied parameter in the laboratory and in the field; also see reviews (Hu et al., 2018; Levine, 2000).

Based on this evaluation of the current literature, we suggest that to improve emission estimates from tropical peatlands, attention should first be focused on the aboveground fuels ($M_{AG} \cdot CF_{AG}$) and peat ($h \cdot BD \cdot C_{PEAT}$), as these are major determinants of estimates.

2.2. Knowledge gaps of the effect of frequent fires on emissions parameters

Over the last two decades about 12% of peatlands in Sumatra and Kalimantan have been burnt more than once, with about 23% of this area burnt more than twice (Vetrita and Cochrane, 2020). Results from just a few studies of degraded and repeatedly burnt forests reveal about 80% loss of aboveground biomass, with litter (5 Mg C ha^{-1}) and deadwood (26 Mg C ha^{-1}) accounting for most of that total (Dharmawan, 2012; Qirom et al., 2018). There is an urgent need for improved data on aboveground carbon stocks and the mass of fuel burnt, so that uncertainty in peat fire emission estimates can be reduced (Austin et al., 2018).

2.3. Knowledge gaps on the importance of pyrogenic carbon for the emissions estimates

Current peat emission estimates do not account for the production of PyC, the thermochemically altered biomass that is created from the pyrolysis and incomplete combustion of organic matter (also referred to as black carbon, soot, elemental carbon, char, charcoal and biochar) (Bird et al., 2015; Surawski et al., 2020). Globally, vegetation fires can produce about 116–385 Tg PyC per year (Santin et al., 2016). In cold temperate peatlands between 2% to 4% of combusted biomass is converted to PyC in fires (Worrall et al., 2013); there are no corresponding studies of PyC production following Indonesian peat fires. Accounting for PyC will assist in constraining carbon loss estimates and improving the accuracy of emissions estimates. Ignoring production of PyC assumes that all biomass consumed in fires is emitted, globally leading to the annual over estimation of carbon emission by 100 Tg (Surawski et al., 2016). Furthermore, PyC that is produced from biomass burning and not emitted to the atmosphere is a potential source of long-term carbon sequestration when stored in soils or sediments (Preston and Schmidt, 2006). Char has been shown to have mean residence times of up to 10,000 years in soils (Swift, 2001); this relative inertness means that it must be considered as a significant component of global cycling (Forbes et al., 2006). Consequently, accounting for PyC in the carbon mass balance will further help to improve the accuracy of peat forest fire emission estimates.

3. Addressing knowledge gaps in the emissions parameters

To address the gaps in emission parameters identified above, a feasible field sampling design, with sufficient replication of biomass components (aboveground live, deadwood, litter, PyC and peat carbon) is required to understand the contribution of individual carbon pools to total peat forest carbon. The sampling intensity for biomass components should enable detection of significant differences in the carbon pools between fire treatments.

For researchers studying the impact of fire regimes on carbon balance of peat forests, sampling design and sample size become non-trivial questions. Long undisturbed peat forests have a dense canopy of overstorey trees that account for the majority of aboveground carbon (Verwer and van der Meer, 2018), while recently and repeatedly burnt peat forest is either dominated by vigorous young regrowth or dominated by bare ground, with a low density of dead trees remaining from previous fires (Konecny et al., 2016; Siahaan et al., 2020). Sampling designs must be flexible enough to characterise differences in the allocation of carbon among pools in relation to the number of fires and fire return interval. Fixed plot designs, such as circular plots, are usually straight-forward to establish in most forest settings, and are traditional choices in many forest inventories (McRoberts et al., 2013). Yet, when site conditions are variable it is often unclear how many samples are required to test the hypotheses of interest. This problem is likely exacerbated when collecting data from systems exposed to novel disturbances, as the variance associated with the data is unknown.

It is a good practice to conduct a pilot study, to design an experiment resulting in analyses with sufficient statistical power to address the research question. Statistical power is defined as the probability of correctly detecting a significant effect if it exists in the population of interest; mathematically $Power = 1 - \beta$ where β is probability of making a Type II error – failing to detect an effect if it exists. The power of an analysis is related to sample size and variance, but also to the effect size (e.g., magnitude of the difference between two groups: a treatment and control) that researchers deem important to detect (Di Stefano, 2001; Foster, 2001). Generally, the smaller the effect size, the greater the sample size required. Researchers must decide the meaningful magnitude of change that is important (Westfall et al., 2013). Chasing a small effect size may also lead to overspending resources or to finding an effect that is either small or doesn't really exist (Hoenig and Heisey, 2001). Statistical power analysis can help to find the minimum sampling effort needed to detect relevant differences between treatments and changes over time in monitored variables (Di Stefano, 2001; Foster, 2001).

In recognizing a general lack of supporting data in the literature, we aimed to address knowledge gaps identified in Table 1 through a field study where we first deal with the sampling intensity required to achieve sufficient power for our research purpose of identifying treatment differences. Specifically, the main aims of this study were: i) to develop practical and achievable field sampling designs for aboveground fuels and peat components in repeatedly burnt peat swamp forests; ii) to identify the impact of recent and repeated fires on peat swamp forest carbon pools and, iii) to identify sampling intensity required to detect with 80% power significant differences in biomass carbon pools (e.g., aboveground live, deadwood) of long unburnt, recently burnt and repeatedly burnt peat swamp forests.

4. Material and methods

4.1. Study sites

An area of degraded peat swamp forest of the former Mega Rice project of Central Kalimantan, Borneo, was selected for the study (Fig. 1). Specifically, the plots were located within Tumbang Nusa Research Forest (KHDTK Tumbang Nusa) (0°8′48“ to 3°27′00” South and 113°2′36“ to 114°44′00” East), about 30 km south east of Palangka Raya, Indonesia. Throughout 2019 and early 2020 a pilot study of 18 plots comprised of 2 blocks × 3 treatments × 3 plots was sampled. Plots were selected to cover different fire history with accessibility in the difficult terrain a key factor due to time constraints and limited resources. Once the treatment locations were identified, selection of the first plot was random, followed by a grid method with a minimum distance of 60 m between plots along a pre-determined compass bearing to locate the second and subsequent plots.

4.2. Treatments

An extensive fire in 1997 burnt through all the Tumbang Nusa area of peat swamp forest that had been drained and logged throughout the 1980s and 1990s. Following the 1997 fire some areas of forest regenerated without subsequent burning while other areas burnt again in 2014 and 2015 (fire history data were provided by the Banjarbaru Forestry and Environment R&D Institute). For this study the following treatments were selected: SF – Secondary peat swamp forest regenerated though natural processes, long unburnt (fire in 1997); SF_1 – Secondary peat swamp forest burnt in one recent fire – a fire in 2015 and also in 1997, and SF_2 – Secondary peat swamp forests burnt in two recent fires - fires in 2015 and 2014 and also in 1997, (Figs. 1-2).

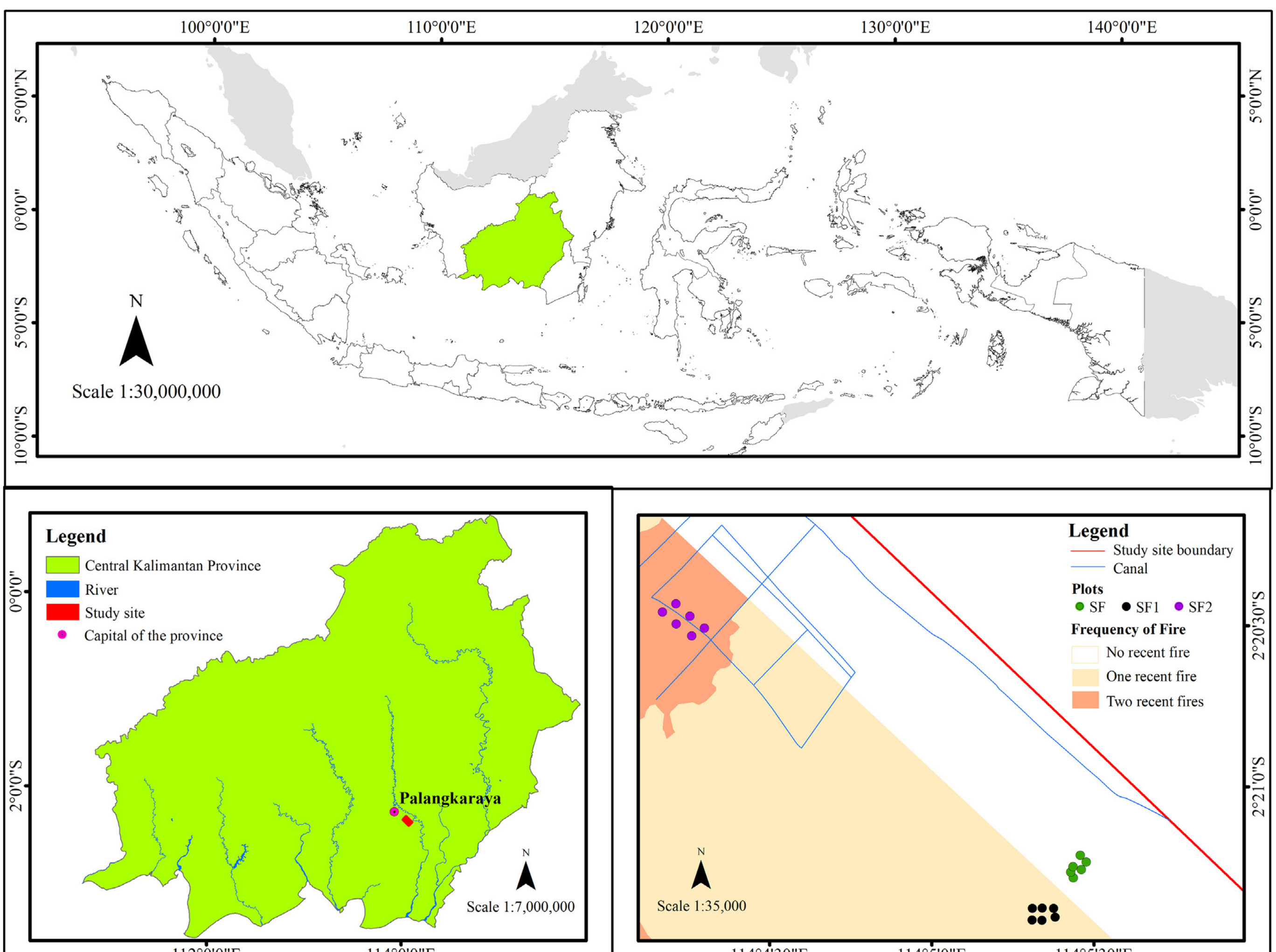

Fig. 1. Study sites location in Central Kalimantan, Indonesia.

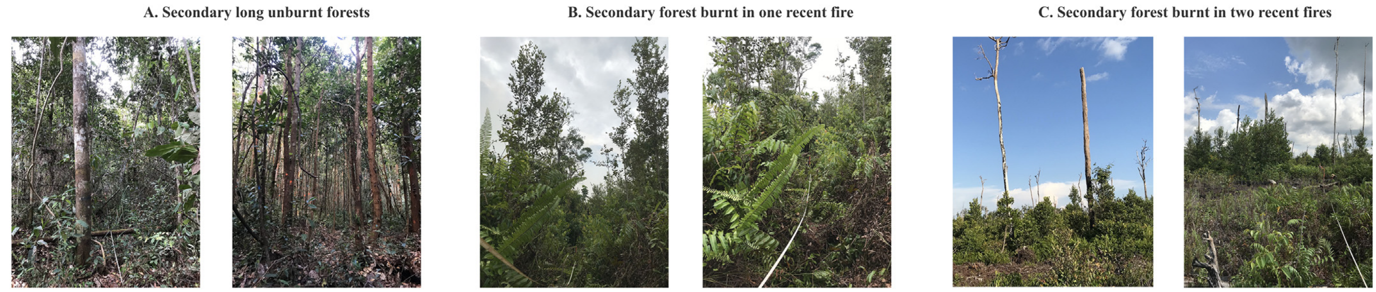

Fig. 2. Photographs of the secondary peat swamp forests at different stages of forest recovery after fires: (A) long unburnt forests, (B) forests burnt in one recent fire showing vigorous regrowth; (C) forests burnt in two consecutive fires.

Given the different structure of aboveground biomass among the three treatments (Fig. 2) the sampling design was varied to capture biomass data in the most efficient way; these sampling designs are described below.

4.3. Sampling design

4.3.1. Secondary long unburnt (SF) peat swamp forests

Trees with a diameter at breast height (DBH) ≥ 10 cm, were measured in 10 m radius circular plots, with the more numerous small trees (DBH < 10 cm) measured within a 3-m radius sub-plot, following a protocol developed by Kauffman et al. (2016). All species names and live or dead status were recorded. Dead trees were assessed for the presence of leaves and branches. Coarse woody debris (CWD), defined as detached woody material with diameter ≥ 2.5 cm lying on the forest floor, were measured along a 50-m transect extending through the plot centre following the methodology of Van Wagner (1968). The diameter of CWD intersected by the transect was measured at the point of intersection with the transect, and placed into one of three classes: sound, rotten (signs of decomposition extended to heartwood) or charred (heavily charred wood). Three representative samples for each class were taken for wood density analysis in the laboratory at the facilities of FORDA, Bogor, Indonesia.

Ground cover (i.e. grasses and small shrubs to 0.5 m high), and litter (i.e. leaves, tree fruits, decomposed organic matter and twigs with d < 2.5 cm) were destructively sampled from within a 0.1 m^2 metal frame placed on the peat surface, with a sample taken from north, east, south and west points of the plot circumference (Fig. 3A).

A sample of the top peat layer (0–10 cm) was collected from the plot centre point using a 10 cm tall metal cylinder (465 cm^3), with two samples per plot collected for *BD* and C_{PEAT} analyses.

Samples of peat were collected throughout the peat profile down to the mineral soil surface, from a location near the plot centre point. The following depths were sampled: 10–50 cm (a peat sample for *BD* and C_{PEAT} analyses was taken from the middle at 20–30 cm depth), 50–100 cm (a sample was taken at 60–70 cm depth), 100+ (a sample was taken midway between 100 cm and the mineral soil surface). Peat was collected using an Eijkelkamp peat sampler (sample length 50 cm; sample diameter 52 mm) attached to the Edelman auger with extension rods enabling sampling up to 6 m (https://en.eijkelkamp.com/products/augering-soil-sampling-equipment/peat-sampler.html). The depth of peat was estimated from the length of the peat auger (rods plus sampling head) inserted to the mineral soil surface (Fig. 3).

4.3.2. Secondary peat swamp forests burnt in one recent fire (SF_1)

A belt transect was selected for sampling the dense vegetation regrowth in this treatment, where moving about on the site was difficult (Fig. 2). Trees were measured along a 50 m transect at sub-plots established at 10 m intervals. Trees were measured within each 1 m radius sub-plot established on both sides of the transect (Fig. 3B), yielding 12 sub-plots per transect. Small trees were counted and placed in the following diameter categories: 0–1 cm, 1–2 cm, 2–3 cm, 3–4 cm,

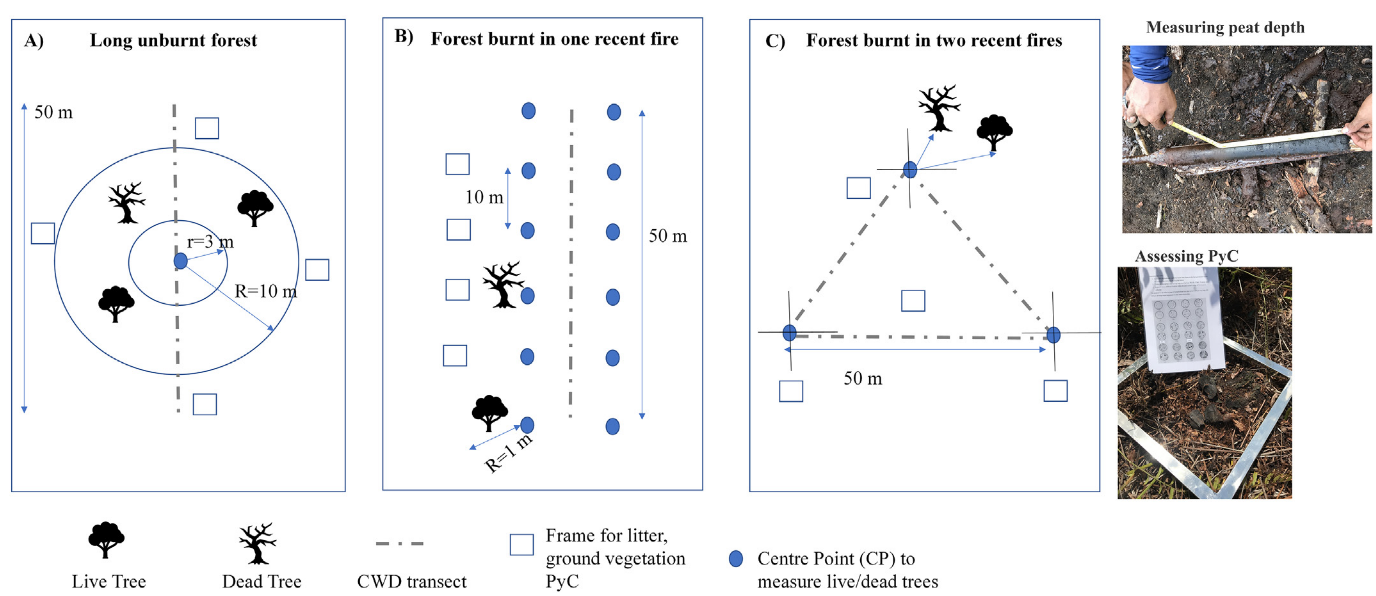

Fig. 3. Sampling design: (A) long unburnt forests, (B) forests burnt in one recent fire, (C) forests burnt in two consecutive fires.

4–5 cm. Live and dead trees with DBH ≥ 5 cm were measured. Dead trees were assessed for presence of leaves and branches.

CWD was measured at each point of intersection with the 50 m transect and CWD status was recorded. Ground cover was sampled from the sub-plots at the 10 m, 20 m, 30 m and 40 m on the transect (4 samples), followed by collection of litter from the same locations (Fig. 3B). Peat was sampled at the beginning of the transect in the same manner as described above.

4.3.3. Secondary peat swamp forests burnt in two recent fires (SF_2)

A centre-point method (Mitchell, 2015) was chosen to measure trees in this treatment. Scattered dead standing trees across the area, and minor regrowth, meant that neither belt transect, nor circular plot design would adequately capture the distribution of live and dead trees in this treatment (Fig. 2). To capture measurements of all biomass components, three 50 m line transects were established at 60° angle to each other to create a triangle, with each apex representing a centre point (CP) as shown in Fig. 3C. At each CP, the area was visually divided into 4 quarters and one nearest live and one nearest dead tree was measured for DBH and the distance to the CP, resulting in 24 tree records (3CPs x 4 quarters × 2 trees). The distance was measured using a Vertex III (Haglof, Sweden). Live or dead status and species name were recorded and the presence or absence of leaves and branches on dead trees was recorded. On the occasions where no dead trees were present in a 15–20 m distance from the centre point, a count of zero dead trees was recorded.

One of the 50 m transects was chosen for CWD measurements. Ground cover and litter were collected at four locations within the triangle. Peat was collected in the middle of the triangle (Fig. 3).

4.4. Pyrogenic carbon (PyC)

A metal frame of 0.1 m^2 was randomly located on the bare ground of a plot and percent cover of PyC was visually assessed following the Braun-Blanquet (1932) cover-abundance scale (Fig. 3). Visually identifiable PyC pieces were collected in plastic zip bags for subsequent dry mass and carbon content analysis in the laboratory; four samples per plot were collected.

4.5. Estimating aboveground live, deadwood and peat carbon

Live tree biomass was calculated using an allometric equation derived for mixed species of Indonesian peat swamp forests, based on the destructive sampling of 148 trees (Manuri et al., 2014). Dead tree biomass was calculated in the same manner as for live tree biomass but adjusted for the absence of leaves and branches by either reducing the biomass by 2.5% (for a minor defoliation) or 20% (where no leaves, branches or tops were present) (Kauffman et al., 2016). Total tree biomass per hectare (Mg ha^{-1}) for the centre-point method (SF_2 treatment) was estimated as the sum of individual tree biomass (kg) divided by the ¼ circle area (m^2), where the distance from a tree to the CP was the plot radius.

4.6. Sample analysis

Ground cover, litter and PyC were oven-dried at 60 °C for about two weeks to a constant weight in the laboratory of FORDA, Bogor, Indonesia. All measurements are given on a dry-weight basis. For BD estimation peat was oven-dried at 105 °C until dry mass was recorded constant (about 2–5 days) following the protocol of Kauffman et al. (2016). Wood density of CWD was estimated using water a dispersion method. Peat, CWD, and PyC were analysed for carbon content at the facilities of an ISO/National Certification (KAN) Centre for Agricultural Land Resource Research and Development using a loss on ignition method. The carbon content of live trees was assumed to be 0.47 (IPCC, 2006a).

4.7. Carbon pools

We followed the IPCC (2006b) definition of carbon pools where live aboveground carbon (AGC_{LIVE}) included live trees and ground cover (i.e. grasses and small shrubs); Deadwood included dead standing tees and CWD; Litter; peat carbon and PyC (this carbon pool is not included in the current IPCC methodology, IPCC (2019)). Total aboveground carbon (AGC_{TOTAL}) was estimated as the sum of AGC_{LIVE}, deadwood, litter and PyC.

4.8. Power analysis

A range of power analyses were tested to determine the sample size required to reject the null hypothesis (i.e. no difference in the means of carbon pools of long unburnt vs recently and repeatedly burnt forests) with at least 80% power and the probability of a type-I error (α) of 0.05. We defined adequate power using an 80% threshold as this is a common practice in ecology, although we acknowledge that higher power may be desirable in some cases (Di Stefano, 2003). We present power and samples size values beyond 80% so that readers can choose their own threshold.

Due to the spatially hierarchical nature of the study design we applied a linear mixed effects model and conducted the power analyses using simulation following the method developed by Green and MacLeod (2016). A linear mixed-effects model (LMM) was applied to detect the contrast between long unburnt forests and the other treatments, where *block* was a random factor. The effect size was considered individually for each of the major carbon pools (AGC_{LIVE}, deadwood, peat BD 0-10 cm) and defined as differences between the SF – SF_1 and SF – SF_2 treatments. To explore trade-offs between sample size and power, we set the analysis to a range of sample sizes extending our simulations by adding more blocks (from 2 to 6) and by increasing the number of plots within blocks (from 3 to 20). Calculations were based on 1000 Monte Carlo simulations for each combination of sample sizes and contrasts. The calculations were made using software R 3.6.3 (R Core Team, 2020), packages lme4 (Bates et al., 2015) and simr (Green and MacLeod, 2016).

5. Results

5.1. Aboveground carbon

Both fire frequency and time since fire had a major impact on the distribution of carbon across aboveground pools among treatments. Live trees accounted for 91% of the AGC_{TOTAL} in long unburnt forests (SF), virtually disappearing with increased frequency of fire. The contribution of ground cover to AGC_{TOTAL} increased with frequency of fires from 0.7% in long unburnt forests to 7% in repeatedly burnt forests (Table 2). Deadwood was a major carbon pool in forests affected by one and two recent fires (68–75% of the AGC_{TOTAL}), with the majority

Table 2
Carbon pools contributing to fires in % of the total AGC in long unburnt forest, SF; forests burnt in one recent fire, SF_1 and forests burnt in two consecutive fires, SF_2. Absolute values in Mg C $ha^{-1}$are given in brackets.

Carbon pool	Treatment		
	SF	SF_1	SF_2
AGC_{LIVE}	92 (150.4)	26 (34.4)	8 (4.5)
Live trees	91	24	1
Ground cover	1	2	7
Deadwood	6 (10.7)	68 (87.6)	75 (44.1)
Dead trees	3	15	12
CWD	3	53	63
Litter	2 (3.2)	3 (3.4)	5 (2.8)
PyC	0	3 (4.5)	12 (7.1)
AGC_{TOTAL}	100 (164.3)	100 (129.9)	100 (58.5)

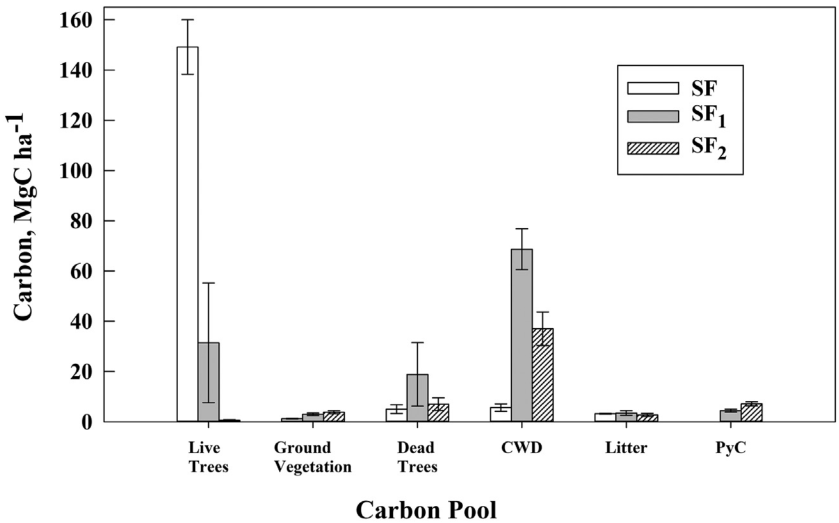

Fig. 4. Carbon pools in long unburnt forest, SF; forests burnt in one recent fire, SF_1 and forests burnt in two consecutive fires, SF_2. Values are means, $n = 6$, Error bars indicate standard error of the mean.

accounted in CWD (Table 2, Fig. 4). Charred CWD was absent from long unburnt forests and accounted for 6% of total CWD mass on sites burnt in one recent fire, increasing to almost 50% of CWD on repeatedly burnt sites (Fig. 5). The density of CWD (and C) ranged from 583 kg m^{-3} (0.52) for sound, 416 kg m^{-3} (0.46) for rotten and 579 kg m^{-3} (0.66) for the charred class.

For all treatments the litter pool, with an average carbon content around 0.52, accounted for between 2% and 5% of the AGC_{TOTAL} mass – consistently a minor component of AGC_{TOTAL} (Table 2, Fig. 4.).

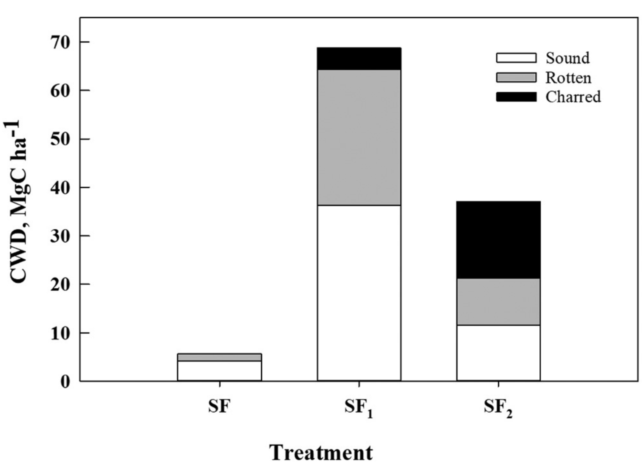

Fig. 5. Loads of Coarse Woody Debris (CWD) by the decay class in long unburnt forest, SF; forests burnt in one recent fire, SF_1; and forests burnt in two consecutive fires, SF_2. Values are means, $n = 6$.

PyC was not visible on the forest floor/peat surface in the long unburnt forests. For forests burnt in one recent fire, PyC covered 25 ± 11% (±95% CI) of the forest floor, increasing to around 46% ± 5% at multiple burn forests. The average C% of PyC was 63.3 ± 1.7% (± s.e. of the mean). The contribution of PyC to the AGC_{TOTAL} increased with fire frequency from 3% (or 4.5 Mg C ha^{-1}) after one fire to 12% (or 7.1 Mg C ha^{-1}) after multiple fires (Table 2, Fig. 4).

Overall, the long unburnt forests stored more aboveground carbon than forests affected by recent fires; by comparison one recent fire reduced this by about 20% of the AGC_{TOTAL}, with repeated fire consuming a further 55% of the AGC_{TOTAL} (Table 2).

5.2. Peat carbon

The depth of peat to a mineral substrate was comparable among the treatments, varying from around 3.5 to 3.65 m (Table 3). Peat BD in the 0–10 cm depth increased with fire frequency (Table 3). The C_{PEAT} increased with increasing frequency of fires from 0.3 in long unburnt forests to 0.37 after one recent fire and to 0.40 after two consecutive fires (Table 3). Reflecting the trend in C_{PEAT}, total peat carbon increased from 2156 Mg C ha^{-1} to 2826 Mg C ha^{-1} with fire frequency (Table 3).

5.3. Power analysis

For determining the optimum sample size, we considered the effect size based on the data variability and the contribution of the individual carbon pools to the emissions estimates.

We observed a significant effect of fire frequency and fire return interval of AGC_{LIVE} carbon and assumed that a 30% (or 45 Mg C ha^{-1}) difference in the means would be a reasonable effect size. A 30% difference in AGC_{LIVE} at 80% power can be detected by either increasing the number of plots within a block or by increasing the number of blocks and

Table 3
Peat characteristics.

Treatment	Peat depth, m	Peat bulk density (BD), g cm^{-3}				Peat carbon content (C_{PEAT}), %				Average	Total, Mg C ha^{-1}
		0–10 cm	10–50 cm	50–100 cm	100+ cm	0–10 cm	10–50 cm	50–100 cm	100+ cm		
SF	3.49 ± 0.12	0.124 ± 0.01	0.221 ± 0.29	0.293 ± 0.08	0.216 ± 0.02	42.9 ± 3.5	28.2 ± 5.5	17.6 ± 2.5	29.2 ± 7.2	29.5 ± 3.5	2156 ± 208
SF_1	3.66 ± 0.09	0.136 ± 0.01	0.221 ± 0.02	0.205 ± 0.02	0.205 ± 0.01	41.7 ± 1.5	28.5 ± 7.4	40.0 ± 0.2	38.9 ± 2.2	37.3 ± 2.3	2511 ± 100
SF_2	3.64 ± 0.05	0.154 ± 0.02	0.198 ± 0.02	0.172 ± 0.01	0.164 ± 0.01	41.4 ± 1.3	39.5 ± 2.6	37.9 ± 1.5	41.5 ± 0.5	40.3 ± 2.3	2826 ± 162

Values are the mean ± s.e. of the mean. $N = 6$ for peat bulk density; $N = 3$ for C%. SF is Long unburnt forests; SF_1 – Forest burnt in one recent fire, and SF_2 – Forests burnt in two consecutive fires.

reducing the number of plots within blocks – each solution results in 12 plots per treatment arranged as either 2 blocks × 6 plots, 3 blocks × 4 plots or 6 blocks × 2 plots (Fig. 6).

Peat BD is an important parameter contributing to the estimates of mass of peat, thus it is important to make an effort to accurately characterise it. For power analysis we focused on the top layer (0–10 cm), for which we had the most accurate sampling. Based on the predicted means, we considered that a difference of 0.06 g cm^{-3} (or 50%) would be a reasonable effect size. The simulations revealed that sample size reduces with the increased number of groups (blocks), similar to the trend observed for AGC_{LIVE} (Fig. 6).

Deadwood was the most variable carbon pool, mainly due to a high variability in dead standing trees in recently burnt SF_1 forests (Fig. 4). Because the long unburnt forests stored only a minor fraction of carbon in deadwood (10.8 Mg C ha^{-1}), setting up an effect size of 30–50% difference would require detecting a difference of 3–5 Mg C ha^{-1}, which is unrealistically small considering that recently burnt forests stored 40–80 Mg C ha^{-1} in deadwood (Figs. 4-5). Thus, for the deadwood, the effect size was set up at the difference of 100% or 22 Mg C ha^{-1}, and even with such a rather large effect size, our power curves indicate that the sample size must be in order of 26–30 plots per treatment to yield greater than 80% power (2 blocks × 13 plots, 3 blocks × 9 plots or 6 blocks × 5 plots; Fig. 6). Increasing the effect size to 150% (or 33 Mg C ha^{-1} difference) produced the same results as for the other two pools (12 plots per treatment, data not shown).

No power analysis was conducted for PyC as this carbon pool is not present on the forest floor of long unburnt forests, thus any combination of block and plot sample sizes discussed above will be able to detect a significant difference between the treatments.

6. Discussion

6.1. Impact of fire frequency on aboveground carbon

In this study we present a comprehensive assessment of the aboveground and peat carbon pools as they are affected by recurring fires. The review of literature showed there is great uncertainty in the estimates of peat fire emissions, especially where peat swamp forest sites are burnt in more than one fire. This pilot study shows that after one recent fire about 90 Mg C ha^{-1} remains aboveground as the deadwood carbon pool (Figs. 1, 4, Table 2), similar to findings of others (Qirom et al., 2018; Siahaan et al., 2020). Following a second consecutive fire, about a half of the deadwood is retained, mainly as CWD, or converted to pyrogenic carbon. Overall, only about one third of the total aboveground carbon in the form of deadwood and PyC remains after two consecutive fires, compared to the long unburnt forests, which mainly stores aboveground carbon in live trees. Both deadwood and PyC are burnt mainly in smouldering combustion that releases an array of potent greenhouse gases (Andreae and Merlet, 2001; Stockwell et al., 2016) so that excluding these fuels from carbon mass balance would lead to greater uncertainties in the emission estimates.

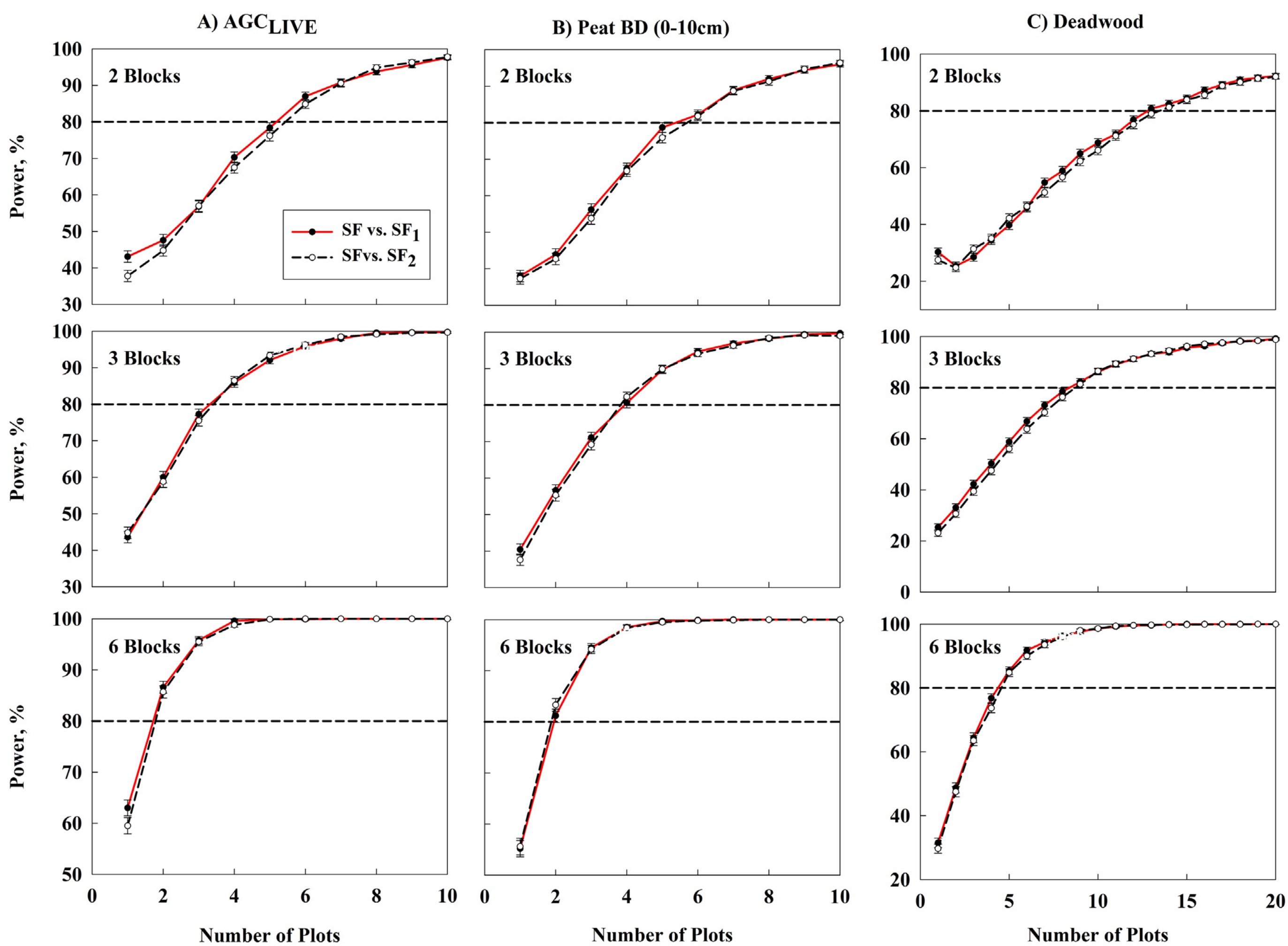

Fig. 6. Power analysis of the major carbon pools using a combination of blocks and plots to achieve 80% power to detect A) a 30% difference in the means for aboveground pools (live trees and ground vegetation); B) a 50% difference in the means for peat bulk density 0-10 cm depth and C) a 100% difference in the means for deadwood (dead trees and CWD) between recently burnt forests vs long unburnt forests. Values are the means based on 1000 simulations; error bars are the standard error of the mean.

We did not observe the impact of fires on litter, with predicted means being similar for all of the treatments ranging from 2.77 (SF_2) to 3.4 (SF_1) and 3.2 (SF), findings similar to other studies for peat swamp forests of Indonesia (Qirom et al., 2018; Siahaan et al., 2020). Considering that litter contributes a rather small fraction of the carbon emitted from peat fires, we advocate that for accounting of this carbon pool in emissions estimates, an average number can be considered.

6.2. Role of the pyrogenic carbon in the emission estimates

The role of PyC in forest carbon balance and its contribution to emissions is largely ignored due to a lack of empirical data; as such the PyC data presented here is novel in addressing this important knowledge gap. Consistent with studies from cold temperate peatlands (Worrall et al., 2013), we observed that one fire produced PyC equivalent to about 3% of aboveground biomass and that repeated burning increased this contribution threefold. Clearly PyC becomes an increasingly important carbon pool in repeatedly burnt peat swamp forests. Ignoring fire produced PyC from carbon mass balance will lead to overestimation of atmospheric emissions, with recent studies pointing to the overestimates of 4% of the global total emissions (Surawski et al., 2016). This study was not designed to estimate emissions from peat fires but rather to address the lack of a more complete knowledge of parameters required for improved peat fire emission estimates. As such we refrain here from giving examples of the difference in emissions estimates where all aboveground fuels and PyC are considered vs peat only released emissions – a subject for follow up studies.

6.3. Peat carbon

In these peat swamp forests, peat to the soil mineral surface stored in excess of 2000 Mg C ha^{-1}, or about 2–7 times more than was stored aboveground. The difference in peat carbon stocks between treatments mostly reflected variability in peat BD and C_{PEAT} among the treatments. While we are cautious that peat data from our pilot study is based on a limited number of samples, the trend of increased carbon concentration with increased frequency of fire is similar to findings from temperate and boreal needleleaf forests, but in contrast to observations from frequently burnt savannas and broadleaf forests (Pellegrini et al., 2018). Often the effect of fires on soil carbon is overlooked because samples are collected shortly after fires (Santín and Doerr, 2016). In this study the peat samples were collected several years after the fires and it is possible that increased C_{PEAT} reflects eluviation of fine PyC from the peat surface down into the peat profile. Similar to findings of Sinclair et al. (2020), we observed an increase in *BD* in the top layer (0–10 cm) with increasing frequency of fires. Peat degradation typically increases the bulk density of peat soil through drainage, heating of the peat surface or from compaction (Ali et al., 2006; Hooijer et al., 2012). Because the C_{PEAT} and *BD* parameters determine M_{PEAT} (Eq. (1)), they should be the focus of further studies to improve emissions estimates from repeatedly burnt forests. Moreover, the *BD* should vary with fire frequency in a similar manner as peat depth, a suggestion echoing Konecny et al. (2016).

The overall difference in peat depth (h) between long unburnt, recently and repeatedly burnt forests was minor and we understand that it was mainly related to the position of plots on the *Mawas* peat dome (Page et al., 1999); that is, to the elevation of the peat surface and the peat base (Silvestri et al., 2019) as well as sampling peat depth with an auger (when it is difficult to pick up a small difference in peat consumption several years after a fire). A more careful sampling of peat loss during fires is required to improve knowledge for the h parameter.

6.4. Sampling design and power analysis

We developed field sampling designs to quantify biomass pools under the contrasting field conditions of our treatments (long unburnt, recently burnt and repeatedly burnt peat forests, Fig. 2). A plotless design was applied to the repeatedly burnt SF_2 treatment to capture the different distribution of live and dead trees in this treatment relative to the other treatments. The average distance from the centre point to live trees was 8 m (range 0.54–38 m) and to dead trees was 15 m (range 1.75–29.6 m), meaning that more traditional plot shapes (circle, square, rectangular) would need to be either very large (thus very time consuming in measuring all trees), or would not be able to capture the observed variability if plot radius is kept to 10 m as for SF treatment. While the sample plots varied in shape from belt transect (SF_1), to circular plot (SF) to quarter-center (SF_2), each comprised a systematic random sampling with the same threshold for measuring carbon pools, making it an unbiased design. For the analysis of data derived from such designs, it should be considered that response variables may not share common residual variances. Therefore models accounting for non-homogeneous errors should be implemented (Harrison et al., 2018).

In this study we applied a power analysis to ensure that future experiments can be designed in a way to adequately test for the effect of fires on peat forest carbon pools with at least 80% probability. Power analysis is a useful tool for investigating the effectiveness of different sampling designs and depending on the structure of the variance, power to detect trends may be increased by altering the sampling design (Perles et al., 2014). We considered a few combinations of *along* and *within* argument by extending the number of groups (blocks) and the number of observations (plots). Depending on the specific objectives, resources and ability to spatially fit the required number of plots within a block, or the required number of blocks within the treatment, various combinations of 'fewer blocks - more plots' or 'more blocks - fewer plots' can be selected with similar power. Considering the challenging field conditions of Indonesian peatlands and the time and effort required to move between blocks and plots, we would recommend a middle approach: fewer blocks (3–4) and more plots (5–6), as the distance between plots is generally shorter than the distance between blocks – yet a greater than two number of blocks would better capture variability of forest carbon among pools and treatments.

For the effect sizes considered in this study, except for the deadwood, the power to detect change was very high using a total of just 12 plots per treatment (in any variation of blocks and plots). For deadwood, the sample size was much greater because the magnitude of detectable changes was smaller, confirming other studies that a small change is difficult to detect with high power (Westfall et al., 2013). Increasing the effect size in the deadwood pool led to similar results as for other pools. It is important to remember that our power analysis is only an approximation of a desired sample size as the outcomes were influenced by the variability in our data, desired effect sizes and the α threshold; changing any of these parameters would alter the outcomes as was observed for deadwood. We based our power analysis on a reasonable detectable change which would make an impact on emissions estimates. To this end we conclude that a minimum of 12 plots per treatment is a good starting point for future sampling strategies and field sampling designs.

7. Conclusion

This study identifies current knowledge gaps in supporting data required to improve our understanding of the emissions from Indonesian peat fires. Despite many publications on peat fire emissions, an important knowledge gap in empirical observations to support estimation parameters remains. Lack of knowledge of the impact of repeated fires on aboveground fuels and on the production of pyrogenic carbon adds to uncertainty in emissions estimates. Using the data from our pilot study we show that PyC plays an important role in the carbon balance of peat swamp forest and that its importance increases with frequency of fires. It can be argued that the major source of fire emissions in tropical peat forests is the peat, while the contribution of aboveground fuels is relatively minor (Tables 2–3), yet to improve the accuracy in peat fire emission estimates and carbon mass balance, we would argue that all aboveground and peat carbon pools must be properly accounted for. This study aimed to develop an appropriate sampling design and to estimate the required sampling intensity for describing and comparing emissions from peat swamp forests at different stages of degradation. As such we refrained from a comprehensive statistical analysis and from providing recommendations for refining peat fire emissions estimates. This study provides crucial information for the design and implementation of further field experiments to evaluate the effect of repeated fires on aboveground carbon pools and peat for reducing uncertainty in peat fire emission estimates.

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CRediT authorship contribution statement

LV, HK, CJW conceived and designed the study, overseen its implementation and contributed to the development of the manuscript idea. LV has analysed the data, written the first draft of the manuscript and conducted literature review with the inputs from HK and CJW. HK overseen logistic of the field campaign. WCA led field sampling and sample analysis, collided the data and conducted data quality control. RI led study sites selections and fire history analysis. All authors participated in field data collection, contributed to data analysis, and writing of the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Carbon balance of tropical peat forests at different fire history and implications for carbon emissions

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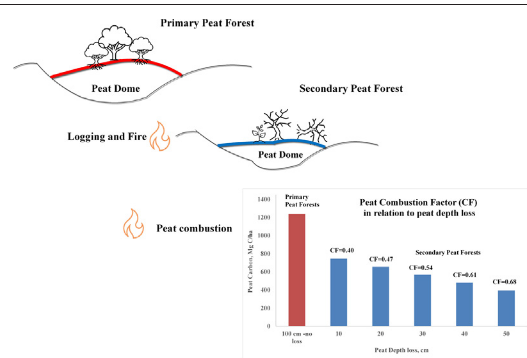
HIGHLIGHTS

- Aboveground C of tropical peat forest recovers up to 17 years after disturbances.
- Fire increases peat bulk density but reduces peat C content.
- Peat C to 10 cm is similar among primary and recently and repeatedly burnt forests.
- The current assumption of complete combustion of peat is an oversimplification.
- Peat combustion factor (CF) increases with the depth of peat burnt.

GRAPHICAL ABSTRACT



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ABSTRACT

Accurate assessment of tropical peat forest carbon stocks and impact of fires on carbon pools is required to determine the magnitude of emissions to the atmosphere and to support emissions reduction policies. We assessed total aboveground carbon (AGC) in biomass pools including trees, shrubs, deadwood, litter and char, and peat carbon to develop empirical estimates of peat swamp forest carbon stocks in response to fire and disturbance. In contrast to the common assumption that peat fires combust all AGC, we observed that about half of undisturbed forest AGC, equivalent to about 70 Mg C ha^{-1}, remains after one or two recent fires – mainly in dead trees, woody debris and pyrogenic carbon. Both recently burnt and repeatedly burnt peat forests store similar amounts of carbon in the top 10 cm of peat when compared with undisturbed forests (70 Mg C ha^{-1}), mainly due to increased peat bulk density after fires that compensates for their lower peat C%.
The proportion of fuel mass consumed in fire, or combustion factor (CF), is required to make accurate estimates of peat fire emissions for both AGC and peat carbon. This study estimated a CF for AGC (CF_{AGC}) of 0.56, comparable to the default value of the Intergovernmental Panel on Climate Change (IPCC). This study estimated a varying CF for peat (CF_{PEAT}) that ranged from 0.4 to 0.68 as depth of burn increased. This revised CF_{PEAT} is one third to one half of the IPCC default value of 1.0. The current assumption of complete combustion of peat (CF = 1.0) is widely acknowledged in the literature as oversimplification and is not supported by our field observations or data. This study provides novel empirical data to improve estimates of peat forests carbon stocks and emissions from tropical peat fires.

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1. Introduction

Tropical peat forests are areas of high carbon (C) density and play an important role in global terrestrial carbon balance. With an estimated C pool of 57 Gt, or 65% of the global total, Indonesia has by far the largest share of global tropical peat forests (Page et al., 2011). Continued drainage of peatlands for agriculture and plantation development, coupled with global warming causes drying of peat forest over extensive areas, making them susceptible to fires. Regional droughts in Indonesia in the 1990's and throughout the early 21st century resulted in an unprecedented increase in peat fires, affecting both natural forests and forested lands undergoing conversion to other land uses, with smoke and pollution affecting not only Indonesia but all Southeast Asia (Khan et al., 2020). Improving the knowledge base of peat carbon balance and reducing emissions from peatlands is an international priority of the United Nations (FAO & Wetlands International, 2012). However, despite strong international commitment to reduce emissions from peatlands, there has been limited progress towards improving the knowledge base of tropical peat forest carbon balance for reducing uncertainty in peat fire emissions estimates (Volkova et al., 2021).

It has been estimated that peat fires of 1997 El Nino events released an equivalent of 13–40% of the mean annual global carbon emissions from fossil fuels (Page et al., 2002). Current emissions from drained or burnt Indonesian peatlands are highly uncertain and claimed to be as high as 2 Gt CO_2 per year, or about 5% of all emissions caused by human activity (UN, 2017), yet these estimates are based on many assumptions. Our comprehensive literature review revealed major gaps in knowledge of the parameters required for peat emissions estimates, with most of the field measurements collected about 20 years ago (Volkova et al., 2021). For instance, combustion factor (CF), the proportion of pre-fire fuel mass consumed (IPCC, 2006), directly influences emissions estimates and is required for both aboveground fuels and peat, yet this parameter is rarely measured in the field and often assumed 0.5 for aboveground fuels for the first fire, with no data provided for subsequent and repeated fires. In the absence of country or region specific data, the IPCC (IPCC, 2014) sets the default CF to 1.0 for organic soils (i.e. 100% combustion of peat), despite limited supporting evidence. In the absence of direct measurements, the initial assumption that all peat carbon exposed to combustion is converted to gas, is unlikely to be true in practice in all cases. Complete combustion requires homogeneous and sustained high temperatures throughout the fuel bed until it is fully consumed. Heterogeneous spatial patterns of combustion are also to be expected, inevitable if the bed is not completely burnt. The evidence for a peat CF = 1 in field situations is limited or non-existent (see (Volkova et al., 2021)). While the CF of 1.0 is only recommended for the Tier 1 level (i.e. where the estimate of peat emission is based on default parameters), most published peat fire emissions estimates (Gaveau et al., 2014; Hooijer et al., 2014; Konecny et al., 2016; Page et al., 2002; Saragi-Sasmito et al., 2019) adopt the CF value of 1.0 while also acknowledging that it is an oversimplification (Hooijer et al., 2014; Konecny et al., 2016). Therefore the IPCC (IPCC, 2014) guidance recommends that country-specific combustion factors be developed and applied to improve the accuracy of emission estimates for organic soils. Moreover it suggests accounting for differences in the bulk density and carbon concentration of peat according to depth of burn and even region of occurrence within a country (IPCC, 2014). Despite these IPCC recommendations, no country or regional level combustion factors have been developed for organic soils, or at least we were not able to find supporting literature (see also Volkova et al. (Volkova et al., 2021), resulting in a continued high level of uncertainty in emissions estimates.

With this background in mind the primary objectives of this study were to measure carbon pools of tropical peat forests following recent and repeated fires as a basis for developing more accurate parameters for peat carbon balance and peat fire emissions estimates.

2. Materials and methods

2.1. Study sites, chrono-sequence approach to establishing treatments and biomass sampling design

Peat swamp forest areas within the Sebangau National Park (NP) and a former Mega Rice project within Tumbang Nusa Research Forest of Central Kalimantan, Indonesia were selected for the study (Fig. 1). For estimating the impact of peat fires on carbon pools and combustion factors we applied a chrono-sequence approach rather than direct comparison of mass before and after a fire in a forest stand. While sampling before and immediately after fires is preferable it is difficult to achieve in practice as predicting where peat fires start is almost impossible. Additionally, the sampling of these forests ahead of peat fires is dangerous due to significant health risks from toxic smoke and the danger of falling trees. Peat swamp forests are known to be inherently spatially variable in terms of carbon stocks due to both position on the peat dome and prior disturbance history. For our chrono-sequence approach we grouped sites according to similarity in disturbance histories, all sites were of similar biotic and abiotic conditions (Foster & Tilman, 2000) and had similar peat depth. We applied the findings from our earlier pilot study and power analysis (Volkova et al., 2021) indicating that at least 12 plots per treatment would be a sufficient replication to observe 30% difference in the key carbon pools between disturbed and undisturbed forests with at least 80% probability.

Throughout 2019 and early 2020, 18 plots per treatment or a total of 72 plots (4 treatments × 3 blocks × 6 plots) were sampled for aboveground biomass and peat. Disturbance history and site accessibility were key factors in choosing sampling sites. The treatments reflect disturbance history ranging from relatively undisturbed forests in the Sebangau NP to forest regrowth following clear-fell logging that has subsequently burnt once or multiple times (Table 1, Fig. 2). An area of Sebangau NP - unburnt, relatively undisturbed by human activities, located in Core Zone/Wilderness Zone (Figs. 1 and 2) was considered primary forest (PF) – and was chosen here as a reference forest to identify the impact of fires on peat forest carbon balance. The peat swamp forests disturbed more than eighteen years ago were considered long undisturbed secondary forests (SF). Secondary peat swamp forests burnt in one (SF1) and two recent fires (SF2) were classified as heavily disturbed forests (Table 1).

Blocks were located at least 1 km, and up to 7 km, from each other; the first plot in each block was located randomly and the following plots located according to a grid method, with at least 60 m between plots. Sampling design is described in detail in Volkova et al. (Volkova et al., 2021) and depending on the treatment, either a circular plot, a line transect plot or a nearest neighbour sampling method (i.e. a centre-point method) was chosen to measure live and dead trees (Table 1, Annex A, Fig. S1). For the SF and PF treatments the circular plot radius was set up to capture an average 10–20 trees per plot, as per the Guidelines for measuring aboveground carbon in peat swamp forests (Kauffman et al., 2016). Coarse woody debris (CWD), defined as detached woody material with diameter ≥ 2.5 cm lying on the forest floor, was measured along a 50-m transect extending through the plot following the methodology of Van Wagner (Wagner, 1968). The diameter of CWD intersected by the transect was measured at the point of intersection with the transect, and placed into one of three decay classes: sound, rotten (signs of decomposition extended to heartwood) or charred (heavily charred wood). Two samples of each decay class per plot were collected for density and carbon content analysis. Ground cover comprising grasses and small shrubs to 0.5 m high, and litter made up of leaves, tree fruits, decomposed organic matter and twigs with $d < 2.5$ cm, were sampled from within a 0.1 m^2 metal frame placed on the forest floor at four locations per plot.

The thermochemically altered biomass that is created from the pyrolysis and incomplete combustion of organic matter (Bird et al., 2015; Surawski et al., 2020), referred to here as pyrogenic carbon

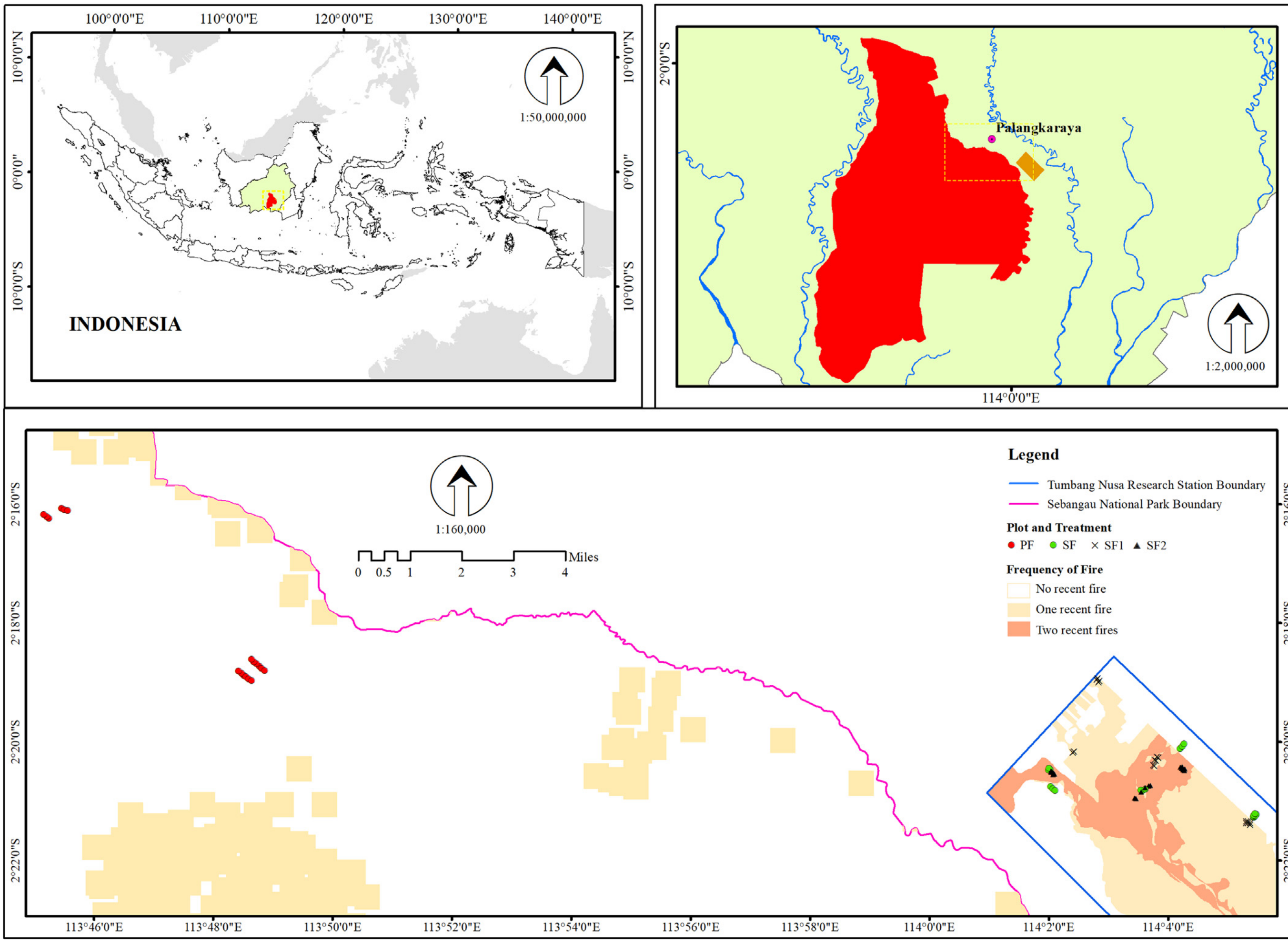

Fig. 1. Study site location.

(PyC), was collected from 0.1 m^2 metal frames randomly located on the peat surface, at four locations near each plot boundary, and percent cover of PyC was visually assessed following the Braun-Blanquet (Braun-Blanquet, 1932) cover-abundance scale. Visually identifiable PyC pieces were collected from the peat surface into plastic zip bags for mass and carbon concentration determination.

2.2. Estimating aboveground carbon

Live tree biomass was calculated using an allometric equation derived for mixed species of Indonesian peat swamp forests (Manuri et al., 2014). Dead tree biomass was adjusted for the absence of leaves and branches by either reducing biomass by 2.5% (for a minor defoliation) or 20% (where no leaves, branches or tops were present) (Kauffman et al., 2016).

CWD, ground cover, litter and PyC were oven-dried at 60 °C for about two weeks to a constant weight in the laboratory of FORDA, Bogor, Indonesia. All measurements are given on a dry-weight basis. Wood density of CWD was estimated using a volumetric water displacement method.

The total aboveground carbon (AGC) was estimated as the sum of carbon in live trees, ground cover, dead trees, CWD, litter and PyC (noting that the PyC carbon pool is not included in the current IPCC methodology, (IPCC, 2019)).

2.3. Peat

Peat was sampled for bulk density and carbon content from near the centre point of each plot to a depth of 1 m, beyond this depth the auger was turned into the peat until mineral soil was detected in the auger head. The top 10 cm of peat was sampled with a metal cylinder of 7.3 cm diameter driven and twisted into the peat surface by hand. For deeper peat the Edelman auger fitted with a half cylinder peat sampler (Eijkelkamp peat sampler; https://en.eijkelkamp.com) was used to sample 10–50 cm and 50–100 cm depths. At each of these depth intervals a 10 cm length sample was collected from the 4.9 cm diameter

Table 1
Characteristics of the peat swamp forest treatments.

Treatment	Description	Disturbance history	Number of plots	Shape of the plot for tree measuring
PF	Primary Forests	Relatively undisturbed. Declared National Park in 2004	18	Circular plot, $R = 10$ m (subplot $r = 3$ m)
SF	Secondary Forests long undisturbed	Fire 1997 or 2003	18	Circular plot, R = 10 m (subplot r = 3 m)
SF1	Secondary Forests one recent fire	Fire 1997, 2015	18	A 50 m line transect, 12 subplots of $r = 2$ m
SF2	Secondary Forests two recent fires	Fire 1997, 2014, 2015	12	Centre - point method
		Fire 2003, 2010, 2014	6	

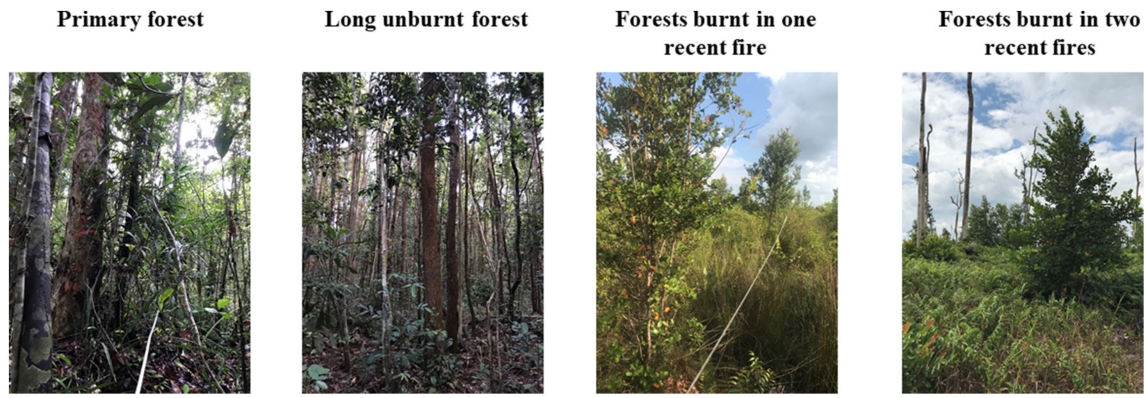

Fig. 2. Photographs of the peat swamp forest treatments.

probe head at the mid-point; either 20–30 cm or 70–80 cm and analysed for mass and carbon content. The depth of peat was estimated from the length of the peat auger (6 m extension rods plus sampler) inserted to the mineral soil surface. When peat depth exceeded length of the extension rod, one meter was added to the measured depth.

Peat was oven-dried at 105 °C until dry mass was recorded constant (about 2–5 days) for bulk density estimates and at 60 °C for carbon analysis following the protocol of Kauffman et al. (Kauffman et al., 2016).

Acknowledging that peat carbon is the biggest carbon pool in peat swamp forests, the impact of fires on peat carbon was estimated only to the first 1 m depth. Peat mass (M_{PEAT}) in Mg C ha^{-1} was estimated by two methods: 1) A fixed depth method also called the IPCC good practice (IPCC, 2003):

$$M_{PEAT\_h} = BD_h \cdot h \cdot C_{org} \tag{1}$$

where: BD is peat bulk density at depth h, g cm^{-3}, h is the sampled depth, cm, $\boldsymbol{C_{org}}$ is peat organic carbon content at the sampled depth, %.

2) An equivalent mass method, not sensitive to bulk density (Wendt & Hauser, 2013):

$$M_{PEAT\_h} = Mass\ of\ sample_h / (\pi \cdot r^2) \cdot C_{org} \cdot 100 \tag{2}$$

where: $Mass\ of\ sample_h$ is the mass of peat sample at depth h, g, r is the inside radius of the sampling probe, mm, $\boldsymbol{C_{org}}$ is peat organic carbon content at the sampled depth, %. To account that only a 10 cm peat sample was taken from the depths 10–50 cm and 50–100 cm, a mass of sample was scaled up to either 40 cm or 50 cm.

Peat carbon to 1 m depth (PeatC$_{1m}$) was estimated as the sum of peat mass for each of sampled depth (0–10 cm, 10–50 cm, 50–100 cm).

Collected samples of CWD, PyC and peat were analysed for carbon content at the facilities of the Centre for Agricultural Land Resource Research and Development using a loss on ignition method (LoI). For each sample, 1–2 g sub-samples were combusted at 550 °C in a muffle furnace for at least 6 h and the residues weighed. Peat carbon content, C_{org} was estimated as organic matter divided by the conversion factor of 1.922 (Hairiah & Mulyani, 2011).

The carbon content of trees was assumed to be 0.47 (IPCC, 2006). Total peat forest carbon was calculated as the sum of AGC and PeatC$_{1m}$.

2.4. Estimating combustion factors

A combustion factor for aboveground carbon (CF$_{AGC}$) was estimated as the difference in AGC before and after fires divided by pre-fire AGC. Because AGC in the SF1 and SF2 treatments was not sampled immediately after fires, regeneration of small trees (DBH < 10 cm), ground cover and litter re-accumulation were excluded from AGC estimates in SF1-SF2 treatments.

Combustion factor for peat (CF$_{PEAT}$) was estimated as the difference in peat mass before and after fires (Eq. (3)) using the peat mass calculated by the equivalent mass method (Eq. (2)). Combustion factors were estimated for a range of increments over the depth range 10 cm - 40 cm, as the literature suggests that between 7 cm and 33 cm of peat is burnt in fires (e.g. (Ballhorn et al., 2009)).

$$CF_{PEAT} = (M_{PEAT_{BF}} - M_{PEAT_{AF}}) / M_{PEAT_{BF}} \tag{3}$$

Where: M_{PEATBF} is mass of peat before fire calculated to 100 cm depth, Mg C ha^{-1}, M_{PEATAF} is mass of peat after fire calculated for peat loss equivalent to the top 10 cm, and then in 10 cm intervals up to 50 cm peat depth burnt, Mg C ha^{-1}.

$$M_{PEAT_{BF\ 0-100cm}} = M_{PEAT\ 0-10cm} + M_{PEAT\ 10-50cm} + M_{PEAT\ 50-100cm} \tag{4}$$

For example, $CF_{Peat\ 10cm}$ *burnt*:

$$M_{PEAT_{AF}} = M_{PEAT\ 10-50cm} + M_{PEAT\ 50-100cm} \tag{5}$$

2.5. Statistical analysis

A linear mixed - effects model (lme) was applied to test the effect of disturbance on each of measured carbon pools. The fixed factor was 'treatment' (PF, SF, SF1, SF2) and 'block' was used as the random part of the model. For peat, fixed factors were "treatment", "depth" and their interactions. The differences were considered significant at 5% level. For each analysis, normality and heterogeneity of variance was assessed using histograms of residuals and fitted value plots. For those variables where residues were not equally distributed and the homogeneity of variance assumption was violated, the variance correction (varIdent) was incorporated following the method described in Zuur et al. (Zuur et al., 2009). The best fit model was selected based on weighing and the lowest Akaike information criterion (AIC, see Annex A Supplementary examples and Fig. S2). Statistical differences among treatments were estimated using the emmeans package (Lenth, 2020) based on unadjusted P-values (Supplementary, Table S3). The analyses were conducted in the R statistical environment version 3.6.0 (R (R Core Team, 2020)).

3. Results

3.1. Aboveground carbon – live and dead pools

Disturbance history had a significant effect on AGC stocks of peat swamp forests. Primary forests and long undisturbed secondary forests stored a similar mass in live trees (about 109 Mg C ha^{-1}) significantly higher than the 3.4 to 12.7 Mg C ha^{-1} of recently burnt forests (Table 2). Conversely primary forests stored less carbon in ground

Table 2
Aboveground carbon pools of peat swamp forest treatments in Mg C ha^{-1}.

Carbon pool	Treatment			
	PF	SF	SF1	SF2
Live trees	115.6 (105.5, 125.7) ^{a}	103.4 (79.9, 126.9) ^{a}	12.7 (−3.7, 29.2) ^{b}	3.4 (1.6, 5.2) ^{b}
Ground cover	0.58 (0.38, 0.78) ^{a}	2.34 (1.74, 2.94) ^{b}	3.45 (2.91, 3.99) ^{c}	2.99 (2.47, 3.51) ^{bc}
Dead trees	22.7 (17.2, 28.4) ^{a}	19.3 (14.2, 24.5) ^{a}	10.6 (1.4, 19.8) ^{a}	24.1 (12.7, 35.5) ^{a}
CWD total	15.7 (10.3, 21.1) ^{a}	16.3 (11.5, 21.1) ^{a}	47.5 (32.7, 62.3) ^{b}	33.3 (22.9, 43.6) ^{b}
Sound	10.2 (5.43, 15.0) ^{a}	8.7 (4.9, 12.4) ^{a}	21.2 (11.9, 30.4) ^{b}	10.4 (5.2, 15.5) ^{a}
Rotten	5.4 (3.1, 7.8) ^{a}	7.5 (4.0, 10.9) ^{ac}	20.5 (12.9, 28.1) ^{b}	11.5 (8.2, 14.9) ^{c}
Charred	0.0 ^{a}	0.11 (−4.4, 4.6) ^{a}	5.8 (1.26, 10.3) ^{b}	11.4 (6.8, 15.9) ^{c}
Litter	4.83 (4.24, 5.42) ^{a}	3.98 (2.68, 5.29) ^{ab}	3.26 (2.33, 4.18) ^{b}	2.50 (1.91, 3.09) ^{b}
PyC	–	0.62 (−0.9, 2.2) ^{a}	5.46 (3.92, 7.00) ^{b}	6.31 (4.77, 7.85) ^{b}
Total AGC	159.4 (147.8, 171.0) ^{a}	146 (120.8171.1) ^{a}	82.9 (52.7, 113.2) ^{b}	72.6 (55.1, 90.2) ^{b}

Values are the predicted means, $n = 18$, values in brackets are 95% CI. Superscript letters indicate the significant difference between the treatments at <0.05 level for each carbon pool. Where PF is primary forests, SF is secondary forests long unburnt, SF1 forests burnt in one recent fire, SF2 forests burnt in two recent fires.

vegetation than fire-disturbed forests, with the size of this AGC pool similar to the litter C pool. Carbon stored in dead standing trees was similar among all treatments ($P = 0.1$), yet recently burnt forests had almost three times more carbon in CWD. This significant difference was driven by the presence of charred CWD in twice burnt forests (mean 11 Mg C ha^{-1}, Table 2). The presence of charred CWD in the SF treatment, burnt most recently in 2003, demonstrates the persistence of this C pool in disturbed forests. The mass of forest floor litter was highest in the PF and SF sites with a closed canopy cover, and lowest in recently burnt forests (SF1 and SF2) where regenerating trees were yet to close canopy. PyC, char fragments on the peat surface, was present in secondary forests burnt in 2003 and was highest in recently burnt forests (Table 2). PyC covered about 30% of the peat surface in recently burnt forests, regardless of fire frequency, and about 10% in secondary forests (SF) burnt in 2003 (Fig. 3). Carbon content in CWD was highest in charred CWD at 65%, followed by sound category at 50.9% and rotten at 47.9% (Table S1). Density of CWD was highest in charred class and lowest in rotten CWD (Table S2). Overall, the primary and long undisturbed secondary forests (PF, SF) stored almost twice more carbon aboveground than recently burnt forests. Forests burnt in two recent fires (SF2) stored a comparable amount in AGC as forest burnt in one recent fire (SF1) (Table 2, Fig. 3).

3.2. Peat carbon

The carbon content of peat (C_{org}%) at each sampled depth was higher by about 6–8% in primary forest (PF; 46–50%) compared with other treatments (35–43%; Table 3). The bulk density of peat was lowest in the surface (0–10 cm; 0.14–0.18 g cm^{-3}) compared to sub-surface peat (0.21–0.29 g cm^{-3}) for all treatments. Bulk density in 0–10 cm was comparable between PF and SF treatments (0.13–0.14 cm^{-3}) but was significantly higher in recently burnt forests (0.18 g cm^{-3}; Table 3).

In estimating the mass of peat carbon, the IPCC 'good practice' method and the equivalent soil mass method produced comparable results (Table 4); for simplicity in describing the results we report here the more widely adopted IPCC method. About 70 Mg C ha^{-1} was stored in the top 10 cm of peat layer and it was comparable between primary and recently burnt forests (Table 4, Fig. 4). Peat carbon to 50 cm depth was highest in primary forests at 535 ± 26 Mg C ha^{-1} and similar among secondary forest treatments at just over 400 Mg C ha^{-1} (Fig. 4). Consequently, primary forests stored almost 30% more carbon to 1 m depth than secondary forests. Peat depth averaged from 3.5 m to 5 m (Table 4).

3.3. Total peat forest carbon to 1 m peat depth

The total carbon mass of peat swamp forests to 1 m depth was greatest at 1385 ± 66 Mg C ha^{-1} for primary forests, and comparable among secondary forests; 950 ± 66 Mg C ha^{-1} (long unburnt), 919 ± 66 Mg C ha^{-1} (one recent fire) and 861 ± 66 Mg C ha^{-1} for forests burnt in two recent fires (Table 4).

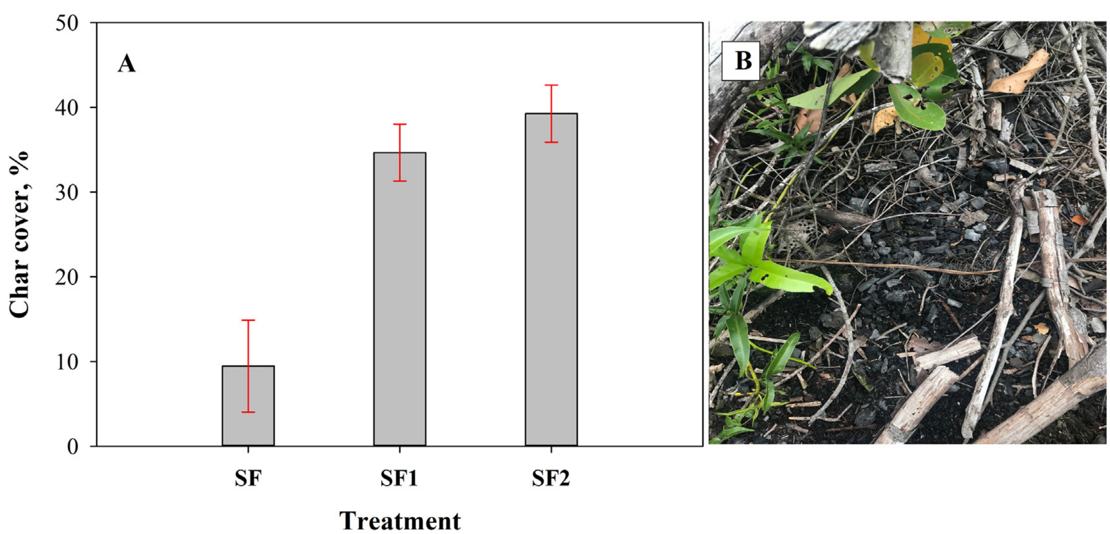

Fig. 3. A) Percent cover of PyC at the secondary peat swamp forest treatments. B) Photograph showing PyC on the peat surface in SF2 forests four years after fires. Where SF is secondary forests long unburnt, SF1 forests burnt in one recent fire, SF2 forests burnt in two recent fires.

Table 3
Peat characteristics.

Treatment	Peat carbon content, C_{org}, %			Peat Bulk density g cm^{-3}		
	0–10 cm	10–50 cm	50–100 cm	0–10 cm	10–50 cm	50–100 cm
PF	50.96 ± 0.417^{a}	46.35 ± 0.730^{a}	46.61 ± 0.792^{a}	0.14 ± 0.01^{a}	0.25 ± 0.01^{a}	0.29 ± 0.01^{a}
SF	43.12 ± 1.688^{b}	36.64 ± 2.676^{b}	34.77 ± 2.592^{b}	0.13 ± 0.01^{a}	0.24 ± 0.01^{a}	0.24 ± 0.02^{b}
SF1	39.66 ± 3.012^{b}	39.30 ± 2.504^{b}	40.72 ± 1.139^{b}	0.18 ± 0.01^{b}	0.22 ± 0.01^{ab}	0.21 ± 0.01^{bc}
SF2	43.25 ± 1.313^{b}	40.81 ± 1.486^{b}	38.52 ± 0.986^{b}	0.18 ± 0.01^{b}	0.21 ± 0.01^{b}	0.19 ± 0.01^{c}

Values are the means, ± se, $n = 18$. Superscript letters indicate the significant difference between the treatments at <0.05 level for C_{org}, % and for Bulk density g cm^{-3} within each peat depth category. Where PF is primary forests, SF – secondary forests long unburnt, SF1 forests burnt in one recent fire, SF2 forests burnt in two recent fires.

Table 4
Mass of peat carbon in Mg C ha^{-1} using two different methods with peat bulk density (BD) and equivalent mass method.

Treatment	Peat Mass estimates based on BD			Equivalent soil mass method (independent from BD)			Average peat depth, m
	PeatC_10cm	PeatC_50cm	PeatC_1m	PeatC_10cm	PeatC_50cm	PeatC_1m	
PF	70.2 ± 0.63^{a}	535 ± 26^{a}	1225 ± 67.6^{a}	77.2 ± 0.69^{a}	547 ± 27^{a}	1237 ± 67.7^{a}	4.7
SF	55.7 ± 3.9^{b}	409 ± 33^{b}	804.7 ± 67.6^{b}	61.3 ± 4.48^{b}	415 ± 33^{b}	810 ± 67.7^{b}	3.8
SF1	73.4 ± 7.1^{a}	423 ± 33^{b}	844.6 ± 67.6^{b}	86.1 ± 7.20^{a}	428 ± 21^{b}	796 ± 67.7^{b}	4.6
SF2	78.3 ± 6.6^{a}	420 ± 21^{b}	789.1 ± 67.6^{b}	80.7 ± 7.8^{a}	430 ± 34^{b}	852 ± 67.7^{b}	3.9
P values	0.002	<0.0001	<0.0001	0.0019	<0.001	<0.001	

Values are the means, ± se, n = 18. Superscript letters indicate the significant difference between the treatments at <0.05 level for each peat depth category. Where PF is primary forests, SF – secondary forests long unburnt, SF1 forests burnt in one recent fire, SF2 forests burnt in two recent fires.

3.4. Combustion factors

Because the PF and SF forests stored a similar amount of aboveground carbon, a combustion factor for AGC (CF_{AGC}) was estimated as the difference between the average AGC of PF and SF (pre-fire) and the average AGC of SF1 and SF2 (post-fire). CF_{AGC} was averaged at 0.564. Combustion factor for peat (CF_{PEAT}) was estimated as the peat mass difference between PF to 1 m depth (pre-fire) and an average of SF1 and SF2 forests (post-fire) calculated for between 10 and 50 cm depth of peat loss. CF_{PEAT} gradually increased with the depth of peat burnt, from 0.399 at 10 cm peat depth burnt, to 0.540 at 30 cm peat depth burnt. Increasing the depth of peat burnt to 50 cm increased peat combustion factor by 26% to 0.681 (Table 5).

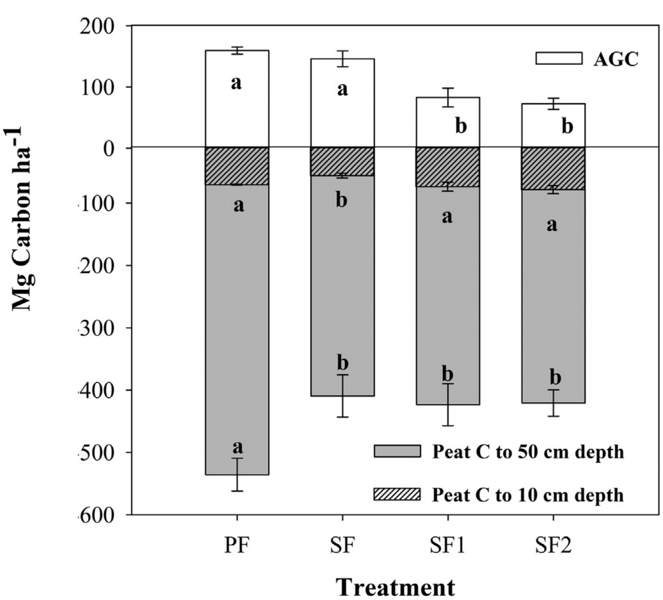

Fig. 4. Total Forest Carbon to 50 cm peat depth. Letters indicate significant difference at <0.0001 level within one carbon pool (AGC only; Peat C to 50 cm only and Peat C to 10 cm depth only). Where PF is primary forests, SF – secondary forests long unburnt, SF1 forests burnt in one recent fire, SF2 forests burnt in two recent fires.

4. Discussion

4.1. Aboveground and peat carbon

Our field measurements show that the primary peat swamp forest stored about 30% more carbon belowground to 1 m depth relative to the group of secondary forests. However, the aboveground carbon was comparable between primary and long unburnt secondary forest (SF), demonstrating a rapid rate of biomass recovery after disturbance. In making this observation we acknowledge that the relatively undisturbed and protected forests of the Sebangau NP are a new baseline for carbon stock estimates, despite their earlier history of human disturbance. Our plot size for PF and SF treatments was big enough to incorporate an average 33 trees per plot (range 24 to 57), supporting the recommendation for peat swamp forests inventories that 'a plot radius that captures an average of 10–20 trees per plot should be sufficient to adequately describe the tree mass of peat forests (Kauffman et al., 2016).

Our study has shown that in secondary forests more than 70 Mg C ha^{-1} remains aboveground mainly in dead trees and as charred CWD and PyC after first and second consecutive fires (Table 2). This finding is in contrast to the assumption that emission from consecutive fires is a result of peat combustion only (Konecny et al., 2016; MoEF, 2016). Furthermore, the AGC that remains after the first fire is mainly redistributed aboveground after a second fire, reducing the loss impact of assumed carbon emission. Rather than AGC pools being mainly combusted in second and subsequent fires, due to the large piece size of residues, much of the AGC, such as sound CWD is transformed to charred CWD of much

Table 5
Combustion factors for aboveground and peat biomass.

Combustion factor	This study	IPCC default
CF_{AGC}[a]	0.564	0.50
$CF_{PEAT\text{- }10cm}$	0.399	1.0
$CF_{PEAT\text{- }20cm}$	0.469	1.0
$CF_{PEAT\text{- }30cm}$	0.540	1.0
$CF_{PEAT\text{- }40cm}$	0.610	1.0
$CF_{PEAT\text{- }50cm}$	0.681	1.0

[a] Assuming that there is no live trees, shrubs or litter remain immediately after fires. i.e. AGC is estimated as the sum of Dead trees +CWD + PyC.

greater C concentration and wood density (Annex A,Tables S1–2). Consequently a proportion of residues remaining after the second or subsequent fires is more resistant to decomposition, thereby acting more as a carbon sink than as a readily decomposable C source.

PyC is not included in the current IPCC definition of carbon pools (IPCC, 2019), yet a growing body of literature suggests its importance in the global carbon cycle, especially in ecosystems subjected to fires (Landry & Matthews, 2017; Santin et al., 2016). In our study PyC was present on the peat surface seventeen years after a single fire, and in recently burnt forests it covered one third of the surface (Fig. 3B). In recently and recurrently burnt forests PyC becomes an important carbon pool accounting for up to 8% of the AGC, equivalent to the mass of carbon stored in regenerating trees and ground cover. With residence times of up to 10,000 years (Swift, 2001), PyC is a potential source of long-term carbon sequestration when stored in soils or sediments (Preston & Schmidt, 2006). Not accounting for fire produced PyC in carbon mass balance will lead to overestimation of atmospheric emissions by between 2% and 27% according to recent studies (Santin et al., 2020; Surawski et al., 2016).

In agreement with many other studies (Hooijer et al., 2012; Sinclair et al., 2020; Taylor & Inubushi, 2006), we observed an increase in peat BD in the top layer (0-10 cm) with fire frequency due to drainage and heat related compaction of the peat surface. Recently burnt forests stored a similar amount of carbon in the top 10 cm of peat as primary forests, which was a result of greater BD compensating for a loss of C_{org} with disturbance (from 51% to 43%). Even though the fixed depth method has been shown to introduce substantial errors when soil BD differs between the treatments (Wendt & Hauser, 2013), in our case the two methods for calculating peat C mass produced remarkably similar results (Table 4), indicating that for peat, both methods are comparable. Peat BD is also influenced by peat maturity with younger (fibric) peat having lower BD than more mature, hemic or fibric, peats (Agus et al., 2012). In our case, every effort was taken to sample from more mature peat by visually assessing peat structure in the field following the nationally adopted guidelines (Hairiah & Mulyani, 2011). Peat C % (C_{org}) varied with depth and degree of forest disturbance (Table 3) and our values, even for primary forests in the top layer (51 ± 0.4%), were lower than reported in the literature e.g. global average for peats of 56 ± 3% (Page et al., 2011), 55.3% (at 20 cm depth) by Konecny et al. (Konecny et al., 2016) or 58% used in 1997 peat fire emission estimates (Page et al., 2002). The difference can be attributed to the analytical technique to quantify peat carbon content, with loss on ignition (LoI) yielding somewhat lower estimates than elemental analysis (Farmer et al., 2014). In our case, the LoI method with a coefficient of 1.922 was applied to convert organic matter to C_{org} following the national guidelines (Hairiah & Mulyani, 2011). A study by Farmer et al. (Farmer et al., 2014), based on a limited number of samples, showed that using 1.922 may underestimate $C_{org}$by around 3.4% (Farmer et al., 2014). Accounting for the difference in the analytical methods, our results still would be on the lower range of C_{org}values reported in the literature.

Average peat depth in our plots was 4.23 m (Table 4), slightly below the 5.5 m depth range reported by Page et al. (Page et al., 2011). Peat depth varied among the treatments and was more a reflection of the position of our forest plots on the peat dome rather than a treatment impact, as has been reported in other studies (Page et al., 1999; Silvestri et al., 2019). For this reason, we estimated forest carbon down to 1 m depth to allow for direct comparison among treatments, and for the calculation of combustion factors that are discussed below.

4.2. Aboveground and peat combustion factors (CF)

Field measurements of all aboveground carbon pools, including PyC, in primary and secondary forests allowed for the calculation of a CF_{AGC} of 0.56, comparable to the default IPCC value of 0.5 (IPCC, 2006) for disturbed and repeatedly burnt forests. Our CF for the AGC purely reflected the fire related losses of AGC, rather than previous disturbance history or biological decomposition, as long unburnt but logged forests stored a similar amount of carbon as primary forests (Table 2).

In adopting peat C to 100 cm depth in primary forests as the "before" available fuel measure, and peat C from 10 to 100 cm, 20–100 cm, 30–100 cm, 40–100 cm and 50–100 cm depths in SF1 and SF2 forests as the "after" measures, the resulting CF_{PEAT} ranged from 0.39 to 0.68, or two to three times lower than the default IPCC value of 1.0. While the IPCC guidelines recommend using a default value of 1.0 only for the Tier 1 peat fire emissions estimates (i.e., in the absence of more specific data), we were not able to find any published and reported peat fire emission estimates using anything but a CF of 1 (see (Volkova et al., 2021)). There appears to have been no attempt to define or improve estimates of peat combustion factors since the release of the 2013 Wetland supplement to the 2006 IPCC Guidelines for National GHG Inventories (IPCC, 2014). Moreover, the IPCC also doesn't provide more specific guidelines to calculate the peat combustion factor. A recent refinement of IPCC Guidelines for National GHG Inventories (IPCC, 2019) provides no change to methodologies or to default parameters. There seems to be a great confusion in estimating fire-related peat carbon loss in the literature. It is assumed that a CF is only to be used to estimate the amount of peat burnt if the amount of peat 'available' for combustion is known (IPCC, 2014), which is difficult to know at the landscape scale. To calculate peat fire emissions many studies have assumed that the mass of organic matter associated with changes in the pre-fire to post-fire surface (i.e. the depth of the burn into the peat surface) is 100% combusted and emitted to the atmosphere. Our field observations indicate that the organic matter burnt is made up of peat, plant roots, organic residues from forest disturbance events and recently added litter from aboveground plant components. Due to the high moisture content and heterogeneity of these organic materials in surface peat, it is highly likely that only a proportion of the total is combusted and emitted to the atmosphere. Therefore, the assumption that all organic matter burnt is (a) peat, and (b) completely combusted is unlikely, and does not support the adoption of a CF of 1.0 (see (Konecny et al., 2016; Hooijer et al., 2014). For these reasons we have proposed a method for estimating peat combustion factors that allows for incomplete combustion of peat and more realistically reflect fire related peat loss (Table 5).

The significantly lower CF_{PEAT} estimated in this study means that emissions from Indonesian peatlands can be up to three times lower than was previously reported (e.g. Page et al., 2002). For example, if all other parameters of the eq. 2.8 of the IPCC (IPCC, 2014) except CF remain constant, for one ha of peat burnt down to 10 cm, emissions would be about 30% of those calculated with the default CF of 1.0 (Table 5, see Appendix A, Supplementary example for details of CO_2 emission calculations). For estimating CF_{PEAT}, we applied an equivalent soil mass method that is not sensitive to treatment effect on soil bulk density (Wendt & Hauser, 2013). The selected depths for CF calculations are based on the range of 7 cm to 33 cm peat consumed in fires, reported by other studies (Ballhorn et al., 2009; Hamada et al., 2012; Stockwell et al., 2016). While not perfect, the method for calculating CF_{PEAT} proposed in this study is based on real field data and it is a transparent approach for reducing uncertainties and misinterpretation in estimating emissions from peat fires. As discussed earlier, the default value of 1.0 is not supported by field observations and is well acknowledged in the literature as an oversimplification (e.g. Konecny et al., 2016; Hooijer et al., 2014). Because there was no significant difference between peat parameters (BD, C_{org}) among the SF-SF1-SF2 treatments (Table 3), it is reasonable to apply one CF value to a second and subsequent fires, so that differences in emission estimates will be driven mainly by the depth of peat burnt (Table 6). Typically there is greater consumption of peat in first fires: up to 33 cm was measured by Konecny et al. (Konecny et al., 2016); Page et al. (Page et al., 2002) assumed 50 cm consumption, while repeated fires burn to a fraction of that depth, with average of 7 cm (Konecny et al., 2016). The results of this study

Table 6
Estimated CO_2 emissions (Mg CO_2-e) from 1 ha of peat burnt down to 10 cm and 30 cm depth using the IPCC default and study derived CF_{PEAT}.

Peat depth burnt	Estimated CO_2 emissions using the IPCC default CF	Estimated CO_2 emissions using study derived CF_{PEAT}	Emission reduction per hector of peat burnt
10 cm	262	104	2.51
30 cm	1275	688	1.85

reflect peat conditions of our study sites in Central Kalimantan and as recommended by the IPCC, region-specific emission equation factors should be developed for each of Indonesia's peat rich regions (Kalimantan, Sumatra and Papua). In the absence of detailed assessments of the fate of organic matter burnt in a peat fire, we argue for the application of the results of this study as an interim method to more realistically represent carbon loss and emissions from peat fires.

5. Conclusion

This comprehensive comparison of primary peat swamp forest with secondary forests of different fire-disturbance history shows that logged and burnt forests can retain up to 35% of the AGC as standing dead trees, CWD and PyC. The mass of carbon in surface peat to 10 cm was similar among primary forest and recently burnt secondary forests, reflecting increased peat compaction due to fires and increased drainage. Using the biomass data from the forests assessed here, the estimated CF_{AGC} of 0.56 is similar to the IPCC default value of 0.5, while the CF_{PEAT} is 0.4–0.7, or 30% to 60% lower than the IPCC default value of 1 that is currently used in the international reporting of peat fire emissions. A comparison of emissions from peat fire calculated using CF_{PEAT} 1 (default) and our study specific CF_{PEAT} (0.4–0.7) yield emission estimates that are 2–4 times lower than default. Findings from this study provide novel data that will reduce uncertainties in the peat fire emissions estimates.

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CRediT authorship contribution statement

HK, CJW and LV designed the study, overseen its implementation and contributed to the development of the manuscript idea. HK and LV have written the first draft of the manuscript. LV has analysed the data and HK overseen logistic of the field campaign. WCA led field sampling and sample analysis, collided the data and conducted data quality control. RI led study sites selections and fire history analysis. Suyoko has overseen sampling in the Sebangau NP. All authors did equal contributions, participated in field data collection, contributed to data analysis, and writing of the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2021.146365.

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fire

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Technical Note

Loss and Recovery of Carbon in Repeatedly Burned Degraded Peatlands of Kalimantan, Indonesia

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Abstract: Although accurate estimates of biomass loss during peat fires, and recovery over time, are critical in understanding net peat ecosystem carbon balance, empirical data to inform carbon models are scarce. During the 2019 dry season, fires burned through 133 631 ha of degraded peatlands of Central Kalimantan. This study reports carbon loss from surface fuels and the top peat layer of 18.5 Mg C ha^{-1} (3.5 from surface fuels and 15.0 from root/peat layer), releasing an average of 2.5 Gg (range 1.8–3.1 Gg) carbon in these fires. Peat surface change measurements over one month, as the fires continued to smolder, indicated that about 20 cm of the surface was lost to combustion of peat and fern rhizomes, roots and recently incorporated organic residues that we sampled as the top peat layer. Time series analysis of live green vegetation (NDVI trend), combined with field observations of vegetation recovery two years after the fires, indicated that vegetation recovery equivalent to fire-released carbon is likely to occur around 3 years after fires.

Keywords: emissions; emission factor; shrub; ferns; NDVI; litter; peat bulk density; carbon content; peat depth

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1. Introduction

Tropical peatlands are areas of high carbon density that sequester an estimated 82-92 Pg C, with Indonesian peatlands sequestering about 10% of the global total [1]. Repeated and extensive fires, following drainage and selective logging, have contributed to peat forest loss in Indonesia over recent decades [2]. Over the last two decades, about 12% of peatlands in Sumatra and Kalimantan have been burned more than once, with about 23% of this area burned more than twice [3]. Carbon loss and emissions from repeatedly burned peatlands have been estimated for peat, but not so well for aboveground components [4]. In degraded peat swamp forests, recent studies indicate that about 50% of aboveground carbon remains after several consecutive fires—as coarse woody debris, standing dead trees and pyrogenic carbon [5,6]. While there are studies that describe the recovery of carbon after fire for northern hemisphere peat ecosystems [7,8], there are few recovery studies for Indonesian peatlands, including peat swamp forests.

During the dry season, in the period of July–September 2019, peat fires were accidentally ignited in a degraded peatland area near Tumbang Nusa camp in Central Kalimantan, Indonesia. We used this opportunity to empirically measure aboveground carbon loss and peat combustion from these areas which were previously peat swamp forests and burned in more than four fires over the last twenty years. Two years after the fires, we revisited the sites to observe the recovery of carbon. Here, we report losses and recovery of carbon from these degraded peatlands of Central Kalimantan.

2. Materials and Methods

The study was developed in degraded peatland where a fire burned from July to October 2019. Site 1 was sampled in July 2019 after the fire was extinguished in the immediate area, with samples taken in unburned and adjacent burned areas. Site 2 was sampled in September 2019 at the active front of the fire, so that the fire burned into areas where peat depth rods were placed prior to the fire advancing. At each site, an equal number of plots was established in unburned and in burned areas (Table 1); these plots were sampled at three points, resulting in 9 samples per treatment in Site 1 and 12 samples per treatment in Site 2 (Table 1, Figures 1 and 2A). Study sites were heavily degraded peatlands dominated by the fern *Stenochlaena palustris*. Aboveground samples comprised mostly ferns, grasses and litter, while belowground samples were made up of peat, fern rhizomes and roots (Figure 2B).

The loss of peat, fern rhizomes and roots in fires was measured at Site 2 during the September 2019 field campaign. Two transects (Figure 1, Site 2), each 30–40 m long, were set up in unburned areas of vegetation just prior to the advance of the fire into that area. For each transect, thirty 1.5 m long metal rods (Figure 2F) were pushed about 70–80 cm into the peat approximately 1–1.5 m apart, numbered (1–30) and the distance from the top of the rods to the surface recorded at the time of installation. The combustion of the surface was measured over 26 days from the 4th to the 30th of September until fires were self-extinguished. The depth and rate of peat surface loss was calculated from the increase in the distance from the top of the rod to the peat surface from prior to the fire (the time of installation) to after the fire, with measurements taken periodically throughout the 26 days until the fire went out.

Table 1. Sampling design at Site 1 and 2 in burned and unburned treatments in degraded peatlands.

Component	Site 1	Site 2
Date of measurements	15 July 2019	05 September 2019
Number of burned plots	3	4
Number of unburned plots	3	4
Number of samples, burned plots	9	12
Number of samples, unburned plots	9	12
Vegetation type	Degraded peatland	Degraded peatland
Fire history	2003, 2006, 2009	2001, 2004, 2006, 2009

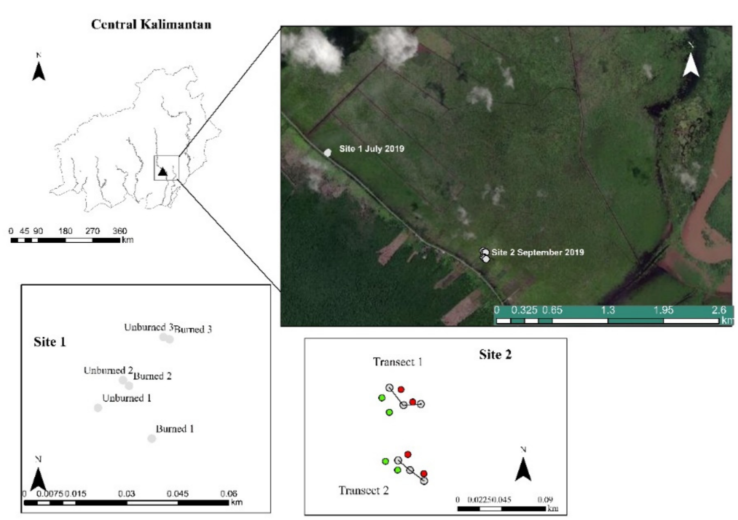

Figure 1. Map of the study area with sampling design. Site 1, showing the location of plots in burned and unburned areas. Site 2, showing the location of 2 transects for measuring the depth of peat burned and location of burned (red) and unburned (green) plots.

Surface fuels were destructively sampled from 0.1 m^2 frames and were separated into a shrub sample (ferns and grasses) and litter (the rest of the organic matter). The peat sample included organic residues, rhizomes and root material to an 11 cm depth, collected using a metal cylinder of 464 cm^3 after shrub and litter had been removed (Figure 2B–E).

All samples (litter, shrubs, peat) were transferred to the facilities of FORDA in Bogor, air dried and weighed for mass of dry matter and calculation of aboveground biomass on a per hectare basis. Sub-samples of litter, shrub and peat were analyzed for C content at the Centre for Agricultural Land Resource Research and Development using a loss on ignition method (LoI). Carbon content, C%, was estimated as organic matter divided by the conversion factor of 1.922 [9]. Peat depth to the mineral soil was measured using an Edelman soil auger fitted with a half cylinder peat sampler (Eijkelkamp peat sampler; https://en.eijkelkamp.com). One auger hole was placed in burned and unburned areas of each transect, near each other (Figures 1, and 2A).

In July 2021, sites were revisited, and the recovery of the biomass was observed and photographed (Figure 2C,G). The recovery process was also assessed from a sequence of change in the Normalized Difference Vegetation Index (NDVI) based on the ratio of the red and NIR band, created from Sentinel-2 MSI: MultiSpectral Instrument, Level-1C image, processed using Google Earth Engine.

A map of the area burned in peat fires was created using data from the Ministry of Environment and Forestry (MoEF) land cover map, Indonesian National Carbon Accounting System (INCAS) burned area maps and peat land areas provided by the Ministry of Agriculture (MoA), Indonesia. The map was developed from hotspot images combined with visual delineation and validation based on information from fire suppression activities.

A linear mixed effect model (GenStat 16.4, VSN International Ltd., Hemel Hempstead, England, UK) was used to investigate the impact of fire on above- and belowground C% and total biomass loss.

As our study used the direct measurements of biomass loss during fires, the emission factor (Mg C ha^{-1}) was estimated as the difference in carbon mass from before fire to after fire for aboveground components (shrubs and litter) and belowground components (peat, rhizomes and roots).

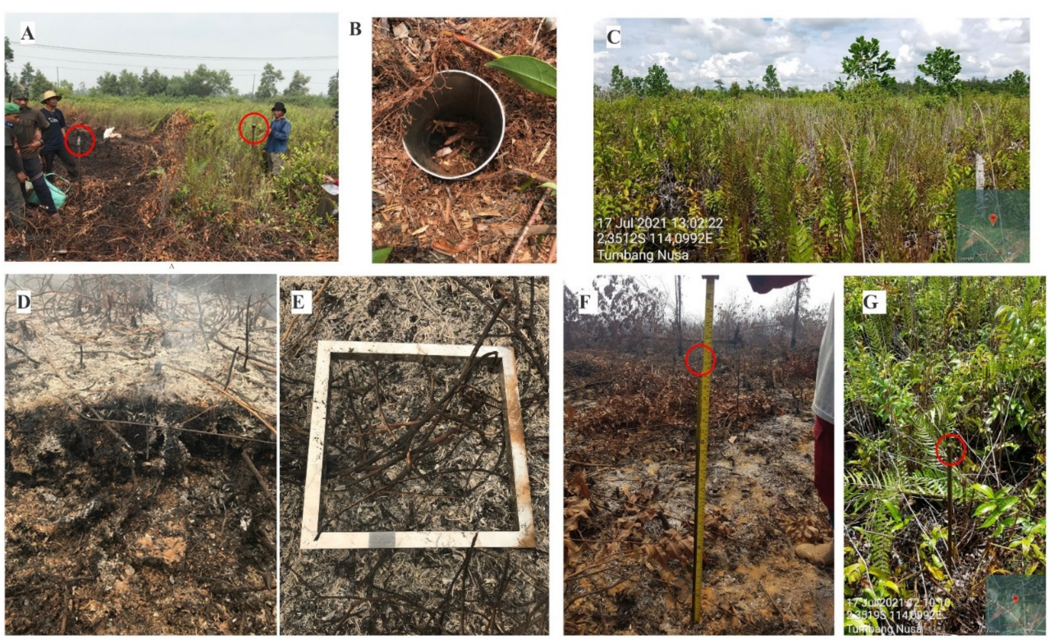

Figure 2. Photos of study sites: (**A**) Site 1 during July 2019 measurements, showing burned and unburned locations, red circles indicate position of peat auger samples taken from burned and unburned sites; (**B**) sampling of roots, rhizomes and

peat using a metal ring; (**C**) Site 1 in July 2021 showing recovery of vegetation; (**D**) Site 2 in September 2019 showing exposed roots, one day after peat fire burned the area; (**E**) sampling of shrubs and litter at burned sites, where the red circle indicates the metal rod; (**F**) Site 2, measurements of surface combustion using a metal rod indicated by the red circle; and (**G**) Site 2 in July 2021 showing recovery of vegetation and litter.

3. Results and Discussion

3.1. Area Burned

The peat fire of July 2019 burned through approximately 194x10^3 ha, with about 70% made up of heavily degraded peatland (Figure 3). Before the fire of 2019, this area was burned in 2001, 2003/4, 2006, and 2009 (Table 1).

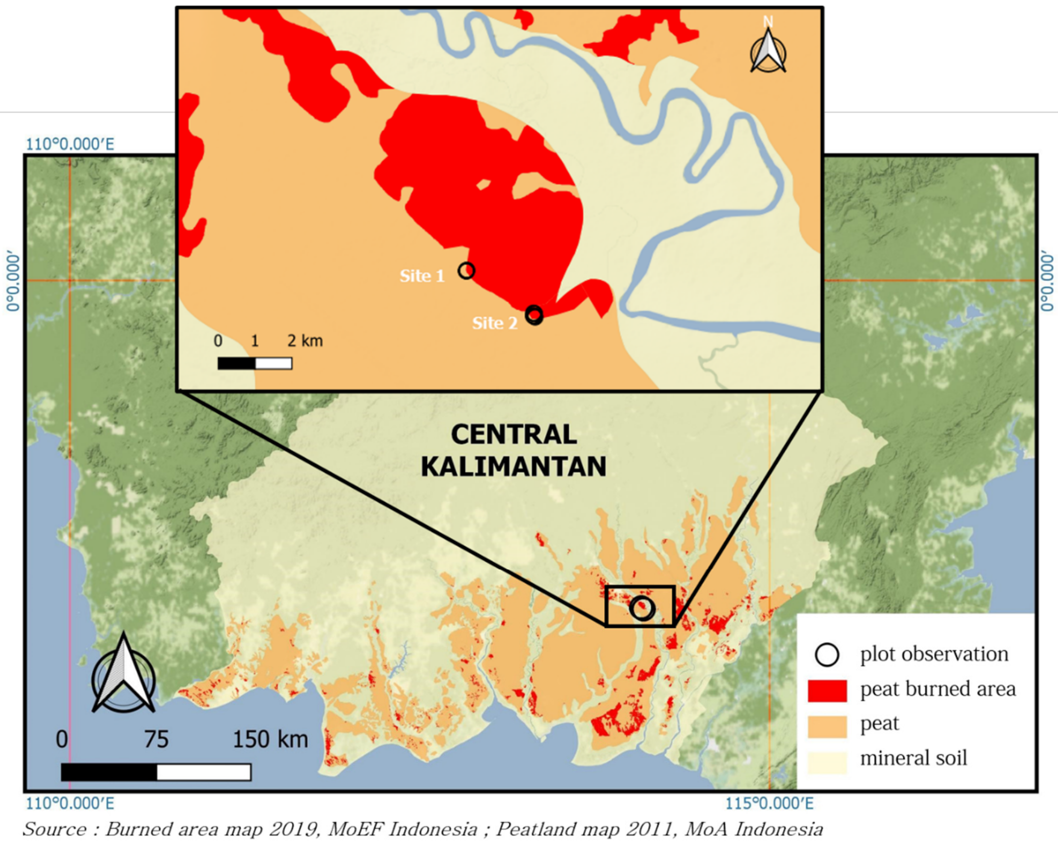

Figure 3. A map of the area burned in peat fires in 2019 in Central Kalimantan.

3.2. Impact of Fires on Carbon Content (C%) of Surface Fuels and Peat

Fires modified the C% of litter and peat but not shrubs. Litter C% in burned sites was reduced by almost 6% compared to the unburned sites, while C% of shrubs remained comparable between burned and unburned locations. The top layer of peat lost about 5% of carbon compared to unburned sites (Table 2). However, both the burned and unburned sites in these degraded peatlands had lower C% than relatively undisturbed peat forest, e.g., 51% for the top layer in the Sebangau National Park, [6], 54% reported by [10] or 56% averaged for the whole of South East Asia by [1]. The impact of recurrent fires on C% (also called C_{org}) has been greatly understudied [5]. Yet, this parameter directly affects peat fire emission estimates as defined by methods developed by the Intergovernmental Panel on Climate Change (IPCC) [11] (see Equation (1) below).

Table 2. Carbon content (C%) of measured above- and belowground components in burned and unburned degraded peatland treatments according to site.

Treatment	Component	Site 1	Site 2	Average
Burned	Litter	39.3 ± 0.46	50.40 ± 1.31	45.2 ± 1.49
	Shrub	Not present	47.35 ± 0.42	47.4 ± 0.43
	Peat, 0–10 cm	45.03 ± 0.23	38.14±2.35	41.1 ± 1.53
Unburned	Litter	49.76 ± 0.42	52.06 ± 0.71	51.1 ± 0.52
	Shrub	46.88 ± 0.41	47.37 ± 0.31	47.2 ± 0.25
	Peat, 0–10 cm	51.41 ± 1.10	41.21 ± 2.51	45.6 ± 1.86

Values are the means, n = 9 for Site 1 and n = 12 for Site 2, ± is the standard error (s.e.) of the mean.

3.3. Mass Loss from Aboveground Shrubs and Litter and from Belowground Rhizomes, Roots and Peat

Peat bulk density was comparable between the treatments and sites, with an average of 0.150 ± 0.005 g cm^{-3} (Table 3, P = 0.067). These values were consistent with our previous estimates for the degraded peatlands [6].

Table 3. Peat bulk density (g cm^{-3}) in burned and unburned treatments in degraded peatlands of Central Kalimantan.

Component	Burned	Unburned
Site 1	0.131 ± 0.008 (9)	0.149 ± 0.007 (9)
Site 2	0.149 ± 0.007 (12)	0.165 ± 0.011 (12)

Values are the means (with the number of samples given in brackets), ± is the standard error (s.e.) of the mean.

Almost 90% of shrub mass was combusted in fires yet the litter mass was comparable between burned and unburned locations (Table 4). No changes in litter loads (or even slightly greater in burned than unburned sites) suggest that carbon was added from the shrub layer (a redistribution of carbon) which was partly combusted or converted to other forms of carbon, such as char and ash, which were difficult to separate (Figure 2E). Overall, fire had a significant impact on shrub + litter mass, which was reduced from 8.09 ± 0.62 to 4.62 ± 0.68 Mg C ha^{-1}, losing 3.5 Mg C ha^{-1} (Table 4). The significantly lower carbon content of peat at burned sites (Table 2) resulted in loss from the peat surface of 15.02 Mg C ha^{-1}, with overall loss from surface and peat mass of 18.50±4.88 Mg C ha^{-1} (Table 4).

Table 4. Mass of above- and belowground carbon and carbon loss (Mg C ha^{-1}) across two sites in degraded peatlands of Central Kalimantan.

Component	Burned	Unburned	Loss	P value
Shrub	0.63 ± 0.27	4.57 ± 0.47	4.04 ± 0.56	< 0.001
Litter	3.99 ± 0.62	3.43 ± 0.41	-0.56 ± 0.79	n/s
Peat (0–11 cm)	63.4 ± 3.21	78.4 ± 3.88	15.02 ± 4.76	0.004
Total			18.50 ± 4.88	

Values are the means, n=20, ± is the s.e. of the mean.

3.4. Combustion of Peat Surface during Fires

The depth of peat to the mineral soil was comparable between unburned (2.44 ± 0.20 m) and burned (2.28 ± 0.11 m) sites and comparable with the peat depth maps derived from the MoA (Figure 4A).

Over almost a month of smoldering peat fires from September 4 to 29, a total of 21-24 cm of surface was lost (Figure 4B). The greatest reduction in the surface depth occurred in the first week, with a loss of up to 15 cm. About 3 cm was lost in the second week and less than 1 cm in the last days of measurements prior to the fire going out. Our measurements were comparable to the average peat layer loss of 15.8 ± 0.5 cm reported by [12].

Yet, burned peat layer depth was much smaller than recorded for a large forest fire in Central Kalimantan in 1997 (40 cm) [13]. Our observations during sampling of the peat surface indicate that it is not necessarily all peat mass that is consumed in fires but rather a combination of roots, fern rhizomes, peat and recently added litter that contributes to the decrease in peat depth (as can be seen in Figure 2D).

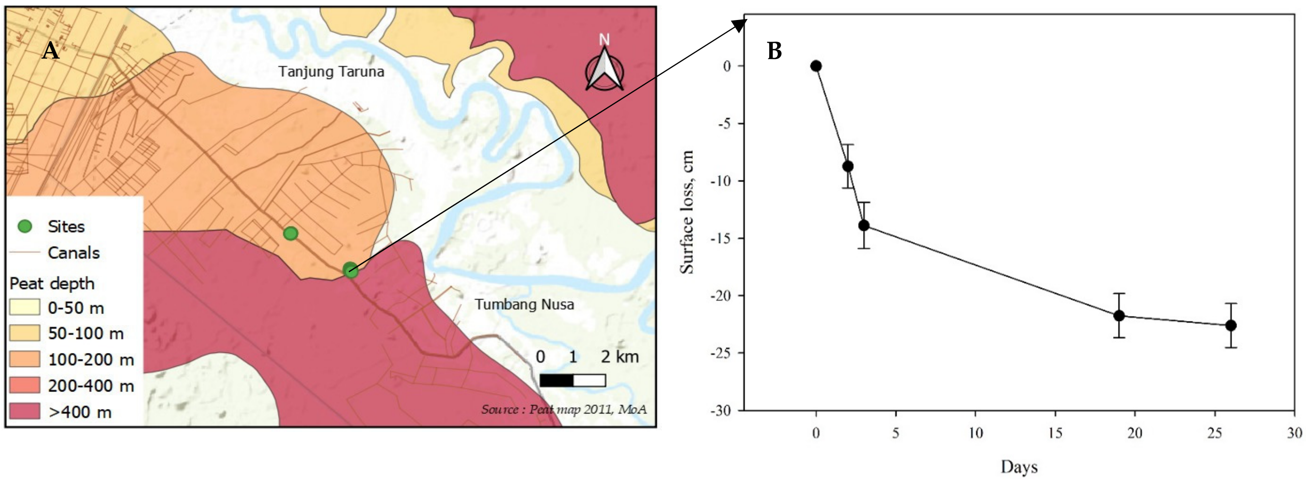

Figure 4. (**A**) Map of the peat depth at the study sites, (**B**) loss of the peat surface during peat fires in September 2019 at Site 2 as measured from two transects, Central Kalimantan. Error bars are the standard error (s.e.) of the mean. As can be seen in Figure 2D, it was not possible to separate the loss of peat from the overall surface loss.

3.5. Emission Factors and Emission from Recurrently Burned Degraded Peatlands

The overall loss of carbon from the surface and top peat layer was 18.5 Mg C ha^{-1} (3.5 from the surface and 15.0 from top peat), an emission factor greater than 13 Mg C ha^{-1} suggested by [4]. However, if only the loss from peat is considered, then our estimates of 15.02 ± 4.76 would be comparable to [4]. We should emphasize that for the estimates of carbon loss, the authors used a lower peat bulk density value of 0.115 g cm^{-3} but greater carbon content of 55.3% compared to our field measurements of 0.150 g cm^{-3} and 45.6%. Consistent with the findings from other studies [14,15], degraded peatlands have compact peat with bulk densities much greater than 0.115 g cm^{-3} which is more representative of undisturbed peatlands [10]. Our previous analyses have shown that C% of 39–43% is a more realistic value for the degraded peatlands [6]—well below the almost universally used 56% reported by Page, Rieley and Banks [1]—irrespective of peat degradation status.

In our study, we recorded a much greater combustion of the peat surface than the relative burned area depth of 2 cm for four or more consecutive fires reported by [4] This suggests that the authors did not consider the contribution of organic matter and roots to the burned area depth in their estimates. Our field observations (Figure 2B,D) indicate that the shrubs, litter and roots in degraded peatlands are the main fuels consumed in fires that determine the depth of peat loss.

Assuming the total loss of 18.5 ± 4.88 Mg C ha^{-1}, we estimate the peat fires of 2019 that burned though about 133 631 ha of degraded peatlands dominated by ferns and other small shrubs of Central Kalimantan released between 1.8 and 3.1 Gg C. Using the IPCC method [11] (Equation (1)) and our field data would produce an estimate of carbon loss in the range 67.5–77.1 Mg C ha^{-1}:

$$EF = DB \cdot C \cdot BD \cdot CF \cdot 100 \quad (1)$$

where average depth burned (DB) is 21–24 cm, average peat bulk density (BD) is 0.150 g cm^{-3}, peat carbon content (C) is 0.4558 and peat combustion factor (CF) is 0.47 from [6]. Multiplying this carbon loss by the peat area burned would produce carbon emissions from the study area of between 9 and 10 Gg C. This IPCC method overestimates emissions from degraded peatlands, where the shrub, litter and root components are the main contributors to emissions.

Similarly, using the IPCC method (Equation (1)), our field data for BD, C% and the relative peat depth burned of 2 cm from [4] would produce carbon loss of 6.42 Mg C ha^{-1}, or half of what we observed in the field, due to the authors [4] not accounting for aboveground and root biomass contributions to the emissions.

Although the recovery of vegetation was visually apparent two years after fires (Figure 2C, G), we do not have biomass estimates for the vegetation in 2021. As a surrogate for biomass measures after fire, we used the trend in the NDVI to estimate equivalence in the vegetation condition from the period prior to fire to two years after fire. The monthly NDVI trend indicated that about 3 years are required for the aboveground carbon to fully recover to pre-fire conditions (Figure 5). An increase in the index value indicates an increase in the greenness value which describes an increase in growth or density of land cover vegetation. Theoretically, the NDVI value interval for shrubs is narrower than the NDVI value interval for forest stands, so it is very possible that shrub recovery can occur in a relatively short time. As the net primary productivity of tropical fern shrublands is about 11 Mg C ha^{-1} yr^{-1} [16], the NDVI estimated vegetation recovery in this study is likely highly conservative.

This study provides one of just a few rare empirical estimates of biomass and peat loss as measured during fires. Our results suggest that following peat fire in degraded peatlands, vegetation carbon recovers within 3 years.

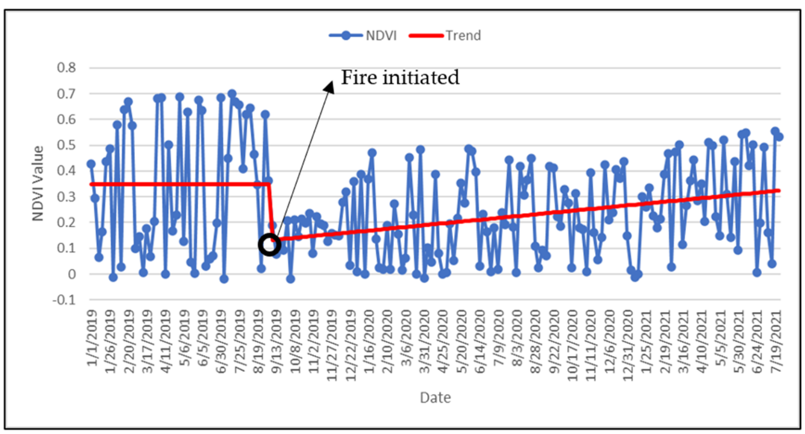

Figure 5. Monthly Normalized Difference Vegetation Index (NDVI) from January 2019 to July 2021 at Site 2, Central Kalimantan.

Author Contributions: Conceptualization, L.V, H.K., C.J.W.; methodology, L.V., W.C.A., H.K., C.J.W.; sample preparation and analysis, W.C.A.; NDVI analysis, W.C.A.; fire map development W.C.A., R.I.; writing—original draft preparation, L.V.; writing—review and editing, W.C.A., H.K., R.I., C.J.W.; project administration, L.V. and H.K.; funding acquisition, L.V., H.K., C.J.W. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The data presented in this study are available from the corresponding authors upon reasonable request.

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Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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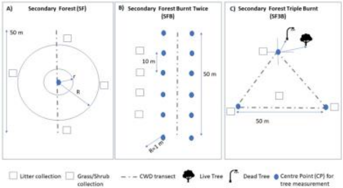
S O P

(Standard Operating Procedure)

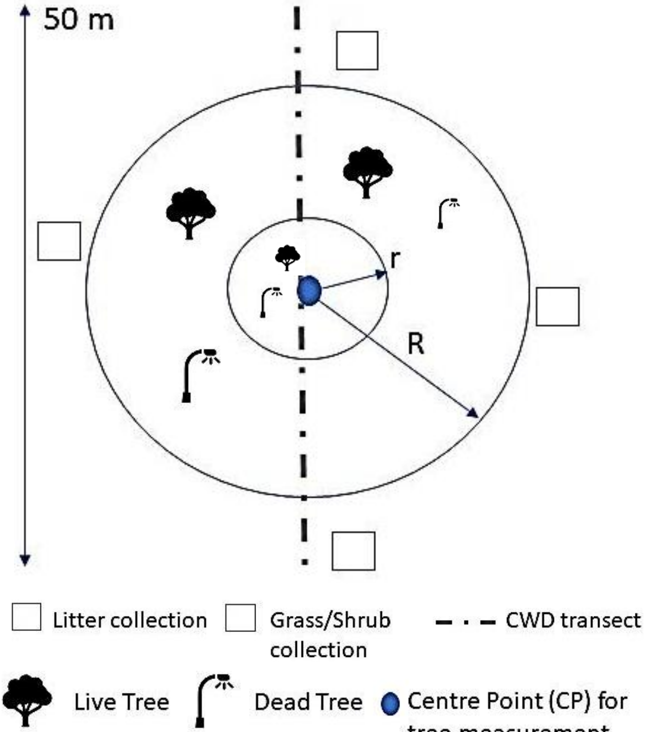
Measuring Fuels
Peat swamp Forest



APFNet Project "Improving Capacities Towards Reducing Greenhouse Gas Emissions from Peat Swamp Forest Fires in Indonesia"

Secondary Forests [SF]

BENTUK PLOT



PEMBUATAN PLOT

1. Tetapkan titik pusat plot (CP) seperti yang ditunjukkan pada Gambar bentuk plot
2. Catat koordinat plot […….. LS/LU;……….BT], simpan dengan kode SF dan no plot **[SF #]**
3. Foto kondisi hutan dari titik pusat plot dalam 4 arah: Utara ,Timur, Selatan, Barat, Tajuk dan Lantai hutan, catat no foto yang tersimpan [U=….., T=……, S=……., B=……., Taj=….., Lantai hutan=…….]

TALLY SHEET : KONDISI PLOT
Plot : **SF….** Tgl : /07/19
Koordinat :
LS :……… BT :………….
Foto :
U :………, T :………., S:…………, B:……….
Taj.:…………., Lt.Hutan:…………………….

PENGUKURAN VEGETASI HIDUP DAN MATI

1. Pohon besar : Ukur semua pohon dengan DBH ≥ 5 cm dalam radius plot, R = 10 m
   - Catat DBH, nama spesies, status (live/dead)
2. Pohon kecil : Ukur semua pohon dengan 2≤ DBH < 5cm in subplot, r = 2m
   - Catat DBH, nama spesies, status (live/dead)

TALLY SHEET : Trees/Small Trees

Plot : **SF….** Tgl : /07/19

No	Dbh (cm)	Nama	Status [L/D]	Ket.

PENGUKURAN CWD (*Coarse Woody Debris*)

1. Buat transek 50 m melintasi plot (U → S)
2. Ukur diameter CWD d≥2.5 cm pada titik yang berpotongan dengan transek
3. Catat diameter dan kategori CWD : Sound/keras [S], Rotten/lunak [R], Charc/Arang [C]

TALLY SHEET : CWD

Plot : **SF….** Tgl : /07/19

No	D (cm)	Kategori CWD [S/R/C]	Ket.

4. Ambil sampel CWD ± 250gr pada masing-masing kategori
   - Catat Tanggal, plot ID [**SF#**], kategori CWD [**Sound/Rotten/Charc**], Berat, pada plastik sampel

CWD

Tgl : /07/19
Plot : **SF….**

[SOUND/ROTTEN/CHARC]

……….. Kg

PENGUKURAN SHRUB DAN LITTER

1. Tempatkan “frame” di ujung batas plot seperti yang ditunjukkan pada Gambar bentuk plot
2. Kumpulkan semua vegetasi (rumput / semak kecil D<2cm) mati dan hidup pada kantong plastik.
   - Catat pada kantong plastik: Plot ID, SHRUB, arah (U / T/ S / B) dan tanggal.

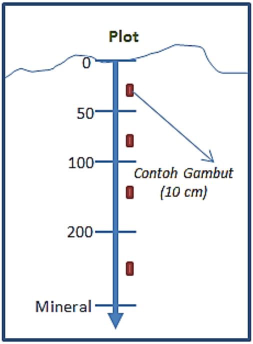
SHRUB
Tgl :   /07/19
Plot : **SF…… [U/T/S/B]**

3. Pada lokasi yang sama, kumpulkan serasah (termasuk daun, buah, dan ranting/cabang yang jatuh dengan D<2.5cm pada kantong plastik.
   - Catat pada kantong plastik: Plot ID, LITTER, arah (U / T/ S / B) dan tanggal.

LITTER
Tgl :   /07/19
Plot : **SF…… [U/T/S/B]**

PENGUKURAN GAMBUT

1. Lakukan pengeboran pada satu titik di didalam plot untuk pengukuran kedalaman gambut dan pengambilan sampel
2. Kedalaman gambut dibagi kedalam beberapa tingkat kedalaman : 0 -50cm, 50 -100cm, 100-200cm, 200-400cm,…., mineral
3. Pada masing-masing tingkat kedalaman, diambil contoh gambut sedalam 10cm (usahakan ditengah tingkat kedalaman)
4. Catat kedalaman gambut dan beri label contoh gambut



Label : Sampel Gambut

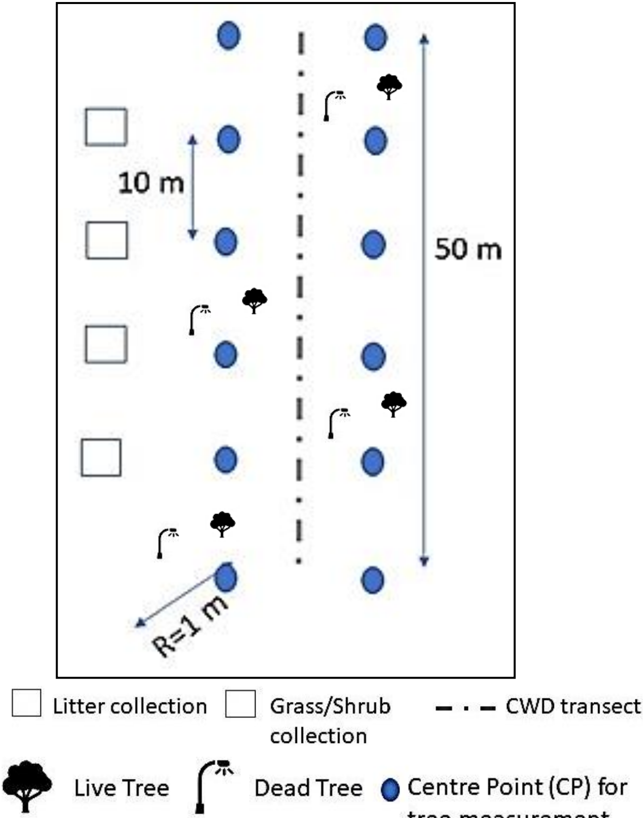
Tgl :   /07/19
Plot : **SF….**
[0-50/50-100/100-200/…..]

TALLY SHEET : Gambut

No	Plot	Tanggal	Kedalaman Gambut (cm)	Σ Sampel

Secondary Forest Burnt twice [SFB]

BENTUK PLOT



PEMBUATAN PLOT

1. Buat transek 50 mseperti yang ditunjukkan pada gambar dan catat arahnya
2. Catat koordinat titik awal dan akhir transek [……..LS; ……….BT], simpan dengan kode **[SFB # _start, SFB # _end]**
3. Foto kondisi hutan dari titik tengah transek dalam 4 arah: Utara ,Timur, Selatan, Barat, Tajuk dan Lantai hutan, catat no foto yang tersimpan [U=….., T=……, S=……., B=……., Taj=….., Lantai hutan=…….]

TALLY SHEET : KONDISI PLOT

Plot : **SFB….** Tgl : /07/19

Arah Transek :

Koordinat :

Awal	LS :………	BT :…………..
Akhir	LS :………	BT :…………..

Foto :

U :………, T :……….., S:…………, B:……….

Taj.:…………., Lt.Hutan:…………………….

PENGUKURAN VEGETASI HIDUP DAN MATI

1. Di kedua sisi transek, 1 m dari transek, hitung jumlah pohon pada tiap kelas diameter: 0-1cm; 1-2cm, 2-3cm, 3-4cm, 4-5cm, > 5cm dalam radius R = 1m.
2. Ulangi langkah di atas pada setiap 10 m pada transek (total 12 titik pengambilan sampel)
3. Ambil contoh 3 - 5 pohon pada berbagai diameter untuk analisis di laboratorium
   - Catat spesies, ukur DBH, total tinggi, berat basah total masing-masing komponen pohon: daun, batang, cabang
   - Ambil sampel masing-masing komponen untuk analisis lab, catat berat basah masing-masing komponen dan beri label (No Pohon, komponen, berat basah)

TALLY SHEET : Trees/Small Trees

Plot : **SFB….** Tgl : /07/19

No	Titik	Σ pohon pada KD						Ket.
		< 1cm	1-2cm	2-3cm	3-4cm	4-5cm	>5cm	

TALLY SHEET : Destructive Sampling

Plot : **SFB….** Tgl : /07/19

No Pohon	Nama	Dbh (cm)	Tinggi (m)	Berat Basah Total			Berat Basah Sampel			Ket.
				Daun	Cabang	Batang	Daun	Cabang	Batang	

PENGUKURAN CWD (*Coarse Woody Debris*)

1. Ukur diameter CWD d≥2.5 cm pada titik yang berpotongan dengan transek
2. Catat diameter dan kategori CWD : Sound/keras [S], Rotten/lunak [R], Charc/Arang [C]

TALLY SHEET : CWD

Plot : **SFB….** Tgl : /07/19

No	D (cm)	Kategori CWD [S/R/C]	Ket.

3. Ambil sampel CWD ± 250gr pada masing-masing kategori
   - Catat Tanggal, plot ID [**SFB#**], kategori CWD [**Sound/Rotten/Charc**], Berat, pada plastik sampel

CWD

Tgl : /07/19

Plot : **SFB….**

[SOUND/ROTTEN/CHARC]

……….. Kg

PENGUKURAN SHRUB DAN LITTER

1. Tempatkan “frame” pada setiap 10 m pada transek seperti pada Gambar bentuk plot [10,20,30,40]
2. Kumpulkan semua vegetasi (rumput / semak kecil D<2cm) mati dan hidup pada kantong plastik.
   - Catat pada kantong plastik: Plot ID, SHRUB, titik sampel [10,20,30,40] dan tanggal.

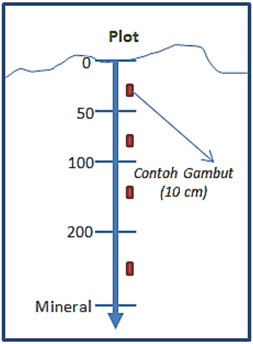
SHRUB
Tgl : /07/19
Plot : **SFB…… [10/20/30/40]**

3. Pada lokasi yang sama, kumpulkan serasah (termasuk daun, buah, dan ranting/cabang yang jatuh dengan D<2.5cm pada kantong plastik.
   - Catat pada kantong plastik: Plot ID, LITTER, titik sampel [10,20,30,40] dan tanggal.

LITTER
Tgl : /07/19
Plot : **SFB…… [10/20/30/40]**

PENGUKURAN GAMBUT

1. Lakukan pengeboran pada satu titik di didalam plot untuk pengukuran kedalaman gambut dan pengambilan sampel
2. Kedalaman gambut dibagi kedalam beberapa tingkat kedalaman : 0 -50cm, 50 -100cm, 100-200cm, 200-400cm,…., mineral
3. Pada masing-masing tingkat kedalaman, diambil contoh gambut sedalam 10cm (usahakan ditengah tingkat kedalaman)
4. Catat kedalaman gambut dan beri label contoh gambut



Label : Sampel Gambut

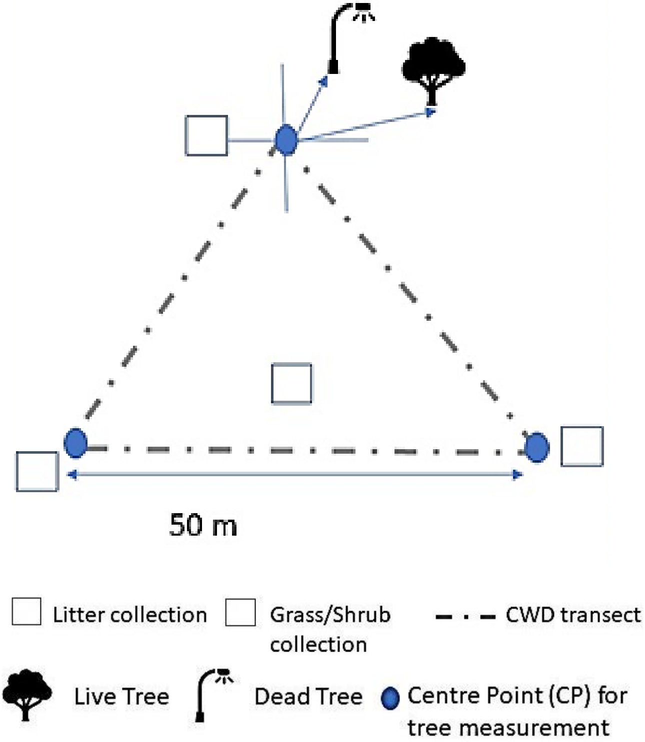
Tgl :   /07/19
Plot : **SFB….**
[0-50/50-100/100-200/…..]

TALLY SHEET : Gambut

No	Plot	Tanggal	Kedalaman Gambut (cm)	Σ Sampel

Secondary Forest Burnt Three Times [SF3B]

BENTUK PLOT



PEMBUATAN PLOT

1. Buat plot berbentuk segitiga sama sisi 50 m, sudut 60^o seperti yang ditunjukkan pada gambar dan catat arahnya
2. Catat koordinat pada masing-masing titik sudut (CP) [……..LS; ……….BT], simpan dengan kode **[SFB # _1, SFB # _2, SFB # _3]**
3. Foto kondisi hutan dari titik tengah plot dalam 4 arah: Utara ,Timur, Selatan, Barat, Tajuk dan Lantai hutan, catat no foto yang tersimpan [U=….., T=……, S=……., B=……., Taj=….., Lantai hutan=…….]

TALLY SHEET : KONDISI PLOT

Plot : SF3B…. Tgl : /07/19

Arah Transek : CP12:….; CP23;…….; CP31;……

Koordinat :

CP 1	LS :………	BT :…………..
CP 2	LS :………	BT :…………..
CP 3	LS :………	BT :…………..

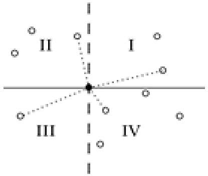
Foto :

U :………, T :……….., S:…………, B:………..

Taj.:………….., Lt.Hutan:…………………….

PENGUKURAN VEGETASI HIDUP DAN MATI

1. Pada setiap titik sudut (CP#), secara visual dibagi dalam 4 kuadran seperti yang ditunjukkan pada Gambar
2. Pada setiap kuadran, temukan satu pohon terdekat yang hidup dan satu pohon terdekat yang mati



   - Catat: CP #, Quarter #, DBH dan jarak untuk satu pohon hidup dan satu pohon mati
3. Ulangi pada masing-masing 3 CP
   - Seharusnya terdapat 24 catatan pohon per plot (3 CP x 4 perempat x 2 pohon)

TALLY SHEET : Trees/Small Trees

Plot : **SF3B….** Tgl : /07/19

No	Kuadran	Parameter					Ket.
		Nama	Jarak (m)	Dbh (cm)	Tinggi (m)	[L/D]	

PENGUKURAN CWD (*Coarse Woody Debris*)

1. Tentukan satu transek 50m untuk pengukuran CWD, ukur diameter CWD d≥2.5 cm pada titik yang berpotongan dengan transek
2. Catat diameter dan kategori CWD : Sound/keras [S], Rotten/lunak [R], Charc/Arang [C]

TALLY SHEET : CWD

Plot : **SF3B….** Tgl : /07/19

No	D (cm)	Kategori CWD [S/R/C]	Ket.

3. Ambil sampel CWD ± 250gr pada masing-masing kategori
   - Catat Tanggal, plot ID [**SFB#**], kategori CWD [**Sound/Rotten/Charc**], Berat, pada plastik sampel

CWD

Tgl : /07/19

Plot : **SF3B….**

[SOUND/ROTTEN/CHARC]

……….. Kg

PENGUKURAN SHRUB DAN LITTER

1. Tempatkan “frame” pada setiap sudut plot (CP) dan tengah plot seperti pada Gambar bentuk plot [CP1,CP2,CP3,Tengah]
2. Kumpulkan semua vegetasi (rumput / semak kecil D<2cm) mati dan hidup pada kantong plastik.
   - Catat pada kantong plastik: Plot ID, SHRUB, titik sampel [CP1,CP2,CP3,Tengah] dan tanggal.

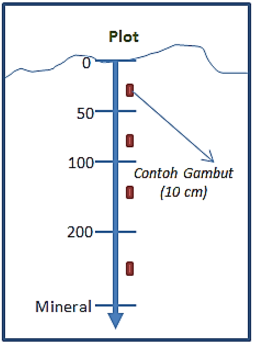
SHRUB
Tgl :   /07/19
Plot : **SF3B…… [CP1/CP2/CP3/Tengah]**

3. Pada lokasi yang sama, kumpulkan serasah (termasuk daun, buah, dan ranting/cabang yang jatuh dengan D<2.5cm pada kantong plastik.
   - Catat pada kantong plastik: Plot ID, LITTER, titik sampel [CP1,CP2,CP3,Tengah] dan tanggal.

LITTER
Tgl :   /07/19
Plot : **SF3B…… [CP1/CP2/CP3/Tengah]**

PENGUKURAN GAMBUT

1. Lakukan pengeboran pada satu titik di didalam plot untuk pengukuran kedalaman gambut dan pengambilan sampel
2. Kedalaman gambut dibagi kedalam beberapa tingkat kedalaman : 0 -50cm, 50 -100cm, 100-200cm, 200-400cm,…., mineral
3. Pada masing-masing tingkat kedalaman, diambil contoh gambut sedalam 10cm (usahakan ditengah tingkat kedalaman)
4. Catat kedalaman gambut dan beri label contoh gambut



Label : Sampel Gambut

Tgl :   /07/19
Plot : **SF3B….**
[0-50/50-100/100-200/…..]

TALLY SHEET : Gambut

No	Plot	Tanggal	Kedalaman Gambut (cm)	Σ Sampel

APFNet Project

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   lubav@unimelb.edu.au

MINISTRY OF ENVIRONMENT AND FORESTRY
RESEARCH, DEVELOPMENT AND INOVATION AGENCY

2018P5-IND
brief INFO
02

Bogor, October 2020

Jl. Gunung Batu No. 5; Telp. (0251) 8633234, 7520067; Facs. 8638111 - www.hutan.litbang.menlhk.go.id

Identifying and Addressing Knowledge Gaps for Improving Greenhouse Gas Emissions Estimates from Tropical Peat Forest Fires

Highlights

1. Lack of data for the parameters to estimate emissions from peat fires in the literature:
   a. Mass of aboveground fuels and combustion factors are covered by fewer than ten studies
   b. Mass of peat is addressed by fewer than ten studies
   c. Only a few studies report on changes in peat bulk density with increased fire frequency
   d. No studies on changes in peat carbon content with increased fire frequency
2. The majority of studies reporting field data collected **at least ten or more years ago.**

Citation: L. Volkova, H. Krisnawati, W.C. Adinugroho, et al., Identifying and addressing knowledge gaps for improving greenhouse gas emissions estimates from trop..., Science of the Total Environment

https://doi.org/10.1016/j.scitotenv.2020.142933

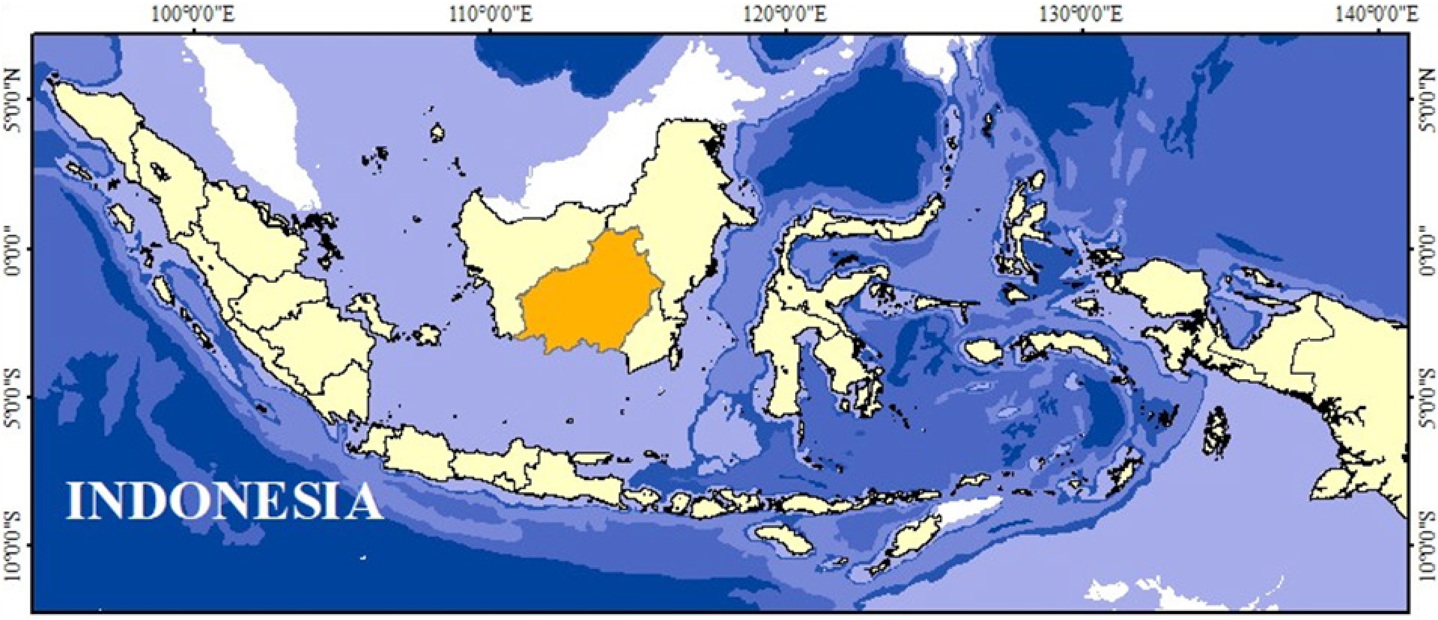
Tropical peat swamp forest is a globally important carbon store.

It is estimated that degraded and burnt peatlands release about 5% of global greenhouse gas (GHG) emissions, **yet there is great uncertainty in these estimates.**

Despite numerous studies of emissions from tropical peat forest fires there is a lack of empirical studies on which to base the estimates of peat fire emissions, limiting our ability to develop effective climate change policies and mitigation actions.

"Improving the assessment of GHG from peatland has been declared by the UN-FAO a global strategic priority"

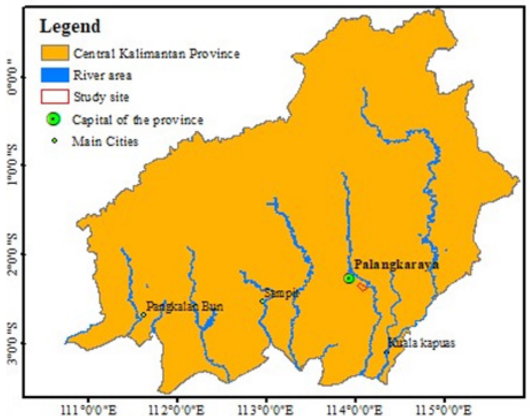
GHG emissions from recurrently burnt peat forest is not estimated in a consistent manner, with aboveground carbon pools such as deadwood and fire-produced pyrogenic carbon are often excluded from estimates.

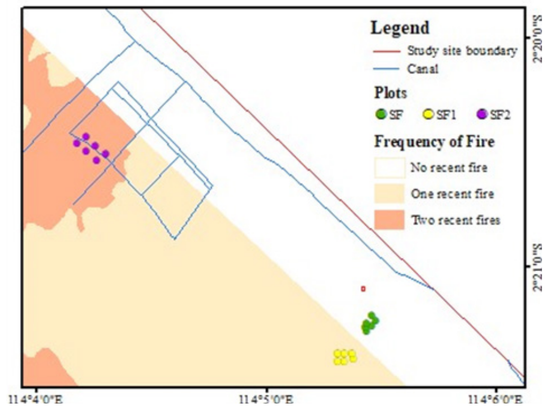


Finding

For peat swamp forests of Kalimantan, following single and multiple fires, the study revealed the contribution of deadwood and PyC to AGC increases with fire frequency, from 6% in long unburnt forests, to 70% after one recent fire, and to 87% after two recent fires.

- A single fire produces 90 MgC/ha as dead organic matter (DOM - dead trees, coarse woody debris and litter).
- One fire produces 4.5±0.6 Mg C/ha of PyC.
- Peat bulk density in the 0-10 cm increases with fire frequency from 0.124 g/ cm^3 in long unburnt forest to 0.154 g/cm^3 after two consecutive fires.
- A second consecutive fire reduces DOM by 50% with carbon retained in charred CWD and pyrogenic carbon (PyC).
- A second fire increasing this to 7.1±0.8 Mg C/ha, or from 3% to 12% of AGC.
- Power analysis indicated as few as 12 plots are required to detect meaningful differences between fire treatments for the major carbon pools such as aboveground live, deadwood and peat bulk density.





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IMPROVING THE KNOWLEDGE BASE OF FUEL LOADS FOR ESTIMATING GHG EMISSIONS FROM DEGRADED PEAT SWAMP FORESTS

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[1]Forest Research and Development Center, Indonesia, [2]The University of Melbourne, Australia

Asia-Pacific Forestry Week 2019
Forests for Peace and Well-being

INTRODUCTION :

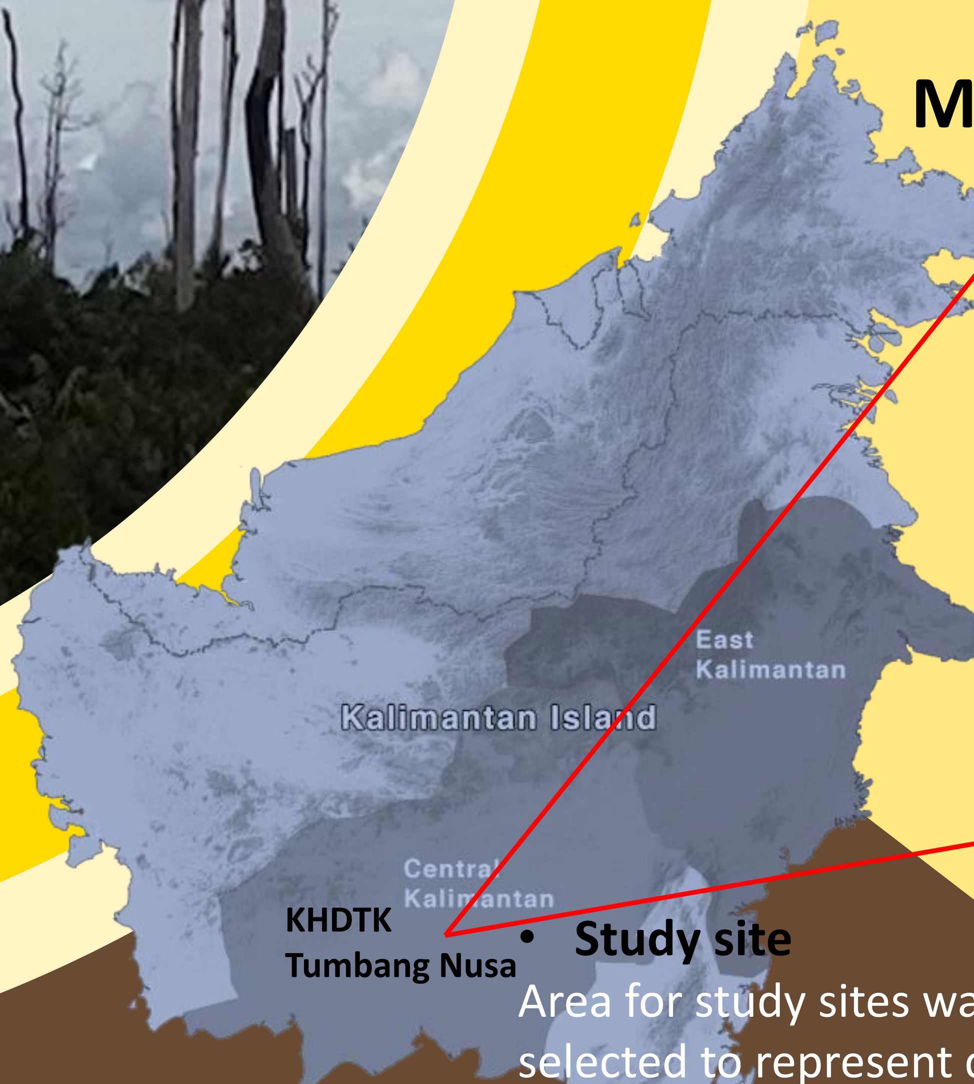
Tropical peatlands are the areas of high carbon density and play an important role in global climate change. Currently, this ecosystem is a subject to rapid degradation due to strong economic and social pressures for timber and land for agriculture and plantations. Clearance and drainage of tropical peatlands over recent decades have resulted in an unprecedented increase in peat fires, with smoke and pollution affecting human livelihood and health. Emissions from peat fires is a subject of great uncertainty as only a few empirically based parameters of fuel loads and their combustion efficiency are available in the literature. Lack of knowledge on how different fuels contribute to greenhouse gas (GHG) emissions makes it difficult to develop well-targeted policy for emission reduction. At present, emissions from peat fires are not reported in the GHG inventory due to high levels of uncertainty in the data. The objective of this study is to improve the knowledge base of fuel loads and their combustion characteristics in peat swamp forests at different stages of degradation. The outputs will help address a significant knowledge gap in greenhouse gas emissions from peat swamp forest fires and to improve methodology for estimating GHG emissions, and policy recommendations for emission reduction actions.

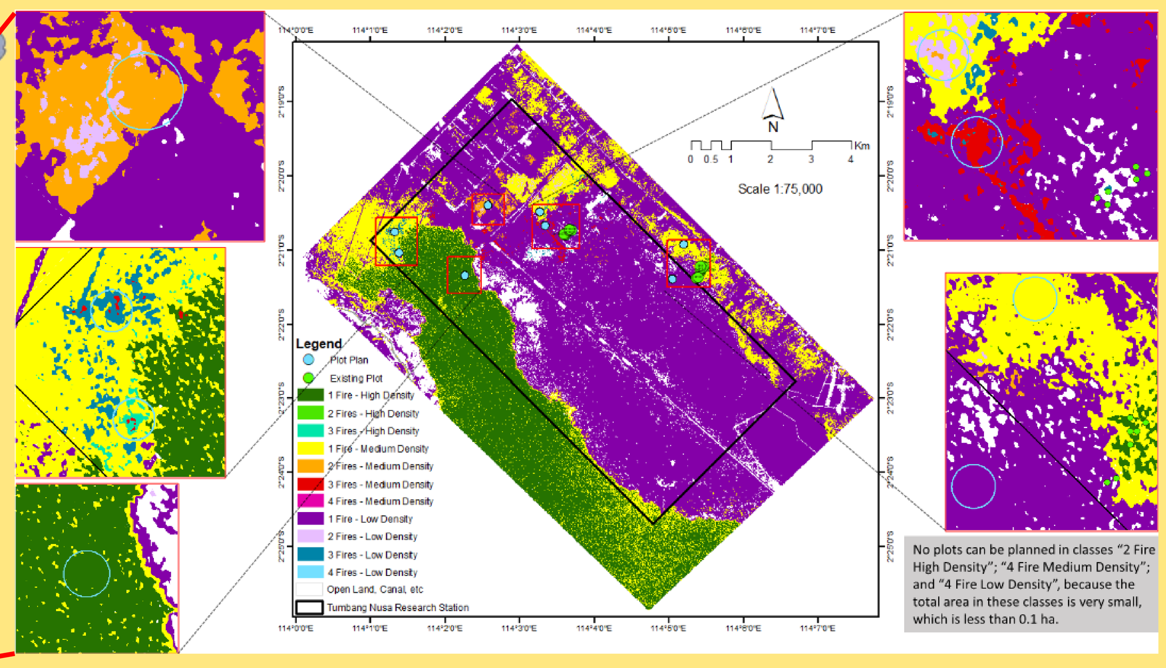
Rationale
- Limited data
- Low accuracy of estimates
- Need for improved national capacity

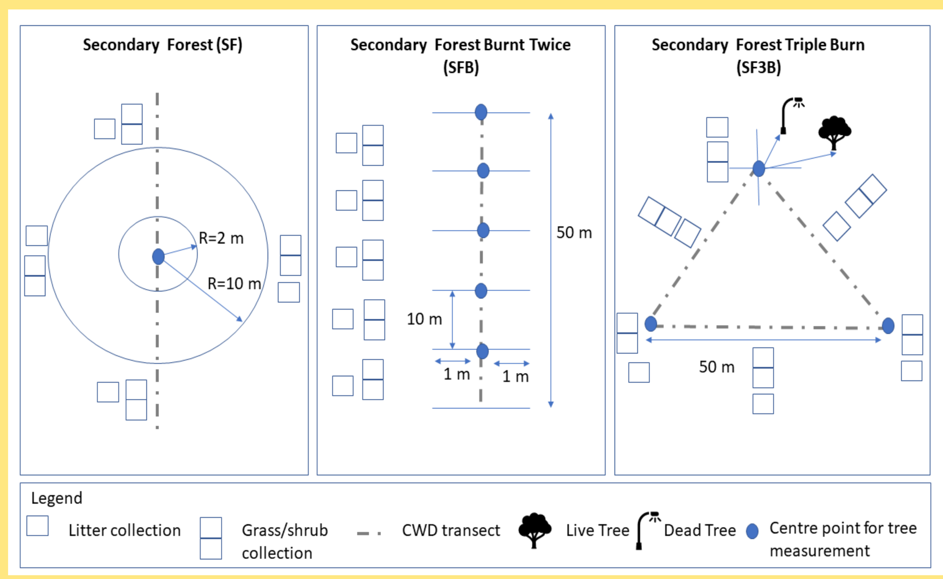
Research
- Statistically robust sampling design
- Updated data: Combustion factors, Fuel load, Patchiness

Output
- More data available
- Improved accuracy of estimates
- Development of national standards
- Improved capacity
- Policy recommendation

METHODS :







- **Sampling plots design**

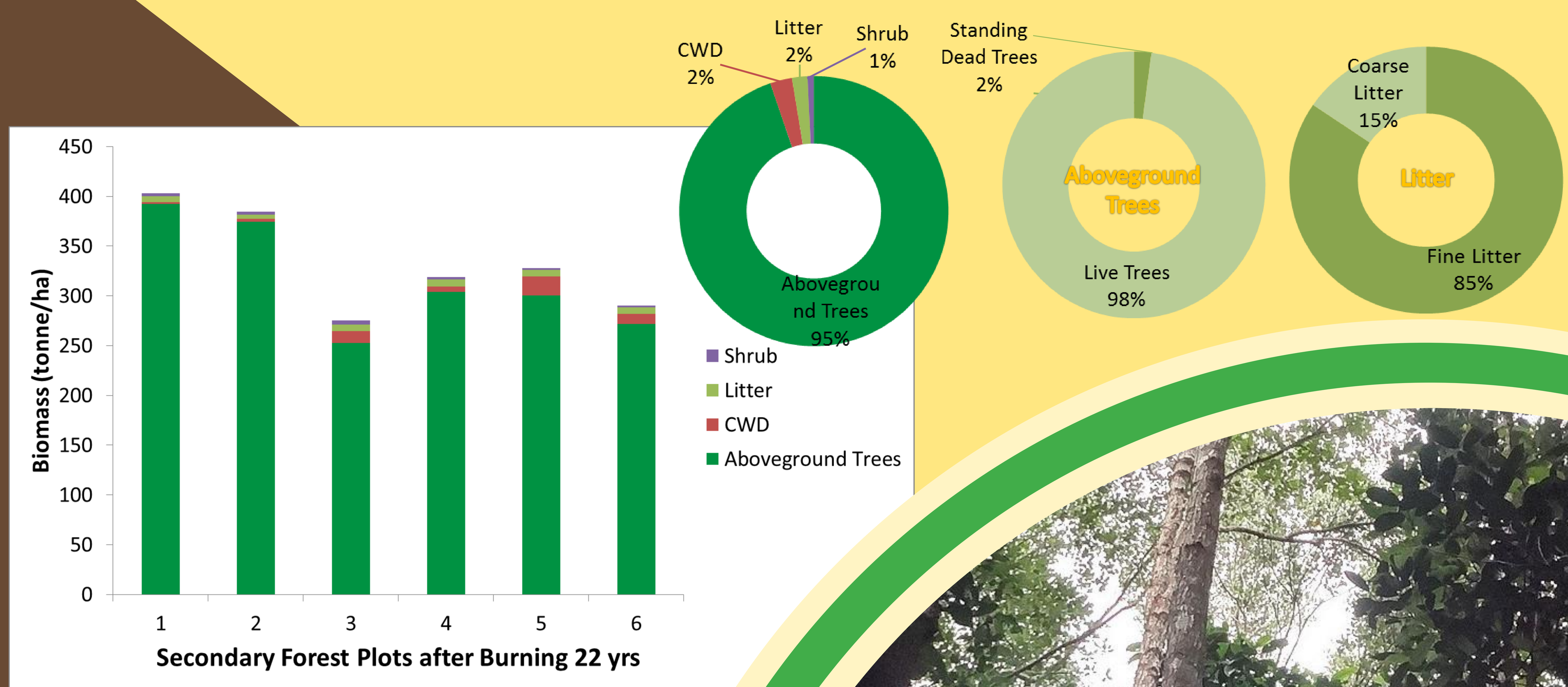
- **Study site**
Area for study sites was selected to represent degraded peat swamp forests due to fires

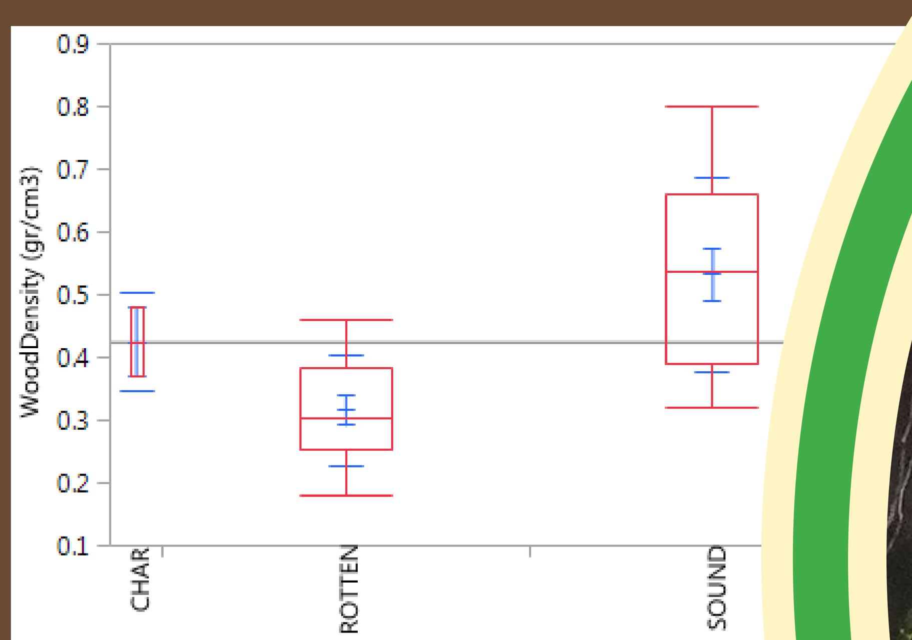
- **Data collection and measurement**

The following aboveground carbon pools were measured: overstorey and understorey trees (DBH, Height, Species, Live/Dead); shrubs, grasses and litter (destructive sampling); coarse woody debris [CWD] (sound, rotten and charred) using line intersect method

RESULT (Preliminary) :

- Standing dead trees, shrubs, litter and coarse woody debris (CWD) are C-pools in burnt forests that need to be considered.
- CWD types : sound, rotten, char need to be considered in calculation for estimating GHG emissions.
- Char is commonly found in burnt forests.





Acknowledgements :

This study is a part of the research project entitled *"Improving Capacities Towards Reducing Greenhouse Gas Emissions from Peat Swamp Forest Fires in Indonesia"*, conducted by the Forest Research and Development Center - Research Development and Innovation Agency of the Ministry of Environment and Forestry, in collaboration with the School of Ecosystem and Forest Sciences - the University of Melbourne and funding support from the APFNet and the Australian Government.

THE UNIVERSITY OF MELBOURNE APFNet Australian Aid

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1. Dr. Haruni Krisnawati *h.krisnawati@yahoo.co.id*
2. Dr. Liubov Volkova *lubav@unimelb.edu.au*

Emission estimation methodologies, uncertainties and drives of the peat fire emissions

THE UNIVERSITY OF MELBOURNE

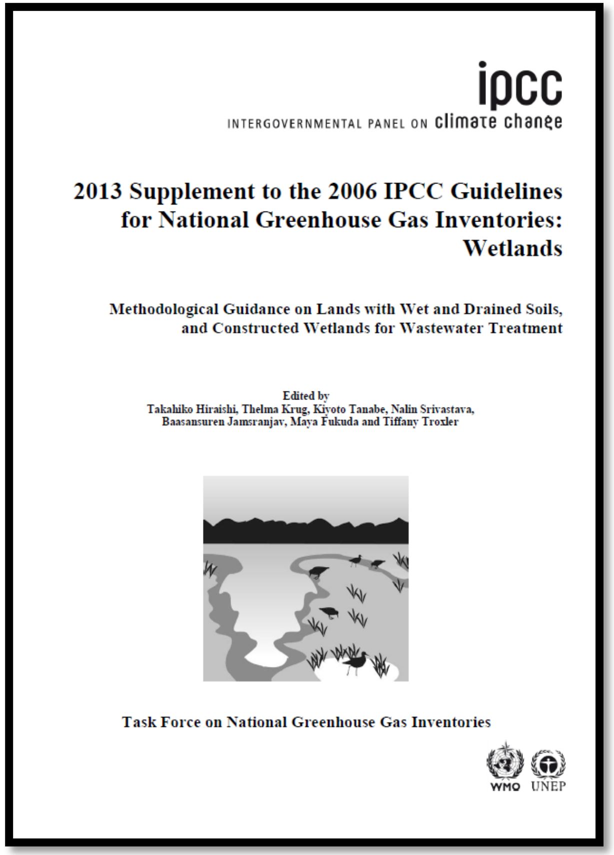
APFNet

Australian Centre for International Agricultural Research

Australian Aid

Estimating fire emissions basics

- **Emission = Area burnt * (Emission Factor $_{Peat}$ + Emission Factor $_{AGB}$)**
- **Tier 2 approach: Methods: IPCC or Country Specific (non-IPCC variants)**


ipcc
INTERGOVERNMENTAL PANEL ON climate change

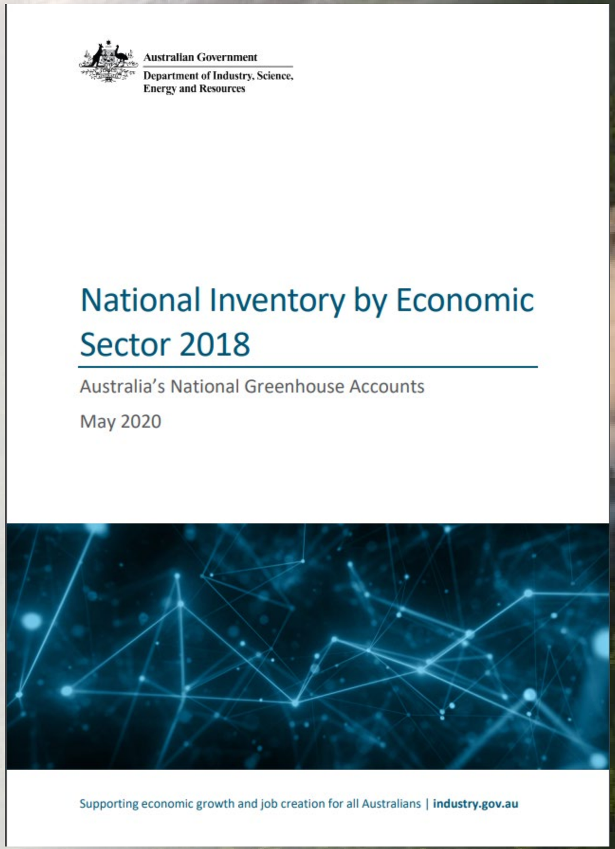
2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands

Methodological Guidance on Lands with Wet and Drained Soils, and Constructed Wetlands for Wastewater Treatment

Edited by
Takahiko Hiraishi, Thelma Krug, Kiyoto Tanabe, Nalin Srivastava, Baasansuren Jamsranjav, Maya Fukuda and Tiffany Troxler

Task Force on National Greenhouse Gas Inventories

WMO UNEP

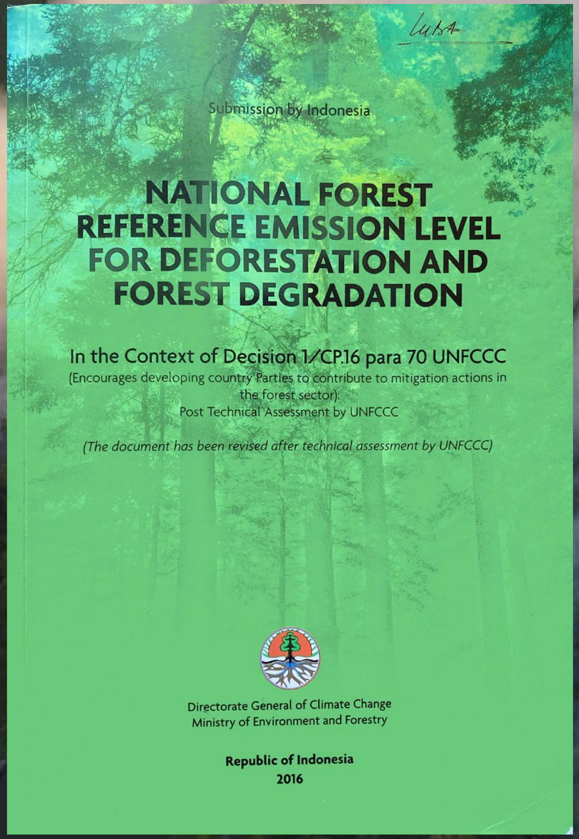

Australian Government
Department of Industry, Science, Energy and Resources

National Inventory by Economic Sector 2018

Australia's National Greenhouse Accounts

May 2020

Supporting economic growth and job creation for all Australians | industry.gov.au


Submission by Indonesia

NATIONAL FOREST REFERENCE EMISSION LEVEL FOR DEFORESTATION AND FOREST DEGRADATION

In the Context of Decision 1/CP.16 para 70 UNFCCC
(Encourages developing country Parties to contribute to mitigation actions in the forest sector)
Post Technical Assessment by UNFCCC

(The document has been revised after technical assessment by UNFCCC)

Directorate General of Climate Change
Ministry of Environment and Forestry

Republic of Indonesia
2016

Source: IPCC 2006, 2013, 2019

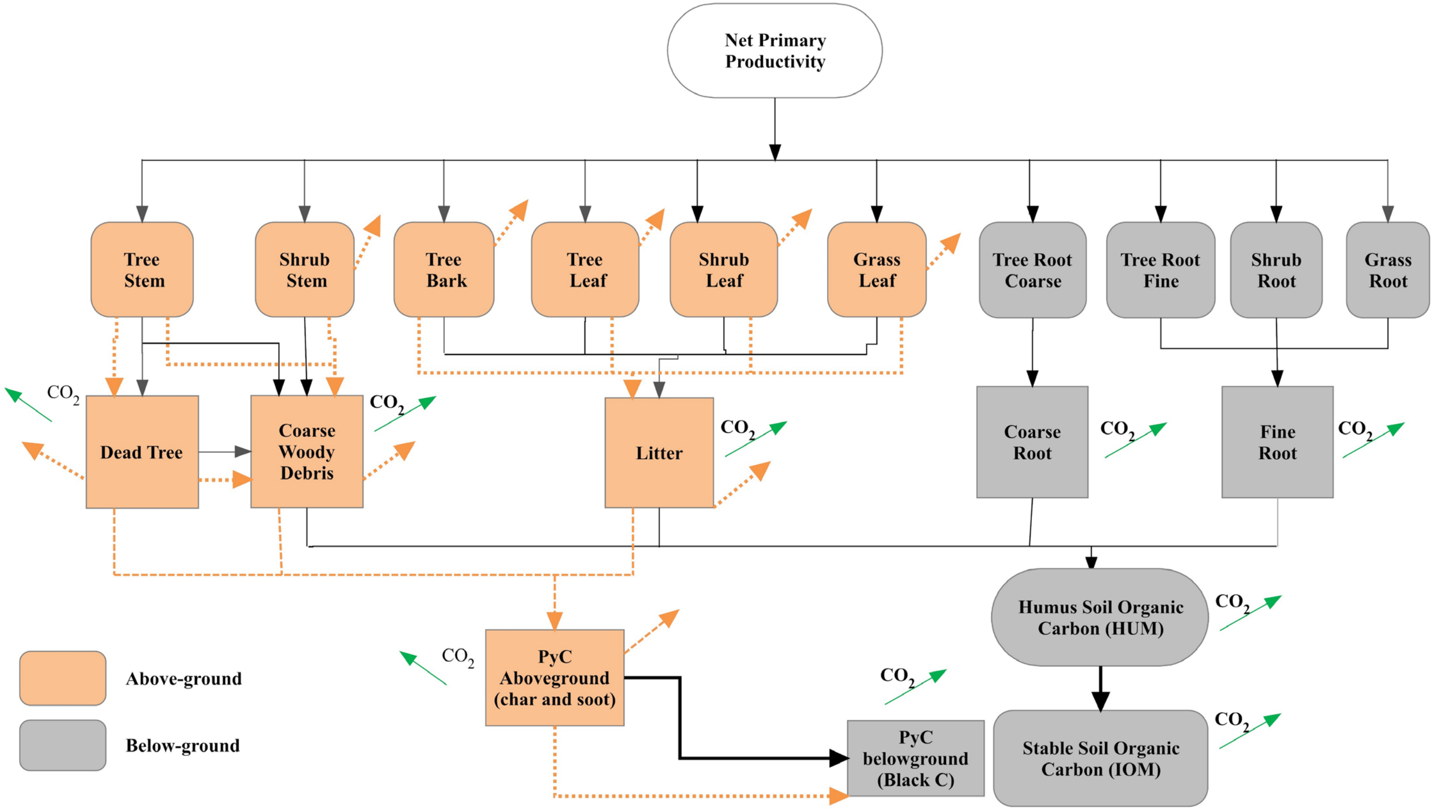
Parameters required for emission estimates

- **Tier 2: 4-7 parameters are required for emission factor estimates**

Parameter to estimate Emission Factor peat	**IPCC**	**Non-IPCC variant**	**FREL - Indonesia**
Peat Bulk Density	✓	✓	✓
Peat Carbon content		✓	✓
Depth of peat burnt	✓	✓	✓
Gas specific emission factor	✓	✓	
Combustion Factor	✓	✓	✓
Elemental to molecular mass ratio		✓	
N:C ratio		✓	
Total parameters	4	7	4

Tier 3 – approach Comprehensive carbon accounting model with a spatial module

- **> 100 parameters for C model**
- Better captures variability in C fluxes
- Can capture long term effects of land use and management
- Can address the transfer between biomass pools
- Better account of Activity data (area burnt)



Combustion Factor = the amount of organic matter combusted

Parameter to estimate EF peat	IPCC	Non-IPCC variant	FREL
Peat Bulk Density	✓	✓	✓
Peat Carbon content		✓	✓
Depth of peat burnt	✓	✓	✓
Gas specific emission factor	✓	✓	
Combustion Factor	✓	✓	✓
Elemental to molecular mass ratio		✓	
N:C ratio		✓	

New Combustion Factors

Science of the Total Environment 779 (2021) 146365

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journal homepage: www.elsevier.com/locate/scitotenv

ELSEVIER

Carbon balance of tropical peat forests at different fire history and implications for carbon emissions

Haruni Krisnawati [a], Wahyu C. Adinugroho [a], Rinaldi Imanuddin [a], Suyoko [b], Christopher J. Weston [c], Liubov Volkova [c,*]

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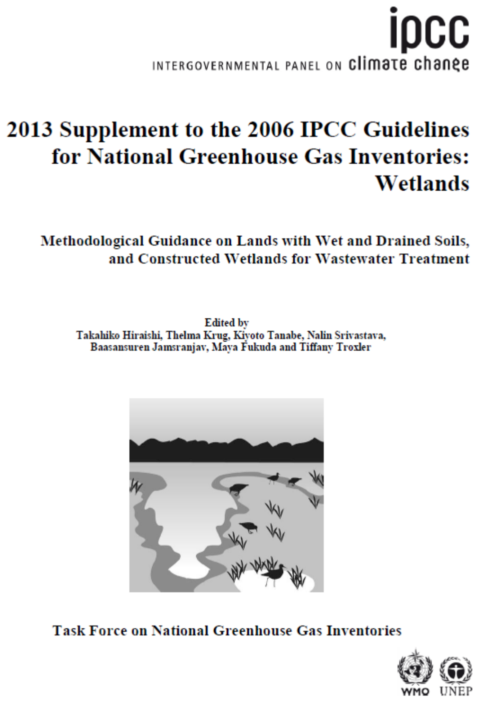
[b] The Sebangau National Park, Jl. Mahir Mahar Km 1.2 Palangka Raya, 73111, Indonesia
[c] School of Ecosystem and Forest Sciences, Faculty of Science, The University of Melbourne, Creswick, Victoria, 3363, Australia

Table 5
Combustion factors for aboveground and peat biomass.

Combustion factor	This study	IPCC default
CF_{AGC}[a]	0.564	0.50
$CF_{PEAT-10cm}$	0.399	1.0
$CF_{PEAT-20cm}$	0.469	1.0
$CF_{PEAT-30cm}$	0.540	1.0
$CF_{PEAT-40cm}$	0.610	1.0
$CF_{PEAT-50cm}$	0.681	1.0

Estimating peat fire emissions – IPCC method



Parameter to estimate EF peat	IPCC	Non-IPCC variant	FREL
Peat Bulk Density	✓	✓	✓
Peat Carbon content		✓	✓
Depth of peat burnt	✓	✓	✓
Gas specific emission factor	✓	✓	
Combustion Factor	✓	✓	✓
Elemental to molecular mass ratio		✓	
N:C ratio		✓	

Source: IPCC 2006, 1996, 2014

Gas specific emission factors G_i

Gas specific emission factors:

- Measured in the field
- Derived from the literature

C. E. Stockwell et al.: Field measurements of tropical peat fire emissions 11723

Table 1. Study-average emission factors ($g\,kg^{-1}$) and 1 standard deviation (stdev) for trace gases significantly elevated above background in Kalimantan peat fire plumes.

Compound (formula)	Study avg (stdev) 35 plumes
MCE	0.772 (0.035)
Carbon dioxide (CO_2)	1564 (77)
Carbon monoxide (CO)	291 (49)
Methane (CH_4)	9.51 (4.74)
Dihydrogen (H_2)	1.22 (1.01)
Acetylene (C_2H_2)	0.121 (0.066)
Ethylene (C_2H_4)	0.961 (0.528)
Propylene (C_3H_6)	1.07 (0.53)
Formaldehyde (HCHO)	0.867 (0.479)
Methanol (CH_3OH)	2.14 (1.22)
Formic acid (HCOOH)	0.180 (0.085)
Acetic acid (CH_3COOH)	3.89 (1.65)
Glycolaldehyde ($C_2H_4O_2$)	0.108 (0.089)
Furan (C_4H_4O)	0.736 (0.392)
Hydroxyacetone ($C_3H_6O_2$)	0.860 (0.433)
Phenol (C_6H_5OH)	0.419 (0.226)
1,3-Butadiene (C_4H_6)	0.189 (0.157)
Isoprene (C_5H_8)	0.0528 (0.0433)
Ammonia (NH_3)	2.86 (1.00)
Hydrogen cyanide (HCN)	5.75 (1.60)
Nitrous acid (HONO)	0.208 (0.059)
Hydrogen chloride (HCl)	0.0346 (0.0205)
Nitric oxide (NO)	0.307 (0.360)
Carbonyl sulfide (OCS)	0.110 (0.036)
DMS (C_2H_6S)	0.00282 (0.00234)
Chloromethane (CH_3Cl)	0.147 (0.057)
Bromomethane (CH_3Br)	0.0101 (0.0035)

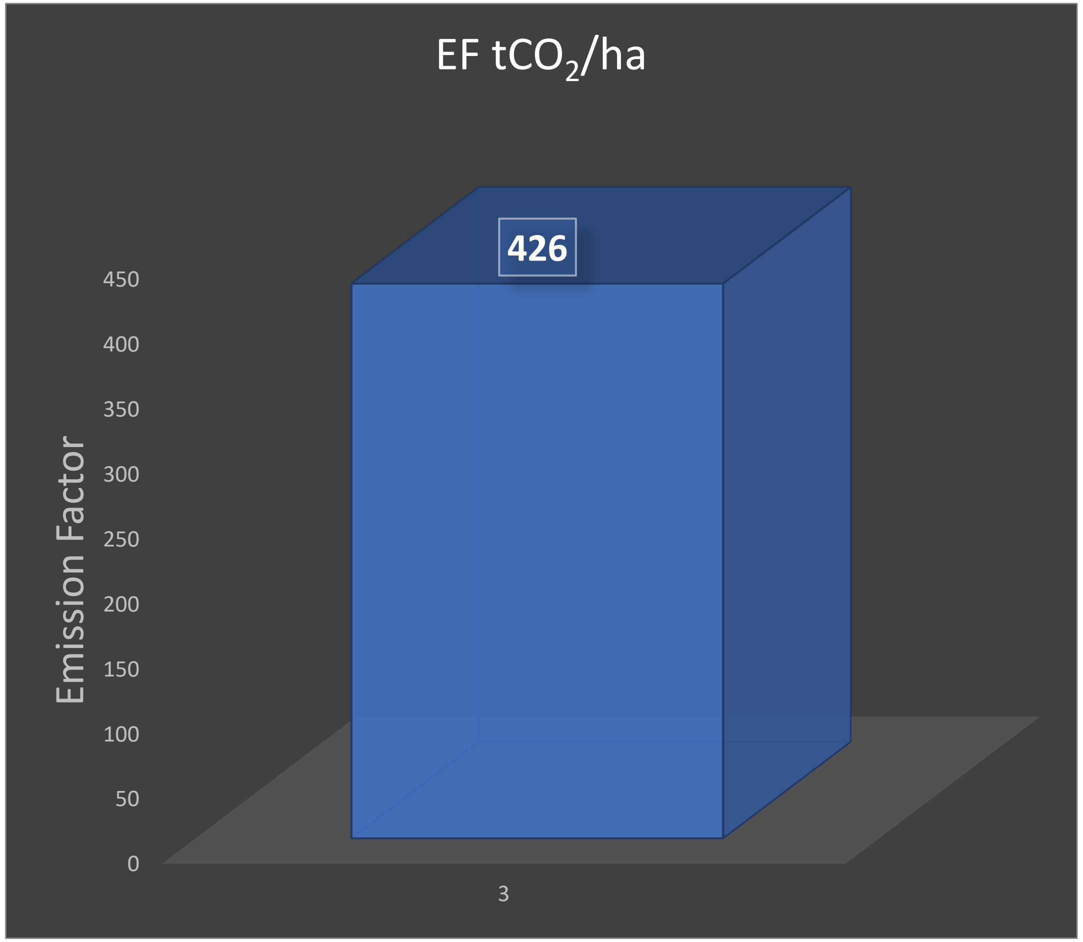
Table 1. Continued.

Compound (formula)	Study avg (stdev) 35 plumes
3-Methyl-1-butene (C_5H_{10})	0.0303 (0.0198)
2-Methyl-1-butene (C_5H_{10})	0.0299 (0.0161)
2-Methyl-2-butene (C_5H_{10})	0.0647 (0.0372)
2-Methyl-1-Pentene (C_6H_{12})	0.109 (0.076)
1,3-Pentadiene (C_5H_8)	0.0198 (0.0104)
1,3-Cyclopentadiene (C_5H_6)	0.00998 (0.00585)
Cyclopentene (C_5H_8)	0.0246 (0.0157)
1-Heptene (C_7H_{14})	0.0790 (0.0540)
1-Octene (C_8H_{16})	0.0652 (0.0424)
1-Decene ($C_{10}H_{20}$)	0.0498 (0.0388)
n-Hexane (C_6H_{14})	0.143 (0.087)
n-Heptane (C_7H_{16})	0.112 (0.074)
n-Octane (C_8H_{18})	0.0980 (0.0690)
n-Nonane (C_9H_{20})	0.0895 (0.0633)
n-Decane ($C_{10}H_{22}$)	0.0744 (0.0509)
2,3-Dimethylbutane (C_6H_{14})	0.00531 (0.00415)
2-Methylpentane (C_6H_{14})	0.0397 (0.0358)
3-Methylpentane (C_6H_{14})	0.00931 (0.00800)
Benzene (C_6H_6)	0.954 (0.394)
Toluene (C_7H_8)	0.370 (0.306)
Ethylbenzene (C_8H_{10})	0.0417 (0.0202)
m/*p*-Xylene (C_8H_{10})	0.122 (0.055)
o-Xylene (C_8H_{10})	0.103 (0.059)
Styrene (C_8H_8)	0.0271 (0.0131)
i-Propylbenzene (C_9H_{12})	0.00534 (0.00374)
n-Propylbenzene (C_9H_{12})	0.0118 (0.0082)
3-Ethyltoluene (C_9H_{12})	0.0270 (0.0228)
4-Ethyltoluene (C_9H_{12})	0.0235 (0.0213)
2-Ethyltoluene (C_9H_{12})	0.0416 (0.0335)
1,3,5-Trimethylbenzene (C_9H_{12})	0.0108 (0.0085)
1,2,4-Trimethylbenzene (C_9H_{12})	0.0696 (0.0552)

Estimating EF_CO_2 - peat layer IPCC method

$$EF\_CO2 = BD * h * CF * G_{EF\_CO2} * 10^{-3}$$

- Peat bulk density BD =0.153 g/cm3
- Depth burnt, h =33 cm
- Peat combustion factor, CF=0.54
- G_{EF_CO2} =1564 g/kg
- $E\_CO2=(0.153*33*100)*0.54*1564*10^{-3}=$ 426 tCO2/ha

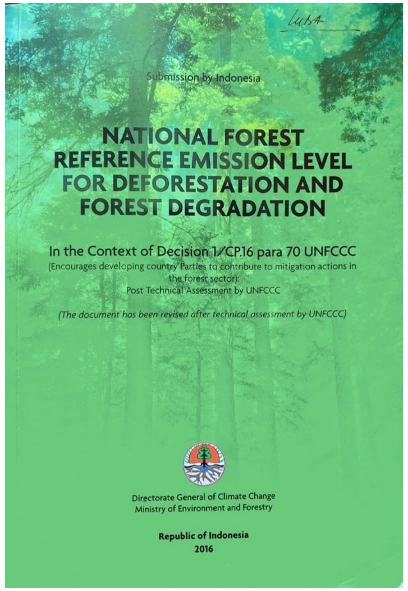


Estimating EF – country specific FREL

$$EF_{CO2} = \text{Bulk Density} \times \text{Depth burnt} \times CF \times \text{Carbon} \times 3.67$$

Method assumes that all emission is CO_2 – no need for gas specific emission factors

Parameter to estimate EF peat	IPCC	Non-IPCC variant	FREL
Peat Bulk Density	✓	✓	✓
Peat Carbon content	✗	✓	✓
Depth of peat burnt	✓	✓	✓
Gas specific emission factor	✓	✓	✗
Combustion Factor	✓	✓	✓
Elemental to molecular mass ratio		✓	
N:C ratio		✓	

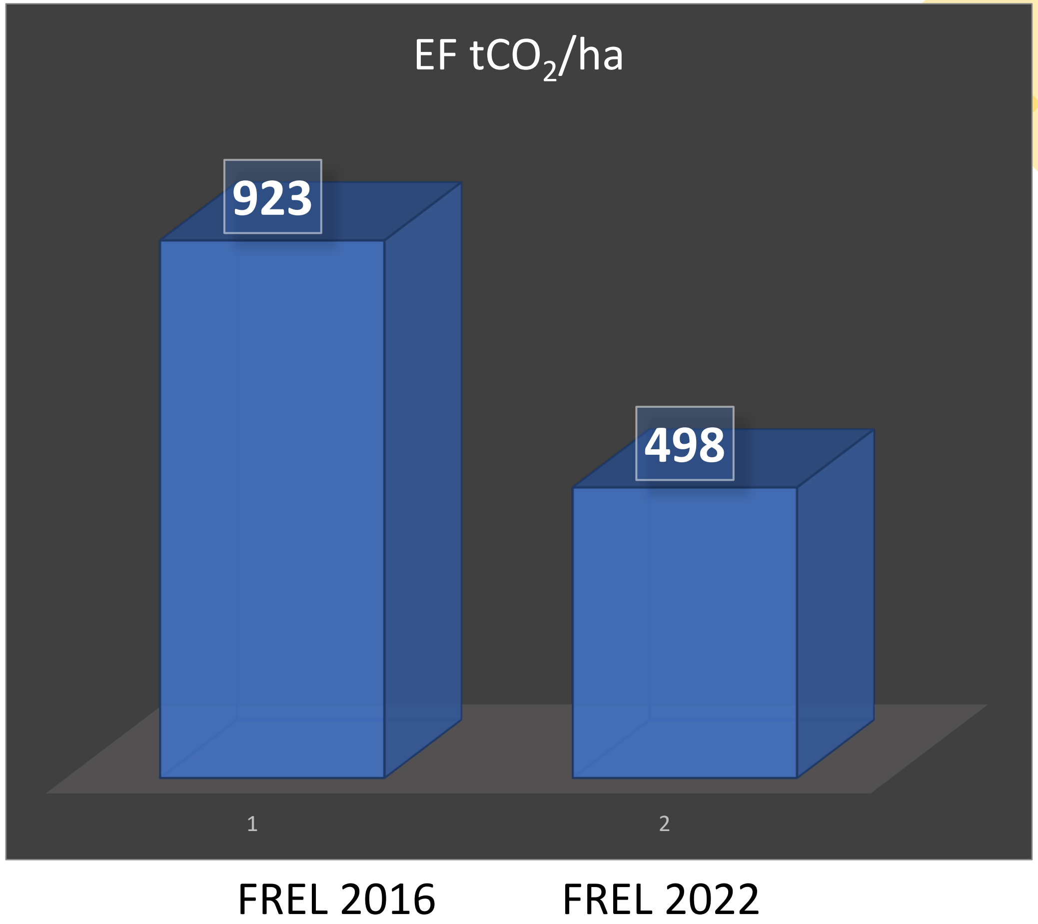


Source: FREL 2016

FREL 2016 & 2022

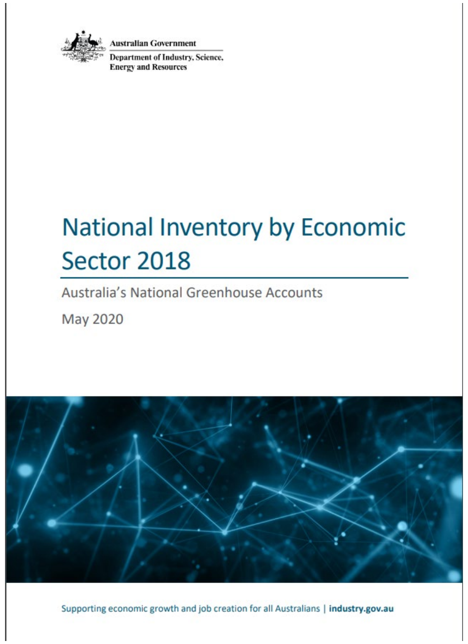
EF_CO_2 =BD* h * CF* G_{org}*$*3.67$

- 3.67 =C to CO2 conversion
- Peat bulk density, BD = 0.153 g/cm3
- Depth burnt, h = 33 cm
- CF = 1 (IPCC default) or 0.54 (new data)
- C_{org}=49.86%
- **EF_CO_2=0.153*33*49.86*3.67*1= 923 tCO_2/ha (FREL#1)**
- **EF_CO_2=0.153*33*49.86*3.67*0.54= 498 tCO_2/ha ↓45% (FREL#2)**



Estimating peat fire emissions – non-IPCC variant

More accurate but more complex - 7 parameters
Gas specific emission factors are in different units to the published for peat! Would require new measurements of GEF


Australian Government
Department of Industry, Science, Energy and Resources

National Inventory by Economic Sector 2018

Australia's National Greenhouse Accounts

May 2020

Supporting economic growth and job creation for all Australians | industry.gov.au

Parameter to estimate EF peat	IPCC	Non-IPCC variant	FREL
Peat Bulk Density	✓	✓	✓
Peat Carbon content		✓	✓
Depth of peat burnt	✓	✓	✓
Gas specific emission factor	✓	✓	
Combustion Factor	✓	✓	✓
Elemental to molecular mass ratio		✓	
N:C ratio		✓	

*Gas specific emission factors are in units of moles GHG/kg C not g/kg

Source: Aust Gov

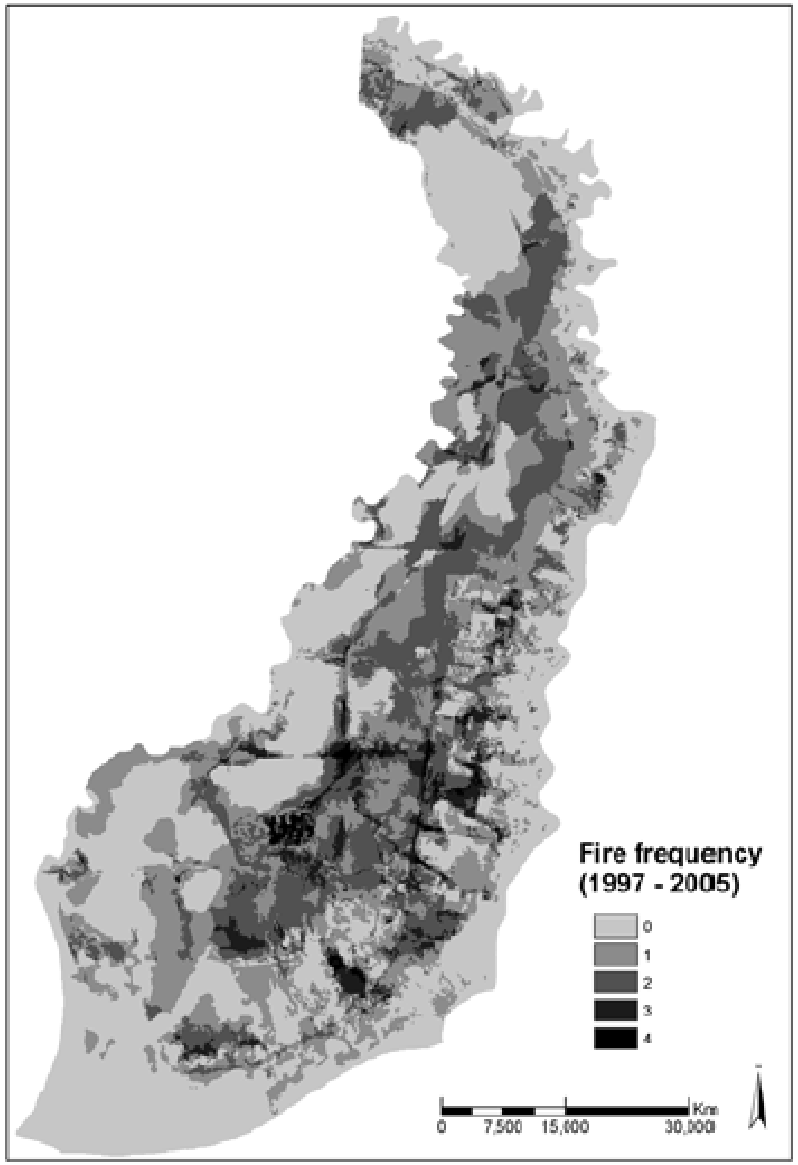
Emission by fire frequency

<u>FREL method</u>

- Emission estimates for second fire =1/2 emission from first fire
- For 3rd fire =1/2 of second fire….

<u>IPCC method and non-IPCC variant</u>

- Emission estimates for consecutive fires are INDEPENDENT from first fire emission estimates

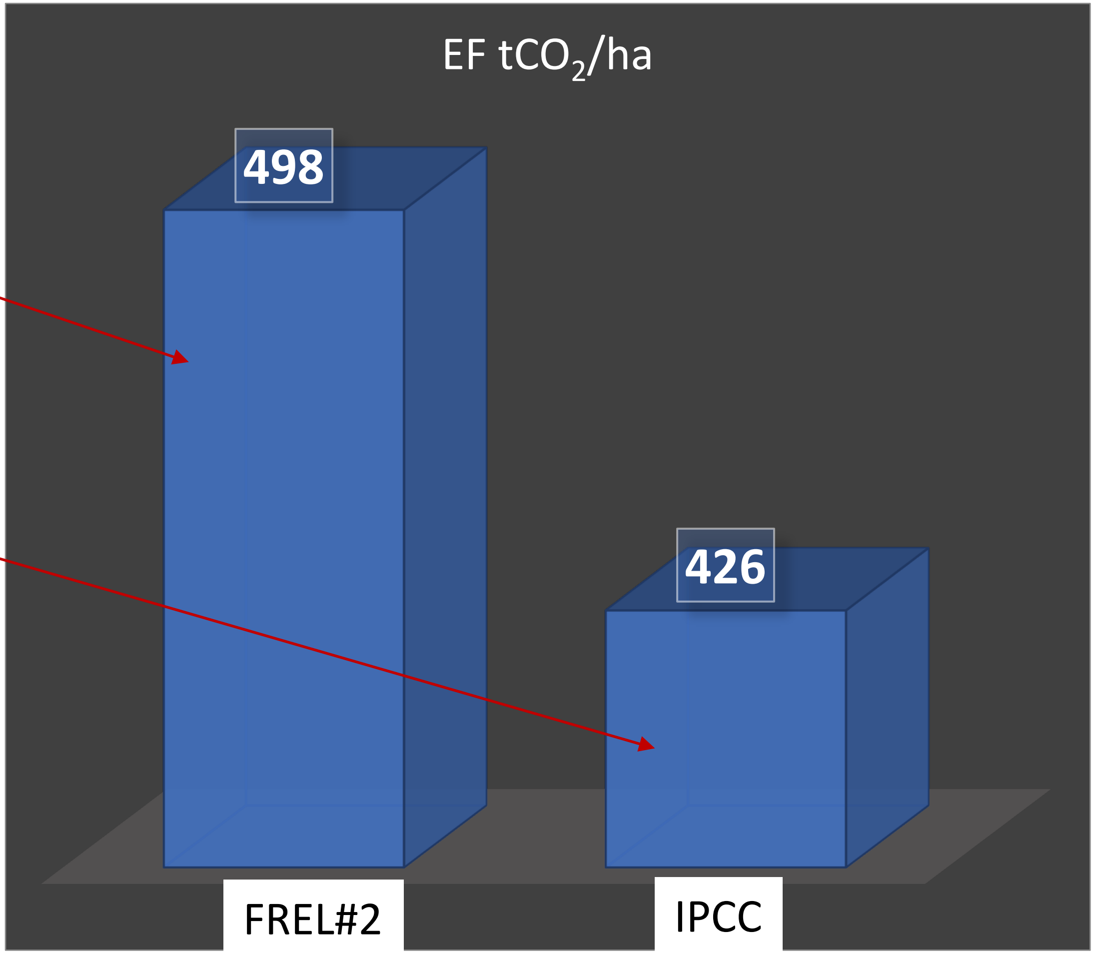


Cochrane et al 2009, Tropical Fire Ecology

What method is the best?

- FREL-Only possible to estimate CO2 emissions and only for peat layer

- IPCC - allows to estimate other GHG emissions for AG and peat



"...Non-Annex I Parties are encouraged, as appropriate, to provide information on anthropogenic emissions by sources of:

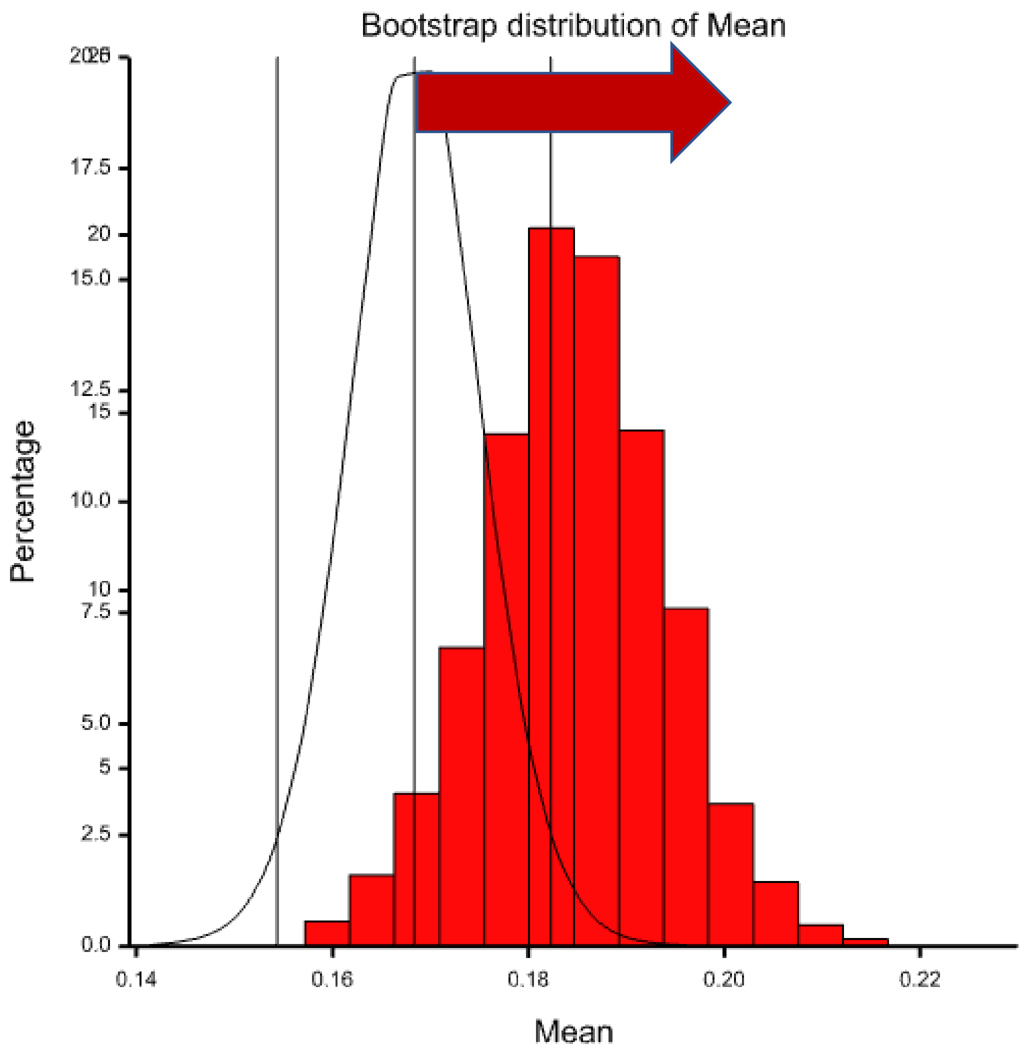
- CO_2; CH_4; N_2O
  - Decision 17/CP.8, annex, paragraph 14
- CO; NOx, NMVOCs
  - Decision 17/CP.8, annex, paragraph 16"

Parameter to estimate EF peat	IPCC	Non-IPCC variant	FREL
Peat Bulk Density	✓	✓	✓
Peat Carbon content		✓	✓
Depth of peat burnt	✓	✓	✓

Uncertainties in the estimates are important!

Peat bulk density; Peat Carbon content and Peat depth burnt change with fire frequency

Uncertainties - emission estimates are sensitive to changes in its parameters: peat Bulk Density



<u>Long unburnt forests</u>

Mean = 0.169

Median = 0.161

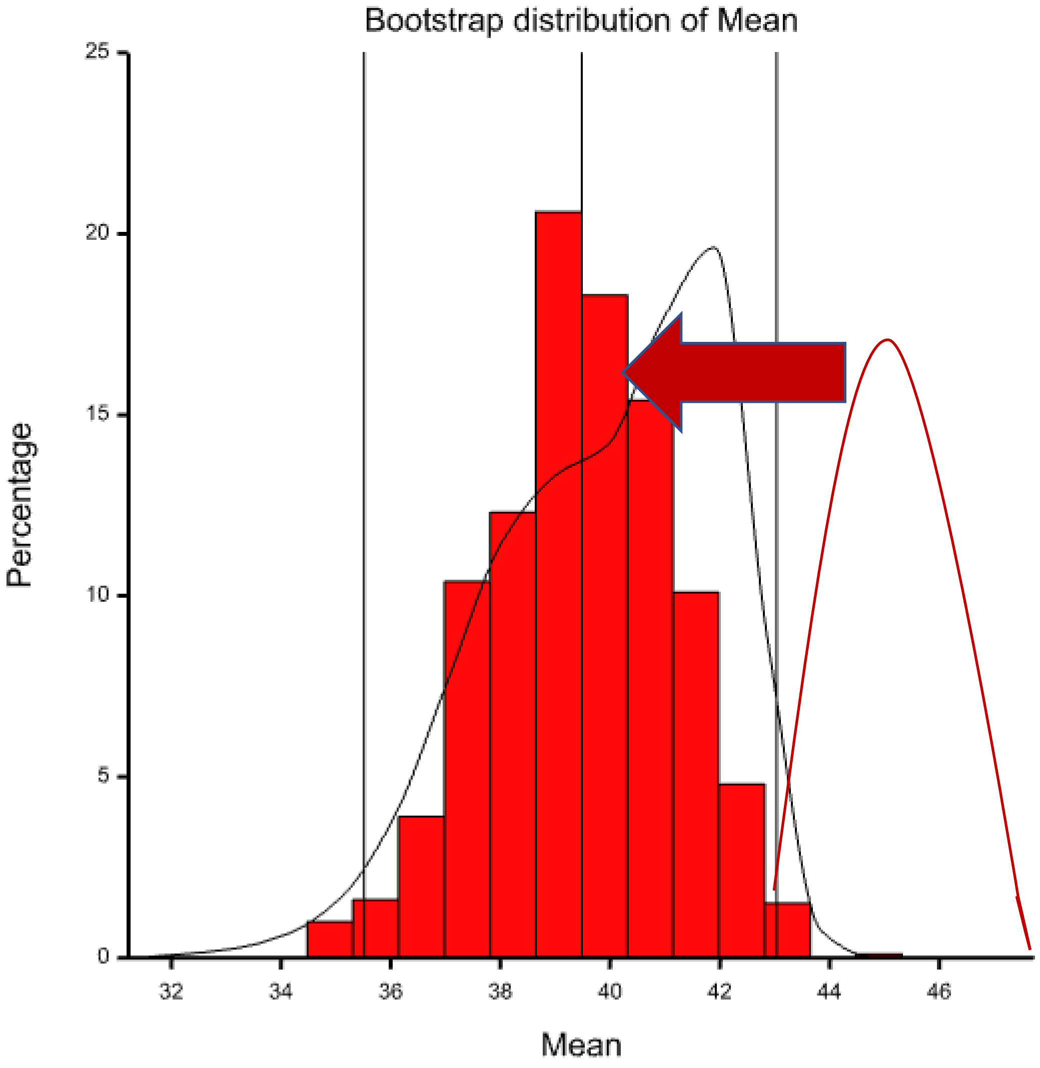
<u>Recurrently burnt forests</u>

Mean = 0.205

Median = 0.213

Peat bulk density increases ↑ with fire frequency

Uncertainties - emission estimates are sensitive to changes in peat Carbon content



Long unburnt forests

Mean = 48.57%

Median = 50.38%

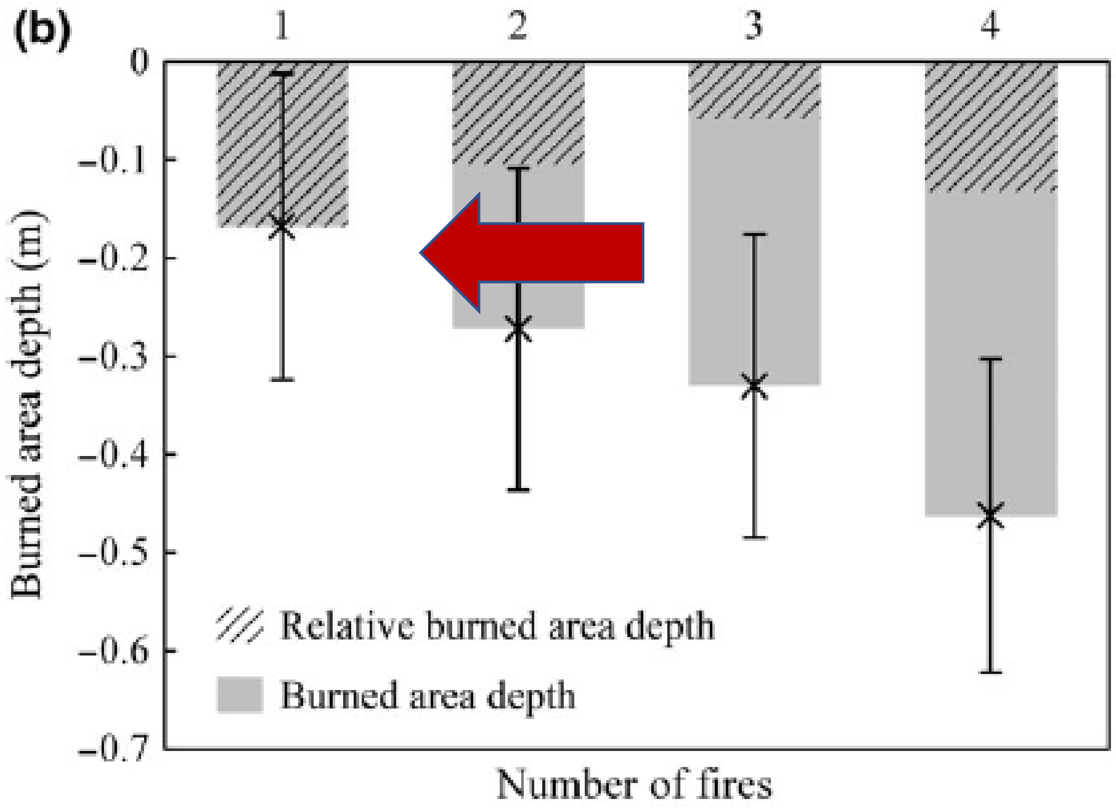
Recurrently burnt forests

Mean = 39.48%

Median = 44.77%

Peat C content decreases ↓ with fire frequency

Uncertainties - emission estimates are sensitive to changes in the depth of peat burnt



First fire = 17 cm

Second fire =10 cm

Third fire=6 cm

Or **33 cm** based on the Ballhorn et al 2009

Peat depth burnt decreases ↓ with fire frequency

Global Change Biology

Global Change Biology (2016), doi: 10.1111/gcb.13186

Variable carbon losses from recurrent fires in drained tropical peatlands

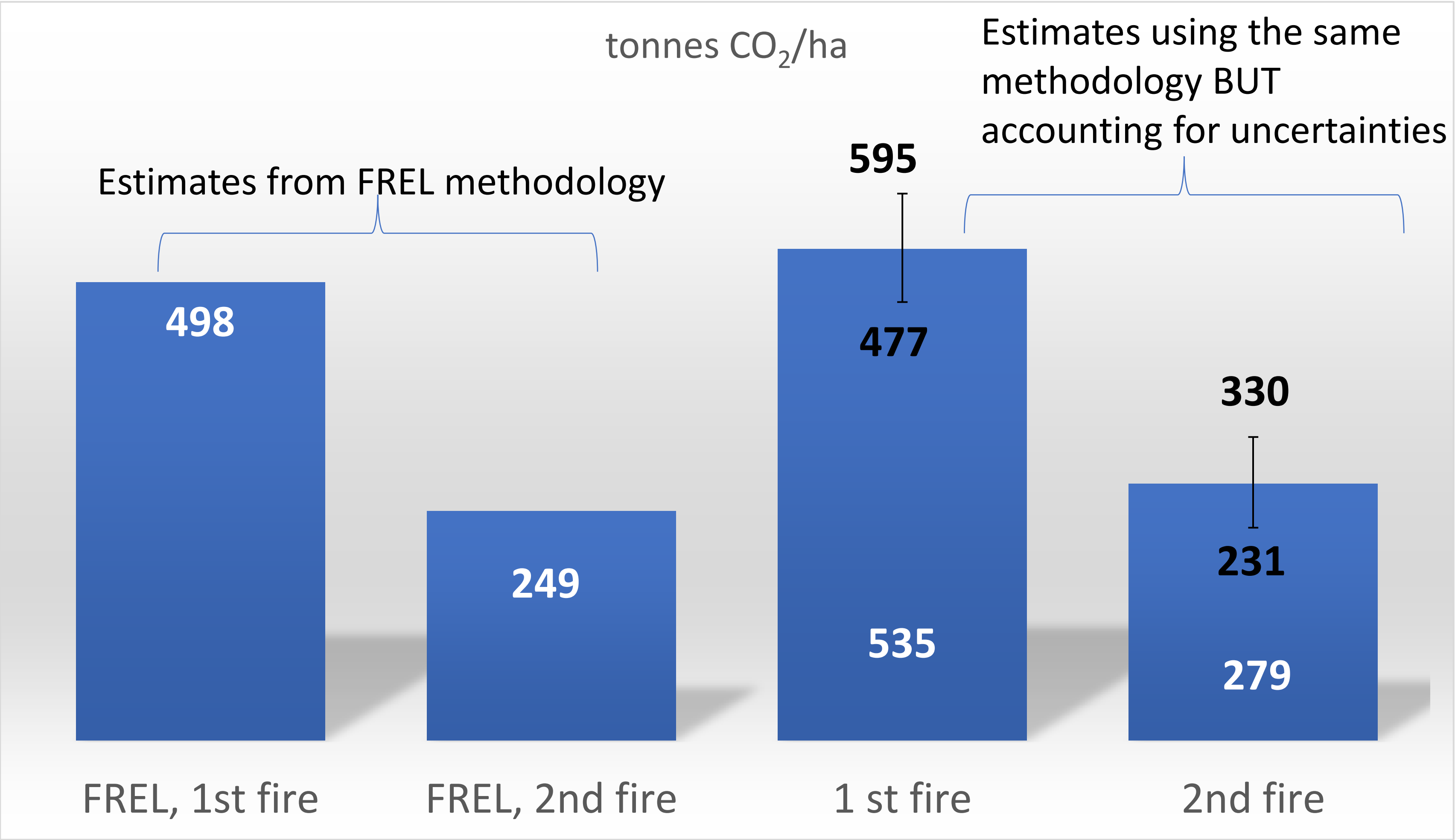
KRISTINA KONECNY[1,2], UWE BALLHORN[2], PETER NAVRATIL[2], JUILSON JUBANSKI[2], SUSAN E. PAGE[3], KEVIN TANSEY[3], ALJOSJA HOOIJER[4], RONALD VERNIMMEN[4] and FLORIAN SIEGERT[1,2]

[1]*Biology Department II, GeoBio Center, Ludwig-Maximilians-University, Grosshaderner Strasse 2, 82152 Planegg-Martinsried, Germany,* [2]*RSS Remote Sensing Solutions GmbH, Isarstr. 3, 82065 Baierbrunn, Germany,* [3]*Department of Geography, University of Leicester, Leicester LE1 7RH, UK,* [4]*Deltares, Rotterdamseweg 185, 2629 HD Delft, The Netherlands*

CO_2 emissions by fire frequency FREL method

Estimates account for:

- variable BD (mean max, min)
- variable C%
- Lower depth burnt in 2nd fire
- Lower CF for 2nd fire



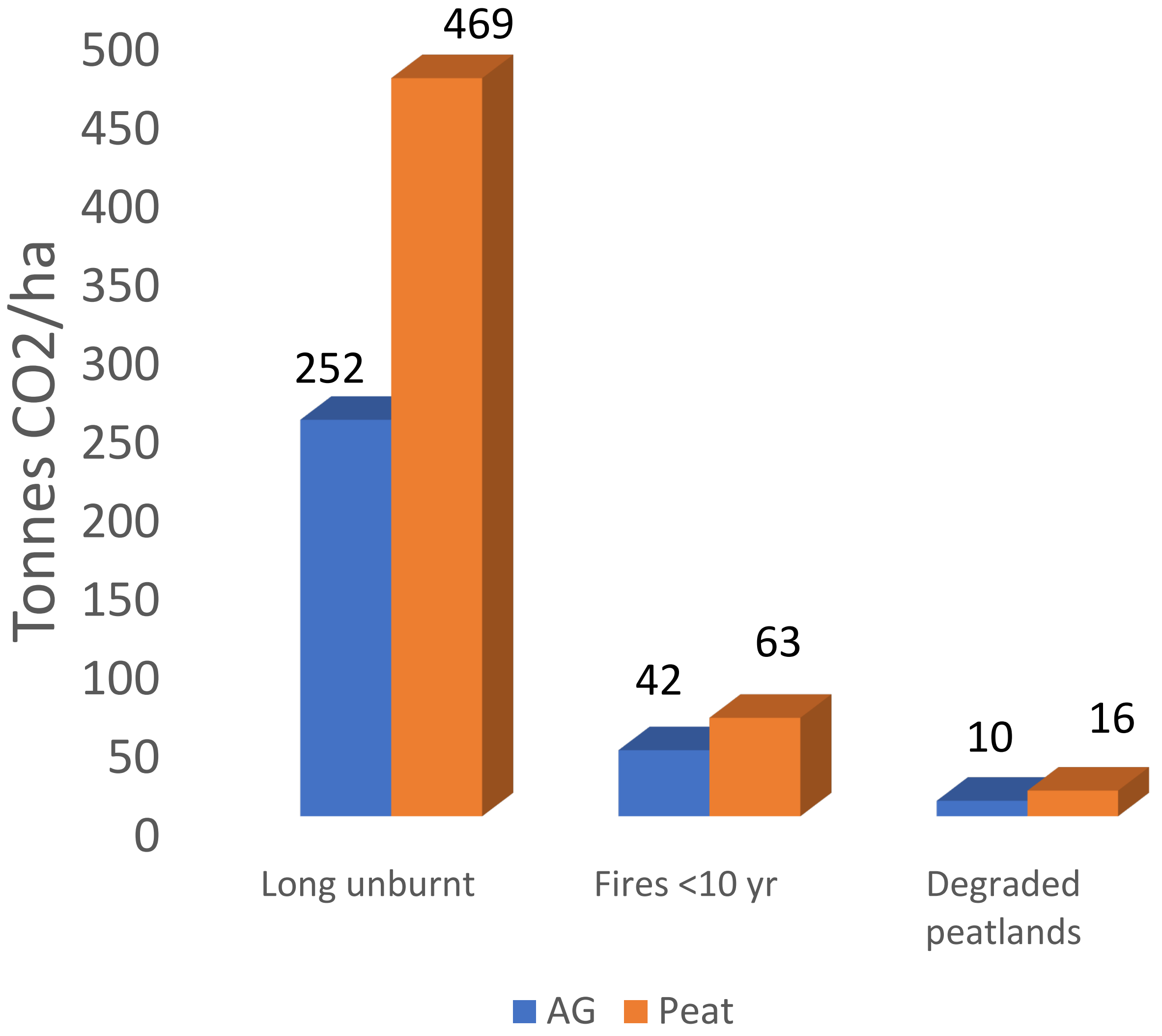
Drivers of emissions – Peat

- Burns in smoldering combustion
- Combusts up to 50 cm of peat in 1^{st} fire and less than 2 cm in 4+ fire
- Peat C recovery is subject to water table level, litterfall, temperature and takes centuries

Drivers of fire emissions – Above Ground Biomass

- Burns in flaming and smoldering combustions
- 50% of C remains as deadwood, chair
- <u>C recovery ~ 15 years</u>
- In degraded peatlands – emissions are mainly due to combustion of roots and shrubs – mainly smoldering emissions
- <u>C recovery ~3 years</u>

CO_2 emissions from aboveground (AG) biomass and peat by fire frequency using IPCC method



Group discussion at the end of the workshop 30 min

Q 1 – Most appropriate methodology for the emission reporting

Q 2 – Possible strategies for emission reduction

Q3 – Capacity building

Thank you

Annex 2

Burning Peat, Field trip September 2019


FORDA Banjarbaru


Zoom Meeting
Harum Krisnawati
Luba Volkova
Budi Harto
Wawan Gunawan
lenovo
T450