Experimental Results (2022), 3, e4, 1–9
doi:10.1017/exp.2022.2

EARTH AND ENVIRONMENTAL SCIENCE

NOVEL-RESULT

Evaluating *ex situ* rates of carbon dioxide flux from northern Borneo peat swamp soils

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(Received 18 September 2021; Revised 14 December 2021; Accepted 05 January 2022)

Abstract

This study quantified CO_2 emissions from tropical peat swamp soils in Brunei Darussalam. At each site, soil was collected from areas of intact and degraded peat and CO_2 flux, and total organic content were measured *ex situ*. Soil organic content (~20–99%) was not significantly different between intact and degraded forest samples. CO_2 flux was higher for intact forest samples than degraded forest samples (~1.0 vs. ~0.6 μmol CO_2 m^{-2} s^{-1}, respectively) but did not differ among forest locations. From our laboratory experiments, we estimated a potential emissions of ~10–20 t CO_2 ha^{-1} y^{-1} which is in the lower range of values reported for other tropical peat swamps. However, our results are likely affected by unmeasured variation in root respiration and the lability of resident carbon. Overall, these findings provide experimental evidence to support that clearance of tropical peat swamp forests can increase CO_2 emissions due to faster rates of decomposition.

Key words: Brunei Darussalam; LI-COR 6400; peatlands; soil respiration; tropical forests

1. Introduction

Although tropical peatlands cover only ~300,000–500,000 km^2 (Page et al., 2011), they are an important carbon store (~2% of global soil carbon; Sabine et al., 2004). Southeast Asia (SEA) contains a large area of tropical peatlands (248,000 km^2), storing up to 68.5 Gt of soil carbon or ~77% of the tropical peat carbon pool (Page et al., 2011). However, between 1990 and 2007, 51,000 km^2 of peat swamp forests in Peninsular Malaysia, Sumatra, and Borneo have been deforested and drained (Miettinen & Liew, 2010). The lowering of groundwater levels and increase in soil temperatures (Sano et al., 2010) have been found to increase CO_2 emissions from soil respiration (Hooijer et al., 2012). Decomposition of these drained peatlands release 355–855 Mt of CO_2 annually (Hooijer et al., 2010), contributing to global carbon emissions.

2. Objective

Recognizing the carbon losses from drained peat suggests that land clearance incurs a high "carbon debt" or "carbon payback time" (Danielsen et al., 2009). A small number of studies report higher soil CO_2 flux from drainage-affected peat swamp forests than deforested burnt peatlands (Jauhiainen et al., 2008), as well as oil and sago palm plantation sites (Melling et al., 2005), which provided evidence to support this proposition. Our goal was to provide additional estimates of CO_2 emissions associated with decomposition from degraded and intact peatland using soils collected in Northern Borneo.

3. Methods

Soil samples (3× per site—10 cm diameter, 10 cm depth) were collected from degraded and intact peat at four sites in July 2014 (Figure 1; Jaafar et al., 2017). Degraded sites had modified drainage and fire damage. Cores were sealed individually and transported to King's College London. CO_2 fluxes per core were measured using the LI-COR 6400-09. An airtight seal using a collar (10 cm diameter and 4.5 cm height) with 2.5 cm between the chamber bottom and peat was used. To avoid CO_2 build-up, 400 ppm and delta of 5 ppm were used; efflux was measured from the mean of five cycles (LI-COR, 2011). A subsample of peat was used for organic content. Two-way ANOVA was used to test for location and forest condition effects on CO_2 flux. Mann–Whitney was used for differences in organic content between forest conditions.

4. Results

Median CO_2 flux of intact peat (0.977 ± 0.167 μmol CO_2 m^{-2} s^{-1}) was greater than degraded peat (0.565 ± 0.085 μmol CO_2 m^{-2} s^{-1}; Figure 2). Among the four locations, Anduki had the lowest flux and

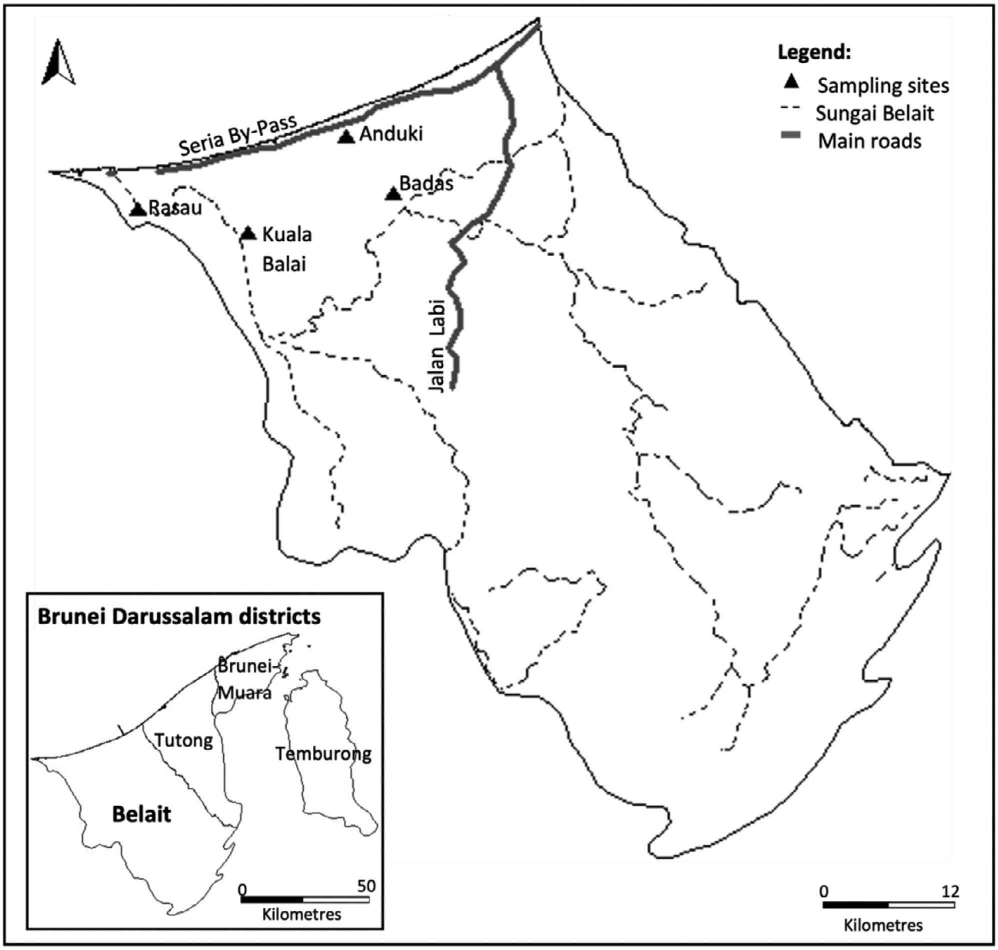

Figure 1. Location of peat sampling sites in the Belait District of Brunei Darussalam.

https://doi.org/10.1017/exp.2022.2 Published online by Cambridge University Press

Badas had the highest (~0.25 vs. ~0.8 μmol CO_2 m^{-2} s^{-1}; Figure 2). Forest condition was a significant effect for CO_2 flux ($p = .022$), but not location ($p > .05$) and there was no forest condition–location interaction ($p > .05$). Organic content (20–99%) was not significantly different between forest conditions ($p > 0.05$). However, Anduki sites had lower organic content and showed a more marked difference between intact and degraded samples. This may be due to Anduki being more similar to secondary forest than the other peat swamp locations (Jaafar et al., 2017). Regardless, CO_2 flux observed between forest types could not be attributed to differences in soil organic content (Figure 3).

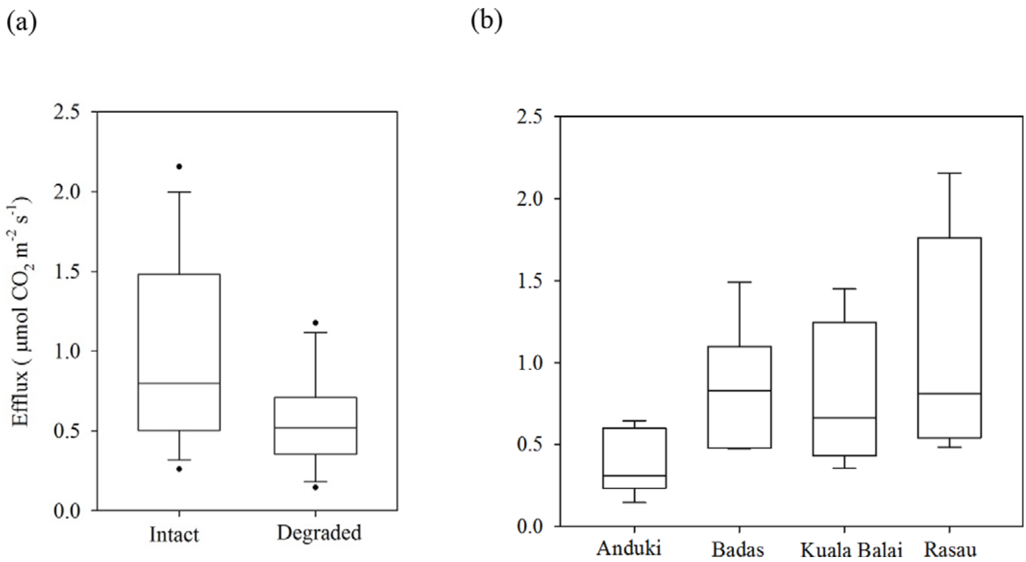

Figure 2. Boxplots of peat CO_2 flux by (a) forest condition ($n = 12$ for each condition) and (b) location ($n = 6$ for each location). Circles represent outliers. *$p < .05$; NS, not significant.

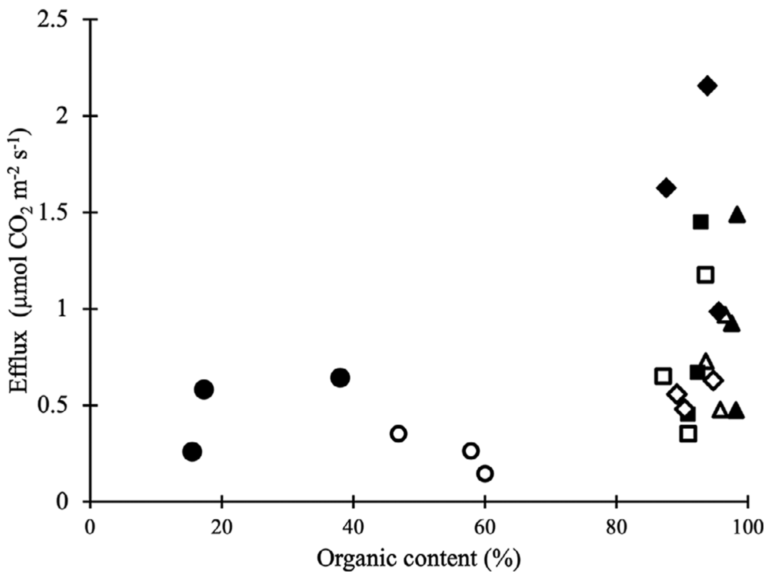

Figure 3. Scatterplot of peat CO_2 flux against soil organic content. Different symbols are used to represent the location (circle: Anduki; inverted triangle: Badas; square: Kuala Balai; diamond: Rasau) and condition (filled: intact; empty: degraded) of sampling sites.

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5. Discussion

We found lower emissions for degraded site compared to drainage-affected peat, oil palm, and Sago plantations (Melling et al., 2005) and from Kalimantan forests (Jauhiainen et al., 2008). These differences are expected because only emissions from peat and no other sources were measured in our lab-based estimates. Organic content for all sites were similar despite flux differences and this suggests more labile carbon at intact sites. One feature of our lab-based protocol is root respiration is eliminated and fluxes represent only decomposition. Nonetheless, *ex situ* measurement will vary from *in situ* values (Wang et al., 2005) and future field-based studies are needed.

6. Conclusions

These results provide evidence of higher CO_2 emissions from intact than degraded forests. We caution that this should not be interpreted as evidence suggesting intact peat swamp forests are greater contributors to CO_2 emissions than degraded lands. Rather, we suggest our findings provides empirical evidence to support the proposition that clearance of undisturbed peat swamp forests will incur a higher carbon debt for biofuel production than conversion of degraded forest sites (Danielsen et al., 2009), due to higher CO_2 emissions from peat decomposition.

Acknowledgments. The authors thank the Forestry Department of Brunei Darussalam and BioRIC for the entry permit and export permit respectively. Field assistance was provided by UBD undergraduates Khalish Hafizhah and Adrian Suhaili. Bruce Main (KCL) provided technical support in the lab. This research is in association with The International Consortium of Universities for the Study of Biodiversity and the Environment (iCUBE), a network of universities aimed at promoting collaborative research and education on biodiversity, climate change and the environment.

Funding Statement. This work was funded in part by the Department of Geography, King's College London, the Royal Geographic Society and the International Consortium of Universities for the Study of Biodiversity and the Environment (iCUBE).

Author Contributions. M.A.C., T.E.L.S., and R.S.S. designed the field experiments and collected the samples. E.L.Y.S.I. designed, planned, and conducted all of the lab work, data analysis, and wrote the first draft. All authors contributed to writing the final draft of this research.

Data availability Statement. All data are presented within the paper.

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Cite this article: Low Ying Si E, Chadwick MA, Smith TEL, Sukmaria Sukri R (2022). Evaluating *ex situ* rates of carbon dioxide flux from northern Borneo peat swamp soils. *Experimental Results,* 3, e4, 1–9. https://doi.org/10.1017/exp.2022.2

Peer Reviews

Reviewing editor: Dr. Bartosz Adamczyk
Natural Resources Institute Finland, Viikki, Helsinki, Finland, 00790

This article has been accepted because it is deemed to be scientifically sound, has the correct controls, has appropriate methodology and is statistically valid, and has been sent for additional statistical evaluation and met required revisions.

doi:10.1017/exp.2022.2.pr1

Review 1: Carbon dioxide flux from peat swamp soils in Brunei Darussalam, northern Borneo

Reviewer: Dr. Jonay Jovani Sancho

University of Nottingham, Nottingham, United Kingdom of Great Britain and Northern Ireland, NG7 2RD

Date of review: 18 November 2021

Conflict of interest statement. Reviewer declares none

Comments to the Author: This is an interesting and well presented manuscript investigation the CO2 emissions from intact and degraded peatlands in SE Asia. I have some, hopefully, minor concerns which are detailed below.

The title could include that this in a lab-based experiment.

Soil respiration is mentioned. Howoever, it would be more appropriate to focus on heteretrophic respiration because you don't have the root respiration component. Compare your results with results from heterotrophic respiration studies rather than total respiration.

It would be nice to define a hypothesis for your study. I found several similitudes between your findings and those from Cooper et al. 2020. For example, your samples from "intact forest" could represent the initial phase of conversion and your degraded peat samples could represent the mature oil palm plantation from such study. Your CO2 efflux was 0.4 umol/m2/s higher in the "intact" forest than in the degraded site and this is comparable to the 50% higher emissions found by the Cooper et al. study during the initial phases of peat swamp forest conversion. Your findings could support the hypothesis that conversion of peat swamp forests to other land uses result in higher CO2 emissions from heterotrophic respiration.

Provide more information about the degraded site (current land use and site-specific conditions)

Was the soil moisture content the same across all samples?)

Fig1. Add part of Peninsular Malaysia to the small map with the "Brunei Darussalam districts" so it is clearer where is located. Add a peatland layer (if available)

Fig3. CO2 seems to exponentially increases with OM. I wonder if it could be possible to fit an exponential regression. Would this be useful? If so, discuss.

Score Card

Presentation

4.4 /5

Is the article written in clear and proper English? (30%)	5/5
Is the data presented in the most useful manner? (40%)	5/5
Does the paper cite relevant and related articles appropriately? (30%)	3/5

Context

4.0 /5

Does the title suitably represent the article? (25%)	4/5
Does the abstract correctly embody the content of the article? (25%)	4/5
Does the introduction give appropriate context? (25%)	5/5
Is the objective of the experiment clearly defined? (25%)	3/5

Analysis

4.0 /5

Does the discussion adequately interpret the results presented? (40%)	4/5
Is the conclusion consistent with the results and discussion? (40%)	4/5
Are the limitations of the experiment as well as the contributions of the experiment clearly outlined? (20%)	4/5

https://doi.org/10.1017/exp.2022.2 Published online by Cambridge University Press

doi:10.1017/exp.2022.2.pr2

Review 2: Carbon dioxide flux from peat swamp soils in Brunei Darussalam, northern Borneo

Reviewer: Dr. Jon McCalmont

Date of review: 07 December 2021

Conflict of interest statement. Reviewer declares none

Comments to the Author: While the intention of the study is useful and may add to a growing literature, there is insufficient information in the methodology to judge the quality of the work. Specifically, there is no information on how the peat cores were handled, stored and prepared prior to flux measurements. No mention of the possible effects of different moisture conditions (which are highly correlated to fluxes). For example, were all samples controlled to the same moisture content to remove this effect in treatment comparisons or were interactions between sample moisture content and the other parameters (site, condition, organic content) considered? See http://doi.org/10.1016/j.geoderma.2018.02.029. If you do not accommodate moisture content in your testing, you cannot draw conclusions about site specific carbon (e.g. lability) on potential fluxes. The literature context provided is inadequate, for example, the newest reference in the introduction is around 10 years old. There have been many studies on tropical peat fluxes since 2012, see DOI: 10.1111/gcb.15147 (and supplementary dataset) for a literature range these results should be compared against. There is not enough information about the statistical testing, did results undergo any transformations prior to testing, were data normally distributed, etc. Only P values are given, F stats, df etc. are missing. Significance letters should be added to figures. Boxplots need detail about what they are showing, means/medians/definition of outliers? In general, this study may well be perfectly sound, but there is not enough information given to judge this so I can only recommend reject and re-submit with more detail.

Score Card

Presentation

3.1 /5

Is the article written in clear and proper English? (30%)	4/5
Is the data presented in the most useful manner? (40%)	4/5
Does the paper cite relevant and related articles appropriately? (30%)	1/5

Context

4.5 /5

Does the title suitably represent the article? (25%)	5/5
Does the abstract correctly embody the content of the article? (25%)	5/5
Does the introduction give appropriate context? (25%)	3/5
Is the objective of the experiment clearly defined? (25%)	5/5

Analysis

2.0 /5

Does the discussion adequately interpret the results presented? (40%)	2/5
Is the conclusion consistent with the results and discussion? (40%)	2/5
Are the limitations of the experiment as well as the contributions of the experiment clearly outlined? (20%)	2/5

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