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Southeast Asian peatland drainage emits 220 Mt of carbon per year, equivalent to 2.2% of global fossil-fuel emissions

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Article

Keywords: carbon budget, peatlands, decomposition, wildfire

Posted Date: September 12th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1995407/v1

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Southeast Asian peatland drainage emits 220 Mt of carbon per year, equivalent to 2.2% of global fossil-fuel emissions

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Key Words

carbon budget, peatlands, decomposition, wildfire

Abstract

Southeast Asian peatlands are climatically important ecosystems, storing approximately 70 billion tons of carbon. Natural and human-induced droughts are lowering peatland water tables, increasing decomposition and the risk of peat-burning wildfires. The rapid nature of carbon losses arising from peatland drainage and accompanying fire-related losses compared to the slow accumulation of peat means that the effects of peatland drainage are essentially irreversible on human timescales. Here, we use a terrestrial biosphere model incorporating vertically-resolved peatland carbon and water dynamics to predict decomposition and fire in Southeast Asia as a result drainage-induced drying. The model captures observed patterns of interannual and seasonal variation in soil moisture and its soil moisture estimates are a better predictor of observed burned area fraction than either precipitation or remotely-sensed estimates of surface soil moisture (r^2=0.63, 0.50, 0.56 respectively). Simulations of a fully-drained 1.4 m peat deposit emit an additional 9 tC ha^{-1} yr^{-1} and 13 tC ha^{-1} yr^{-1} from decomposition and fire respectively. The emissions from decomposition are linearly related to the depth of drainage and can reach up to 31 tC ha^{-1} yr^{-1} when fully drained. At regional scales, these estimates imply that 220 MtC yr^{-1}, or 2.2% of global fossil fuel emissions, are being emitted from Indonesian and Malaysian peatlands due to drainage. The vulnerability of these large, concentrated carbon stocks, combined with their long timescale of accumulation, underscore the importance for preserving tropical peatlands to avoid further exacerbation of human induced climate change.

Introduction

Peatlands have been a terrestrial carbon sink since the Holocene and contributed to cooling the global climate [1–3]. Anoxic conditions existing in saturated peat soils prevent efficient decomposition of plant litter, which accumulates as peat. Typical peat accumulation rates are about 1 mm yr^{-1}, and consequently it takes millennia to develop deep peat deposits. Globally, peatlands store about as much carbon as the atmosphere [4] and this vast store of carbon is at risk of becoming a net source to the atmosphere. Climate change is drying peatlands, causing them to decompose and also increasing the frequency of fires (4). In addition, the draining of peatlands for oil palm, acacia, and rice plantations amplifies these carbon cycle feedbacks through the drying and burning of carbon rich peat. Southeast (SE) Asian peatlands store globally significant amounts of carbon, 69 GtC, which accounts for 65 % of global tropical peat deposits, and are especially at risk due to drainage [1,5,6]. Carbon released from these peatlands poses a serious feedback on anthropogenic climate change. Furthermore, fire emissions in SE Asia negatively affect air quality and health in a highly populated part of the world [7,8]. Due to the smoldering nature of peat, these fires emit more smoke than forest fires and consequently have greater effects on regional air quality [9]causing 100,000s of excess deaths in bad fire years (8).

When the water table is lowered, peat is exposed to oxygen and is vulnerable to decomposition [10–12]. This occurs naturally during the dry season in SE Asia [13]. The flux of CO_2 emitted from the peat is thus highly correlated with the water table depth[10,11,14,15]. As peatlands are drained for logging and agriculture, peat in drained areas shift from anoxic to aerobic conditions, resulting in substantial increases in decomposition and accompanying increases the rate of carbon emissions to the atmosphere [11]. Several studies have estimated the carbon flux from drained peatlands and found values ranging from 11-20 tC ha^{-1} yr^{-1} [6,14,16–19] with more recent studies in the lower part of that range.

The risk and severity of fires in SE Asian peatlands also depends on soil moisture and the water table [20,21]. Fires occur every dry season; however, interannual variability is substantial, with El Niño years often resulting in severe droughts and heightened fire activity [22]. Drained peatlands are even more susceptible to fire [7]. Both peat burn depth and peat fire frequency are correlated with distance to drainage canals in Kalimantan [11]. Carbon emissions from global peatland fires are significant, accounting for 5% of the total global fire emissions between 1997 and 2009 [22]. SE Asian wildfires emitted 0.8 +/- 0.5 kgC m^{-2} yr^{-1} over this period. Although SE Asian peatlands cover a relatively small area, they have the highest carbon emission density in the world. Anomalously dry years can have enormous impacts, with the 1997-8 El Niño caused a particularly severe drought and large wildfire season in Indonesia. It is estimated that fires burned to an average depth of 0.5m and emitted 0.81-2.57 GtC to the atmosphere, equivalent to 12-40% of global fossil fuel emissions [23]. Eighty percent of the emissions that year were from combustion of peat, with the remaining 20% coming from above ground biomass [23]. Furthermore, radiocarbon measurements of the PM2.5 smoke particles during the 2015 El Niño fire season indicate that the mean age of the combusted carbon was 800 years old, identifying that the source is ancient peat [8]. There is concern that with on-going drainage, even more of the carbon-rich peatlands of SE Asia will become vulnerable to future fires.

To date, there have been few efforts to quantify carbon emissions arising from excess decomposition and fire linked to the drainage of peatlands [10,14,20,21,24–26]. Models and observations have established important links between the water table and carbon and between soil moisture and fire [10,14,20,21,24,25] however most of these efforts have been based on simple statistical associations between these quantities, and thus lack the ability to predict long term changes under conditions outside those covered by the observations. The models rely on water table depth, soil moisture, or surface subsidence to predict carbon fluxes, however, they do consider how emissions affect the underlying carbon stock abundance or composition, which is crucial for long term predictions. Furthermore, they often do not consider how different depths of peat and drainage canals affect the potential for carbon loss, which is sensitive to both of these spatially heterogenous factors. Finally, most observational and modeling studies have considered the effects of decomposition and fire on peatland separately, whereas in reality both are enhanced by drainage canals and contribute to the total emissions change. Warren et al. [26] conducted a series of simulations to estimate carbon emissions arising from drained peatlands. They used a process based tropical peat model to predict long term dynamics due to different precipitation and fire regimes, as well as forest conversion to plantations; however, they did not explicitly explore drainage depth as an emission predictor.

In this study, we combine satellite remote sensing data with process-based modeling to quantify the relationships between water and carbon in tropical peatlands in central Kalimantan. We chose Kalimantan because of its abundant peatlands including pristine and drained areas. Specifically, we use a terrestrial biosphere model, ED2-peatlands, that conserves energy, water, and carbon and simulates the physical processes that control the terrestrial carbon budget including vegetation growth, mortality and autotrophic respiration as well as vertically resolved soil decomposition and its dependence on temperature and moisture [27]. ED2 is driven by meteorological data and accounts for feedbacks between the drainage depth, water table and peat depth which are critical for calculating the long-term dynamics of peat under a given precipitation scenario. We simulate drained and undrained conditions to estimate the enhanced decomposition of peat carbon due to drainage. Furthermore, predicted soil moisture is regressed against MODerate resolution Imaging Spectroradiometer (MODIS) burn area fraction to quantify the relationship between surface soil moisture and wildfires. We then use that relationship to predict the loss of soil carbon due to wildfire. We find that the enhanced decomposition is strongly sensitive to both drainage depth and peat depth. The combined carbon emissions from these two processes are substantial under drained conditions and indicates a clear need for preserving these carbon rich ecosystems.

Results

Predictions of burn area from precipitation and soil moisture: Fire occurrence in central Kalimantan strongly depends on surface soil moisture (Figure 1). Figure 1 shows MODIS-derived estimates of the dry season burn area fraction plotted against three soil moisture-related metrics. Regression analyses indicate that dry season precipitation explains 50% of the variance in dry season burn area fraction ($r^2 = 0.50$, Figure 1a). Remotely-sensed estimates of surface soil moisture explain slightly more of the variability in burn area fraction ($r^2 = 0.56$, Figure 1b); while ED2-peatlands predictions of surface soil moisture are a better predictor, explaining 63% of the variance in the burn area fraction ($r^2 = 0.63$, Figure 1c).

Comparison of the two soil moisture estimates: The remote sensing-based soil moisture estimates, (which come from the Soil Moisture Active Passive (SMAP) instrument, see Methods section), exhibit a high degree of spatial and temporal variability: values range from 0.1 to 0.6 cm^3 cm^{-3} reflecting the range of elevation and hydrological conditions across ~500×500 m pixels (Fig S2). Further analysis shows that the pattern of temporal variability across the SMAP soil moisture pixels are relatively consistent, with obvious drought conditions in 2015 and 2019 (Figure S2). In contrast, the biosphere model soil moisture predictions reflect a single larger-scale (0.5^o x 0.5^o) spatial average and exhibit lower degree of absolute temporal variability than the satellite data (compare Fig. 1, panels b and c see also Figure S2). The biosphere model predictions nonetheless capture significant decreases in soil moisture during drought years such as 2015 (black, lines Figure S2), and analysis of Z-scores, or standard scores, (Figure S2, inset) indicate that the model predictions of soil moisture have a relatively larger seasonal amplitude than remote-sensing derived estimates. This likely explains why the biosphere model captures more of the observed temporal variability in dry season burn area fraction compared to the SMAP-based estimates (Figure S2).

Soil moisture decreases markedly during the dry season; however, the magnitude of the decrease varies between years with the severity being linked to the El Niño Southern Oscillation (ENSO) (Figure 2a, Figure S3). The impact of El Niño on soil moisture is demonstrated in Figure 2 (a,b), which shows the timeseries of soil moisture for intact and fully-drained peatlands, respectively. For example, the 2015 El Niño caused the depth at which the level of relative soil moisture of 0.9 occurs in intact peatlands to drop from the surface to almost 3 m, and the near surface relative soil moisture to decrease to 0.65 (Figure 2a). For comparison, during the 2010 La Niña the entire soil column remained above 0.9 relative soil moisture (Figure 2a).

To examine the impacts of drainage on the peatland, we simulate a 1.4m peat deposit under two drainage depth scenarios, a 1 m canal and >1.4m canal that fully drains the peat column. The 1.4 m peat depth was chosen because simulations indicate that this amount of peat is that represents ~50% of the long-term equilibrium under the current climate. Simulations of drainage canals dug in the year 2000 causes relative soil moisture above the level of drainage to decrease within a matter of weeks to about 0.7 and creates year-round hydrological drought (severe soil water deficit) in the peat column comparable to the drying that occurred during the 2015 El Niño dry season (Figure 2b, Figure S3).

Soil moisture impact on decomposition and fire prevalence: Carbon fluxes from decomposition and fire prevalence are both highly sensitive to soil moisture. Figure 2c shows the time series of carbon emissions due to decomposition in intact and drained peatlands. The annual average carbon dioxide (CO_2) flux arising from decomposition in an intact peatland is approximately 7 tC ha^{-1} yr^{-1} with CO_2 emissions being largely confined to the dry season corresponding to the seasonal cycle of soil moisture (blue line, Figure 2c).

However, following the draining of a peatland, the ensuing drying of the peat column causes decomposition rates to increase markedly (red and green lines, Figure 2c) initiating a spike in CO_2 emissions as the labile carbon within in the peat column decomposes rapidly. Following the initial post-drainage spike, soil carbon emissions decrease rapidly, within two years, to a lower, but nonetheless enhanced, level of CO_2 emissions compared to the intact peatland (Figure 2c). Under a fully-drained peat scenario (red line), the enhanced post-spike CO_2 flux from soil decomposition is approximately 15 tC ha^{-1} yr^{-1} with a slightly decreasing temporal trend as the mass of peat in the soil column decreases. Under a 1m drainage canal scenario, both the initial spike and post-spike emissions are lower than a fully-drained scenario, the latter being approximately 12 tC ha^{-1} yr^{-1}. In contrast to the strongly seasonal nature of CO_2 emissions in the intact peatland, CO_2 emissions in both drainage scenarios exhibit little to no seasonality because the drainage canals effectively remove excess water during the wet season thereby enabling decomposition to occur throughout the year (Figure 2c).

Dry surface conditions within peatlands also enhance the risk of peat fires [16,20,28]. Figure 2d shows the timeseries of emissions due to fire. Under natural conditions, large CO_2 fluxes arising from fires occur only during El Niño years, corresponding to the driest conditions (blue line, Figure 2d). Under both drainage scenarios, however, the surface soil moisture is low enough to be at risk of peat fires year-round with an average flux of 10 tC ha^{-1} yr^{-1} between 2000 and 2020 and with higher fire emissions (up to 18.5 tC ha^{-1} yr^{-1}) during the dry season (green and red lines Figure 2d) . The predicted fire emissions are based on surface soil moisture which is equivalent in the 1 m and fully-drained simulations.

Sensitivity of decomposition on peat thickness and drainage depth: The magnitude of enhanced carbon fluxes from drained peatlands is strongly dependent on the depth of the drainage canal and the depth of peatlands into which they are dug (Fig. 3). Figure 3 shows a sensitivity analysis of the carbon flux due to decomposition as function of canal depth and initial peat depth. The black line indicates the zero-flux contour, which corresponds to the equilibrium peat depth, i.e. where decomposition balances net primary productivity, for a given level of drainage in the absence of fire. Under the meteorological conditions analyzed here, 2.76 m annual precipitation in Central Kalimantan, 2.8 m of peat are in equilibrium in the intact peatland (indicated by where the zero-flux contour intercepts the x axis in Figure 3). As the figure shows, installation of drainage canals ≥0.5m causes the equilibrium peat depth to reduce dramatically to only 30 cm of organic material. The baseline simulations with 1.4 m of peat and no drainage are accumulating at 0.5 tC ha^{-1} yr^{-1}, or roughly 1 mm yr^{-1}; however they lose a similar amount due to fires under natural conditions (Figure 4). Peat accumulates slowly under conditions left of the equilibrium line (Figure 3), however peat is lost much more rapidly to the right of the equilibrium line, where drainage conditions occur.

Figure 4a shows the long-term average and interannual variability of the predicted carbon fluxes arising from enhanced decomposition and fire and are compared with existing estimates of tropical peatland decomposition rates (excluding fire losses). The predicted mean decomposition in a fully-drained 1.4 m deep peatland is within the range several recent estimates in the literature; however, the 1 m drainage mean estimate is lower (Figure 4a). More generally, our simulations suggest that over the last 20 years, the range of carbon lost due to enhanced decomposition is 0-30 tC ha^{-1} yr^{-1} based on the depth of peat and drainage, a range that mirrors the range of literature estimates (11-29.5 tC ha^{-1} yr^{-1}). Figure 4b, shows that between 2000 and 2020, we estimate 120 to 180 tC ha^{-1} have been lost as result of enhanced decomposition in drained peatlands. Adding in the enhanced risk of fire increases this range substantially to 370-430 tC ha^{-1} (Figure 4b). This corresponds to a reduction in soil depth of 66-77 cm over 20 years, or 3.3-3.9 cm yr^{-1}. For comparison, satellite remote sensing estimates indicate an average reduction of 2.2 cm yr^{-1} over drained peatland between 2007 and 2011 in SE Asia, in the absence of any large fire years [18].

Regional carbon loss: These results can be extrapolated to estimate regional CO_2 fluxes based on estimates of drained peatland area, peat depth, and drainage canal depth. If the peatland is deeper than the drainage canal, then the CO_2 flux is relatively independent of peat depth and becomes primarily a function of drainage depth (Figure 3). Indonesia and Malaysia have mean peat depths of 5.5 and 7 m, respectively, which is deeper than any known drainage canals (5). We assume a typical value of 1.5 m drainage canals in this region, which yields average emission rates of 10 tC ha^{-1} yr^{-1} from enhanced decomposition and 12 tC ha^{-1} yr^{-1} from fire between 2000 and 2020 (Figs 3 and 4). Integrating this over the estimated 10 Mha of drained peatland in Indonesia and Malaysia (6) implies that the peatlands in this region are emitting 100 MtC yr^{-1} as a result of enhanced decomposition and 120 MtC yr^{-1} from fire caused by the installation of drainage canals. Combined, these emissions are equivalent to 2.2% of annual fossil fuel emissions despite coming from only 0.074% of the global land area [29].

Discussion

SE Asian peatlands store about 70 Pg of carbon, which is vulnerable to loss via decomposition and increased fire risk if the water table decreases (1). Our analysis shows that terrestrial biosphere model predictions of surface soil moisture predictions explain significantly more of the interannual observed variation in remotely sensed burned area fraction than either monthly precipitation or satellite-derived estimates of surface soil moisture in Kalimantan peatlands (Figure 1). The ability of the model to predict burn area fraction is important for accurately estimating carbon emissions from fires.

A substantial fraction of the peatlands in SE Asia (>70%) have either been drained, or are actively being drained for agriculture and timber (7, 11, 31). We find that after drainage is initiated, soil moisture drops within a few weeks to the depth of the drainage canals (Figure 2a,b). The resulting hydrological drought in the drained peatland soil column creates year-round soil moisture conditions comparable those occurring during strong El Niño dry seasons such as 2015. Several studies have shown that the water table and carbon fluxes are affected for hundreds of meters to kilometers away from the drainage canals [6,11,30]; however, the timescale to drain peatland may be longer due to the slower timescale of lateral water movement which is currently not accounted for in the current model estimates [6,18,30].

We also find commensurate increases in carbon emissions after drainage is initiated due to labile carbon being exposed to oxygen (Figure 2c). As the available labile carbon is depleted, the carbon emission rate decreases to an enhanced background carbon flux throughout the year. Because the remaining carbon stock is primarily composed of structural and recalcitrant carbon, which has a longer decomposition lifetime, the background flux then slowly decreases over the 20-year period as the total carbon stock gradually declines. Previous studies have documented similar decreases in the rate of emissions over time from drained peatlands [12,18,31,32].

Between 2000 and 2020 -- the time period analyzed in this study -- the intact peatland carbon is roughly in equilibrium in undrained peatlands. However, under 1 m and fully-drained scenarios with a 1.4 m initial peat depth, peatland carbon is lost at rates of 6 and 9 tC ha^{-1} yr^{-1} respectively due to enhanced decomposition (Figure 4a). However, as seen in Figure 3, the carbon emissions arising due to enhanced decomposition depends strongly as a function of the peat depth and drainage depth, and these two key controls are rarely reported in studies of peatland emissions. Our sensitivity tests indicate that peatland emissions range from –4 to -31 tC ha^{-1} yr^{-1}, depending on the depth of the initial peat and canal (Figure 3). Estimates of carbon emissions from drained peatlands under oil palm cultivation which vary from 5 - 29 tC ha^{-1} yr^{-1} [14,31–38]. This observed range is consistent with our sensitivity study. Furthermore, average regional emissions of 11 tC ha^{-1} yr^{-1} are consistent with ~1.5 m drainage depths based on our sensitivity study [18].

Many studies have established the link between peatland fire and hydrologic drought conditions [11,23,28]. Areas under hydrological drought, which is experienced by ecosystems near drainage canals, are much more likely to burn [21]. The drained peatland scenario examined in this study is 20 times more likely to burn than under undrained conditions and emits 13 tC ha^{-1} yr^{-1} from enhanced fire emissions (Figure 2d). Increased fires not only emit more carbon to the atmosphere, they also cause more smoke pollution. SE Asia fires harm human health by increasing particulate matter and ozone in major population centers [39]. Marlier et al. [40] predict that 37-48% of future Sumatra emissions from land use change will come from peatlands, despite peatlands only accounting for 16% of the total land. This is due to the abundance of soil carbon that becomes vulnerable to fires after drainage. They find that the future air quality in SE Asia will be decided in part based on the conservation of peatlands. Inclusion of process-based fire emissions, could provide improved boundary conditions for atmospheric models and thus be used to better predict air quality predictions based on land use change.

SE Asia peatland forest cover declined from 85% to 36% between 1985 and 2010 [41,42]. Since the 1980's peatlands have been logged, drained, and converted to agriculture, primarily Acacia, oil palm, and the mega rice project. Of Indonesia's 20-21 Mha of peatland including 13 Mha in Sumatra and Kalimantan that existed in 1980, 6.3 Mha in Kalimantan had been converted to plantations, 2.9 Mha was logged and degraded, leaving about 3.8 Mha preserved in 2015 [5,43]. Extrapolating the carbon loss estimates calculated in this study to the regional scale implies that Kalimantan currently emits an extra 220 MtC yr^{-1} as a composition of enhanced decomposition and fires arising from peatland drainage.

Peatlands are unique and globally important due to their ability to sequester carbon and high carbon density. Peat in Kalimantan accumulates at about 1 mm yr^{-1}, or 0.15-0.5 tC ha^{-1} yr^{-1} [2]. This accumulation rate varies by location and in time due to fluctuations in climate; however, the rate of peat accumulation of ~1000 years per meter is representative of the timescales on which peat has been estimated to form [1–3]. Critically, the time required to restore belowground carbon in peatlands is at least an order of magnitude longer than restoring aboveground carbon in a closed canopy old growth forest, making the loss of carbon from peatlands effectively permanent. Furthermore, peatland carbon density, 1,000-4,000 tC ha^{-1}, is much greater than in a forest stand, 100-200 tC ha^{-1}, highlighting their potential climatic effect per area [44]. While peatland restoration will not sequester the lost carbon quickly, it will limit further rapid loss of peatland carbon to the atmosphere.

We estimate that preserving one hectare of peatland from drainage would prevent 440 tons of carbon or 1600 tons of CO_2 from entering the atmosphere over the next 20 years (Figure 4b). For comparison, preserving one hectare of tropical forest from deforestation would prevent the loss of 100-200 tons of carbon or 670-730 tons of CO_2 [44]. Meanwhile, reforestation of one hectare of forest might net 70 tons of carbon or 257 tons CO_2 in 20 years. In other words, from a carbon standpoint, we find that conserving peatland saves ~3 times as much carbon as saving tropical forests over 20 years on a per area basis. Furthermore, the lost carbon cannot be recaptured.

Carbon credits provide one way of comparing the societal value of ecosystems. In 2019, the mean market rates of carbon credits range between \$1.4 - \$4.3 per ton of CO_2e depending on the type and sustainability of the practice [45]. At \$3 per tCO2e, preserving SE Asian peatlands is potentially worth \$240 ha^{-1} yr^{-1}.

Draining peatlands increases carbon emissions through enhanced decomposition and fire. This loss of carbon to the atmosphere raises the CO_2 concentration and could accelerate climate change. Those interested in limiting CO_2 emissions should consider prioritizing the protection and restoration of tropical peatlands.

Methods

We simulate the carbon budget of intact and drained peatland in Taman Nasional Tanjung Puting, in Central Kalimantan, Indonesia in Southern Borneo using the ED2-peatlands model. A regional map indicating the areas of analysis is shown in Figure S1. ED2-peatlands is a mechanistic biosphere model that conserves energy, water, and carbon and simulates the physical processes that control the terrestrial carbon budget including vegetation growth, mortality and autotrophic respiration as well as vertically resolved soil decomposition and its dependence on temperature and moisture [27]. The basic formulation for simulations come from [46], with added vertical processes in soil column from [47]. This version has vertically resolved soil carbon and biophysical processes that allow peatlands to grow and accumulate carbon. These updates are critical for assessing the long-term dynamics of peat under a given precipitation scenario, including the role of drainage affecting decomposition and fire susceptibility. ED2-peatlands is driven with 3-hourly ERA5 meteorology [48] and CHIRPS precipitation [49]. Simulations have a 300-year spin-up during which the soil carbon and vegetation come to equilibrium. The 20-year simulations testing the effects of drainage branch off of the spin up simulation and start in the year 2000. Intact peatlands are represented with a non-permeable bottom boundary condition, so precipitation is balanced by evapotranspiration and runoff. Surface water runoff was represented with an eight-hour e-folding time. To simulate fully- drained peatlands we changed the bottom boundary condition in the soil to include drainage. Detailed aspects of the boundary conditions can be found in a technical description of the model [46].

The soil decomposition component of ED2-peatlands was run offline to calculate the sensitivity of emissions to peat depth and drainage depth. For this decomposition scheme, a soil moisture profile had to be assumed. We assumed that the soil moisture was the same as the drained scenario 2 layers or more above the level of drainage, and the same as the intact scenario below the level of drainage. At the level or just above the level of drainage, we linearly interpolated the soil moisture between the fully-drained and intact peatlands scenarios (Figure S4a). From the modified soil moisture profile, the decomposition scalar and rate can be calculated (Figure S4b,c). The offline decomposition model was driven with monthly Net Primary Productivity

(NPP) from the ED2-peatlands model. Carbon fluxes from the offline decomposition model have remarkably good agreement with the ED2-peatlands despite being run with monthly inputs (Figure S5). After 20 years, the soil carbon abundances are within 1-2% (10 tC ha^{-1}) between the models. This computationally efficient offline model allows for the >1000 simulations used in the sensitivity analysis of Figure 3.

Soil moisture data is obtained from the NASA SMAP satellite. The baseline retrieval algorithm in the official SMAP product is error prone due to an upper limit constraint that is not appropriate for peatlands, so we use an alternative dataset derived using a Multi-temporal Dual Channel Algorithm ("MT-DCA") as applied to SMAP observations at 9 km resolution [50]. This data was previously found to have a mean upper bound RMSE < 0.07 $m^3 m^{-3}$, suggesting sufficient accuracy across regional peatlands [20].

Fire emissions were calculated offline as follows. The burn fraction was calculated using, monthly hotspot and burned area fraction version 1.2 from MODerate resolution Imaging Spectroradiometer (MODIS) [51] over a 150x300 km around the study location in southern Kalimantan. This size gave a large enough area to statistically sample the fire frequency while remaining in the peatlands. We fit a linear model to the log of the dry season burn area fraction and predicted dry season surface soil moisture. This relationship is used to estimate the burn area fraction in the model given the predicted soil moisture. We limit the maximum monthly burn area fraction to 0.025, which is slightly larger than the maximum fraction observed over this time period in the data, ~0.2 [20]. Fire emissions were calculated by multiplying the monthly burned area fraction, burn depth, and bulk density, assuming a burn depth of 10.7 cm and a bulk density of 57.9 kgC m^{-3} [11].

Acknowledgements

This research was supported by NASA Earth Sciences grant (16- CARBON16-0130) to PM, SS and AK. The research carried out at the Jet Propulsion Laboratory, California Institute of Technology, was under a contract with the National Aeronautics and Space Administration. M.L. was supported by the NASA Postdoctoral Program, administered by Universities Space Research Association under contract with NASA and the Next Generation Ecosystem Experiments- Tropics, funded by the U.S. Department of Energy, Office of Science, Office of Biological and Environmental Research. N.C.D. and A.G.K were supported by NSF under Award EAR-1923478. N.C.D was also supported by the NASA Earth and Space Science Fellowship Program - Grant 80NSSC18K1341.

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Figures and Tables.

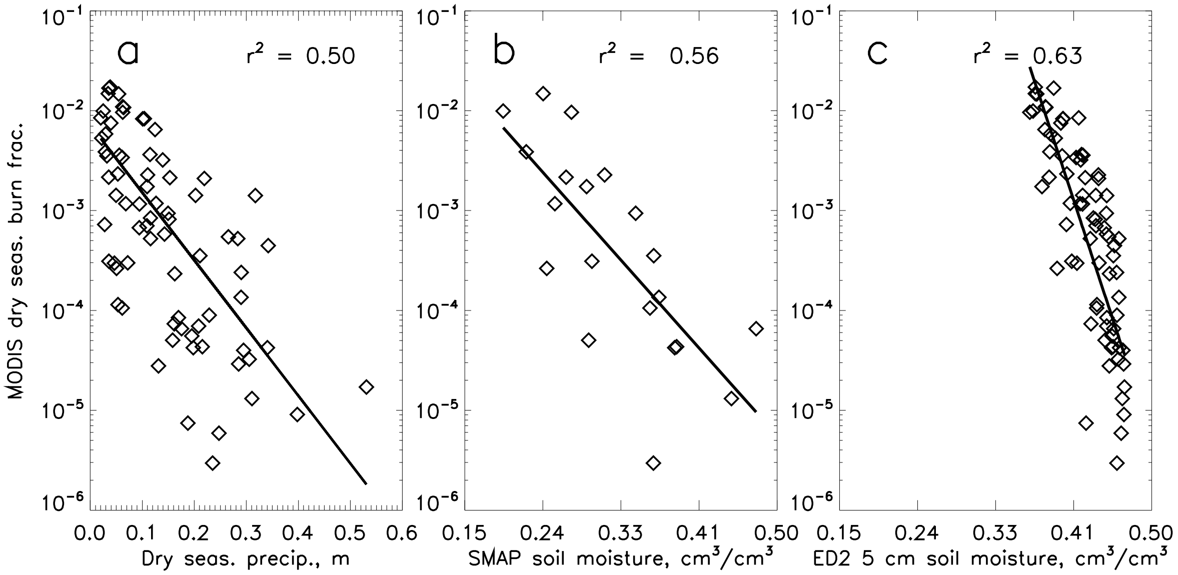

Figure 1. Linear regression between MODIS dry season burn area fraction and different soil moisture metrics; a) dry season monthly precipitation, b) SMAP surface soil moisture, and c) ED2 predicted surface soil moisture. The SMAP regression is performed on the 90th percentile pixel (out of 140 surrounding the study site) representing inundated peatland conditions similar to those model predictions in panel c.

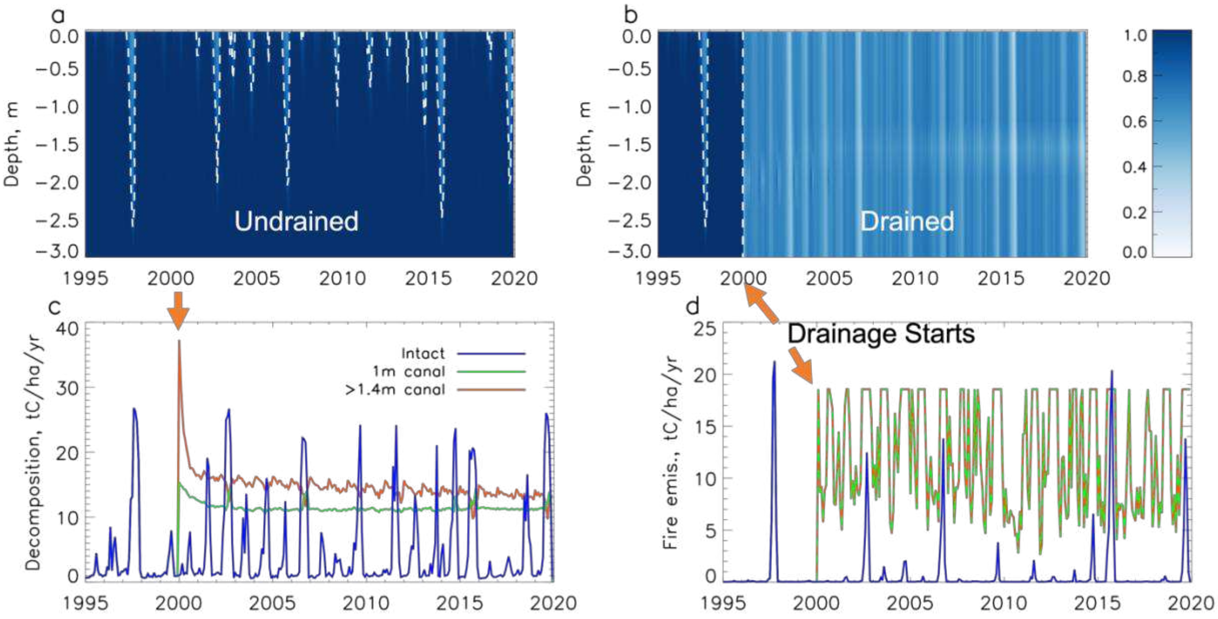

Figure 2. Predicted relative soil moisture in intact (a) and drained (b) peatlands with an initial peat deposit of 1.4 m. The white line indicates the 0.9 relative moisture contour. ED2 predicted monthly decomposition (solid lines) compared with offline estimations (dashed lines) for three drainage conditions (c). Predicted fire emissions from undrained and drained peatlands (d). Note that the annual fire emission rate reaches a maximum rate of burning that is determined by the value of the burn-depth, which is assumed to be constant at 10.7 cm [11], and a maximum fractional burn area of 0.25 based on remote sensing observations [20]. Orange arrows indicate the start of drainage in these simulations.

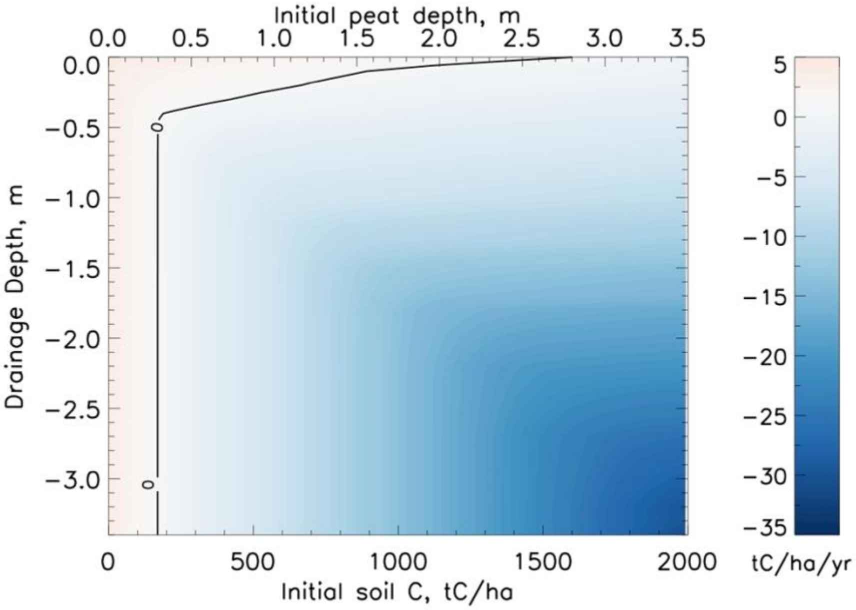

Figure 3. Mean decomposition (tC ha^{-1} yr^{-1}) between 2000 and 2020 as a function of initial soil carbon and drainage depth. The black contour line indicates zero net flux and corresponds to the equilibrium peat depth for a given level of drainage. Under the meteorological conditions analyzed and in the absence of drainage, this line intercepts the x-axis at 2.8 m. Fully-drained tropical soils have an equilibrium carbon-rich soil depth of 30 cm.

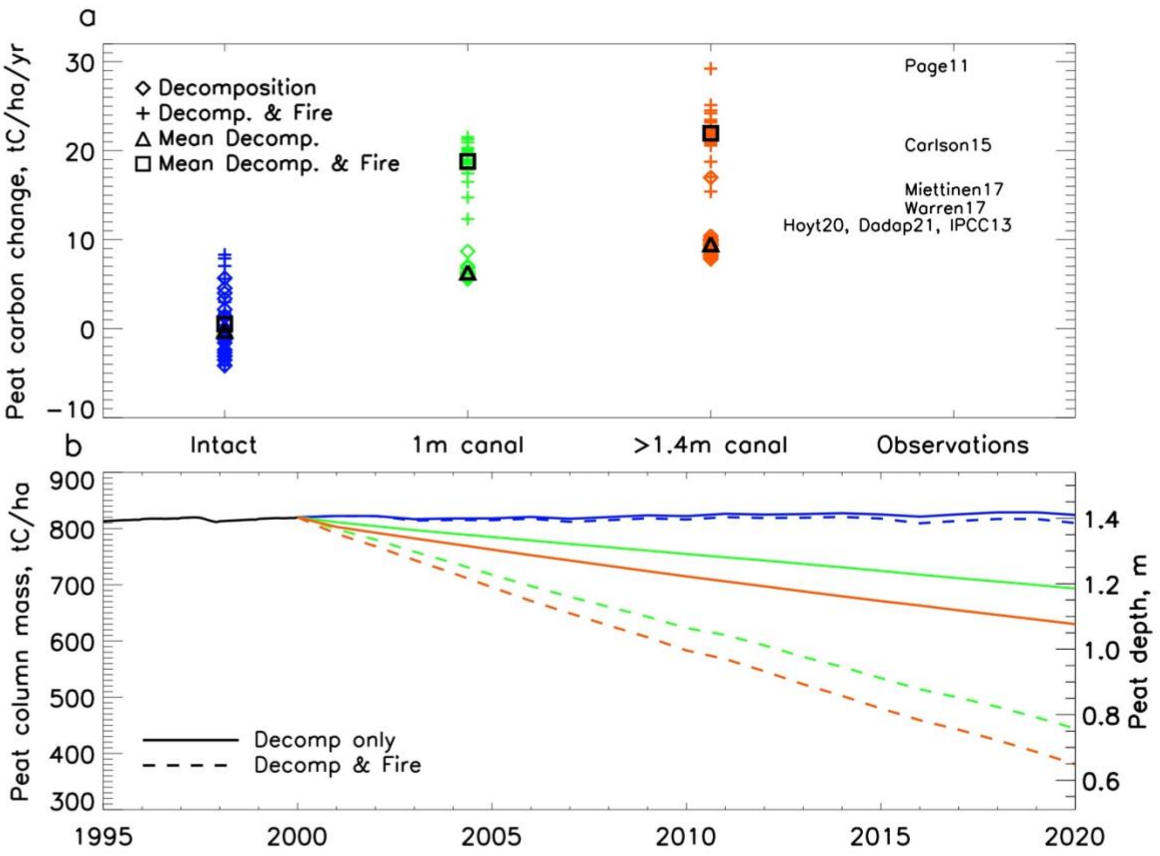

Figure 4. a) Annual emissions between 2000 and 2020 under three drainage scenarios for a starting peat depth of 1.4 m due to enhanced decomposition with and without fire. b) The cumulative carbon loss under those same scenarios.

Supplementary Files

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