Fluvial organic carbon fluxes reveal deep instability of deforested tropical peatlands

Sam Moore[1], Chris D. Evans[2], Susan E. Page[3], Mark H. Garnett[4], Tim G. Jones[5], Chris Freeman[5], Aljosja Hooijer[6], Andy Wiltshire,[7] Suwido H. Limin[8] and Vincent Gauci[1*]

[1] Centre for Earth, Planetary, Space and Astronomical Research (CEPSAR), Department of Environment, Earth and Ecosystems, The Open University, Walton Hall, Milton Keynes, MK7 6AA, UK.
*Author for correspondence (v.gauci@open.ac.uk).
[2] Centre for Ecology and Hydrology, Environment Centre Wales, Deiniol Road, Bangor, LL57 2UW, UK.
[3] Department of Geography, University of Leicester, University Road, Leicester, LE1 7RH, UK.
[4] Natural Environment Research Council Radiocarbon Facility, Rankine Avenue, Scottish Enterprise Technology Park, East Kilbride, G75 0QF, UK.
[5] School of Biological Sciences, Bangor University, Deiniol Road, Gwynedd, LL57 2UW, UK.
[6] Deltares – Delft Hydraulics, P.O. Box 177, 2600 MH Delft, The Netherlands
[7] Met Office Hadley Centre FitzRoy Road Exeter Devon EX1 3PB United Kingdom
[8] CIMTROP, University of Palangka Raya, Palangka Raya, Central Kalimantan, 73112, Indonesia.

Tropical peatlands contain one of the largest pools of terrestrial organic carbon (C), amounting to ~89,000 Tg[1] (1 Tg = 10^{12} g). Approximately 65% of this C store is located in Indonesia, where extensive anthropogenic degradation in the form of deforestation, drainage and fire are converting it into a globally significant atmospheric CO_2 source[1-3]. Here we quantify the annual export of fluvial organic C from both intact peat swamp forest (PSF) and PSF subject to past anthropogenic disturbance. We find that the total fluvial organic carbon (TOC) flux from disturbed PSF is ~50% larger than that from intact PSF. ^{14}C dating of the largest organic fraction of TOC, dissolved organic carbon (DOC, >91% of TOC) reveals that, while DOC leaching from intact PSF derives mainly from recent primary production, DOC from disturbed PSF is predominantly comprised of much older (centuries to millennia) C from deep within the peat column. Including the routinely-ignored fluvial C loss term in the C budget increases the estimate of total C lost from disturbed peatlands by 22%. We estimate that, since 1990, peatland disturbance has resulted in a 32% increase in fluvial organic C flux from Southeast Asia, an increase that alone, is more than half of the entire annual fluvial organic C flux from all European peatlands. Given the unprecedented levels of anthropogenic modification to tropical peatlands, our study highlights the risks to climate of continued peatland deforestation and underscores the need to properly quantify fluvial C losses if true estimates of the impact of deforestation and drainage on tropical peatland C balances are to be achieved.

Peatlands, by virtue of their high water-table and consequent low decomposition rates, form large carbon stores[4]. Southeast Asian PSFs currently experience extensive anthropogenic degradation in the form of deforestation, drainage and associated fire, all of which are converting C stored in peat into atmospheric CO_2 via either direct combustion or through oxidation within the peat column[2,3]. Unlike boreal and temperate forests[5,6], and higher latitude wetlands[7], however, the loss of fluvial organic carbon from tropical peats has yet to be fully quantified.

To quantify the effect of peatland degradation on fluvial organic C loss, we monitored DOC and particulate organic C (POC) concentrations and water discharge rates from channels draining areas of both intact and disturbed PSF in a portion of Central Kalimantan (Indonesia, Borneo) affected by

severe deforestation, drainage and fire associated with the implementation of the Mega Rice Project (MRP). Initiated in 1995, the MRP was a failed agricultural development project which aimed to convert one million hectares of peatland into rice fields[8]. We selected three PSF land-cover classes that differed in their recent disturbance history, located in or near to the Sebangau River basin (Fig. S1; Supplementary): (1) intact PSF (IPSF) (3 channels in the Sebangau forest), (2) moderately drained disturbed PSF (DPSF1) (2 channels in Tubangnusa) and (3) severely drained disturbed PSF (DPSF2) (3 channels in Kalampangan). All DPSF catchments to the east of the Sebangau River were comprised of lowland PSF of similar topography, peat thickness and vegetation to IPSF prior to the MRP disturbance[9], and experienced similar annual rainfall (Table 1).

TOC (DOC+POC) fluxes were monitored from each channel outlet at weekly intervals from June 2008 to May 2009. Results demonstrate larger mean annual TOC fluxes in both DPSF1 and DPSF2 (105 and 88 g C m^{-2} yr^{-1}, respectively) than in IPSF (63 g C m^{-2} yr^{-1}; Fig. 1). This represents a 55% increase in TOC export from the disturbed sites (DPSF1 and 2) over IPSF. Of the annual TOC flux from each land-cover class, 94% was lost during the wet season (October-June), the result of higher measured discharge rates (3.9 m^3 s^{-1} cf. 1.0 m^3 s^{-1} in the dry season). This was associated with high rainfall rather than changes in C concentration, which remained relatively constant over the study period. As with seasonal flux variability, differences in discharge between land-cover classes determined TOC flux with higher discharge rates causing larger fluxes in DPSF1 and DPSF2 (1744 mm and 1724 mm, respectively) than in IPSF (907 mm). These higher discharge rates in disturbed land-cover classes were not counterbalanced by lower TOC concentrations, and occurred despite uniform rainfall across sites (Table 1). This likely reflects a decline in evapotranspiration and increased runoff as a consequence of large scale biomass loss and drainage in both disturbed land-cover classes. DOC accounted for between 91-98 % of the TOC lost, with lower DOC:POC ratios for disturbed sites (Table 1) suggesting that the drained and exposed peat is vulnerable to mechanical breakdown associated with the increased runoff.

Surface water DOC can derive from multiple sources, ranging from recent photosynthates to decomposition or dissolution products from deep within the peat column. We used radiocarbon (^{14}C) measurements to evaluate whether increased fluvial C loss from disturbed sites was due to increased inputs of fresh material or the result of destabilisation and loss from peat that had been accumulating since the Last Glacial Maximum[10]. Previous DO^{14}C measurements from waters draining intact, peat-dominated catchments in North America[11], Siberia[12] and Europe[13,14] commonly show enrichment of DOC with 'bomb' carbon (associated with above-ground nuclear testing in the 1950s-60s), suggesting that the bulk of DOC leached from these systems is of recent origin probably dominated by C fixed from the atmosphere within the last 1-10 years[15]. This implies that DOC export does not represent a major loss pathway for long-term stored carbon[14]. However, none of these studies specifically examined disturbed (e.g. deforested and drained) peatlands, and to our knowledge no measurements of DO^{14}C from tropical peatlands, either pristine or disturbed, have previously been reported.

We collected samples for DO^{14}C analysis from all sites at which we determined TOC fluxes, in August 2008 (dry season) and May 2011 (wet season). Significant between-land-cover class differences were observed during both seasons (Fig. 1; Table 2). DOC lost from intact PSF was ^{14}C-enriched in both seasons (average of 110-108% modern). If all C in these samples is assumed to be of post-bomb origin[15], this ^{14}C signature can be reproduced by a simple model with >99% of DOC deriving from C

fixed from the atmosphere within the last 50 years (Fig. 2c). In contrast, DOC from channels draining disturbed land-cover classes was ^{14}C-depleted, ranging from 98.9-75.5% modern (equivalent to ^{14}C ages of 92-2260 years BP). This ^{14}C depletion was observed in both dry and wet season samples. These data indicate that the increased DOC fluxes from disturbed peatlands are derived from previously stable C stored within the peat column, and suggest that this loss of C from depth is occurring throughout the seasonal hydrologic cycle. Application of an age attribution model (Fig. 2d) suggests that two-thirds of DOC in runoff from the DPSF2 site derives from peat carbon of 500-5000 years age.

We also measured DO[14]C from two channels draining oil palm plantations in Peninsular Malaysia that were previously PSF. Approximately 28,000 km^2 of industrial plantations are found in Peninsular Malaysia, Sumatra and Borneo[16], making them a major contributor to PSF deforestation in the region. These samples had even lower DO[14]C levels of 59% and 67% modern, corresponding to mean ages of 4180 and 3180 years BP respectively (Table 2). To our knowledge, these are among the oldest surface water DO[14]C measurements ever reported. We do not have comparable TOC flux data from these sites, although we note that measured concentrations at the time of sampling were lower than in Borneo (Table 2), and that these had fallen markedly from our initial measurements at the site in 1995 (48.8 and 64.3 mg l^{-1} for IPSF and DPSF sites respectively). Our findings demonstrate that destabilisation of the peat column at depth is responsible for the increases in organic C fluxes we observe from disturbed PSF. These large fluvial losses of old peat-derived C play an important role in altering the C balance of such ecosystems, yet because they are assumed to be small in comparison to gross primary productivity and ecosystem respiration, they are seldom measured. While measurements of net ecosystem exchange (NEE) for intact PSF are rare, we have a peat core derived C accumulation rate estimate of 94 g C m^{-2} yr^{-1} from the IPSF[17] site (Fig. 2a). Including our fluvial C loss estimate of 63 g C m^{-2} yr^{-1}, this suggests an approximate gaseous exchange (NEE) of -157 g C m^{-2} yr^{-1} for IPSF. Measured NEE within our DPSF sites is +433 g C m^{-2} yr^{-1} [(18)] which results in an increased net ecosystem C balance (NECB) of 530 g C m^{-2} yr^{-1} (net C loss), when including our intermediate DPSF fluvial C loss estimate (97 g C m^{-2} yr^{-1}, the mean value for DPSF1 and 2). Thus, including fluvial C losses resulted in a 22% higher estimate of C loss from this disturbed site than was previously inferred from gaseous exchange measurements alone.

Applying our calculated TOC fluxes of 63 g C m^{-2} yr^{-1} for intact PSF and our intermediate value of 97 g C m^{-2} yr^{-1} for disturbed PSF, we estimate the annual TOC loss from the Sebangau basin (5,200 km^2) to be 0.41 Tg yr^{-1}. This is within 10% of a basin scale TOC loss estimate (0.46 Tg yr^{-1}) for the River Sebangau[19] obtained during our study period. The broad agreement in flux estimates derived over contrasting scales gives us confidence that our calculated flux estimates for sub-catchments are representative of fluxes occurring at larger scales.

To quantify the impact peatland disturbance has had on regional long-term fluvial C loss, we applied our TOC flux estimates to land areas of intact and deforested PSF prior to and after peatland disturbance. We omitted industrial plantations from our calculations as, to our knowledge, there are no quantitative data on fluvial C flux from this land cover class, although our DO[14]C data suggest that these ecosystems may also be highly unstable due to land-use change. We estimate that since 1990, the conversion of intact PSF into disturbed peatland has resulted in around a 45% increase in the fluvial TOC flux, from 4.7 Tg C yr^{-1} to 6.8 Tg C yr^{-1} in Borneo, Sumatra and Peninsular Malaysia, and a 32% (2.4 Tg C yr^{-1}) increase across the whole of SE Asia (Table 3). This increase alone is more than

1 half the entire annual European peatland fluvial organic C flux (4.3 Tg C yr^{-1}; estimated using
2 European peatland area of 292,000 km^2 [20] and an average fluvial C flux estimate of 14.6 g C m^{-2} yr^{-1}
3 [21,22]). Given the exclusion of peatland converted to plantations in our calculations, our estimated
4 increase in regional fluvial organic C flux should be considered conservative.

5 The eventual fate of this additional fluvial carbon loss remains to be fully characterised, but it is
6 known from other studies that the majority of DOC is processed and emitted to the atmosphere as
7 CO_2 and/or CH_4 through biotic decomposition in aquatic systems[23,24] and that in other, less perturbed
8 catchments in the humid tropics, evaded CO_2 originates from the degradation of terrestrially-derived
9 organic C[25]. It has also been shown that old terrestrially-derived organic matter is biologically
10 processed in both rivers and estuaries[26]. Our analysis of the relative aromaticity of the DOC, (an
11 indicator of the recalcitrance of organic C within the sample as derived by specific UV absorbance
12 (SUVA); Table 2) suggests no significant difference in the relative lability of both young and old DOC
13 leaching different land cover classes. We therefore expect that much of the additional, old fluvial
14 carbon loss will be converted to CO_2 in the aquatic system, indirectly adding to greenhouse gas
15 emissions from the disturbed sites.

16 Our data show that drainage of tropical peat leads to destabilisation and an ongoing collapse of its C
17 store, resulting in the hitherto overlooked yet quantitatively important release of C via fluvial organic
18 pathways. Our findings emphasise the need to include these fluxes in models which seek to quantify
19 the impact of disturbance on the peatland C balance, and in the emission factors used by the
20 Intergovernmental Panel on Climate Change[27]. Given that the oil palm biofuel industry contributes to
21 regional forest destruction, our findings highlight, in the United Nations International Year of
22 Sustainable Energy for All, that it is essential to incorporate fluvial organic carbon losses within
23 guidelines for the measurement, reporting and verification of carbon emissions under the UN REDD
24 programme. On current understanding, such omissions may undervalue the benefits to SE Asian
25 nations of maintaining and restoring the peatland C sink function[28].

26

27 **Methods Summary**

28 DOC and POC samples were collected and discharge measurements taken at weekly intervals for two 12 week
29 periods during the peak of the dry and wet seasons (Dry season; June - August 2008, Wet season; February -
30 May, 2009) and fortnightly for the remaining weeks in the year, totalling 38 weeks. 2008 was unexceptional
31 with respect to fire incidences and climate, being neither an El Niňo nor La Niňa year. For the remaining weeks,
32 samples were collected and discharge data were inferred from rainfall data (via catchment-specific
33 relationships between weekly rainfall data and discharge data). Five replicate flow rates and water samples
34 were collected from each catchment outlet, representing the drainage channel cross-sectional area. Samples
35 were collected in pre-rinsed 60ml Nalgene® bottles and water temperature, pH and electrical conductivity (EC)
36 were recorded immediately after collection using portable pH (Hanna HI9024D) and EC (Hanna HI8633) meters.
37 To derive POC concentration, a known volume of river water was filtered using pre-rinsed 0.45μm cellulose
38 acetate membrane filters (Whatman®) under partial vacuum (Mityvac, Nalgene®). The residue and filter were
39 retained and oven dried (24 hours at 40°C) to quantify particulate matter, assumed equal to particulate organic
40 matter (POM) given the dominance of peat soil in the catchment. POM was converted to POC assuming a 50%
41 carbon content[29]. Samples of filtrate were acidified to pH 2.0 with dilute sulphuric acid (20%), stored at ~2°C
42 and analysed upon return to the UK. DOC was determined using a Total Organic Carboniser (Shimadzu, TOC-
43 V$_{CPN}$) following the non-purgeable organic carbon (NPOC) method. DOC/POC concentrations were then
44 combined with discharge rates to calculate the TOC flux from each of the catchments. The analysis,
45 interpretation and age attribution of DO^{14}C data are described in the Supplementary Information. UV-visible

absorbance measurements were performed on a Molecular Sciences plate reader (model M2e) and a Milli-Q blank reading was taken to subtract from each sample. A quartz cell with 1.0 cm path length was used.

Author contributions

V.G., S.E.P. and C.D.E. conceived and led the research conducted in Kalimantan. S.M., V.G., S.E.P. and C.D.E. designed the study and S.M. performed all the Kalimantan field data collection and analysis. C.D.E. and M.G. coordinated, analysed and interpreted the radiocarbon component of the work. S.M., V.G. and S.E.P. performed the up-scaling calculations. C.F. conceived and led the Malaysian study, T.J. performed the field data collection and analysis, A.H. provided hydrological data and interpreted land surface information to allow catchment definition. A.W. provided modelled estimates of evapotranspiration. S.L. provided expertise on history of land-cover change and field site selection. S.M., V.G., S.E.P. and C.D.E. led the writing of the paper. All authors discussed results and commented on the manuscript.

References

1. Page, S.E., Rieley, J.O. & Banks, C.J. Global and regional importance of the tropical peatland carbon pool. *Global Change Biol.* **17**, 798-818 (2011).

2. Page, S.E. *et al.* The amount of carbon released from peat and forest fires in Indonesia during 1997. *Nature* **420**, 61-65 (2002).

3. Hooijer, A. *et al*. Current and future CO_2 emissions from drained peatlands in Southeast Asia. *Biogeosciences* **7**, 1505-1514 (2010).

4. Gorham, E. Northern peatlands: Role in the carbon cycle and probable responses to climatic warming. *Ecol. Appl.* **1**, 182-195 (1991).

5. McDowell, W.H. & Likens, G.E. Origin, composition and flux of dissolved organic carbon in the Hubbard Brook valley. *Ecol. Monogr.* **58**, 177–195 (1988).

6. Michalzik, B., Kalbitz, K., Park, J.H., Solinger, S. & Matzner, E. Fluxes and concentrations of dissolved organic carbon and nitrogen - a synthesis for temperate forests. *Biogeochemistry* **52**, 173–205 (2001).

7. Mulholland, P.J. & Kuenzler, P.J. Organic carbon export from upland and forested wetland watersheds. *Limnol. Oceanogr.* **24**, 960-966 (1979).

8. Hooijer, A., Van der Vat, M., Prinsen, G., Vernimmen, R., Brinkman, J. J., & Zijl, F., 2008. Hydrology of the EMRP Area – Water Management Implications for Peatlands, Technical Report Number 2 of the Master Plan for the Rehabilitation and Revitalisation of the Ex-Mega

Rice Project Area in Central Kalimantan. Euroconsult Mott MacDonald and Deltares, Delft Hydraulics.

9. Hoscilo, A., Page, S.E., Tansey, K.J. & Rieley, J.O. Effect of repeated fires on land-cover change on peatland in southern Central Kalimantan, Indonesia, from 1973 to 2005. *Int. J. Wildland Fire* **20**, 578-588 (2011).

10. Limpens, J. *et al*. Peatlands and the carbon cycle: from local processes to global implications – a synthesis. *Biogeosciences* **5**, 1475-1491 (2008).

11. Schiff, S. L. *et al*. Export of DOC from forested catchments on the Precambrian Shield of central Ontario: Clues from ^{13}C and ^{14}C, *Biogeochemistry* **36**, 43– 65 (1997).

12. Benner, R., Benitez-Nelson, B., Kaiser, K., & Amon R.M.W. Export of young terrigenous dissolved organic carbon from rivers to the Arctic Ocean, *Geophys. Res. Lett.* **31**, L05305, doi:10.1029/2003GL019251 (2004).

13. Palmer, S.M. *et al*. Sources of organic and inorganic carbon in a headwater stream: Evidence from carbon isotope studies, *Biogeochemistry* **52**, 321-338 (2001).

14. Evans, C.D. *et al*. Evidence against recent climate-induced destabilisation of soil carbon from ^{14}C analysis of riverine dissolved organic matter. *Geophys. Res. Lett.* **34**, L07407, doi:10.1029/2007GL029431 (2007).

15. Raymond, P.A. *et al*. Flux and age of dissolved organic carbon exported to the Arctic Ocean: A carbon isotopic study of the five largest arctic rivers. *Global Biogeochem. Cy.* **21,** GB4011, doi:10.1029/2007GB002934 (2007).

16. Miettinen, J. & Liew, S.C. Degradation and development of peatlands in peninsular Malaysia and in the islands of Sumatra and Borneo since 1990. *Land Degrad. Dev.* **21**, 285-296 (2010).

17. Page, S.E. *et al*. A record of late Pleistocene and Holocene carbon accumulation and climate change from an equatorial peat bog (Kalimantan, Indonesia): implications for past, present and future carbon dynamics. *J. Quaternary Sci.* **19**, 625-635 (2004).

18. Hirano, T. *et al*. Carbon dioxide balance of a tropical peat swamp forest in Kalimantan, Indonesia. *Global Change Biol.* **13**, 412-425 (2007).

19. Moore, S., Gauci, V., Evans, C. D. & Page, S. E. Fluvial organic carbon losses from a Bornean blackwater river. *Biogeosciences* **8**, 901-909 (2011).

20. Montanarella, L., Jones, R.J.A. & Hiederer, R. The distribution of peatland in Europe. *Mires & Peat* **1**, 1-10 (2006).

21. Billett, M.F. *et al*. Carbon balance of UK peatlands: current state of knowledge and future research challenges. *Climate Res.* **45**, 13-29 (2010).

1   22. Nilsson, M. *et al*. Contemporary carbon accumulation in a boreal oligotrophic minerogenic
2   mire - a significant sink after accounting for all C-fluxes. *Global Change Biol.* **14**, 2317-2332
3   (2008).

4   23. Battin, T.J. *et al*. The boundless carbon cycle. *Nat. Geosci.* **2**, 598-600 (2009).

5   24. Cole, J.J. *et al*. Plumbing the global carbon cycle: Integrating inland waters into the terrestrial
6   carbon budget. *Ecosystems* **10**, 171-184 (2007).

7   25. Mayorga, E. *et al.* Young organic matter as a source of carbon dioxide outgassing from
8   Amazonian rivers. *Nature* **436**, 538-541 (2005).

9   26. Caraco, N., Bauer, J.E., Cole, J.J., Petsch, S. & Raymond, P. Millennial-aged organic carbon
10   subsidies to a modern river food web. *Ecology* **91**, 2385-2393 (2010).

11   27. IPCC, 2003. Good Practice Guidance for Land Use, Land-Use Change and Forestry (LULUCF),
12   edited by Penman, J., Gytarsky, M., Hiraishi, T., Krug, T., Kruger, D., Pipatti, R., Buendia, L.,
13   Miwa, K., Ngara, T., Tanabe, K. & Wagner, F. Section 3.2 & 3.5. IPCC National Greenhouse
14   Gas Inventories Programme, Technical Support Unit, Kanagawa, Japan.

15   28. Murdiyarso, D., Hergoualc'h, K. & Verchot, L.V. Opportunities for reducing greenhouse gas
16   emissions in tropical peatlands. *P. Natl. Acad. Sci.* **107**, 19655-19660 (2010).

17   29. Hope, D., Billett, M.F. & Cresser, M.S. A review of the export of carbon in river water: fluxes
18   and processes. *Environ. Pollut.* **84**, 301-324 (1994).

19   30. Boehm, H.-D.V. & Siegert, F., 2001. *Ecological impact of the one million hectare rice project*
20   *in Central Kalimantan, Indonesia using remote sensing and GIS*. Paper presented at the 22nd
21   Asian Conference on remote sensing, 5-9th November, 2001, Singapore.
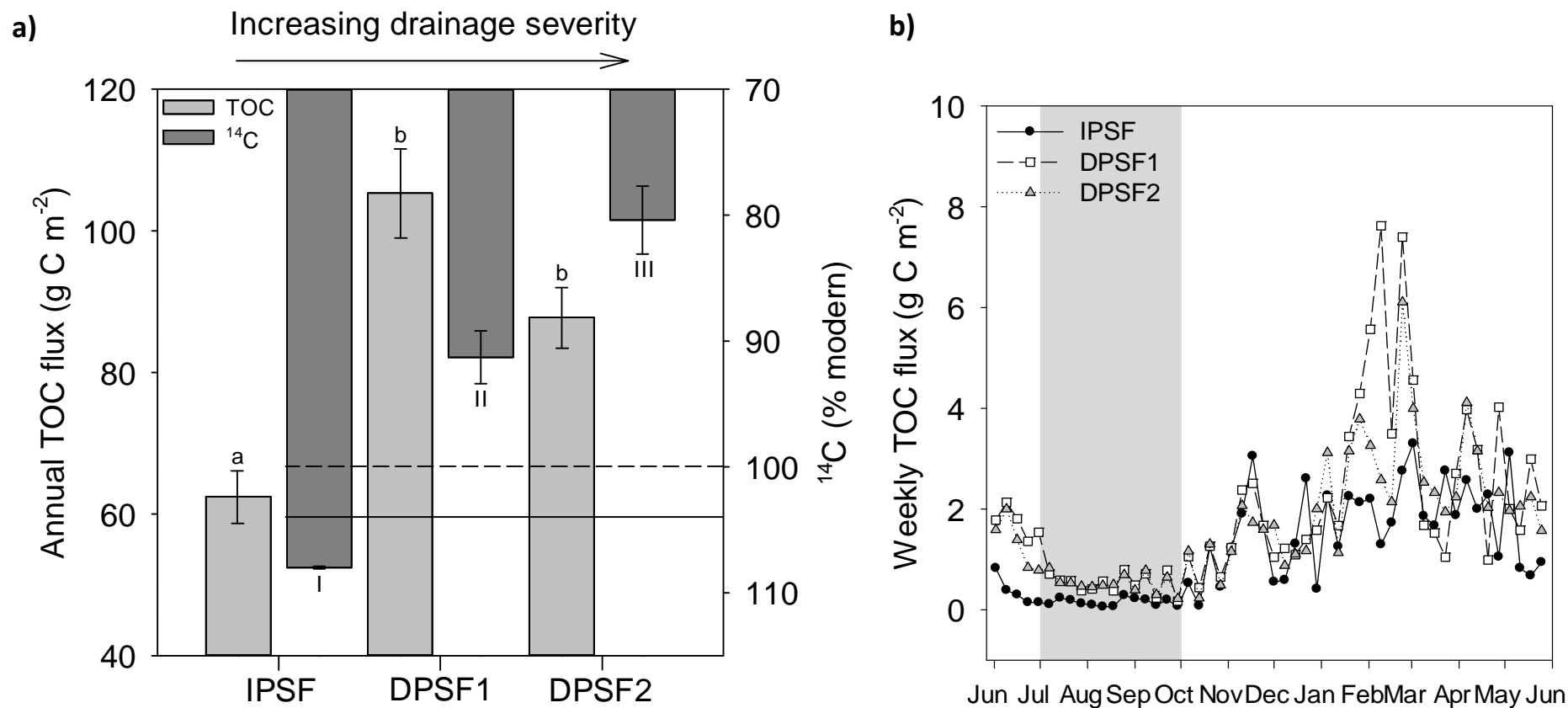
Figure 1: a) Annual TOC flux (± s.e.m), 'a' and 'b' denote significant differences between land-cover classes (p<0.05, unpaired, two-sample t-test) and mean radiocarbon (^{14}C) levels (± s.e.m) measured in DOC (wet season samples), 'I', 'II' and 'III' denote significant differences (p<0.05, unpaired, two-sample t-test). Solid horizontal line (104% modern) represents the current atmospheric $^{14}CO_2$ level, dashed horizontal line (100% modern) represents the composition of the atmosphere in 1950, in the absence of any anthropogenic influences (i.e. fossil fuel burning and above-ground nuclear testing), b) Weekly TOC flux from all land-cover classes from June 2008 to June 2009 (grey shading indicates dry season). IPSF TOC is the sum of fluxes from 3 channels, DPSF1 is the sum of 2 channels and DPSF2 is the sum of 3 channels, all divided by the total area of the land-cover class.
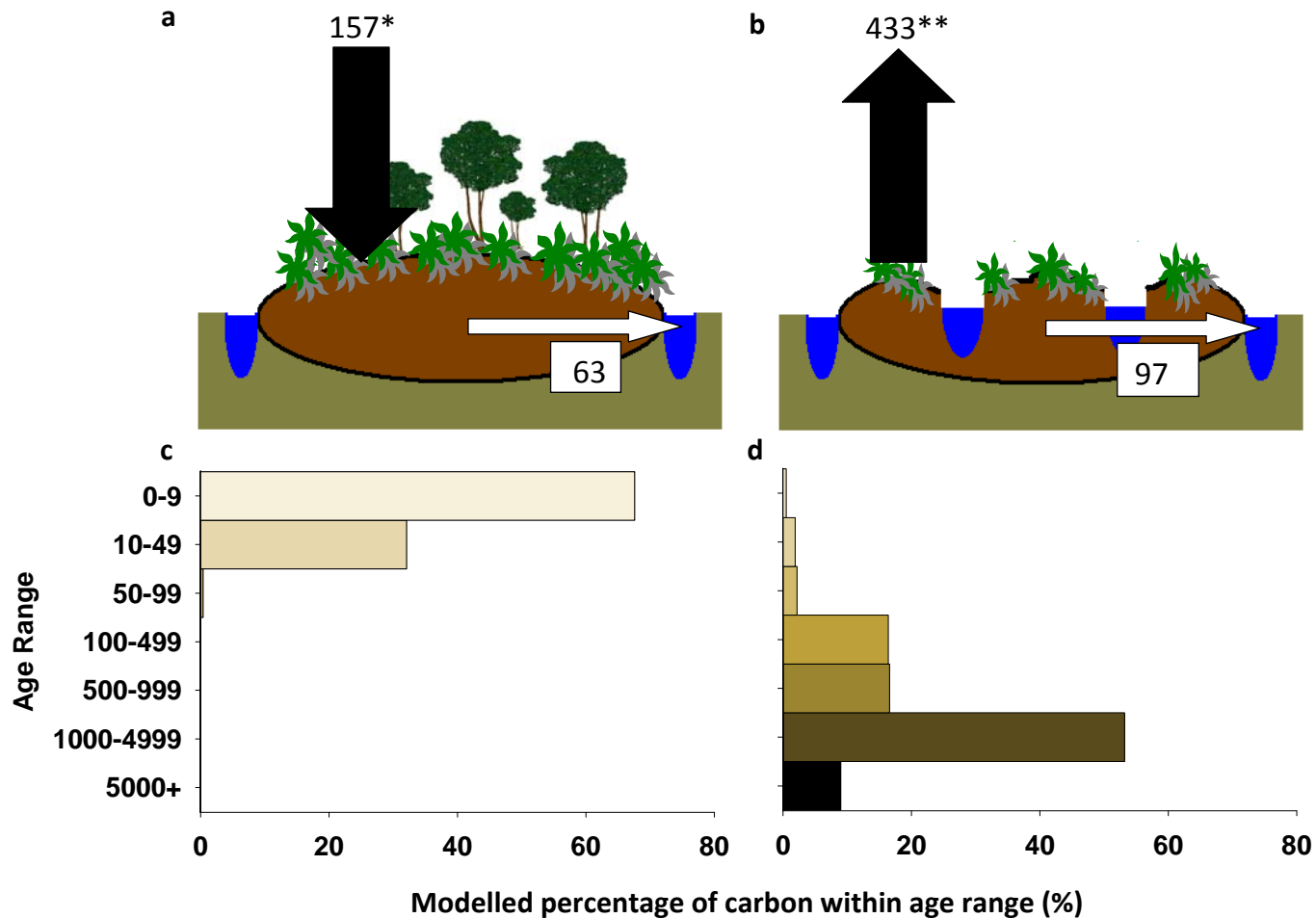
Figure 2. Schematic showing NEE (black arrows) and fluvial C loss (TOC) (white arrows) estimates in a) IPSF and b) DPSF land-cover classes. *NEE estimated from average 500 year long-term apparent rate of carbon accumulation (LORCA) from a peat core taken within IPSF[17] to which mean fluvial C loss (63 g C m^{-2} yr^{-1}) has been added thus approximating NEE as would be measured by gaseous exchange alone. C gain of intact PSF estimated to be 94 g C m^{-2} yr^{-1} (net C sink). ** NEE measured from tower-based gaseous exchange measurements (eddy covariance) within the DPSF catchments, with N, S, E and W fetches covering flat, deforested areas of the MRP that are drained but not containing drainage channels (which are beyond fetch extremities)[18]. NECB of DPSF estimated to be 530 g C m^{-2} yr^{-1} (net C source). c) and d) modelled down-profile attribution of DO^{14}C age from IPSF and DPSF2 land-cover classes respectively (wet season) as estimated from an age attribution model of DO^{14}C age (see supplementary information for explanation).

9

Table 1. Borneo study sites and land-cover class properties.

Land-cover class	Number of channels	Area (km^2)	Rainfall (mm)	Total Discharge (mm)	Mean DOC Con[c] (mg l^{-1})	Mean POC Con[c] (mg l^{-1})	Mean TOC Con[c] (mg l^{-1})	DOC:POC ratio	Annual TOC flux (g C m^{-2} yr^{-1})
IPSF	3	34.2	2810	907	68.0 ± 0.3	1.4 ± 0.1	69.5 ± 0.4	49:1	62.5 ± 7.5
DPSF1	2	13.2	2810	1744	55.0 ± 0.7	5.3 ± 0.2	60.3 ± 0.8	10:1	105.3 ± 12.6
DPSF2	3	64.0	2810	1724	48.3 ± 0.5	3.6 ± 0.1	51.9 ± 0.5	13:1	87.8 ± 8.6

Number of channels, Area (total area of land-cover class), Rainfall (total annual, standardised using ground station records and TRMM), Total annual discharge (area standardised), Mean annual DOC concentration (± s.d.m), Mean annual POC concentration (± s.d.m), Mean annual TOC concentration (± s.d.m), DOC:POC ratio (DOC con[c]/POC con[c]), Annual TOC flux (± s.d.m).

Table 2. Bornean and Malaysian study sites - Hydrological, DOC, DO^{14}C and qualitative (SUVA$_{254}$ and % aromaticity) data.

Land-cover class	Number of channels	Season	Total rainfall (mm; during 3 months prior to sampling)	Mean DOC Conc (mg l^{-1})	DO^{14}C (%modern)	DO^{14}C age (yrs BP)	SUVA$_{254}$ (l mg-C^{-1} m^{-1})	Aromaticity (%)
IPSF	3	Dry	172	62.0	109.1 ± 0.3	modern	4.06 ± 0.04	30.10
	3	Wet	1141	64.1	108.0 ± 0.1	modern	4.03 ± 0.08	29.91
DPSF1	2	Dry	263	62.4	97.7 ± 0.6	188 ± 47	3.95 ± 0.15	29.38
	2	Wet	1018	54.7	91.3 ± 2.1	735 ± 179	3.69 ± 0.19	27.69
DPSF2	3	Dry	100	39.1	85.0 ± 0.6	1308 ± 54	4.00 ± 0.14	29.71
	3	Wet	922	47.9	80.4 ± 2.7	1760 ± 268	3.94 ± 0.10	29.32
Malaysia (OP - abandoned)	1	Dry	499	6.0	67.3 ± 0.3	3184 ± 37	4.93 ± 0.30	35.80
Malaysia (OP - active)	1	Dry	499	13.3	59.4 ± 0.3	4183 ± 37	4.14 ± 0.10	30.60

OP = Oil Palm. DO^{14}C levels (mean from 3 DOC replicate samples) ± 1 s.e.m, DO^{14}C Age (deduced from % modern, mean of three samples) ± 1σ level for overall analytical confidence. Specific UV Absorbance (SUVA$_{254}$) and % aromaticity data are means of 10 samples collected at weekly intervals during the wet and dry season. SUVA$_{254}$ is an indicator of relative aromaticity of aquatic humic substances and DOC as a whole with high aromaticity being indicative of a high degree of recalcitrance.

Table 3. Annual TOC fluxes pre and post disturbance at various spatial scales.

Region	Intact area 'pre' (km^2)	Intact area 'post' (km^2)	Disturbed area (km^2)	Total TOC flux 'pre' (Tg)	Total TOC flux 'post' (Tg)	Increase (Tg)
MRP*	15604	11102	4502	1.0	1.2	0.2
Borneo, Sumatra and Peninsular Malaysia	75805[†]	15600	60205	4.7	6.8	2.1
South East Asia	121272[††]	49344	71928[§]	7.6	10.0	2.4

The MRP forms part of the ~155,000 km^2 of peatlands that cover Borneo (Kalimantan, Sabah and Sarawak), Sumatra and Peninsular Malaysia (~60% of total peatlands in Southeast Asia[16]). In 1990, approximately 50% (75,800 km^2) of this land area was classed as intact PSF, with 'minor or no sign of human activity'[16]. In 2008 it was estimated that as a result of anthropogenic peatland disturbance, only 10% (15,600 km^2) of intact PSF remained, which equates to a PSF loss of 2.15 % yr^{-1} [16]. 'Pre'/'Post' dates for regions as follows: MRP, 1991/2000; Borneo, Sumatra and Peninsular Malaysia & South East Asia, 1990/2008. TOC fluxes used in calculations are: 62.5 g C m^{-2} yr^{-1} for intact PSF and 96.6 g C m^{-2} yr^{-1} for disturbed PSF. * Area data taken from Boehm & Siegert, 2001[30]. † Area of remaining intact PSF in 1990: 48.9% of 155,020 km^2 (data taken from Miettinen & Liew, 2010[16]) †† Area of remaining intact PSF in 1990: 48.9% of 248,000 km^2 (data taken from Miettinen & Liew, 2010[16] & Page et al. 2011[1]). § Area of disturbed peatland (excluding industrial plantations) calculated using actual rates of PSF loss for individual regions (as reported in Miettinen & Liew, 2010[16] & Hooijer et al. 2010[3]).

1 **Supplementary information**

2 **Site Descriptions:** IPSF is situated in the Sebangau National Park to the west of the River Sebangau
3 and consists of a continuum of forest types from the river (riverine forest) to the centre of the peat
4 dome (tall interior forest)[S1]. The peat dome that makes up IPSF ranges in thickness from <1 m at the
5 edge to 12.6 m in the centre, averaging 7.8 m over the whole dome[S1]. The water table is above the
6 surface for most of the year and reaches a maximum depth of 40 cm during the dry season in dry
7 years[S2]. DPSF1 was deforested, moderately drained (3-6 m wide, 2-3 m deep channels, peat
8 thickness <1 – 5 m) and had been subject to three fire events prior to the study and since MRP
9 implementation (1997, 2002 and 2006). DPSF2 was also deforested, but subject to more intense
10 drainage (15-25 m wide, 4-7 m deep channels, peat thickness <1 – 8 m) and had burned on two
11 occasions prior to the study (1997 and 2006). The vegetation at DPSF1 and DPSF2 is dominated by
12 ferns with limited woody re-growth. Stream flow in all study sites is unregulated. Water tables
13 fluctuate according to rainfall but as a consequence of artificial drainage in DPSF1 and 2, they remain
14 below the peat surface for most of the year reaching maximum depths of 140 cm in dry years[S3]. The
15 effect of such extreme drainage includes high rates of subsidence, indicative of aerobic
16 decomposition of the peat, concentrated in the first few hundred metres from drainage channels[S3].
17 This is not the case in drained industrial plantations where, under usual practice, the water table is
18 regulated at the most favourable depths for crop growth (ideally 60-80 cm for oil palm and Acacia
19 but often deeper).
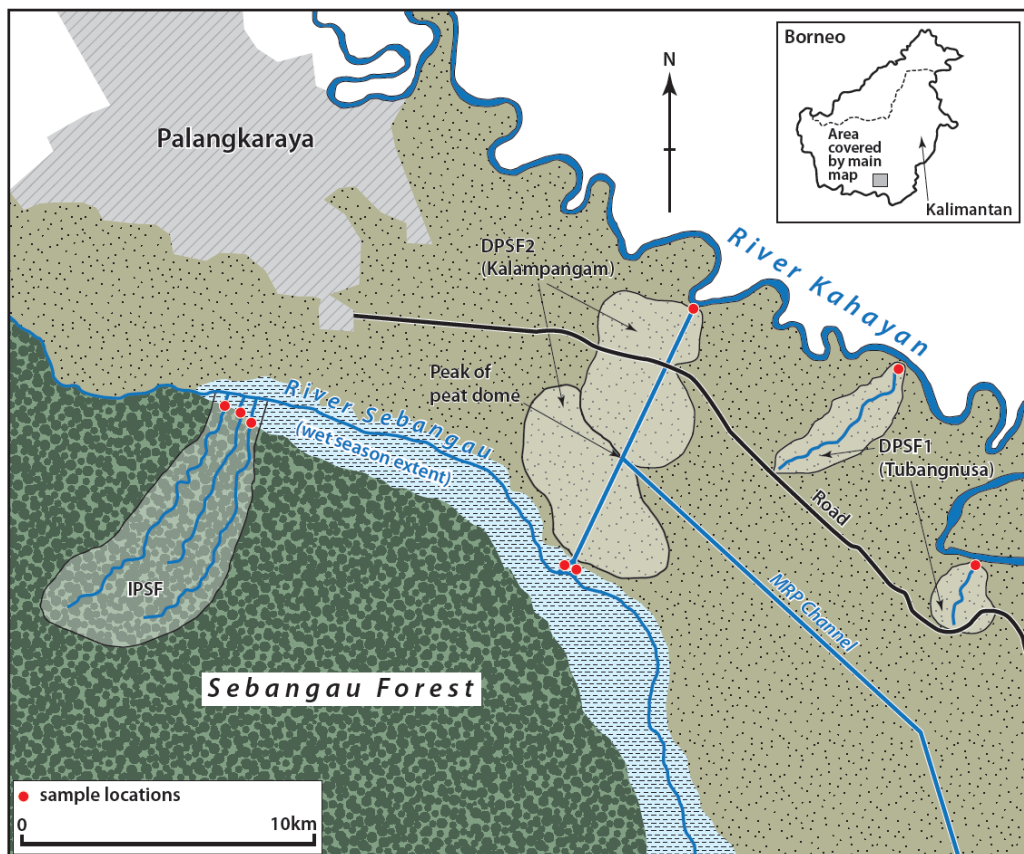
20 **Figure. S1**: Location of study sites in Central Kalimantan, Borneo, Indonesia (inset). All sites lie within
21 30 km of Palangka Raya, the provincial capital of Central Kalimantan and formed part of the same
22 ecosystem, prior to disturbance induced by the MRP in 1995. IPSF (3 channels) drains into the River
23 Sebangau. DPSF1 (2 channels) drains into the River Kahayan. DPSF2 (3 channels) 2 channels drain
24 into the River Sebangau and 1 channel into the River Kahayan.

Discharge measurement, hydrology and flux calculation

The cross-sectional area *(CSA)* and five replicate flow rate measurements *(FR)* (converted from impeller counts *(C)* per minute using the formula: *FR* = 0.000854*C* + 0.05) using a handheld impeller flow meter were also taken and used to calculate the discharge *(Q)* from each channel using the formula: *Q* (m^3 s^{-1}) = *FR* (m s^{-1}) × *CSA* (m^2). Precision for this method was better than ±5%. Weekly TOC fluxes were estimated by multiplying TOC concentration by discharge for each catchment which was divided by the total catchment area. For each of the three study catchments, areas were estimated on the basis of the limited data available on elevation and peat depth, derived from the Shuttle Radar Topography Mission (SRTM) 90 data and field surveys. These areas were then refined using field observations of artificial drainage systems, which dominate discharge patterns in the DPSF sites. This enabled us to make estimates of discharges and C fluxes at each measurement time point which were then annualized. We evaluated whether these specific discharges, in combination with rainfall rates as determined from field measurements and "Tropical Rainfall Measuring Mission" (TRMM) satellite monitoring[S4], yielded acceptable evapotranspiration (ET) values as judged against literature values and where no data exist (i.e. for deforested DPSF type catchments), simulations in the JULES land surface model.

ET for each land-cover class was inferred as the difference between rainfall and the sum of discharge. Inferred ET rates are estimated as IPSF = 1903 mm/yr; DPSF1 = 1066 and DPSF2 = 1086. For tropical lowland forest with rainfall over 2000 mm/yr, worldwide, values of between 1200 to 1800 mm/y are reported[S5] and for high rainfall sites such as ours (i.e. >2500-2700mm rainfall), ET rates as high as 2180 and 2420 mm have been recorded[S6]. It is thought that at such high rainfall rates, canopy interception and potential evaporation take on far greater importance than is currently represented in models[S7] causing such models to underestimate ET. After forest clearing, ET has been shown generally to decrease[S8], but there are no known measurements of ET for deforested areas of the MRP with which to validate our estimates. We therefore performed simulations of the effect of forest clearance on evapotranspiration for the Palangkaraya region using the Joint UK Land Environment Simulator JULES version 3.0[S9, S10]. The model was parameterised to represent DPSF1 and DPSF2 as combinations of C3, C4 grasses and bare soil. The model was spun-up by looping over 1950-1970 until soil moisture stores stabilised and then run between 1970-2000 to derive 30 year climatology values of evapotranspiration for our two DPSF sites. The model does not simulate the effects of drainage and is parameterised using ancillary information on soil properties taken from the Harmonised Soils and Wetlands Database (HWSD)[S11].

The model was forced by extracting a single half-degree gridbox of meteorological forcing data from the WATCH 20th Century forcing data set[S12]. In addition the model was forced with seasonally varying leaf area index (LAI) for vegetated surface types. These were derived from climatological values of LAI from MODIS 1km product classified using IGBP land cover classes and aggregated to the half-degree scale. Results of the simulations yielded ET rates of 799 mm/yr for bare soil and ~1150 mm/yr for C3/C4 grasses which are consistent with our inferred ET rates using the stated measurement approach given that much of our catchments are sparsely vegetated bare soil. Finally, we checked our estimates of ET for the IPSF and DPSF areas against measured concentrations of chloride (Cl$^-$, measured by ion chromatography) for samples collected across all sites. The chloride balance approach to ET estimation assumes that all runoff Cl$^-$ is derived from atmospheric deposition, that these inputs are consistent across the sites, and that it is unreactive during transport through the catchment (e.g. S13). Based on our water balance estimates, we predicted that Cl$^-$ concentrations in the DPSF channels should be 53% of those from the IPSF areas, due to reduced evaporative concentration. The measured value was 43%, agreeing fairly well with this prediction, and suggesting that, if anything, ET reduction between the IPSF and DPSF might be greater than our hydrological measurements suggest. In this case, our calculated increases in DOC flux following peatland drainage and deforestation would represent conservative estimates.

1

2

3 **Table S1: Individual DO^{14}C sample data and DOC concentration at point of sample collection.**

4

Site	RCL Code	Country	Land cover class	Season	Drainage Status	Drainage spacing (m)	DOC mg l^{-1}	DO^{14}C (% modern)	Age Years BP
ID1	SUERC-28121	Indonesia	IPSF	Dry	Undrained		60.1	109.75	modern
	SUERC-35171			Wet	Undrained		60.2	107.90	modern
ID2	SUERC-28122	Indonesia	IPSF	Dry	Undrained		62.5	108.74	modern
	SUERC-35172			Wet	Undrained		70.8	108.09	modern
ID3	SUERC-28123	Indonesia	IPSF	Dry	Undrained		63.5	108.80	modern
	SUERC-35173			Wet	Undrained		61.5	107.91	modern
ID4	SUERC-28126	Indonesia	DPSF2	Dry	Drained	> 1000	42.0	83.82	1417
	SUERC-35174			Wet	Drained	> 1000	51.4	84.62	1342
ID5	SUERC-28127	Indonesia	DPSF2	Dry	Drained	> 1000	35.6	85.49	1259
	SUERC-35175			Wet	Drained	> 1000	49.2	81.16	1677
ID6	SUERC-28128	Indonesia	DPSF2	Dry	Drained	> 1000	39.6	85.60	1249
	SUERC-35176			Wet	Drained	> 1000	43.1	75.47	2260
ID7	SUERC-28129	Indonesia	DPSF1	Dry	Drained	> 1000	62.6	98.86	92
	SUERC-35179			Wet	Drained	> 1000	64.6	95.35	382
ID8	SUERC-28130	Indonesia	DPSF1	Dry	Drained	> 1000	61.7	97.18	229
	SUERC-35180			Wet	Drained	> 1000	50.2	89.94	852
ID9	SUERC-28131	Indonesia	DPSF1	Dry	Drained	> 1000	62.8	97.07	239
	SUERC-35181			Wet	Drained	> 1000	49.3	88.61	972
MY1	SUERC-26030	Malaysia	Oil palm plantation (abandoned)	Dry	Drained	70	6.0	67.28	3184
MY2	SUERC-26031	Malaysia	Oil palm plantation (active)	Dry	Drained	70	13.3	59.41	4183

5

6 **Radiocarbon data and DOC age attribution model**
7 Samples were prepared for ^{14}C analysis at the NERC Radiocarbon Facility using standard methods
8 described by Evans et al.[S14], and analysed by accelerator mass spectrometry (AMS) at the Scottish
9 Universities Environmental Research Centre, East Kilbride. ^{14}C results were normalised to δ^{13}C -25‰
10 and expressed as %modern and conventional radiocarbon years (BP; before present, where 0 BP =
11 AD 1950); see Evans et al.[S14] and references within.

12

13 DO^{14}C levels in water samples represent the composite signal obtained by mixing organic matter
14 from a range of ages. Although this is conventionally represented by a single, indicative 'mean age',
15 this observed value may be obtained by different combinations of old (pre-bomb, i.e. pre-1950s) and
16 new (post bomb) material. Furthermore, samples dominated by bomb carbon cannot be assigned a
17 mean age using this approach. To infer an estimated age distribution for the organic carbon in each
18 sample, we therefore applied a simple model of DOC production as a function of peat depth, which
19 corresponds to carbon age. We assumed that the largest input of DOC production occurred from
20 carbon fixed via photosynthesis in the year of sampling, and that the amount of DOC production
21 declined exponentially with each subsequent year (i.e. down the peat profile). This conceptual model
22 is consistent with general understanding of the relationship between peat depth and decomposition
23 rates[S15], and with a previous model of DOC input relative to age applied to Arctic river samples by
24 Raymond et al.[S16]. To permit a unique solution to this model, Raymond et al.[S16] assumed that all DOC

1 included in their samples was derived from post-1970 material, accumulated since the atmospheric
2 $^{14}CO_2$ peak. This assumption does not hold for all of our data, since some samples clearly contained
3 pre-bomb carbon, therefore we applied a similar model extended to 10,000 years, based on a
4 reconstructed sequence of atmospheric $^{14}CO_2$ concentrations[S17] (Fig. S2). The model applied was:
5
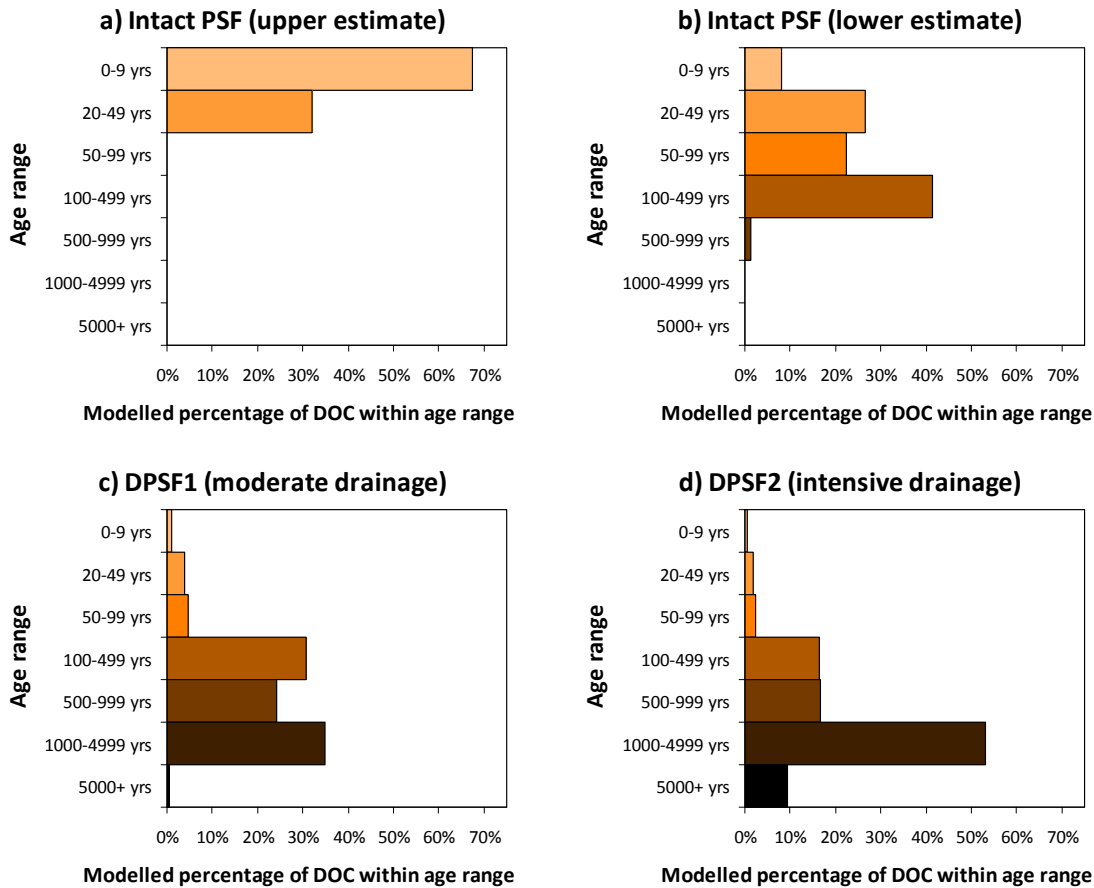6 $$DO^{14}C = t = 1 - t = 10,000 - \left(^{14}CO_2t \times exp^{(-kt \, D)}\right).$$
7 *(Equation S1)*
8
9 Where $DO^{14}C$ is the measured ^{14}C level of the sample, t is year prior to present day, $^{14}CO_2t$ is the ^{14}C
10 level of atmospheric CO_2 in year t, and k is a decay constant with a value between 0 and 1. For each
11 sample, the value of k was solved iteratively based on measured $DO^{14}C$ and the atmospheric $^{14}CO_2$
12 sequence shown in Fig. S2, using the Microsoft Excel Goal Seek function.
13
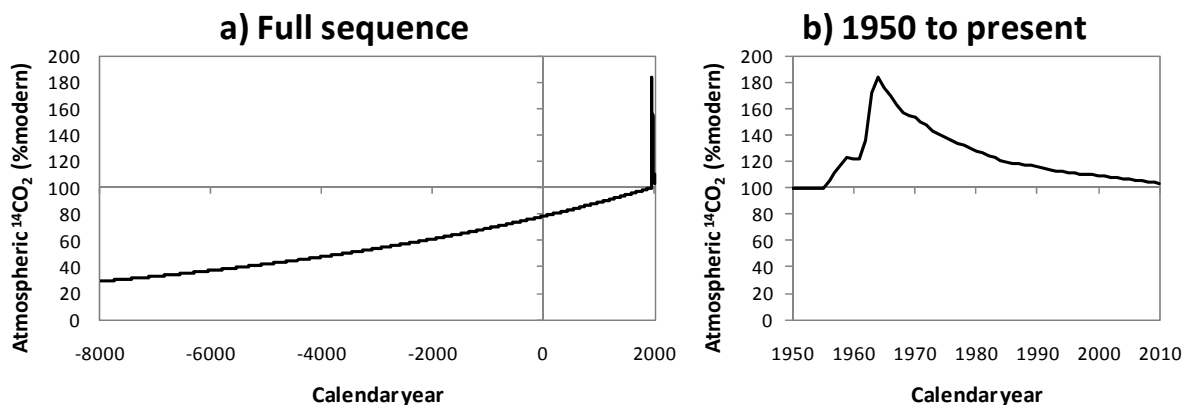
14
15
16 **Figure. S2**. Atmospheric $^{14}CO_2$ sequence used for age attribution model for a) full period of model
17 application and b) period of 'bomb' atmospheric $^{14}CO_2$ enrichment, 1950 to present day[S7].
18
19 For all samples with $DO^{14}C$ < 104.63 % modern (atmospheric $^{14}CO_2$ in the year of sampling), equation
20 S1 can be solved with a unique value of k. For samples with a higher bomb carbon content, two
21 solutions are possible. The first (with a value of k > 0.033) assigns virtually all the carbon to years
22 after the peak of atmospheric $^{14}CO_2$ in 1964. The second (with k < 0.033) includes a greater
23 proportion of C fixed prior to the bomb peak. Although it is not possible to conclusively determine
24 which of these solutions is correct for these samples, we note that the former solution is consistent
25 with the model of Raymond et al.[S16], and with many studies in high-latitude peatlands that have
26 inferred a largely recent (< 10 year) source of runoff DOC based on 'modern' $DO^{14}C$ measurements
27 (see main manuscript). The age attribution model was applied to all samples, and the DOC was
28 apportioned into 0-9, 10-49, 50-99, 100-499, 500-999, 1000-4999 and 5000+ year age categories.
29 Samples from each land-use class were then aggregated to give a mean modelled percentage of DOC
30 within each age range (Fig. S3). For samples with $DO^{14}C$ > 104.63 % modern, all of which were
31 collected from the intact PSF, age distributions based on the two possible solutions to the model are
32 shown.
33
34 The age attribution model is indicative, since different assumptions about the decrease in DOC
35 production down the peat profile would somewhat alter the distributions obtained. However the
36 differences in $DO^{14}C$ measured between intact and disturbed sites is so great that altering the
37 assumptions in the model would not greatly alter the interpretation of relative age distributions; the
38 lower values measured in the disturbed sites (combined with higher fluxes) can only be explained by
39 a much larger release of DOC from much older, and thus deeper, peat organic matter.
40

a) Intact PSF (upper estimate)

b) Intact PSF (lower estimate)

c) DPSF1 (moderate drainage)

d) DPSF2 (intensive drainage)

Fig. S3. Modelled age distribution of DOC samples collected from intact PSF (wet season); deforested and moderately drained (DPSF1); and deforested and intensively drained (DPSF2) sites in Borneo. Modelling approach is described in text. Upper and lower estimates for intact PSF reflect alternative model solutions to fit observed DO[14]C.

Malaysian DO[14]C samples

Two exploratory samples for DO[14]C analysis were collected from an area of oil palm plantation on former PSF near Kuala Lumpur. One sample was collected from an active plantation, and one from an adjacent area of abandoned plantation, with sparse oil palm and secondary re-growth. Both locations were located within a dense (70 m spacing) ditch drainage network. The two samples had exceptionally low DO[14]C values (67.3 and 59.4% modern respectively). Application of the age attribution model described above based on mean DO[14]C of the two sites (Figure S4) suggests that 83% of the DOC derives from peat carbon over 1000 years old, and 37% from peat carbon over 5000 years old.

Given that only two measurements are available, we report these data to provide an indication of the potential impact of oil palm plantation on peat fluvial C losses, and to highlight the need for further measurements for this major SE Asian land-use class. We note that the DOC concentrations in the samples collected were much lower (mean 10 mg l^{-1}) than in the drained Borneo sites (mean 51 mg l^{-1}). The reasons for this are unclear; one possibility is that the DOC production in the upper part of the peat profile at intensively drained Malaysian sites has largely ceased due to severe water table drawdown and drying, resulting in only a small residual DOC loss from depth within the peat profile

16

as suggested by the extreme age measurements, and supported by the higher DOC concentrations observed when the site was first studied in 1995.

We examined the data from these sites to evaluate whether other factors could explain the very low observed DO^{14}C values, such as autotrophic conversion of geogenic dissolved inorganic carbon (DIC) within the drainage channels. Since the samples collected were highly acid (pH 4.1 and 3.1 respectively), we believe it is highly unlikely that the signal could be explained by assimilation of DIC from the water column. Furthermore, measured δ^{13}C values on the samples were similar to those obtained from the drained Borneo sites (Malaysia site mean -27.3 ‰ (VPDB), Borneo site mean -29.7 ‰). These values are typical for DOC derived from peatlands, and thus suggest that the very low DO^{14}C values can only be explained by release of stored carbon from depth within the peat profile at these sites.
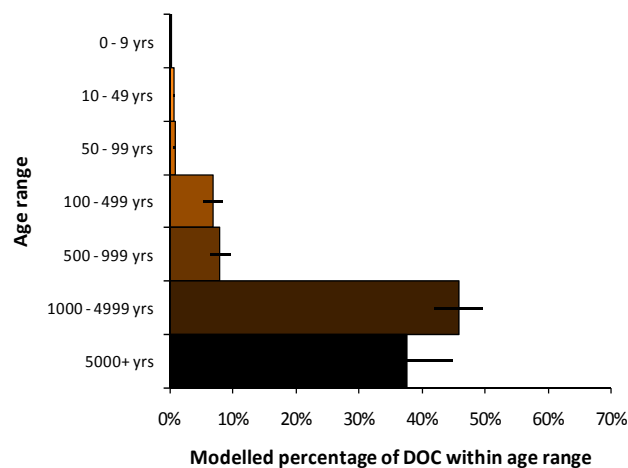
Fig. S4. Modelled age distribution of DOC measured in ditches draining oil palm plantation sites in Peninsular Malaysia. Error bars represent standard error of two samples. Modelling method corresponds to that used for Borneo samples.

Supplementary References

1. Page, S.E., Rieley, J.O., Shotyk, Ø.W. & Weiss, D. Interdependence of peat and vegetation in a tropical peat swamp forest. *Philos. T R Soc. B* **354**, 1885-1897 (1999).
2. Takahashi, H., Usup, A., Hayasaka, H. & Limin, S.H., 2003. Estimation of ground water level in a peat swamp forest as an index of peat/forest fire. In: *Proceedings of the International Symposium on Land Management and Biodiversity in Southeast Asia, Bali, Indonesia, 17–20 September 2002* (eds Osaki M., Iwakuma T., Kohyama et al.), pp. 311–314. Hokkaido University & Indonesian Institute of Sciences, Sapporo, Japan and Bogor, Indonesia.
3. Hooijer, A. *et al.*, 2008. Hydrology of the EMRP Area – Water Management Implications for Peatlands, Technical Report Number 2 of the Master Plan for the Rehabilitation and Revitalisation of the Ex-Mega Rice Project Area in Central Kalimantan. Euroconsult Mott MacDonald and Deltares, Delft Hydraulics.
4. Vernimmen, R.R.E., Hooijer, A., Mamenun, Aldrian, E. & van Dijk, A.I.J.M. Evaluation and bias correction of satellite rainfall data for drought monitoring in Indonesia. *Hydrol. Earth Syst. Sci.* **16**, 133–146 (2012).

5. Bruijnzeel, L.A., 1990. Hydrology of moist tropical forests and effects of conversion: A state of knowledge review. UNESCO International Hydrological Programme, Netherlands.

6. Schellekens, J., Bruijnzeel, L.A., Scatena, F.N., Bink, N.J. & Holwerda, F. Evaporation from a tropical rain forest, Luquillo Experimental Forest, eastern Puerto Rico. *Water Resour. Res.* **36**, 2183–2196, doi:10.1029/2000WR900074 (2000).

7. Komatsu, H., Cho, J., Matsumoto, K. & Otsuki, K. Simple modeling of the global variation in annual forest evapotranspiration. *J Hydrol.* **420-1**, 380-390 (2012).

8. Bonell, M. & Bruiznzeel, L.A., 2005. *Forests, Water and People in the Humid Tropics*. Cambridge University Press, Cambridge.

9. Best, M.J. *et al.* The Joint UK Land Environment Simulator (JULES), model description - Part 1: Energy and water fluxes. *Geosci. Model Dev.* **4**, 677-699 (2011).

10. Clark, D.B. *et al.* The Joint UK Land Environment Simulator (JULES), model description - Part 2: Carbon fluxes and vegetation dynamics. *Geosci. Model Dev.* **4**, 701-722 (2011).

11. FAO/IIASA/ISRIC/ISS-CAS/JRC, 2009. Harmonized World Soil Database (version 1.1). FAO, Rome, Italy and IIASA, Laxenburg, Austria.

12. Weedon, G.P. *et al.* Creation of the WATCH Forcing Data and its use to assess global and regional reference crop evaporation over land during the twentieth century. *J Hydrometeorol.* (2011).

13. Hedin, L.O. *et al*. Patterns of nutrient loss from unpolluted, old-growth temperate forests— evaluation of biogeochemical theory. *Ecology* **76**(2):493–509 (1995)

14. Evans, C.D. *et al*. Evidence against recent climate-induced destabilisation of soil carbon from ^{14}C analysis of riverine dissolved organic matter. *Geophys. Res. Lett.* **34**, L07407, doi:10.1029/2007GL029431 (2007).

15. Limpens, J. *et al*. Peatlands and the carbon cycle: from local processes to global implications – a synthesis. *Biogeosciences* **5**, 1475–1491 (2008).

16. Raymond, P.A. *et al*. Flux and age of dissolved organic carbon exported to the Arctic Ocean: A carbon isotopic study of the five largest arctic rivers. *Global Biogeochem. Cycl.* **21,** GB4011, doi:10.1029/2007GB002934 (2007).

17. Levin, I., Hammer, S., Kromer, B., & Meinhardt, F. Radiocarbon observations in atmospheric CO_2: Determining fossil fuel CO_2 over Europe using Jungfraujoch observations as background. *Sci. Total Environ.* **391**, 211-216 (2008).