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Global vulnerability of peatlands to fire and carbon loss

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Globally, the amount of carbon stored in peats exceeds that stored in vegetation and is similar in size to the current atmospheric carbon pool. Fire is a threat to many peat-rich biomes and has the potential to disturb these carbon stocks. Peat fires are dominated by smouldering combustion, which is ignited more readily than flaming combustion and can persist in wet conditions. In undisturbed peatlands, most of the peat carbon stock typically is protected from smouldering, and resistance to fire has led to a build-up of peat carbon storage in boreal and tropical regions over long timescales. But drying as a result of climate change and human activity lowers the water table in peatlands and increases the frequency and extent of peat fires. The combustion of deep peat affects older soil carbon that has not been part of the active carbon cycle for centuries to millennia, and thus will dictate the importance of peat fire emissions to the carbon cycle and feedbacks to the climate.

Peatland ecosystems accumulate thick organic soil layers because plant production exceeds decomposition throughout the entire organic soil column (Fig. 1). Peatlands cover only about 2–3% of the Earth's land surface but store around 25% of the world's soil carbon[1]. They are most abundant at northern high latitudes (Fig. 2a), where they cover roughly 4,000,000 km^2 of land[1] and store an estimated 500–600 gigatonnes of carbon (1 Gt = 10^{15} g). Tropical peatlands store an additional ~100 GtC across 400,000 km^2, primarily in Southeast Asia[1,2]. Hence the global peat carbon pool exceeds that of global vegetation (~560 GtC) and may be of similar magnitude to the atmospheric carbon pool (~850 GtC)[3].

Peat is defined as an organic soil composed of partially decayed plant remains with less than 20–35% mineral content. Slow decomposition rates created by anaerobic conditions are viewed as a necessary condition for peatland development[4]. Plant remains are deposited into the upper peat layer, which usually is located above the mean water table for at least part of the year, and undergo aerobic decomposition. The remaining organic matter is buried and transferred to the saturated peat layer below the water table where decomposition is minimal. Thus, water-table depth is a key regulator of peatland decomposition and peat accumulation rates. If warming or disturbance lowers the water table in peatlands, removal of anaerobic constraints on decomposition will stimulate loss of peat carbon to the atmosphere[5]. Moreover, a lower water table also will stimulate the loss of peat carbon through combustion during wildfires[2,6], which we discuss in more detail in the sections below.

Peatland vulnerability to burning

Because of high moisture contents, the bulk of peat soils in pristine peatlands is naturally protected from burning, aiding the accumulation of peat over centuries to millennia in both boreal and tropical settings[7,8]. In contrast, although a shallow peat layer accumulates in many well-drained boreal forests, these soil organic layers are typically consumed during wildfires, resulting in negligible soil carbon accumulation across multiple fire cycles[9].

As with all wildland fires, peatlands burn when an ignition event occurs in the presence of fuel and the right conditions to support combustion. In low-biomass systems, such as grasslands, availability and continuity of fuel load controls fire spread. In high-biomass systems such as peatlands, however, fires are controlled by heat transfer[10] and water content[11]. Peat fires generally are dominated by smouldering combustion, a flameless form of combustion that occurs more readily than flaming combustion[12]. Smouldering fires can persist under low temperatures, high moisture content and low oxygen concentrations[13] and as a result can burn for long periods (for example weeks, months or occasionally longer) despite rain events or changes in fire weather[12]. Although fast-moving flaming fires can travel at over 10 km h^{-1}, the rate of spread of smouldering can be as slow as 0.5 m per week[14]. Smouldering and flaming combustion during wildfires often are coupled. For example, smouldering peat can provide a pathway to a flaming fire even if the heat sources (embers or lightning) are too weak to ignite a flame directly[12].

In general, the peat carbon stock is protected from deep smouldering because of hydrologic self-regulation in peatlands[15,16]. The high porosity and storativity (storage coefficient) of surface peat layers minimize water-table variability and help to maintain peatland conditions that are too wet to sustain smouldering. If surface peat does dry and becomes flammable, the wet dense organic layers that occur deeper in the peat profile typically serve as a fire barrier. When natural or anthropogenic disturbances interfere with hydrologic self-regulation and allow further drying, however, deep peat becomes vulnerable to more frequent or more severe burning.

Across some boreal regions, particularly continental North America, the mean annual burn area has more than doubled in the past several decades, associated at least in part with regional warming[17,18]. Even during severe fire years, however, burning in undisturbed boreal peatlands typically is limited to the upper 10–20 cm of peat[19,20]. Forestry, agriculture, peat harvesting and road construction in boreal regions all lead to peatland drainage, which can greatly exacerbate the burning of peat. For example, the experimental

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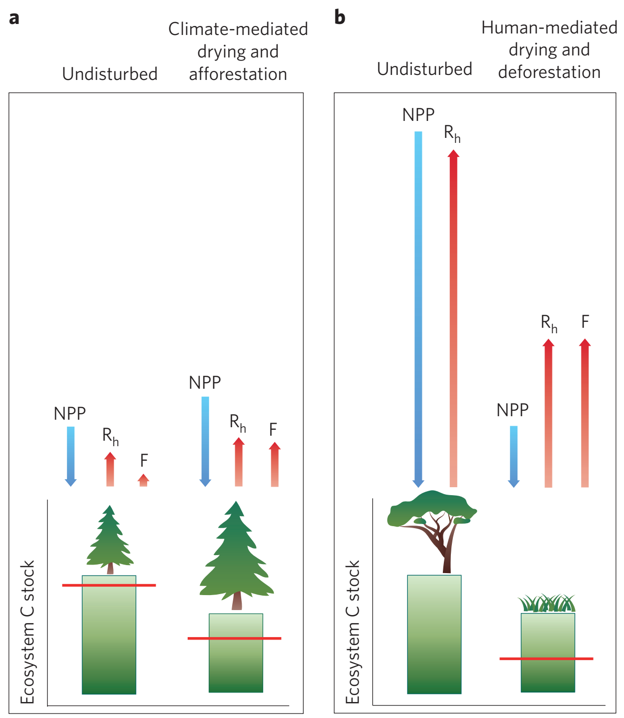

Figure 1 | Fire and drying losses of peat carbon to the atmosphere. **a**,**b**, Changes in net CO_2 uptake by plants (NPP) and carbon losses due to decomposition (heterotrophic respiration, R_h) and combustion (F) in response to fire and drying scenarios in (**a**) North American continental boreal peatlands and (**b**) Southeast Asian tropical swamps. The red lines denote changes in belowground fuels with drying. Arrows depict the direction of carbon transfer; arrow length indicates the magnitude of flux changes over a 100-year period relative to the undisturbed state (see Supplementary Information). Cooling and warming effects on climate are shown by blue and red arrows, respectively.

drainage of a Canadian fen increased emissions from burning ninefold, resulting in the emission of more than 450 years' worth of peat accumulation during a single fire[6].

In the tropics, abundant and regular rainfall combined with a humid understorey microclimate ensures that water inputs usually exceed evapotranspiration losses from peatlands, maintaining high peat moisture[21]. As a result, tropical swamps in their natural state are fire-resistant, owing to moist microclimate and low-flammability soils. Prior to large-scale settlement and agricultural conversion of peatlands, only occasional fires were detected on peatlands in Southeast Asia, even during drought spells. There was sufficient time between fires to allow recovery of forest cover[22]. Human activities in the tropics, including plantation development, agriculture and logging, have made peatlands more vulnerable to burning[23]. For example, disturbed peatlands in Southeast Asia are fire-prone because of the build-up of dry, flammable fuels as well as lower humidity resulting from a reduced tree canopy. Additionally, increased human access and activities increase the number of accidental and intentional fire ignitions. As a result, drained tropical peats tend to burn extensively. Fires consumed peat up to depths of 50 cm during the ENSO events of 1997–1998 and 2006[24,25]. Drainage and logging in tropical peatlands have also shortened fire frequencies, and repeated burning has further reduced the peatland carbon stock[26].

Fire and ecological feedbacks

Owing to natural fire resistance, fire has not played a significant historic role in the ecology of tropical peatlands. In contrast, wildfire plays an important role in the functioning of undisturbed boreal peatlands. Fire in boreal peatlands initiates plant successional change, increases soil temperatures and increases nutrient availability, in a manner similar to burning in other ecosystems[27,28]. Heterogeneous patterns in the combustion of peat promote biodiversity by supporting the establishment of more species-rich pioneer plant communities[27]. Spatial variation in combustion also influences the undulating hummocks and hollows that characterize the ground surface of most northern peatlands. In part because of the water-use strategies of *Sphagnum* (peat mosses), hummock peat has greater water-holding capacity and burns less extensively than peat in hollows, which reinforces these microtopographic features[29,30].

Deeper burning of peat resulting from water-table drawdown has consequences for post-fire ecosystem function and succession in both boreal and tropical regions. Although the energy release rate from flaming fires is greater than from smouldering, flaming produces high temperatures at the ground surface for only a brief period of time, with minimal heating of even shallow soil layers[31]. The longer duration of smouldering transfers more heat to surrounding soils and plants than active flaming. As a result, smouldering fires transfer heat deeper into the soil, and can lead to extensive fuel consumption that can be two orders of magnitude larger than that in flaming fires[12]. Increased smouldering of deeper peat as a result of water-table drawdown will increase damage to heat-sensitive plant roots and microorganisms such as ectomycorrhizae and bacteria[32,33]. These altered fire effects are likely to be more long-lived in disturbed peatlands. In both boreal and tropical peatlands, post-fire succession can cause shifts from non-flammable to more flammable fuel types, further increasing fire risk[26]. These post-fire shifts also are indicative of a loss of hydrological regulation in these systems, which is likely to cause a diminishment of peat accumulation even in the absence of repeated fires.

Carbon emissions from peatland burning

Throughout the Holocene, peatlands have had a net cooling effect on the Earth's climate[34] because the accumulation of peat has served as a persistent global sink of atmospheric CO_2. This is despite the fact that these systems also serve as a source of methane[34], which is produced by microbes under anaerobic conditions. Increased soil carbon losses from disturbed peatlands may, however, have significant climate impacts in the future[35]. From an atmospheric viewpoint, fires in undisturbed peatlands are most likely to be CO_2-neutral because the combustion of surface peat influences carbon that is cycling rapidly (that is, released carbon is quickly re-sequestered by recovering vegetation). This type of burning results in a near-neutral effect on atmospheric carbon over timescales of decades to centuries[36]. Yet increases in the depth of peat combustion have the potential to affect older soil carbon that has not been part of the active carbon cycle for centuries to millennia. If increases in fire frequency or burn severity lead to deeper burning in peatlands, these fires will no longer be carbon-neutral.

Perhaps as a harbinger of future emissions, the widespread and deep-burning peat fires in Indonesia in 1997 and 1998 released approximately 0.95 Gt of carbon[24,37], equivalent to ~15% of global fossil fuel emissions at that time. Peat fire emissions also have indirect climate impacts. Smoke produced by peat smouldering leads to regional haze and reduced light levels, which suppresses plant CO_2 uptake[38,39]. Smoke from peat fires could have more widespread influences, such as on marine ecosystems[40]. Smouldering is known to produce larger emissions of CO and CH_4, volatile organic compounds, polyaromatic hydrocarbons and particulate matter than flaming combustion. For example, tropical peat fires can emit three to six times as much particulate matter as grassland, forest or plantation fires per unit carbon combusted[8]. An understanding of the contribution of aerosols from biomass burning to radiative forcing in general is limited[3], and the lack of attention to aerosols from peat fires creates a striking knowledge gap with respect to future

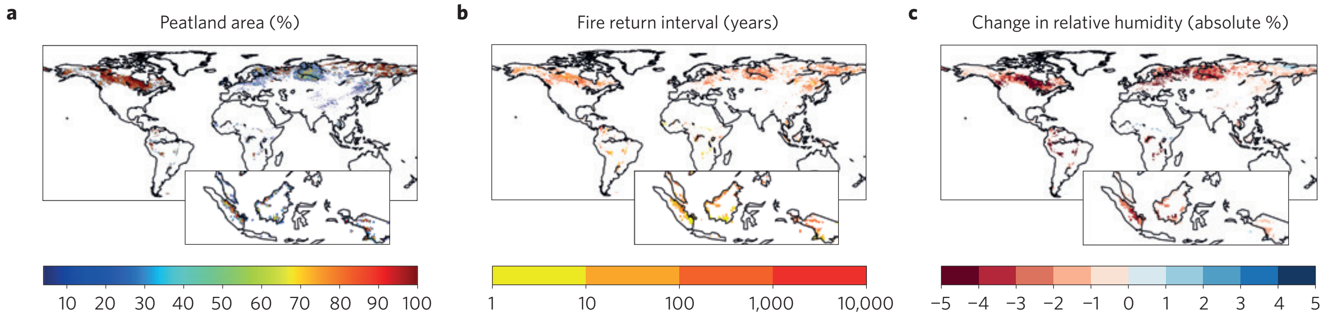

Figure 2 | Fire and climate dynamics in peatlands. a, Global peatland abundance as a percentage of each 0.25° × 0.25° grid cell based on multiple data sources[49]. **b**, Average fire return intervals based on satellite-derived burned area[50] in 0.25° × 0.25° grid cells coinciding with the peatland abundance data. **c**, Average change in relative humidity in the peatland grid cells based on the multimodel mean CMIP5 climate projections (http://cmip-pcmdi.llnl.gov/cmip5) in 2081–2100 compared with 1991–2010. In all panels, insets show an enlargement of Southeast Asia for visual purposes.

global climate change[41]. The quantity of peat-fire-derived emissions and the amounts emitted under different flaming and smouldering phases are poorly understood[12] and represent important areas of future research.

At regional to global scales, estimates of fire carbon emissions usually are derived from coarse-scale models, typically at spatial resolutions of 0.50° or 0.25° (Fig. 2), that have not been specifically designed to estimate peatland fire emissions. Peatlands themselves are difficult to map[42], and as a result there are few remote sensing products that allow for spatially explicit assessments of peatland abundance or the effects of wildfire on peatland carbon dynamics. Smouldering fires also are inherently difficult to detect with thermal anomaly maps, which often are used in wildfire detection[43]. For these reasons, estimates of fire carbon emissions depend on rough indications of fire frequencies (Fig. 2) and cannot resolve the high spatial variability typically associated with peatland fire dynamics. Despite these uncertainties, it is clear that peat fires have the potential to contribute significantly to global emissions of greenhouse gases.

Current and future risks of peat fires

Tropical and boreal peatlands differ in fire vulnerability. Low-latitude peatlands, like those of Indonesia, Malaysia, Peru, Brazil and the Caribbean region, are juxtaposed with densely populated urban areas. In these regions, drainage due to anthropogenic activities and increased frequency of human-caused ignitions have converted many peatlands from fire-resistant to fire-prone systems. In contrast, drier soils and increased lightning ignitions as a result of a warming climate are the most important factors increasing the likelihood of peat fires in the northern high latitudes; the role of human activities is less well understood in this region. It seems likely that future climate change will increase the vulnerability of peatlands to fire at a global scale. In virtually all areas where peatlands are abundant, relative humidity is expected to decrease during the burning season (Fig. 2c), which may increase the likelihood of peat fires.

Our synthesis of the current state of knowledge on carbon fluxes in peatland ecosystems indicates that losses via fire have the potential to equal or exceed those due to enhanced decomposition in disturbed boreal and tropical peatlands (Fig. 1; see also Supplementary Information). Climatic drying or anthropogenic drainage of peatlands enhances microbial decomposition of organic soils and stimulates fire activity. Drying in some boreal peatlands will stimulate tree growth and enhance total vegetation carbon uptake, but reduced moss productivity combined with a more frequent and severe fire regime will diminish peat accumulation and long-term carbon storage. In the tropics, anthropogenic drainage and deforestation reduces the vegetation carbon sink and shifts vegetation towards more flammable fuels. Drying in peatlands also increases the depth of belowground fuel combustion, releasing carbon to the atmosphere that has been stored in soils for centuries to millennia, thus creating a positive feedback to the climate system (Fig. 1). However, some processes relevant to peatland carbon balance are not presently understood. For example, because of lack of information we do not account for fluvial carbon losses under the drained or undrained scenarios. Our synthesis of available data on ecosystem carbon fluxes from boreal and tropical peatlands does, however, clearly point to the importance of fire to future peatland carbon balance.

Our understanding of the controls on peat fires, their effects on ecosystems and feedbacks to climate has greatly improved in the past decade. Increases in the frequency of peat fires also have consequences for landscape evolution and health that extend beyond the geosciences. Because smouldering peat fires are difficult to suppress, land managers will require new tools to respond to situations of extreme fire danger in areas where peatlands are prone to burning. Peat fire emissions cause diminished air quality[44], resulting in respiratory disease and human mortality[45–47]. In some cases, fire can cause a long-term change in the environment, such as the thawing of the underlying frozen ground in permafrost peatlands, the initiation of extensive peat erosion in upland temperate peatlands[48] or replacement of biodiverse forested peatlands in Southeast Asia by species-poor herbaceous communities[26].

If these changes enhance peat drying and lead to the accumulation of flammable fuels, they will increase fire frequencies and lead to even more severe burning of peat. Alternatively, if vegetation regrowth decreases insolation and wind penetrance, increases in local humidity could reduce peatland fire risk. Similarly, a reduction in woody fuels in favour of sparse, discontinuous vegetation could limit the spread of wildland fires in peatlands. The ecology of peat fires and the role of peat fires in long-term Earth system processes need to be explored more thoroughly in future research.

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Author contributions

M.R.T. led this synthesis and all authors contributed to writing and ideas presented.

Additional information

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Competing financial interests

The authors declare no competing financial interests.