This paper is published as:

Page, S.E. & Hooijer, A. (2016) In the line of fire: the peatlands of Southeast Asia. *Philosophical Transactions of the Royal Society B.,* 371, 20150176. Doi: 10.1098/rstb.2015.0176

In the line of fire: the peatlands of Southeast Asia

Page, S.E.[1*] & Hooijer, A.[2]

1: Department of Geography, University of Leicester, Leicester, UK, LE1 7RH

2: Stichting Deltares, Rotterdamseweg 185, 2629 HD Delft, The Netherlands

*: Author for correspondence: sep5@le.ac.uk

Abstract

Peatlands are a significant component of the global carbon (C) cycle, yet despite their role as a long-term C sink throughout the Holocene, they are increasingly vulnerable to destabilisation. Nowhere is this shift from sink to source happening more rapidly than in Southeast Asia, and nowhere else are the combined pressures of land use change and fire on peatland ecosystem C dynamics more evident nor the consequences more apparent. This review focuses on the peatlands of this region, tracing the link between deforestation and drainage and accelerating C emissions arising from peat mineralization and fire. It focuses on the implications of the recent increase in fire occurrence for air quality, human health, ecosystem resilience and the global C cycle. The scale and controls on peat driven C emissions are addressed, noting that although fires cause large, temporary peaks in C flux to the atmosphere, year-round emissions from peat mineralization are of a similar magnitude. The review concludes by advocating land management options to reduce future fire risk as part of wider peatland management strategies, while also proposing that this region's peat fire dynamic could become increasingly relevant to northern peatlands in a warming world.

Keywords: peat fire, peat mineralisation, peat swamp forest, tropical peatland, Southeast Asia, carbon

Introduction

Peatlands are a globally important carbon (C) pool. While covering only ~3% of the Earth's land surface, they contain an estimated 500 to 700 Gt (=Pg) of C, which is between 32 and 46% of the total soil C pool (~1500 Gt [1]) and likely exceeding that contained in the world's vegetation (500 Gt [2]). By any comparison, therefore, peat-forming ecosystems are a significant component of the global C cycle. In terms of both area (3.6 million km^2 [3]) and C storage (400-600 Gt [4]), the most extensive peatlands are found in northern regions of the world, but there are also significant deposits in the humid tropics. Collectively, these tropical peatlands cover some 0.4 million km^2 with a total C pool of 80 to 90 Gt [5]. Their greatest extent is in Southeast Asia (0.25 million km^2; 69 Gt C), with 57 Gt C in Indonesian peatlands and a smaller 9 Gt C in Malaysia [5]. Recent studies have also revealed smaller but none the less significant peatlands in the river basins of the Amazon [6] and Congo (Dargie et al., unpublished data). In some countries, the contribution made by peat to national C stocks can be substantial: there is more than ten times the amount of C stored in Canada's peatlands (150 Gt [7]) than in its managed forests (13.9 Gt [8]), while Indonesia's peat C pool comprises 74% of the country's total forest C pool (97 Gt; biomass plus soil) [5].

Most peat C has accumulated over long time periods; in northern peatlands, more than half was sequestered before 7,000 yrs BP [4], while some tropical deposits had an earlier genesis prior to the Last Glacial Maximum (< 18,000 yrs BP [9]). Yet despite their role as a long-term C sink throughout the Holocene, peat C pools are increasingly vulnerable to destabilisation through a combination of climatic warming, land use change and fire. In some regions of the world, the scale of anthropogenic activities has been such that peatland ecosystems have switched from long-term C sinks to short-term C sources, with the potential for further escalation of C loss as global warming accelerates into the future. Nowhere is this shift from sink to source happening more rapidly than in insular Southeast Asia, and nowhere else are the combined pressures of land use change and fire on peatland ecosystem C dynamics more evident nor the consequences more apparent. For these reasons, this review focuses on the peatlands of this region, initially tracing the link between land use change and C emissions from peat mineralization and fires before moving on to focus on the implications of increasing fire occurrence and frequency for ecosystem resilience, human health and the global C cycle. The review concludes by advocating land management options to reduce future fire risk while also proposing that the knowledge that has developed on Southeast Asia's peat fire dynamic could become increasingly relevant to northern peatlands that are subject to intensifying levels of human disturbance in a warming world.

Peatlands as vulnerable carbon pools

Hydrology plays a critical role in the peatland C cycle because the position of the water table controls the rate at which aerobic microbial decomposition (mineralization) of organic matter, and hence the rates of peat and C accumulation, can proceed. Under conditions of near permanent waterlogging, the absence of oxygen in the soil profile favours the accumulation of undecayed or partially decayed organic matter facilitating long-term ecosystem C storage over millennial time scales [4, 9]. But alterations accompanying anthropogenic land use changes and conversion for economic utilisation lead to drawdown of the water table. This exposes the upper part of the peat column to aerobic mineralization triggering the loss of peat

C from long-term storage, principally as a direct flux of CO_2 to the atmosphere, e.g. [10, 11, 12], but also as CH_4 from drainage ditches [13] and as dissolved organic C (DOC) in drainage waters [14, 15].

Across the world, peatlands have been drained to enable a range of land uses including livestock grazing, crop cultivation, forestry and peat extraction. Over the last three decades these changes have been most rapid and widespread in the tropics, where drainage combined with year-round warm temperatures drives high rates of mineralisation, while fire can also be an additional and often substantial source of greenhouse gas (GHG) emissions to the atmosphere. Drained tropical peatlands contribute almost 70% (~200 Mt C) of global drainage- and fire-derived GHG emissions from organic soils [16], with a smaller 30% from drained northern peatlands.

Peat fires have been recorded from many parts of the world including the UK [17]; Eurasia, e.g. the Moscow region of Russia [18, 19]; Canada and Alaska [20, 21, 22, 23]; Africa, e.g. the Okavango Delta [23]; South America, in Peru [24] and Brazil [25]; and Southeast Asia, particularly Indonesia [26, 27, 28, 29]. Some of these fires have been substantial, both in terms of area burnt and the severity of combustion, e.g. [21, 26, 30], but the peat fires of one region, insular Southeast Asia, are unique in exhibiting a rapidly escalating scale of fire extent, frequency and severity combined with serious immediate and longer-term consequences for climate, environment and society.

In an undisturbed state, the peatlands of lowland, insular Southeast Asia have a high degree of fire resistance. Intact peat swamp forest has a ground water table that is close to the forest floor. Thus the entire peat column, together with the living forest biomass, is nearly permanently moist. Nevertheless, the peat palaeo-record provides some evidence of intermittent fire-driven disturbances in this ecosystem. Cole et al. [31], for example, discuss the role that episodes of climatic variability, linked primarily with ENSO-related droughts over the last two to three millennia, may have played in facilitating occasional wildfires in the peat swamp forests of Sarawak. Their analysis of the pollen record indicates, however, that the vegetation remained relatively resilient despite these infrequent disturbances. There have been few studies of the palaeo-fire record in Southeast Asian peats, and thus it remains to be determined whether this picture of disturbance and post-fire recovery is typical of the developmental history of peat swamps elsewhere in this region. Nevertheless, it is likely that contemporary peat fires in Southeast Asia are now occurring at a much higher magnitude and frequency than those described from the palaeo-record.

The present-day peat fire dynamic of insular Southeast Asia is the consequence of what might be described as a 'perfect storm' of events that provide the key ingredients for fire activity, namely an abundance both of fuel and of ignition sources. Rapid forest degradation and loss driven by land use change to cash crop plantations has been powered by a burgeoning global demand for cheap supplies of forest and plantation products, notably timber, vegetable oil and pulpwood. Over the last two decades, this region has experienced some of the highest rates of forest loss and disturbance anywhere in the tropics. For the period 2000-2010, forest loss amounted to some 14,500 km^2 (0.59% yr^{-1}) with at least two-thirds of this occurring in Indonesia and Malaysia [32]. Peat swamp forests, however, underwent a still more rapid rate of decline compared to other forest types with a loss rate of 2.25% yr^{-1} (2000-2010), largely as a result of conversion to large-scale oil palm and pulpwood plantations [33] that increased in area by 12% annually between 2007 and 2010 [34]. The advent of these monoculture plantations has seen landscape-scale forest clearance and peat drainage but also widespread use of fire as a cheap, fast and effective means to clear large areas of forest debris and regrowth. Some of the most rapid transformation of peat swamp forest to plantation agriculture has taken place in eastern Sumatra [35] and in the Malaysian state of Sarawak [36, 37]. In these 'hot spots' of land conversion there is clear evidence that transformation of peatland has proceeded hand-in-hand with an increase in fire activity. In eastern Sumatra, most fires over the period 1996-2010 were concentrated in areas of heavily degraded forest on a land use change trajectory towards plantation or small-holder agriculture; in contrast, there were almost no fires in intact peat swamp forest which remained resilient to combustion [35]. A similar picture emerges for Sarawak where the peat swamp forest conversion rate to plantation was 8% per year for the period 2000 to 2010 [35], with rapid expansion to 5250 km^2 under oil palm accompanied by widespread use of fire [37] (Figure 1).

<< FIGURE 1 HERE>>

Outside the immediate boundaries of plantation concessions or small-holder farms, the fire-resilience of the remaining fragments of peat swamp forest has been greatly reduced, placing them at increased risk of accidental and purposeful ignitions through the combined effects of logging and drainage. Logging opens up the forest canopy, resulting in a warmer, drier forest microclimate which increases the flammability of above and belowground fuels. In addition, drainage from channels located either inside the forest to float out logged timber or at the forest-plantation boundary have lowered peatland water tables, even at distances of up to several kilometres beyond the drainage feature [11, 38]. Where peat swamp forest has burnt once, it will undergo a secondary succession back to closed forest. But in reality, it is far more likely that standing and dead timber remaining from the first fire increase the chance of a second fire, placing the ecosystem on a trajectory towards fire-prone fern- and sedge-dominated open vegetation with very limited opportunity for forest recovery [29, 39].

In Indonesia, there are now extensive areas of deforested and drained peatland that have no current economic use but are at high risk of accidental or purposeful ignitions. A portion of this fire-prone ‘idle’ land is in a temporary stage before eventual conversion to plantation agriculture, enabling those involved in plantation development to decouple from the original act of deforestation and claim no involvement in fires set to keep the land clear of encroaching scrub [35, 40]. Elsewhere, degraded peat-covered landscapes are the result of moribund agricultural schemes. The former Mega Rice Project (MRP) in southern Central Kalimantan, for example, was developed on 10,000 km^2 of peatland during the mid-1990s with the intention of converting the peat swamp forest to rice cultivation. The construction of more than 4000 km of canals combined with widespread forest disturbance resulted in more than half of this area burning during the intense ENSO-driven drought of 1997-8 [26]; much of this land was subsequently abandoned without further large-scale economic development taking place. Yet fire continues to be used on a regular basis to assert land tenure rights and to clear agricultural waste on small-holdings; if not carefully controlled, these fires escape into the wider landscape where they are very difficult to extinguish. The situation is further complicated by the arrival of migrant farmers from other parts of Indonesia who have little or no understanding of cultivating peat soils or the risk that land management fires pose in what is now a highly combustible environment.

The recent increase in the incidence of forest fires in insular Southeast Asia and their link to land use change has been emphasised by several studies. Using the region’s airport visibility records, Field et al. [41] demonstrated that large forest fires (not necessarily peat fires) have occurred on Sumatra since at least the 1960s linked to severe droughts during strong ENSO events. By contrast, in Kalimantan, and despite several previous severe ENSO-related drought years, large fires did not occur until the 1982-83 ENSO at a time of increasing land use change. While this study does not differentiate between fires on peat and non-peat soils, Goldammer and Siebert [42] suggest that of the 50,000 km^2 of forest affected by the 1982-83 fires on Borneo only some 10% (5,500 km^2) was peat swamp forest. Other studies also support the view that the peat covered landscapes have become increasingly fire prone since the onset of large scale human alteration, particularly from 1990 onwards. For example, during the intense drought of the 1997-98 ENSO, some 24,000 km^2 of peatland in Indonesia (12% of the total peat area [5]) burnt, releasing around 0.9 Gt carbon into the atmosphere (intermediate estimate [26]). In the decade that followed, extensive fires again occurred in peat swamp forest, particularly in western Indonesia. During the moderate ENSO of 2002, 73% of the forest area of the island of Borneo affected by fire was in peat swamp forest while during the weaker ENSO of 2005, it was 55% [43]. But although the most severe fires of recent years can be linked to droughts driven by the ENSO climate anomaly [26, 41], peat fires are now a regular feature of every dry season, even those of short duration [40]. Thus fire return intervals are decreasing to typically just a few years [29], in strong contrast to those for northern peatlands which range from centuries to millennia [21, 44, 45]. This current fire dynamic means that peat fires in insular Southeast Asia can no longer be considered occasional ecological events that result in short-term perturbations of peatland hydrology, structure and biodiversity followed by medium-term recovery to a new stable state. With every fire season, they are an escalating and intensifying environmental disaster with very profound implications for GHG emissions, air quality, human health, local livelihoods and regional economies. Indeed the very survival of the remaining peat swamp forests is threatened. Outside of Papua and the small sultanate of Brunei where relatively intact peat swamp forests still remain, the next decade could see total loss of this ecosystem in Southeast Asia through a combination of sustained land use change and fire.

Where there's smoke, there's (peat) fire

In peatland ecosystems, fires comprise both flaming and smouldering combustion [46]. While flaming, surface fires consume vegetation and litter, smouldering fires burn into and below the ground consuming the peat itself as a fuel source. Flaming fires may pass rapidly through the vegetation but smouldering fires burn slowly and persist for long periods of time, burning repeatedly in response to changing soil moisture and penetrating to different peat depths. Smouldering combustion is a low-temperature process that proceeds under reduced oxygen availability [46]. Peat moisture is the main factor limiting peat ignition and the start of the smouldering combustion process and fires will not usually establish in peat with a high moisture content [47, 48]. But once established, peat fires in Southeast Asia may burn for days, weeks or even months and are very difficult to control. Many occur in remote, off-road locations where they are difficult to extinguish using conventional fire-fighting techniques. They can also re-ignite, even after rain, and are often only fully extinguished by a rising ground water table following heavy rain.

<<FIGURE 2 HERE>>

The incomplete combustion that occurs during smouldering peat fires means that they are responsible for more substantial atmospheric and air quality impacts than vegetation fires. In addition to emissions of direct (CO_2, CH_4) and indirect (CO[1]) GHGs, they are the source of toxic compounds (e.g. benzene, hydrogen cyanide) and also high levels of small particulates ($PM_{2.5}$ - particulate matter with diameter less than 2.5 μm). This dense, toxic smoke (or 'haze', as it is disingenuously termed in Southeast Asia) poses significant health risks to human communities both within immediate proximity of the fires and at greater distances since smoke plumes can be transported over tens or even hundreds of kilometres from the source of the fires [49] (Figure 2). This is a pertinent issue for this densely-populated region where there is the potential for exposure of large numbers of people to smoke inhalation [50]. In 1997, 2002, 2006, 2009, 2013, 2014 and again in 2015, smoke from Indonesian peat fires resulted in severe haze pollution incidents affecting not only the inhabitants of Indonesia but also of Peninsular Malaysia, Singapore and even countries further afield, such as Thailand and the Phillipines. These pollution events are so acute that they result in serious economic and social impacts, including the closure of schools, the cancellation of flights, a downturn in business revenues and tourism, and human health problems, even for those experiencing short-term exposure to the smoke. Johnston et al. [51, 52] discuss the toll that regular peat fires in this region take on human health, estimating that the inhalation of particulates in smoke haze may be responsible for an additional 110,000 deaths per year through increased incidence of respiratory and cardiovascular conditions, particularly amongst children, the elderly and those with pre-existing respiratory problems. In addition, peat smoke also contains many carcinogenic gases such as hydrogen cyanide, ammonia and benzene that will inevitably result in a longer-term increase in ill health and mortality in the smoke-affected population.

---

[1] Carbon monoxide (CO) is an indirect GHG as it can produce increases in tropospheric ozone concentrations that increase radiative forcing (warming of the atmosphere).

The economic consequences of 'haze' events in Southeast Asia are difficult to quantify. A global comparison of the costs of fires over the period 1990-2013 ranks Indonesia as the second most affected country after Canada [53]. For the 1997-98 fires, Doerr & Santini [53], citing data from [54], rank this fire event, with a total cost of US$8 billion, as globally the most economically damaging on record over a 30 year period (1984-2013). Similarly, the 2015 Indonesian peat fires, which have been burning for several weeks as this review is being written, are estimated to have already cost billions of US dollars, accounting simply for the direct costs of fire-fighting and the loss of timber and crops, rather than any wider consequences. It could be argued, however, that a holistic financial account of the costs associated with land use change on peatland in this region should include an assessment of the impact that peat-derived GHG emissions have on the global climate system, whether those emissions are from fires or the slower but constant process of peat mineralization.

Fire feedbacks to the climate system

Knowledge of the amount of organic matter that is consumed during a fire is critical in estimating C and GHG emissions to the atmosphere. Fuel consumption per unit area burned during a peat fire can be ten times that of fires in other land covers [55] yet there are only a very limited number of studies providing ground- or laboratory-based data on the volume of peat consumed during peat fires. This requires quantitative estimation of the depth of burn as well as peat characteristics (i.e. bulk density and C content), which are not easy to determine in the field, particularly when fires are active in remote locations.

For North American peatlands, estimates of depth of burn range from 0.5 to 100 cm [56, 57, 58] but often with significant spatial heterogeneity [56] and with enhanced combustion during droughts and/or where there has been anthropogenic disturbance and drainage [57]. For tropical peatlands, there has been an even more limited number of field measurements. Page et al. [26] estimated that the 1997-98 fires in the former MRP area in Indonesia burnt to an average depth of around 50 cm. This was a high level of fuel consumption reflecting (a) fire occurrence in a landscape with high above ground biomass (intact and degraded forest); and (b) the low peat moisture content resulting from uncontrolled drainage and an ENSO drought (water levels were at or greater than 100 cm below the peat surface). Subsequent studies in the same area estimated a shallower depth of burn value of 33 cm during the less intense ENSO of 2006 [28].

<<FIGURE 3 HERE>>

In recognition of the need for more robust methodologies to assess burn severity in fire-prone tropical peatlands and its climate implications, a recent study has examined fire-driven peat loss at another location within the former MRP where up to eight successive fires occurred over a 15 year period [59, 60] (Figure 3). This investigation demonstrates a strong interdependence between depth of burn and both distance from nearest drainage canal (as a proxy for peat moisture conditions) and fire frequency. Regardless of fire frequency, the depth of peat consumed over the period 1996-2011 decreases from nearly 40 cm within close proximity to a canal (200-300 m), to 20 cm or less at distances of 800 m or more, illustrating that fire severity (in terms of peat combustion and C loss) increases with decreasing peat moisture content. A further finding is that the highest fire frequencies appeared only close to canals, indicating that the impact of canal drainage not only influences the volume of combusted peat, but also the probability of the re-occurrence of fires in these areas. Moreover, the study demonstrates differential depth of burn according to fire frequency, reducing from an average depth of 17 cm during a first fire, to 10 cm, 6 cm and 2 cm for second, third and fourth/subsequent fires, respectively. These values are averages obtained across all fire years in the study location and hence can be considered to be more representative of typical dry season fires rather than those occurring during ENSO droughts. The reducing depth of burn for second and subsequent fires is also noteworthy and can be interpreted as the result of several factors: (a) Initial fires occur in a landscape with high aboveground fuel load (forest), thus flaming, surface fires propel more intense drying of the peat surface resulting in deeper combustion than occurs during subsequent fires when the aboveground fuel load is reduced. Second fires may also take place in the presence of a sizeable aboveground fuel load (standing and fallen dead timber left from the first fire) but by third and subsequent fires, woody fire fuels have greatly diminished [29]. (b) Combustion lowers the peat surface bringing it closer to the position of the water table, thereby increasing peat moisture content and limiting the depth of dry peat fuel available for subsequent fires. (c) Fire alters the peat surface organic geochemistry, with labile C constituents replaced by more recalcitrant compounds with greater resistance to combustion during subsequent fires [61]. The reducing mass of peat consumed during successive fires is an important finding;

for the MRP area, where this study was undertaken, C emissions amount to 114 t C ha^{-1} for first fires, reducing to 13 t C ha^{-1} for fourth and subsequent fires, illustrating a considerable reduction in emissions for repeat fires in the same location and allowing more accurate, stratified reporting of emissions based on fire history. This knowledge should enable the climate modelling community to adopt a more realistic value for C emissions from recurring tropical peat fires in degraded, drained landscapes.

Another knowledge limitation is our understanding of the climate impact of smouldering peat fires, i.e. the amount and composition of gaseous emissions. IPCC guidance [62] on GHG emission factors for fires on organic soils is derived from only four studies, with only one addressing tropical peat fire emissions. While two subsequent studies [63] [Tom Smith, pers. comm.] confirm that IPCC tropical peat emission factors for CO_2 and CO are of the correct order of magnitude they also highlight variability in CH_4 emissions. Given the high Global Warming Potential of this gas (25 times that of CO_2 over a 100 year time scale [64]) this could have critical implications for the climate impact of peat fires and further studies are warranted to better understand the controls on fire-driven CH_4 emissions.

In addition to particulate and gaseous emissions, tropical peat fires also result in enhanced loss of fluvial C (dissolved and particulate organic C, DOC and POC) in waterways draining from fire-affected peatlands. In a study comparing total organic C fluxes (TOC = DOC + POC) from a peatland in Central Kalimantan, Gauci et al. [65] demonstrate that TOC fluxes are 32 to 68% larger in catchment channels affected by fires when compared to fluxes over the same time interval in a previous non-fire year. Increased fluvial C export will have direct impacts on the downstream aquatic ecosystem [66] and ultimately initiate enhanced evasion of CO_2 and CH_4 to the atmosphere through in-stream processing, further adding to the atmospheric loading of GHGs derived from peat fires.

Scaling Up

For insular Southeast Asia, peat fires have resulted in a magnitude of fire-related C emissions of the same order as that arising from peat mineralization, with a conservative C emissions estimate of around 0.1 Gt yr^{-1} from each source [59, 67], but excluding the initial spike in C emissions from peat mineralization within the first 5 years following drainage [59]. At around 0.2 Gt C yr^{-1}, this flux equals the annual C emissions from Malaysia and Indonesia arising from fossil fuel burning, cement production and gas flaring (0.215 Gt C yr^{-1};

http://cdiac.ornl.gov/trends/emis/top2011.tot) and is equivalent to around 2% of global fossil fuel emissions (9 Gt C yr^{-1}; *ibid*). The high C density of tropical peatland means that even a small change in the peat C store can lead to a large percentage change in the atmospheric C pool. This was evidenced by the 1997-98 forest and peat fires which contributed greatly to the largest annual increase in the atmospheric CO_2 concentration recorded at the Mauna Loa observatory since records began in 1957 [68]. Indications are that the scale of C emissions from the current 2015 fires will exceed that from recent fires in 2006 and 2009, and could approach that of the 1997-98 fires. These are large emissions. But it also needs to be recognized that while fires may cause temporary peaks, C emissions from peat mineralization are occurring continuously, year-round and are of a similar magnitude [16, 67].

In the firing line: managing and preventing peat fire

Peat fires in insular Southeast Asia involve interactions between different forms of land ownership, land management and land covers. In pre-disturbance landscapes there was limited risk of accidental ignitions or fire spread since the landscape was resistant to fire. The new landscapes of fragmented forests and drained peatlands are, by contrast, highly fire-prone, but while landscape resilience to fire has changed, human behaviours and land planning policies have either failed to take this into account or have purposefully exploited the flammability of the drained peat soils. The increasingly regular occurrence of peat fires can therefore be considered both a consequence of human activity (land use change, increased human access and an increased risk of anthropic ignitions) and of the absence of strong policy initiatives (e.g. no drain and no burn policies) and effective policy implementation. The occurrence of extended droughts associated with ENSO-events undoubtedly exacerbates the intensity of peat fires, but this climatic phenomenon is not, in itself, the root cause. Successful solutions to the haze must ultimately focus on the substrate for the fires – i.e. the peat itself. This will require a radical shift in human behaviours and practices, but also a fundamental recognition that solutions will require strong political leadership and investment.

The scientific evidence on both the drivers and scale of C emissions from peat fires in insular Southeast Asia and their local to global consequences has been well established for at least 10 years. But this body of scientific knowledge has been inadequately translated into land use policy and land management practices during a period when the region has been undergoing wide-ranging economic and societal transformations. Peatland drainage has been allowed and, indeed, even encouraged to continue apace while at the same time peat fires have become increasingly more frequent and severe, with ever more wide-ranging and acute consequences. Understanding the cause of the recent escalation in fire activity is neither challenging nor ambiguous: a combination of forest degradation and drainage has removed the intrinsic fire-resistance of the peat swamp forest ecosystem. And once drainage is initiated, it can have only one end point – oxidative loss of the peat substrate, either relatively slowly as a result of mineralization or rapidly as a result of fire. In seeking to find culprits for recent fires, large companies have been blamed for clearing land for plantation development. But a study of the 2006 peat fires established that 59% of the fire emissions from Sumatra and 73% of the emissions from Kalimantan actually originated outside timber and oil-palm concession boundaries [69], emphasising that there are many actors in the line of fire, from large multi-national companies through to medium-sized enterprises and small-holder farmers. While the largest plantation companies, such as Wilmar, have made recent commitments to 'zero burn', 'no deforestation' and 'no planting on peatlands', small and medium sized companies with smaller plantation estates have made less tangible and visible commitments to the 'sustainability' of their activities [70].

Any long-term solution seeking to slow down both the loss of tropical peat and the incidence of peat fires must strive to restore ecosystem resilience; in essence, the peat has to be kept wet. This will require hydrological interventions on drained peatlands at an unprecedented scale in order to slow down peat mineralization and reduce the risk of fire. This will come with inevitable economic consequences for stakeholders involved in agricultural production. There are now 130,000 km^2 of drained peatland in insular Southeast Asia [67], of which at least 30,000 km^2 in Peninsular Malaysia, Sumatra and Borneo are currently under industrial-scale oil palm and pulpwood plantations [34]. However, business-as-usual projections of future conversion rates for peatlands, based on historical rates, indicate that by 2020, 60,000 to 90,000 km^2 (40-60% of the total peatland area) could be converted to plantations [34]. Thus the geographical magnitude of the problem is daunting. There are technical challenges to be overcome in persuading policy makers and land managers that peat water tables should be maintained at a sufficiently high level to reduce fire risk, as well as substantial governance and political challenges, including uncertainties over land rights and weak policy implementation.

Some of the key steps that will be needed to reduce the incidence of peatland fires include:

- Preventing, absolutely, any further peatland forest clearance and drainage, while also mitigating fire risk and peat loss in existing plantation landscapes by improving water management, i.e. by maintaining water tables within narrow limits, accepting that while this may yield a reduction in fire occurrence there may be consequences for reduced crop yields. The economic cost benefit analysis of reduced yields should, however, be set against the much greater environmental and socio-economic costs associated with air pollution from peat fires. A water table depth in the range 50-70 cm is already accepted as best management practice by the Roundtable on Sustainable Palm Oil [71], but in many plantations the variability in rainfall and practicalities and costs of effective water management mean that water tables often fall well below 100 cm.
- Where plantation drainage abuts onto remnant blocks of peat swamp forest, initiatives will be needed to rehabilitate (i.e. re-wet) drained peat in critical areas – e.g. where remaining peat domes and peat forests are threatened by total loss to fire or mineralization. Residual forest is usually located on the deepest peat, so fire prevention will not only protect carbon stocks but also contribute to the protection of biodiversity and other forest ecosystem services. Effective protection will require concerted efforts by plantation owners to block canals and retire land from intensive plantation production. Further research is required to establish whether some of these hydrological buffer zones could support plantations of economically-useful native tree species that are tolerant of high water levels.
- Some of the larger companies involved in plantation agriculture on peat, e.g. several palm oil producers, have sustainability statements that include a commitment to zero burning. But zero burning needs to be accepted not just by these few big companies, but by all involved in peatland management. Small-holder farmers collectively manage a large land area on peat, but are poor and use fire as a cheap means to clear land. They need education programmes on land management and fire risk and guidance on cost-effective alternatives to the use of fire. Government no burn policies also need to be strictly enforced, with legal penalties for those found to be flouting the law.
- Rehabilitation of 'idle' peatlands with unregulated drainage needs to be initiated through landscape-scale restoration programmes. Re-wetting the peat can be achieved by blocking and infilling artificial drainage features and restoring a moist

microclimate through reforestation with appropriate native tree species. In the initial stages (at least for the first 20 years) these actions will need to be accompanied by active fire suppression and management until the ecosystem starts to recover some of its inherent fire resilience.

- All land managers and those involved in land use planning need to be educated that peat is a problem substrate entirely different from mineral soil. They need to understand that landscape resilience to fire has altered and that human behaviours, i.e. land management practices, need to adapt to this loss of resilience. Communities around peatlands needs to be informed about the risk of fire. There are probably important lessons that can be learnt from successful community engagement programmes in other fire-prone regions of the world, e.g. the charismatic Smokey Bear campaign in the United States [72].
- At a political level, solutions have to focus on fire prevention rather than fire fighting with a recognition that the haze problem does not disappear with the onset of the rainy season. Awareness of fire risk inevitably falls during wet years, but with ongoing peatland degradation and drainage, the risk (i.e. the fuel load) actually continues to increase until the next dry season brings a return of fires and hazy skies.

Conclusions

Fires on the peatlands of insular Southeast Asia have been substantial both in terms of area burnt and the severity of combustion. They are recognised as an important source of atmospheric GHGs, trace gases and aerosols, as well as having consequences for human health, livelihoods and economies. Both fire and peat mineralization have been the inevitable consequence of peatland conversion to large-scale agriculture driven by rapid economic and social transformations, largely unfettered by effective land use policy. While these changes have been unprecedented in their extent and rapidity, they provide a forewarning that future C losses from peat fires in climate zones outside the tropics could, without adequate controls, come to equal those from Southeast Asia.

On a global scale, fire weather seasons have lengthened over the last three decades [73] but in peatland regions, a change in weather pattern is only one of the drivers for increased fire occurrence. Given the natural resilience of peatlands to hydrological shifts, fire tipping points usually only occur when dry weather occurs in combination with human disturbance and increased access that together provide fire fuels and ignition sources. The 2010 fires around Moscow, for example, led to an extreme air pollution incident during a prolonged heatwave; but it was the combination of dry weather plus the availability of large amounts of dry fuel in drainage-affected peatlands that were the causal factors [74]. In boreal Canada, the potential for increased emissions from peat fires is also recognised [75]. Peat fires already make a significant contribution to fire C emissions in this country, with fires on peatlands in western Canada emitting an estimated 6 Mt C yr^{-1}, compared with an emission of 27 Mt C yr^{-1} from fires across the whole country [76]. It is predicted, however, that climate-and/or human-induced drying will increase fire occurrence [57, 75], raising concerns for GHG emissions and also for human health since boreal peat fires release not only particulates but also mercury into the atmosphere [77].

Peatlands across the globe have served as a long-term C sink, nevertheless predicted climatic changes towards drier conditions and longer fire seasons combined with ongoing human disturbances will inevitably lead to modified peat C mineralization and fire regimes and faster rates of GHG emissions to the atmosphere [45]. On the balance of available evidence, it therefore seems highly likely that the consequences of disturbance and drainage of peatlands in Southeast Asia are a harbinger of the potential for the destabilisation of the much larger peat C stocks located in northern peatlands.

Competing Interests

The authors declare no competing interests.

References

[1] Scharlemann, J.P.W., Tanner, E.V.J., Hiederer, R. & Kapos, V. 2014. Global soil carbon: understanding and managing the largest terrestrial carbon pool. *Carbon Man.* **5**: 81-91.

[2] Ruesch, A. S. & Gibbs, H. K. 2008. New global biomass carbon map for the year 2000 based on IPCC Tier-1 Methodology. Available online from the Carbon Dioxide Information Analysis Center *[http://cdiac.ornl.gov]*, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

[3] Immirzi, C. P., Maltby, E. & Clymo, R.S. 1992. *The global status of peatlands and their role in carbon cycling*. London, Wetland Ecosystems Research Group, Dept. Geography, University of Exeter, 145 pp.
[4] Yu, Z.C. 2012. Northern peatland carbon stocks and dynamics: a review. *Biogeosci*. **9**: 4071-4085.
[5] Page, S.E., Rieley, J.O. & Banks, C.J. 2011 Global and regional importance of the tropical peatland carbon pool. *Glob. Change Biol.* **17**: 798-818
[6] Lahteenoja, O., Reategui, Y., Rasanen, M., del Castillo, D., Oinonen, M. & Page, S.E. 2011. The large Amazonian bio-geological peatland carbon sink: the subsiding Pastaza-Marañón foreland basin, Peru. *Glob. Change Biol.* **18**:164–78.
[7] Tarnocai, C., Kettles, I. M. & Lacelle. B. 2005. *Peatlands of Canada*.
Ottawa, Agriculture and Agri-Food Canada, Research Branch, Ottawa, Canada.
[8] Food and Agriculture Organization (FAO) 2006. *Global Forest Resources Assessment 2005: Progress Towards Sustainable Forest Management*. FAO Forestry Paper 147, Rome. Available at: http://www.fao.org/forestry/site/1191/en/
[9] Page, S.E., Wűst, R.A.J., Weiss, D., Rieley, J.O., Shotyk, W. & Limin, S.H. 2004. 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. Quat. Sci.* **19**: 625-635.
[10] Kasimir-Klemedtsson, Å., Klemedtsson, L., Berglund, K., Martikainen, P., Silvola, J. & Oenema, O. 1997. Greenhouse gas emissions from farmed organic soils: a review. *Soil Use & Man*. **13**: 245–250.
[11] Hooijer, A., Page, S.E., Jauhiainen, J., Lee, W.A., Idris, A. & Anshari, G. 2012. Subsidence and carbon loss in drained tropical peatlands. *Biogeosciences* **9**: 1053-1071.
[12] Jauhiainen, J., Hooijer, A. & Page, S.E. 2012. Carbon dioxide emissions from an *Acacia* plantation on peatland in Sumatra, Indonesia. *Biogeosciences* **9**: 617-630.
[13] Jauhiainen, J. & Silvennoinen, H. 2012. Diffusion of GHG fluxes at tropical peatland drainage canal water surfaces. *Suo* **63**: 93–105.
[14] Moore, S., Evans, C.D., Page, S.E., Garnett, M.H., Jones, T.G., Freeman, C., Limin, S.H. & Gauci, V. 2013 Fluvial organic carbon fluxes reveal deep instability of deforested tropical peatlands. *Nature* **493**: 660-663.
[15] Evans, C.D, Page, S.E., Jones, T., Moore, S., Gauci, V., Laiho, R., Hruska, J., Allott, E., Billett, M., Freeman, C. & Garnett, M. 2014 Contrasting susceptibility of tropical and high-

latitude peats to fluvial loss of stored carbon following drainage. *Glob. Biogeochem. Cycles* **28**: 1215-1234.
[16] Biancalani, R. & Avagyan, A. (eds) 2014. *Towards climate responsible peatland management practices: Part 1.* FAO, Rome.
[17] McMorrow et al., this vol.
[18] Chubarova, N., Prilepsky, N. G., Rublev, A. N. & Riebau, A. R. 2009. *A Mega-Fire Event in Central Russia: Fire Weather, Radiative, and Optical Properties of the Atmosphere, and Consequences for Sub-boreal Forest Plants.* In: A. Bytnerowicz, M. Arbaugh, A. Riebau & C. Andersen (eds.) Developments in Environmental Science, Volume 8, Elsevier, doi:10.1016/S1474- 8177(08)00011-9.
[19] Konovalov, I.B., Beekmann, M., Kuznetsova, I.N., Yurova, A. & Zvyagintsev, A.M. 2011. Atmospheric impacts of the 2010 Russian wild fires: integrating modelling and measurements of the extreme air pollution episode in the Moscow megacity region. *Atmos. Chem. Phys*. **11**: 10031-10056.
[20] Benscoter, B. W. and R. K. Wieder 2003. Variability in organic matter lost by combustion in a boreal bog during the 2001 Chisholm fire. *Can. J. For. Res.* **33**: 2509-2513.
[21] Turetsky, M.R., Amiro, B. & J. Bhatti. 2004. Peatland burning and its relationship to fire weather in western Canada. *Glob. Biogeochem. Cycles* **18**: GB4014
[22] Kasischke, E. S., E. J. Hyer, P. C. Novelli, L. P. Bruhwiler, N. H. F. French, A. I. Sukhinin, J. H. Hewson & B. J. Stocks 2005. Influences of boreal fire emissions on Northern Hemisphere atmospheric carbon and carbon monoxide. *Glob. Biogeochem. Cycles* **19**: GB1012, doi:10.1029/2004GB002300.
[23] Ellery, W. N., Ellery, K., McCarthy, T. S., Cairncross, B. & Oeflofse, R. 1989. A peat fire in the Okavango Delta, Botswana, and its importance as an ecosystem process. *Afric. J. Ecol*. **27**: 7-21.
[24] Román-Cuesta, RM., Salinas, N., Asbjornsen, H. Oliveras, I., Huaman, V., Gutierrez, Y., Puelles, L., Kala, J., Yabar, D., Rojas, M., Astete, R., Jordan, D., Silman, M., Mosandl, R., Weber, M., Stimm, B., Gunter, S., Knoke, T. & Malhi, Y. 2011. Implications of fires on carbon budgets in Andean cloud montane forests: The importance of peat soils and tree resprouting. *For. Ecol. & Man.* **261**: 1987–1997.
[25] Flores, B.M., Piedade, M-TF. & Nelson, B.W. 2014. Fire disturbance in Amazonian blackwater floodplain forests. *Plant Ecol. & Div.*, **7**: 319-327.

[26] Page, S.E., Siegert, F., Rieley, J.O., Boehm, H-D.V., Jaya, A. & Limin, S. 2002. The amount of carbon released from peat and forest fires in Indonesia in 1997. *Nature* **420**: 61-65.

[27] Usup, A., Hashimoto, Y., Takahashi, H. & Hayasaka, H. 2004. Combustion and thermal characteristics of peat fire in tropical peatland in Central Kalimantan, Indonesia. *Tropics* **14**: 1-19.

[28] Ballhorn, U., Siegert, F., Mason, M. & Limin, S. 2009 Derivation of burn scar depths and estimation of carbon emissions with LIDAR in Indonesian peatlands. *PNAS* **106**: 21213–21218.

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

[30] Reddy, A.D., Hawbaker, T.J., Wurster, F., Zhu, Z., Ward, S., Newcomb, D. & Murray, D. 2015. Quantifying soil carbon loss and uncertainty from a peatland wildfire using multi-temporal LiDAR. Rem. Sens. Env. 170: 306-316. doi:10.1016/j.rse.2015.09.017

[31] Cole, L.E.S., Bhagwat, S.A. & Willis, K.J. 2015. Long-term disturbance dynamics and resilience of tropical peat swamp forests. *J. Ecol*. **103**: 16-30.

[32] Stibig, H-J., Achard, F., Carboni, S., Rasi, R. & Miettinen, J. 2014. Change in tropical forest cover of Southeast Asia from 1990 to 2010. *Biogeosci.* **11**: 247-258.

[33] Miettinen, J., Shi, C., & Liew, S. C. 2011. Deforestation rates in insular Southeast Asia between 2000 and 2010. *Glob. Change Biol*. **17**: 2261–2270.

[34] Mietinnen, J, Hooijer, A., Shi, C., Tollenaar, D., Vernimmen, R., Liew, S.C., Malins, C. & Page, S.E. 2012a. Extent of industrial plantations on Southeast Asian peatlands in 2010 with analysis of historical expansion and future projections. *Glob. Change Biol. – Bioenergy* **4**: 908-918.

[35] Miettinen, J., Hooijer, A., Wang, J., Shi, C. & Liew, S.C. 2012b. Peatland degradation and conversion sequences and interrelations in Sumatra. *Reg. Environ. Change* **12**: 729–37.

[36] Sarvision 2011. *Impact of oil palm plantations on peatland conversion in Sarawak 2005-2010: Summary Report.* Sarvision, Wageningen, The Netherlands, 14 pp. (http://www.wetlands.org/Portals/0/publications/Report/Malaysia%20Sarvision.pdf)

[37] Hooijer, A., Vernimmen, R., Visser, M. & Mawdsley, N. 2015. *Flooding projections from elevation and subsidence models for oil palm plantations in the Rajang Delta peatlands, Sarawak, Malaysia*. Deltares report 1207384, The Netherlands, 76 pp.

[38] DID Sarawak, 2001. *Water management guidelines for agricultural development in lowland peat swamps of Sarawak*. Report of the Department of Irrigation and Drainage, Sarawak, Malaysia, 78 pp.

[39] Page, S., Hosciło, A., Wösten, H., Jauhiainen, J., Silvius, M., Rieley, J., Ritzema, H., Tansey, K., Graham, L., Vasander, H. & Limin, S. 2009. Restoration ecology of lowland tropical peatlands in Southeast Asia: Current knowledge and future research directions. *Ecosystems*, **12**: 888–905.
[40] Gaveau, D.L.A., Salim, M.A., Hergoualc'h, K., Locatelli, B., Sloan, S., Wooster, M., Marlier, M.E., Molidena, E., Yaen, H., DeFries, R., Verchot, L., Murdiyarso, D., Nasi, R., Holmgren, P. & Sheil, D. 2014. Major atmospheric emissions from peat fires in Southeast Asia during non-drought years: evidence from the 2013 Sumatran fires. *Sci. Rep*. **4:** 6112 doi:10.1038/srep06112
[41] Field, R.D., van der Werf, G.R. & Shen, S.S.P. 2009. Human amplification of drought-induced biomass burning in Indonesia since 1960. *Nat. Geosci*. **2**: 185–8.
[42] Goldammer, J.G., and B. Seibert. 1990. The impact of droughts and forest fires on tropical lowland rain forest of Eastern Borneo. In: *Fire in the tropical biota. Ecosystem processes and global challenges* (J.G. Goldammer, ed.), 11-31. Ecological Studies 84, Springer-Verlag, Berlin-Heidelberg-New York, 497pp.
[43] Langner, A., Miettinen, J. & Siegert, F. 2007. Land cover change 2002–2005 in Borneo and the role of fire derived from MODIS imagery. *Glob. Change Biol.* **13**: 2329–2340.
[44] Kuhry, P. 1994. The role of fire in the development of Sphagnum-dominated peatlands in western boreal Canada. *J. Ecol.* **82**: 899-910.
[45] Turetsky, M., Benscoter, B., Page, S.E., Rein, G., van der Werf, G. & Watts, A. 2015 Global vulnerability of peatlands to fire and carbon loss. *Nature Geosci.,* DOI: 10.1038/NGEO2325
[46] Rein, G., Cleaver, N., Ashton, C., Pironi, P. & Torero, J.L. 2008 The severity of smouldering peat fires and damage to the forest soil. *Catena* **74**: 304-309.
[47] Frandsen, W.H. 1987. The influence of moisture and mineral soil on the combustion limits of smoldering forest duff. *Can. J. For. Res*. **17**:1540-1544.
[48] Frandsen, W.H. 1997. Ignition probability of organic soils. *Can. J. For. Res*. **27**:1471-1477.
[49] Wooster (this volume)
[50] Doerr (this volume)
[51] Johnston, F.H., Henderson, S.B., Chen, Y., Randerson, J.T., Marlier, M., DeFries, R.S., Kinney, P., Bowman, D.M.J.S. & Brauer, M. 2012. Estimated global mortality attributable to smoke from landscape fires. *Env. Health Persp*. **120**: 695-701.
[52] Johnston, F.H., this vol.

[53] Doerr, S. & Santin, C. 2013. *Wildfire: A Burning Issue for Insurers?* Lloyds.
[54] EM-DAT 2013. *The OFDA/CRED International Disaster Database*. Université Catholique de Louvain, Brussels, Belgium (www.emdat.be).
[55] Van Leeuwen, T.T., van der Werf, G.R., Hoffmann, A.A., Detmers, R.G., Rücker, G., French, N.H.F., Archibald, S., Carvalho Jr., J.A., Cook, G.D., de Groot, W.J., Hely, E.S., Kasischke, E.S., Kloster, S., McCarty, J.L., Pettinari, M.L., Savadogo, P., Alvarado, E.C., Bsochetti, L., Manuri, S., Meyer, C.P., Siegert, F., Trollope, L.A. & Trollope, W.S.W. 2014. Biomass burning fuel consumption rates: a field measurement database. *Biogeosci*. **11**: 7305-7329.
[56] Poulter, B., Christensen, N. L. & Halpin, P. N. 2006. Carbon emissions from a temperate peat fire and its relevance to interannual variability of trace atmospheric greenhouse gases. *J. Geophys. Res.* **111**: D06301, doi:10.1029/2005JD006455
[57] Turetsky, M. R., Donahue, W. F. & Benscoter, B. W. 2011. Experimental drying intensifies burning and carbon losses in a northern peatland. *Nature Comm.* **2**, 514 (2011).
[58] Zoltai, S. C., Morrissey, L. A., Livingston, G. P. & de Groot, W. J. 1998. Effects of fires on carbon cycling in North American boreal peatlands. *Env. Revs* **6**: 13-24.
[59] Hooijer, A., Page, S.E., Navratil, P., Vernimmen, R., Van der Vat, M., Tansey, K., Konecny, K., Siegert, F., Ballhorn, U. & Mawdsley, N. 2014. *Carbon emissions from drained and degraded peatland in Indonesia and emission factors for measurement, reporting and verification (MRV) of peatland greenhouse gas emissions – a summary of KFCP research results for practitioners*. IAFCP, Jakarta, Indonesia.
[60] Konecny, K., Ballhorn, U., Navratil, P., Jubanski, J., Page, S.E., Tansey, K.T., Hooijer, A., Vernimmen, R. & Siegert, F. 2016. Carbon emissions from recurrent fires in drained tropical peatlands. *Global Change Biology*. DOI: 10.1111/gcb.13186.
[61] Milner, L., Boom, A., Page, S.E. & Matthews, R. (*in prep*). Effects of fire on the organic matter composition of a tropical peatland in Central Kalimantan, Indonesia.
[62] IPCC 2014. *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands.* Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M. & Troxler, T.G. (eds). IPCC, Switzerland.
[63] Hamada, Y., Darung, U., Limin, S. & Hatano, R. 2013. Characteristics of fire-generated gas emission observed during a large peatland fire in 2009 at Kalimantan, Indonesia. *Atmos. Env*. **74**: 177-181.

[64] IPCC 2007. *Climate Change 2007: Working Group I: The Physical Science Basis.* Cambridge University Press, UK.
[65] Gauci, V., Moore, S., Evans, C.D., Page, S.E., Hoscilo, A. & Limin, S. (in prep.) A large fluvial carbon pulse from El Nino fire-affected tropical peatlands.
[66] Martin, this vol.
[67] Hooijer, A., Page, S.E., Canadell, J.G., Silvius, M., Kwadijk, J., Wösten, H. & Jauhiainen, J. 2010. Current and future CO_2 emissions from drained peatlands in Southeast Asia. *Biogeosciences* **7**: 1505-1514.
[68] IPCC, 2001. Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change [Houghton, J.T., Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell, and C.A. Johnson (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 881pp.
[69] Marlier, M.E., DeFries, R.S., Kim, P.S., Koplitz, S.N., Jacob, D.J., Mickley, L.J. & Myers, S.S. 2015. Fire emissions and regional air quality impacts from fires in oil palm, timber, and logging concessions in Indonesia. *Env. Res. Letts*. **10**: 085005
[70] Padfield, R. et al. (*in press*) Landscapes in transition: An analysis of sustainable policy initiatives and emerging corporate commitments in the palm oil industry. *Landscape Research*.
[71] Parish, F., Lim, S.S., Perumal, B. & Giesen, W. (eds) RSPO Manual on Best Management Practices (BMPs) for Management and Rehabilitation of Natural Vegetation Associated with Oil Palm Cultivation on Peat. Roundtable on Sustainable Palm Oil, Kuala Lumpur
[72] Pyne, this vol.
[73] Jolly, W.M., Cochrane, M.A., Freeborn, P.H., Holden, Z.A., Brown, T.J., Williamson, G.J. & Bowman, D.M.J.S. 2015. Climate-induced variations in global wildfire danger from 1979 to 2013. *Nat. Comms*. **6**: 7537.
[74] Zvyagintsev, A.M., Blum, O.B., Glazkova, A.A., Kotel'nikov, S.N., Kuznetsova, I.N., Lapchenko, V.A., Lezina, E.A., Miller, E.A., Milyaev, V.A., Popikov, A.P. 2011 Air pollution over European Russia and Ukraine under the hot summer conditions of 2010. *Izvestiya, Atmos. Ocean Phys*. **47**: 699–707.

[75] Kettridge, N., Turetsky, M.R., Sherwood, J.H., Thompson, D.K., Miller, C.A., Benscoter, B.W., Flannigan, M.D., Wotton, B.M. & Waddington, J.M. 2015. Moderate drop in water table increases peatland vulnerability to post-fire regime shift. *Sci. Rep*. **5**: 8063.
[76] Canadian Forest Service, 2012. *Peatland Fires and Carbon Emissions*. Frontline Express Bulletin 50, Natural Resources Canada.
[77] Turetsky, M.R., Harden, J.W., Friedli, H., Flannigan, M., Payne, N., Crock, J. & Radke, L. 2006. Wildfires threaten mercury stocks in northern soils. *Geophys. Res. Letts* **33**: 10.1029/2005GL025595.

Figure Captions

Figure 1 (a): Land cover change for the Rajang Delta in Sarawak, northern Borneo (reclassified from Miettinen et al., 2012) with 2014 industrial plantation cover added as determined from Landsat. Top: Land cover in 2000. Middle: Plantation extent in 2004 and 2009. Bottom: Land cover in 2014. A major decrease in forest cover occurs between 2000 and 2010 (from 56% to 16%), while plantation cover increases from 2000 to 2014 (from 6% to 47%).
Figure 1 (b): Extent of current (June 2014) plantations and MODIS fire hotspots.
[Source: Hooijer et al., 2015]

Figure 2: Smoke haze from peat fires shrouds the centre of the provincial capital of Palangkaraya, Central Kalimantan, October 2015 (photo source: Suzanne Turnock and Outrop).

Figure 3 (a): Map showing the location of the Kalimantan Forests & Carbon Partnership project area on deep peat in Central Kalimantan province, Indonesian Borneo

Figure 3 (b): Fire frequency in the KFCP project area over the period 1990-2011. [Source: Hooijer et al., 2014 & Konecny et al., in review].