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Key Points:

- Permeability of the most common type of tropical peatland is higher than expected and like that of unconsolidated gravel
- High permeability does not cause rapid drainage of undisturbed tropical peatlands
- High permeability leads to deep water tables in ditched tropical peatlands, and associated high rates of peat oxidation

Supporting Information:

- Supporting Information S1

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High permeability explains the vulnerability of the carbon store in drained tropical peatlands

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Abstract Tropical peatlands are an important global carbon (C) store but are threatened by drainage for palm oil and wood pulp production. The store's stability depends on the dynamics of the peatland water table, which in turn depend on peat permeability. We found that an example of the most abundant type of tropical peatland—ombrotrophic domes—has an unexpectedly high permeability similar to that of gravel. Using computer simulations of a natural peat dome (NPD) and a ditch-drained peat dome (DPD) we explored how such high permeability affects water tables and peat decay. High permeability has little effect on NPD water tables because of low hydraulic gradients from the center to the margin of the peatland. In contrast, DPD water tables are consistently deep, leaving the upper meter of peat exposed to rapid decay. Our results reveal why ditch drainage precipitates a rapid destabilization of the tropical peatland C store.

1. Introduction

Tropical peatlands contain at least 87 Pg of carbon (C) [*Page et al.*, 2011], equivalent to the C store in the aboveground biomass of the Amazon rainforest [*Fauset et al.*, 2015]. Most are found in Southeast Asia, with parts of central Africa, Mesoamerica, and the Amazon also important [*Page et al.*, 2011]. The majority of tropical peatlands are domed [*Anderson*, 1983; *Page et al.*, 2004; *Phillips et al.*, 1997; *Winston*, 1994], and their role as C stores is intimately related to how they function hydrologically, with, for example, the position of the water table affecting rates of plant litter production (C inputs; net photosynthesis) and peat decay (C outputs) [*Kurnianto et al.*, 2014; *Moore et al.*, 2011].

The sole source of water in most domed tropical peatlands is rainfall; they are ombrotrophic [*Ingram*, 1983; *Moore et al.*, 2011]. Water losses may occur via one of five pathways: direct evaporation of liquid water trapped on leaf surfaces, direct evaporation from the ground surface, as water vapor leaving the stomata (transpiration), groundwater flow through the peatland to its margin, and overland flow [*Ingram*, 1983]. However, the relative importance of these controls on the tropical peatland water budget and water-table dynamics is poorly understood. In particular, very little is known about how much water flows below the peatland surface, which is, in part, controlled by peat permeability (or, more strictly, the hydraulic conductivity, K). There is a paucity of data on this critical parameter for tropical peatlands, and little is known about its magnitude or variability [*Kelly et al.*, 2014].

To help close this important knowledge gap we measured the K of an ombrotrophic peatland in Panama. The site was chosen because of its broad similarities with lowland ombrotrophic peatlands found throughout the tropics (see section 2). We used our K data in a groundwater model [*Baird et al.*, 2012] to simulate peatland water-table fluctuations in both a natural peatland dome, and one that has undergone artificial drainage, to evaluate the relative importance of K and subsurface groundwater flow in the hydrological budget. We then used the groundwater model's output in a separate decay model to investigate the effect of K and artificial drainage on the vulnerability of the tropical peatland C store.

2. Peat Hydraulic Conductivity (K)

Our K measurements were made in part of the Changuinola swamp in Bocas del Toro province in northwest Panama. We chose the swamp because of the general similarity of its component peatlands to ombrotrophic peatlands found widely in the tropics, particularly Southeast Asia (see above) [*Page et al.*, 2006; *Phillips et al.*, 1997]. The ombrotrophic peatlands in the swamp have a characteristic pattern of vegetation from open,

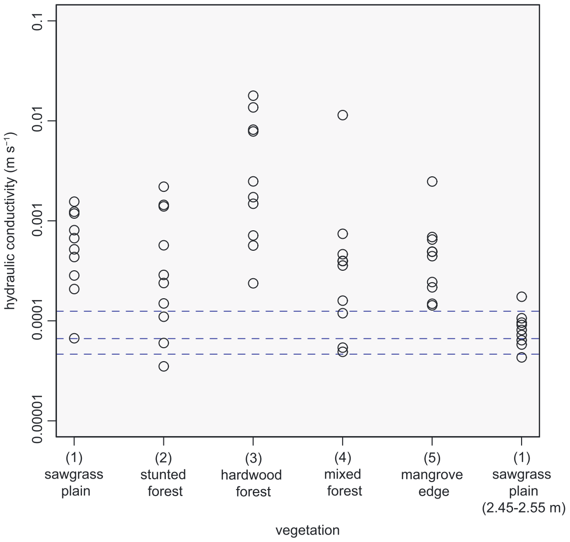

Figure 1. Hydraulic conductivity values (corrected to 25°C) measured in each vegetation zone. Note the log scale on the *y* axis. The dashed horizontal lines correspond to the medians reported for three Amazonian floodplain peatlands [*Kelly et al.*, 2014] (see main text).

sawgrass-dominated interiors that give way to concentric zones with varying domination by tropical hardwoods and palms as one moves to the margins. Although there are differences in species between Mesoamerican and Southeast Asian peatlands, species from the same genus occur commonly in both areas. For example, the hardwood *Campnosperma panamensis* is dominant in parts of Changuinola and is common in peatlands across Mesoamerica, while *Campnosperma coriacea* and *Campnosperma squamata* occur widely in Southeast Asian peatlands [*Rydin and Jeglum*, 2006]. Even when species differ, the growth forms and traits, including buttress roots and pneumatophores (breathing roots), are the same in peatlands from the two regions. The climate is also very similar, with temperatures, annual rainfall, and evapotranspiration from the study area (section 3) all within the range for Southeast Asian sites [*Page et al.*, 2006]. Finally, the morphology of the peatlands is similar: the large peatland dome of San San Pond Sak in Changuinola, which we used for our groundwater model of a natural dome (see sections 1 and 3 and the supporting information), is of a similar size and shape to many in Southeast Asia, although some Southeast Asian domes are characterized by steeper margins [*Winston*, 1994]. Given the above similarities, we believe that our findings have applicability beyond the study area.

Ten *K* measurements were made within each of the following five vegetation zones: sawgrass plain (zone 1—center), stunted forest (2), hardwood forest (3), mixed forest (4), and mangrove edge (5—margin) (see the supporting information). *K* was measured at a depth of 0.55–0.65 m in each zone by using piezometers. Additional measurements were made in zone 1 (sawgrass plain) at a depth of 2.45–2.55 m, also using piezometers. We employed a variant of the slug test method to measure *K* (see the supporting information and its reference to *Hvorslev* [1951]) and followed best practice when installing and cleaning the piezometers prior to the tests [*Butler*, 1998; *Baird et al.*, 2004; *Surridge et al.*, 2005]. The shallow peat in zone 1 comprised poorly decomposed sawgrass (*Cladium*) remains with woody inclusions and an admixture of well-decomposed amorphous organic matter. In all other zones, the peat was a mass of living and dead (mostly) tree roots, the latter in various stages of decay, set within a loose matrix of amorphous organic matter. The deeper peat in zone 1 was like the shallow peat but with moderately to well-decomposed sawgrass remains. The pH of the pore water at the site ranged from 3.9 to 4.4 except at the peatland margin where it was higher (~5.5) because of periodic tidal inundation. Pore water electrical conductivity away from the mangrove edge varied between 3.8 and 6.9 $\mathrm{mS\,m^{-1}}$.

We found that *K* was unexpectedly high—similar to that of unconsolidated coarse sand or fine gravel [*Domenico and Schwartz*, 1990] (Figure 1), with the arithmetic mean ranging from $8.7 \times 10^{-5}\ \mathrm{m\,s^{-1}}$ (zone 1 deep peat) to $5.462 \times 10^{-3}\ \mathrm{m\,s^{-1}}$ (zone 3—hardwood forest) (values corrected to 25°C). This range is, in $\mathrm{m\,d^{-1}}$, 7.5 to 471.9 (units commonly used in groundwater studies), while in $\mathrm{cm\,s^{-1}}$ it is 8.7×10^{-3} to 5.462×10^{-1} (units commonly used by soil scientists). Statistical analysis revealed that the deeper peat had a significantly ($p < 0.01$) lower *K* than the shallower peat. Differences in shallow-peat *K* between the different zones were less clear-cut (see the supporting information).

These *K* values are among the highest recorded anywhere for peat at depths below the immediate surface layers (i.e., depths below ~0.2–0.3 m), including temperate and boreal ombrotrophic peatlands [*Baird et al.*, 2016; *Kelly et al.*, 2014], where upper end values rarely exceed $1 \times 10^{-4}\ \mathrm{m\,s^{-1}}$. They are also considerably higher than values recently recorded for three Peruvian Amazonian floodplain peatlands [*Kelly et al.*, 2014] —two flat and one shallowly domed—that are likely to be different from the widespread ombrotrophic domes found elsewhere in the tropics because they are (or have been until the last few hundred years (T. J. Kelly, personal communication)) regularly overtopped by river floodwaters which will affect their biogeochemistry and therefore peat properties. As shown in Figure 1, our median values are between two and more than 30 times higher than found in these Peruvian Amazonian floodplain peatlands [*Kelly et al.*, 2014].

As noted by *Kelly et al.* [2014] [see also *Dommain et al.*, 2010] very few other studies exist on the *K* of tropical peat. *Takahashi and Yonetani* [1997] measured *K* at depths of 1 to 1.7 m in an Indonesian forest swamp by using piezometers but published only a rounded value ($K \geq 1 \times 10^{-4}$ m s^{-1}) for depths <1 m. *Hoekman* [2007] suggests a much higher value of 2.3×10^{-3} m s^{-1} but provides no information on how it was obtained. *Nugroho et al.* [1997] provide a more detailed data set for an Indonesian peatland, with a *K* range ($n = 28$) of 3.5×10^{-5} to 1.9×10^{-3} m s^{-1} but do not indicate how measurements were made or the depths from which they were obtained. Finally, *Sayok et al.* [2007] present *K* values for Malaysian swamp forest, obtained by using slug tests in auger holes, with a mean value of 3.9×10^{-4} m s^{-1} ($n = 15$). Notwithstanding uncertainty over the reliability of some of these estimates, they show that our values are mostly within the range of, but also exceed, the values for Southeast Asian peatlands.

3. Water-Table Dynamics and Peat Decay in Natural and Ditch-Drained Domed Tropical Peatlands

Many tropical peatlands occur in areas with a distinct dry season. Drought duration and frequency may also be set to increase in the tropics as the climate changes [*Chadwick et al.*, 2015; *Corlett*, 2016]. High *K* values could be taken to indicate an inherent vulnerability of the tropical peatland C store, with even brief periods of dry weather allowing the peatland to drain and the peat to oxidize. However, *K* is not the sole control of the hydrological responsiveness of a peatland. It is necessary also to consider how hydraulic gradients develop in the peat and how these, in combination with *K*, affect groundwater flow [*Ingram*, 1983]. To simulate such water losses we modeled a typical tropical peatland dome (see section 2)—the San San Pond Sak dome in the Changuinola peat swamp close to where we measured *K*—using the groundwater component of the DigiBog peatland model [*Baird et al.*, 2012; *Morris et al.*, 2012]. The groundwater model is based on the Boussinesq equation for shallow unconfined aquifers [*McWhorter and Sunada*, 1977]. The San San Pond Sak dome is roughly circular in plan, with a diameter of close to 8 km. Because it is circular, we did not model all of it; rather, we modeled a sector (Figure 2b). We used our *K* data to parameterize the model (see the supporting information and its reference to *Binley et al.* [1989]). The part of the sector representing the center of the dome had a no-flow or Neumann boundary condition [*Franke et al.*, 1987]. The edge of the dome terminated in a mangrove creek, where the boundary condition was a fixed water level (type of Dirichlet condition) set 0.45 m below the peatland surface (mean sea level) (see the supporting information).

We also considered a theoretical situation where the dome had been ditch drained and converted to agricultural use such as palm oil production. We used ditch/drain spacings commonly found in such plantations on peat soils (parallel field ditches at 20 m and interceptor or collector ditches at 90 m) (AA Resources, 2016, goo.gl/skWOya, (last accessed 31st August 2016); Figure 2c) and set maximum (wet period) water levels in the ditches toward the upper end of the commonly used range (0.4 m below ground level (bgl) in the field ditches and 0.6 m bgl in the interceptor ditches). These levels in the ditches represent the boundary condition of the ditched peatland model.

Henceforth, we refer to the two peatland models as the natural peat dome (NPD) and the drained peat dome (DPD). We assumed that the upper layers of the DPD had a lower *K* than the NPD because of compaction associated with drainage (see the supporting information and its reference to *Whittington et al.* [2007]). In both the NPD and DPD we set up the model to simulate surface ponding and overland flow by introducing a model layer above those which represent peat. We modeled just one part of the drainage network in the DPD. Once water has drained into the collector or interceptor drain for each 90 m × 20 m block, it is conveyed to the peatland margin, so is effectively lost from the peatland. Therefore, our DPD results will apply to all of those areas of the peatland that have been ditched. More detail of the NPD and DPD groundwater models is provided in the supporting information.

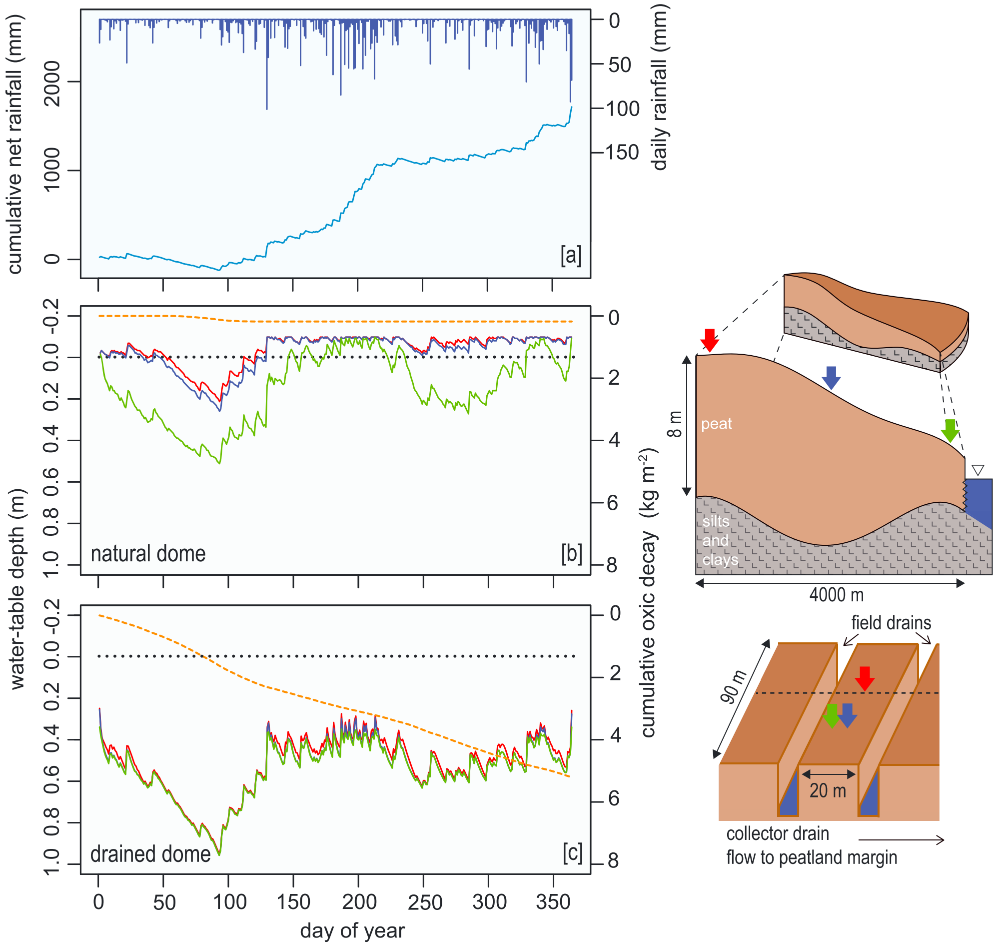

Figure 2. (a) Cumulative net rainfall (rainfall minus evapotranspiration) and daily rainfall used in the hydrological simulations. (b) Modeled water tables and cumulative mass lost in the NPD. The black dotted line indicates peatland surface; the red line indicates central dome water table; the blue line indicates water table halfway between dome center and margin; the green line indicates dome edge (40 m from margin) water table; the dashed orange line indicates cumulative organic matter mass lost. (c) Modeled water tables and cumulative mass lost in the DPD. The black dotted line indicates peatland surface; the red line indicates the center of rectangular plot, the blue line indicates halfway between center of plot and collector drain; the green line indicates 2 m from field drain; the dashed orange line indicates cumulative mass lost. The cartoons to the right of Figures 2b and 2c show, respectively, the NPD and the DPD as represented in the groundwater model. The colored arrows show the locations from which the water-table time series in the graphs were obtained.

We ran our simulations for 1 year and "forced" each model with a net rainfall (rainfall minus evapotranspiration) series derived from measurements made in 2014 close to the study area (Figure 2a) (see the supporting information and its reference to *Kaufman and Thompson* [2005], *Fábrega et al.* [2013], and *Paton* [2015]). Year 2014 was a typical rainfall year [*Paton*, 2015] for the area, which experiences a seasonal dry period between January and March. The annual net rainfall of 1715 mm (rainfall of 3175 mm minus evapotranspiration of 1460 mm) used in the model runs is similar to that reported for peatland sites in Southeast Asia (e.g., Central Kalimantan, Indonesia) [*Hirano et al.*, 2015]. The 90 day dry period coincided with the beginning of our model runs, but the initial condition of each model peatland was wet (water table at the peatland surface) to reflect what would normally be a wet prior period in November and December.

We also calculated the loss of C via oxic decay for each model peatland (see the supporting information), using a simple exponential decay model. Water-table depths from the centers of the NPD and DPD provided the thickness of the oxic zone. For each day, the exponential decay model was used to calculate the total oxic zone decay. By summing these losses over time we were able to calculate cumulative oxic decay and compare it between the NPD and DPD. We used a decay coefficient in the oxic decay model from the

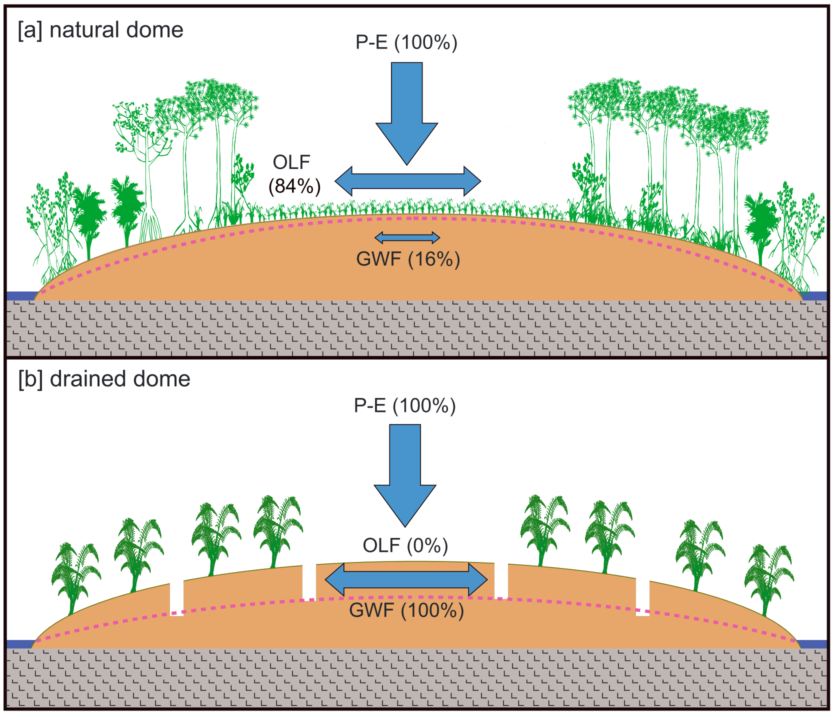

Figure 3. Conceptual model of hydrological pathways and degree of aeration in natural tropical peat domes and drained domes. P-E denotes net rainfall (rainfall minus evapotranspiration), OLF denotes overland flow, and GWF denotes groundwater flow. Arrow sizes (area of arrow) are approximately proportional to magnitude. The zone above the dashed line in each case indicates where oxic decomposition occurs during some or all of the year.

lower end of observed values (see the supporting information and its reference to *Brady* [1997], *Chimner and Ewel* [2005], and *Sjögersten et al.* [2014]), so our estimates of cumulative decay are probably conservative.

During the dry season (days 1–90; Figure 2a) at the beginning of the simulation, water tables in the bulk of the NPD (Figure 2b) respond mainly to evapotranspiration losses; there is little difference in water-table position relative to the peatland surface between the center of the dome (Figure 2b, red line) and 2 km distant (Figure 2b, blue line). Only close to the peatland margin is a clear groundwater flow effect seen, with water tables responding to both evapotranspiration and subsurface losses. In the bulk of the peatland outside of the initial 90 day dry season, the water level is above the ground surface and most water leaves the peatland via overland flow. This prediction of surface inundation is consistent with observations of "standing water" across much of the San San Pond Sak dome by *Phillips et al.* [1997]. Overall, relatively little water is lost from the NPD via subsurface groundwater flow: ~16% of net rainfall (equal to ~9% of rainfall). In stark comparison, all net rainfall at the DPD leaves the site via subsurface flow. As shown in Figure 2c, water levels in this scenario are always below the ground surface. Rainfall on the DPD causes brief rises in water tables followed by rapid falls, and water-table depths during dry periods are frequently greater than 0.50 m, reaching a maximum depth of close to 0.95 m.

These strongly contrasting results are summarized in Figure 3. The differences between the scenarios and the —apparently surprising—unimportance of subsurface groundwater flow in the NPD may be explained by differences in hydraulic gradients between the NPD and the DPD. Hydraulic gradients in shallow aquifers like the NPD are controlled by the surface topography. Because of its great lateral extent, such gradients in the NPD are very low which means that relatively little water is lost via subsurface groundwater flow. Conversely, relatively steep hydraulic gradients develop between the peat and the nearby drainage ditches in the DPD; rapid flow into the ditches occurs, keeping water tables well below the surface for most of the time.

The substantial differences in hydrological behavior are mirrored in the amount of peat decay that occurs, with that in the DPD exceeding by a factor of 31 that in the NPD: 5.20 kg m^{-2} yr^{-1} versus 0.17 kg m^{-2} yr^{-1}

(Figures 2b and 2c), or in C terms 2.86 and 0.09 kg C m^{-2} yr^{-1}. Notably, loss of organic matter occurs throughout the year in the DPD but only in the dry season in the NPD. The much higher rates of oxic decay in the DPD, together with the fundamental change from surface to subsurface flow after drainage—the latter meaning that dissolved decay products (principally dissolved organic C) are transported from the peat—help explain the recently observed destabilization of the C store in drained tropical peatlands [*Moore et al.*, 2011]. Although our simulations are based on data from a Mesoamerican peatland we show above (beginning of section 2 and discussion of *K* results at end of section 2) that it is broadly representative of tropical ombrotrophic peatlands more generally, including those in Southeast Asia. Therefore, it is, perhaps, not surprising that our independently modeled decay rate for the DPD is similar to the mean from a range of drained sites in Southeast Asia [*Hooijer et al.*, 2012] (see the supporting information and its reference to *Couwenberg et al.* [2010] and *den Haan et al.* [2012]).

4. Conclusion

Our model runs show how the effect of a high *K* is very different between natural and ditch-drained peatlands and reveal the mechanism for the contrast in rates of oxic decay between the two. Our results also suggest that ditch drainage of tropical peatlands and the plantation products it supports are unsustainable and that ditch blocking and re-wetting are necessary to protect the C store in tropical peatlands. This suggestion is based on the assumption that *K* in ditched peatlands does not decline with time after initial compaction. If *K* declines strongly as the peat decomposes, then the effects of drainage may be, to some degree, self-limiting. However, the available data on oxidation-related peat subsidence appear to indicate that such self-limiting behavior does not occur [*Hooijer et al.*, 2012] (see also the supporting information), with rates of oxidation and peat subsidence remaining high many years after drainage (>5–10 years).

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