Tropical peatlands in the anthropocene: lessons from the past

Authors:
Lydia E.S. Cole[1C]
Christine M. Åkesson[1]
K. Anggi Hapsari[2]
Donna Hawthorne[1]
Katherine H. Roucoux[1]
Nicholas T. Girkin[3]
Hannah V. Cooper[4]
Martha J. Ledger[4]
Patrick O'Reilly[5,6]
Sara A. Thornton[5,7]

Affiliations:
[1]School of Geography and Sustainable Development, University of St Andrews, UK
[2]Albrecht-von-Haller Institute, University of Goettingen, DE
[3]Cranfield Soil and Agrifood Institute, Cranfield University, UK
[4]School of Biosciences, University of Nottingham, UK
[5]School of Geography, Geology and the Environment, University of Leicester, UK
[6]Liverpool John Moores University
[7]Borneo Nature Foundation International, Tremough Innovation Centre, Penryn, Cornwall, UK

[C]Corresponding author: *School of Geography* and Sustainable Development, University of *St Andrews,* Irvine Building, North Street, *St Andrews. Fife, Scotland,* KY16 9AL, lesc1@st-andrews.ac.uk

Key words: Anthropocene, carbon, climate change, drainage, fire, palaeoecology, palaeoanthropocene, tropical peat

Abstract
The status of tropical peatlands, one of Earth's most efficient natural carbon stores, is of increasing international concern as they experience rising threat from deforestation and drainage. Peatlands form over thousands of years, where waterlogged conditions result in accumulation of organic matter. Vast areas of Southeast Asian peatlands have been impacted by land use change and fires, whilst lowland tropical peatlands of Central Africa and South America remain largely hydrologically intact. To predict accurately how these peatlands may respond to potential future disturbances, an understanding of their long-term history is necessary. This paper reviews the palaeoecological literature on tropical peatlands of Southeast Asia, Central Africa and South America. It addresses the following questions: (i) what were the past ecological dynamics of peatlands before human activity?; (ii) how did they respond to anthropogenic and natural disturbances through the palaeoanthropocene, the period from whence evidence for human presence first appeared?; and, (iii) given their past ecological resilience and current exposure to accelerating human impacts, how might the peatlands respond to drivers of change prevalent in the anthropocene? Through~~y~~ synthesising palaeoecological records, this review demonstrates how tropical peatland ecosystems have responded dynamically, persisting through fire (both natural and anthropogenic), climatic and

human-induced disturbances in the palaeoanthropocene. Ecosystem resilience does, however, appear to be compromised in the past *c*. 200 years in Southeast Asian peatlands, faced with transformative anthropogenic impacts. In combination, this review's findings present a pantropical perspective on peatland ecosystem dynamics, providing useful insights for informing conservation and more responsible management.

1.1 Introduction

Tropical peatlands play a major role in the global carbon cycle (Sjögersten et al., 2014). Containing approximately 152 – 288 billion tonnes of carbon (Ribeiro et al., 2021), they represent one of Earth's most efficient terrestrial carbon stores, illustrated by their capacity to contain up to *c*. 20 times more carbon per hectare than tropical forest (Murdiyarso et al., 2019; Saatchi et al., 2011). When hydrologically intact, waterlogged conditions create an anaerobic environment which, along with high acidity and low nutrient content, slow the rate of organic matter decomposition, leading to the accumulation of peat, a carbon-rich soil (Page and Baird, 2016). Within the last decade, investment in mapping and modelling the carbon dynamics and distribution (Lawson et al., 2015) has increased across the *c*. 58.7 Mha of peatlands between *c*. 23.5°N and 23.5°S (modelled by Leifeld & Menichetti, 2018). Research has focused on the three largest tropical areas: Southeast Asia (Koh et al., 2011; Miettinen et al., 2016; Wijedasa et al., 2018); Africa's Central Congo Basin (Dargie et al., 2017); and western Amazonia in South America (Draper et al., 2014) (Fig. 1).

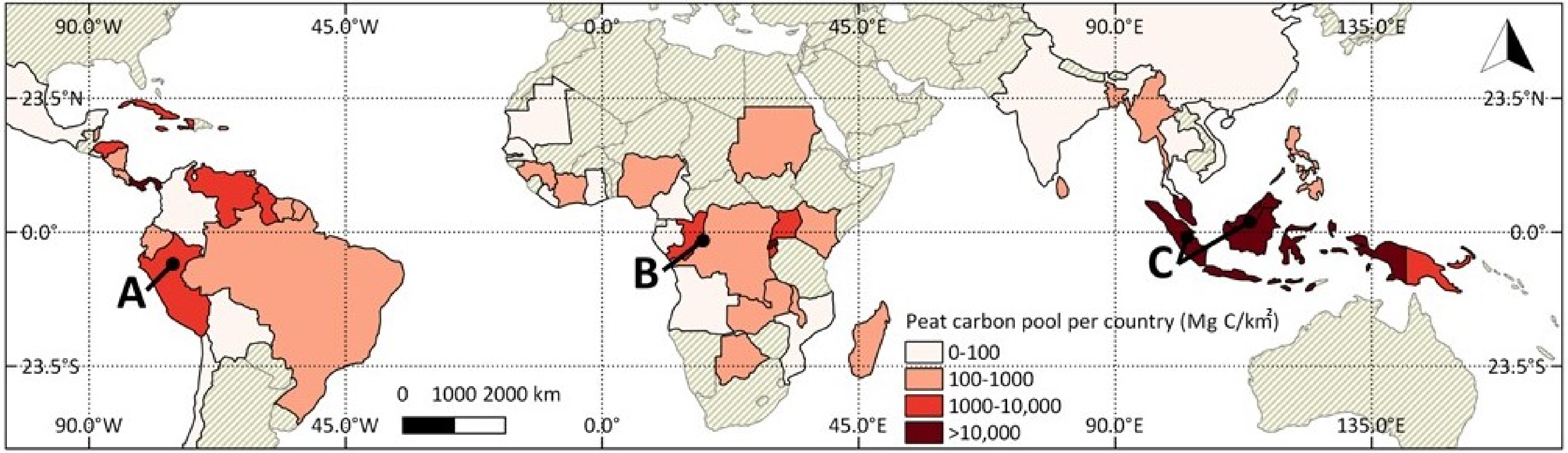

Fig. 1 Estimated peat carbon density at (in Mg C/km^2) for countries in the tropical latitudes for which data exist (grey dashing represents a lack of data). Data was sourced from Dargie et al. (2017) and Page et al. (2011). The three main regions of tropical peatlands discussed herein are labelled: A – Amazonia (Peru); B – Central Congo Basin (Democratic Republic of Congo, Republic of Congo); C – Southeast Asia (pointer indicating Sumatra, Indonesia, and Sarawak, Malaysian Borneo).

Lowland tropical peatlands are generally covered in dense swamp forest, providing habitats for a diversity of plants and animals, many of which are adapted to the low-nutrient, waterlogged conditions (Draper et al., 2018; Posa et al., 2011). They also provide a range of tangible and intangible services to people: fishing grounds (Thornton et al., 2018), water for agriculture and human consumption throughout drier seasons, a range of timber and non-timber forest products (NTFPs) (Posa et al., 2011), and as spaces of cultural significance for local communities (e.g., Schulz et al., 2019a; Thornton et al., 2020).

Over the last half century, the services people have sought from these ecosystems have changed, most notably in Indonesia and Malaysia. In these vast areas of tropical peat swamps, deforestation, drainage, and conversion into commercial plantations have occurred, commonly oil palm and wood pulp for paper production (Koh et al., 2011; Miettinen et al., 2016). This conversion has turned the peatland carbon sink into a huge carbon source (Leifeld and Menichetti, 2018). The transformation of landscapes, from being shaped predominantly by natural processes to anthropogenic drivers, is one of the key indicators used to define the existence and onset of the "Anthropocene" (Corlett, 2015; Ellis et al., 2010; Lewis and Maslin, 2015; Smith and Zeder, 2013), with associated debates on how to manage the emerging novel ecosystems (Clement and Standish, 2018; Folke et al., 2021; Hobbs et al., 2014). To contextualise contemporary changes, understanding how human interactions with these ecosystems have unravelled in the past is important.

For the purpose of this review, the "anthropocene" refers to the last *c*. 200 years, encompassing the period since the first evidence of transformative human impacts on tropical peatlands. This evidence is from Southeast Asian peatlands (e.g., Cole et al., 2015), where observations at *c*. 200 years ago noted reductions in typical intact peatland vegetation indicating the compromise of ecosystem resilience by human activity. Analysing human-peatland interaction before and after this point allows exploration of the real and potential impact of people. Patterns of anthropogenic transformative change across tropical peatlands has, however, as in tropical forests (Roberts et al., 2018), occurred at different times in different places. Central African and Amazonian peatlands have not experienced impacts in the same forms or scales as those in Southeast Asia over the last 200 years (Lilleskov et al., 2019). Analysis of these largely intact tropical peatlands provides insights into the non-transformative human interactions with peatlands that are possible (Roberts et al., 2018). In this paper, we contextualise the large-scale, transformative human-peatland interactions of the last 200 years by reviewing and synthesizing the palaeoecological evidence for long-term peatland dynamics and resilience in the face of past human and non-human perturbations. A corresponding paper in progress by Girkin et al. outlines the present and likely future human interactions with peatlands.

1.2 Palaeoecological insights into the palaeoanthropocene

Palaeoecology is important for understanding contemporary ecological dynamics, exploring ecosystem resilience (e.g., Cole et al., 2014; Davies et al., 2018; Willis et al., 2010) and predicting environmental changes (e.g., Froyd & Willis, 2008; Githumbi et al., 2020; Seddon et al., 2014). It uses a variety of evidence preserved in sediments, for example fossil pollen, to understand past interactions between plants, animals, people and climate (Bennett and Willis, 2001; Birks, 2008). In the wet tropics, where vegetation does not easily burn unaided, fossil charcoal, an important proxy for fire (Whitlock and Larsen, 2002), is used to indicate human activity. Cole et al. (2019) measured various palaeoecological proxies to explore human interaction with tropical peatlands in the Late Holocene, from *c*. 5,000 Cal. yr BP (Fig. 2). Their record is interpreted to encompass the palaeoanthropocene (open vegetation, a proxy for human-induced deforestation, extends into the deeper past, *c*. 2500 Cal. yr BP; e.g., Foley et al., 2013) and the more recent anthropocene *sensu lato* (open vegetation, microcharcoal and macrocharcoal concentrations increase, coincident with a decline in peat swamp forest vegetation, from *c*. 200 Cal. yr BP).

Palaeoecology can be deployed to investigate the local environmental changes that typify the 'palaeoanthropocene' (Foley et al., 2013). The palaeoanthropocene defines the interval of Earth's history when human activities left a mark on the environment, demonstrated in archaeological and palaeoecological records (Streeter et al., 2015), but likely did not contribute to large-scale reorganisations of Earth's systems, as in the anthropocene. As a "transitional period", the palaeoanthropocene exhibits asynchronous local manifestations not anchored to the geological timescale in any universal way (Foley et al., 2013). The Holocene series/epoch, in contrast, has an accepted formal definition and date for the base/start – the period from 11,700 years ago up to and including the present day (Walker et al., 2009). The central idea of the palaeoanthropocene is that humans have influenced the dynamics of Earth's system to some extent throughout prehistory; they are a part of nature and not apart from it.

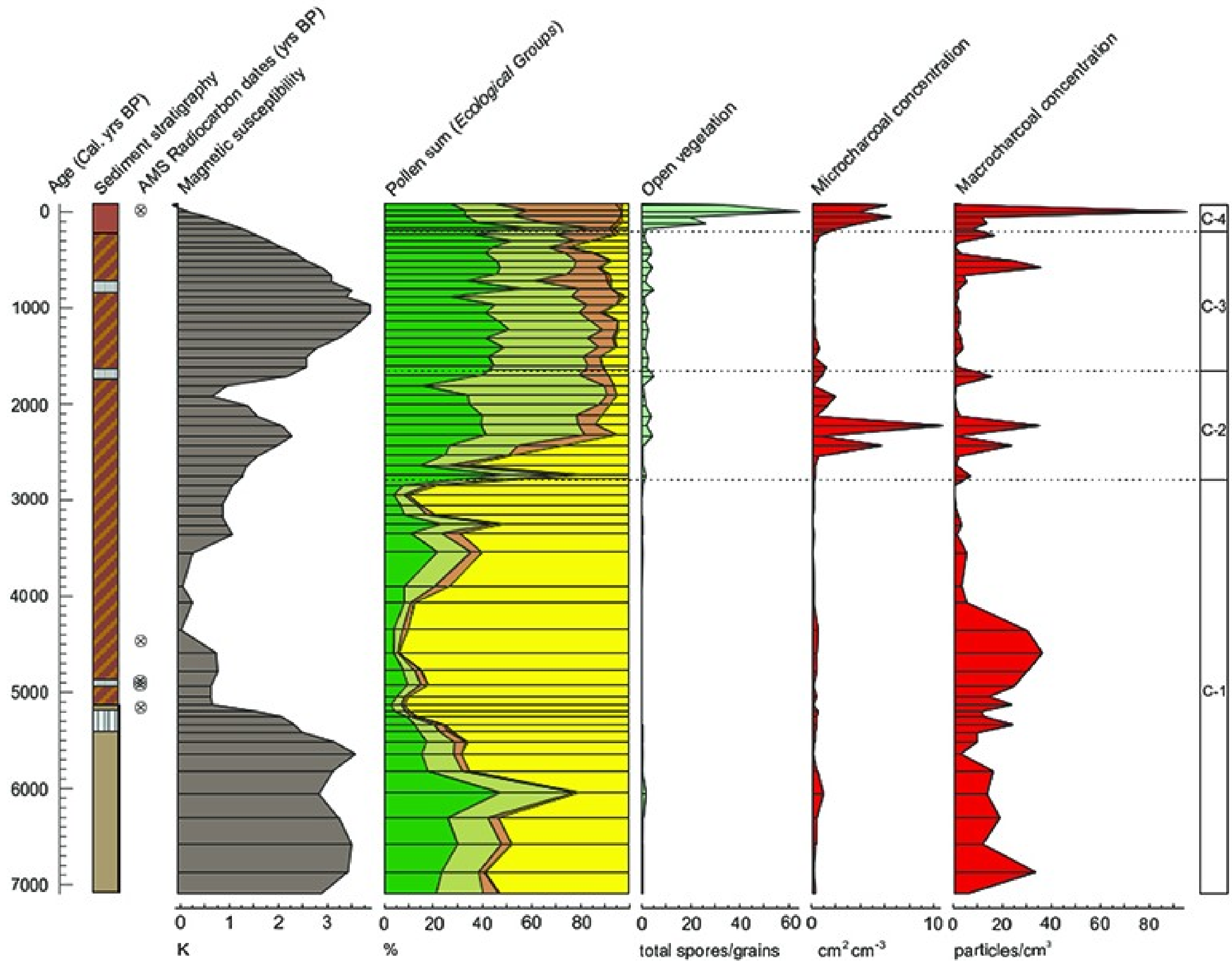

Fig. 2 Results from a palaeoecological study on a peat core from Sarawak, Malaysian Borneo, showing sediment stratigraphy, magnetic susceptibility (grey), pollen sum for five ecological groups (peat swamp forest taxa - green; peat swamp forest pioneer taxa - pale green; degraded peatland taxa – brown; non-peatland/other forest taxa – orange; and, coastal vegetation - yellow; open vegetation – aquamarine, and microcharcoal and macrocharcoal - red. Significant pollen zones are shown for each (labelled C-). Cal. yr(s) BP refers to calendar years before present (i.e., 1950 (Hajdas, 2008)). (For further details, see Cole et al., 2019).

This review adopts the palaeoanthropocene, i.e., prior to *c*. 200 years ago, as a conceptual and temporal framing to explore the spatially asynchronous and idiosyncratic human-peatland interactions in lowland tropical latitudes. Insights from palaeoecological records inform understanding of how these ecosystems could respond to larger-scale, more intensive environmental and climatic perturbations of the anthropocene. This review focuses on the three largest areas of tropical peatlands: Southeast Asia, the Central Congo Basin and Amazonia, with the most published research on palaeoecology and early human-peatland interactions (albeit still limited for the latter two regions). Although studies of peat-forming environments exist elsewhere in tropical latitudes (including coastal Venezuela and Panama (Phillips et al., 1997), montane Peru (Cooper et al., 2019; Fonkén, 2014) and East Africa (e.g., Mumbi et al., 2014), and across central Africa (e.g., Langan et al., 2019)) few have explored patterns of prehistoric human interaction with these ecosystems (Page and Baird, 2016). This review addresses three questions: (i) what were the past ecological dynamics of the peatlands of lowland Southeast Asia, the Central Congo Basin and Amazonia prior to human activity; (ii) how have they responded to disturbances, both anthropogenic and natural, over time; and, (iii) given their ecological resilience, how might they respond to the drivers of change prevalent in the last *c*. 200 years? The three broad categories of disturbance emphasized are fire (both natural and anthropogenic), climatic change and other human impacts for which evidence exists in palaeoecological and palaeoenvironmental records. We synthesize the similarities and differences in exposure and responses to disturbance between the three regions. We conclude by identifying future research needs for understanding and enhancing the persistence of these ecosystems.

2.1 Tracing the palaeoanthropocene in tropical peatlands

Despite the paucity of studies exploring past human-peatland interactions in the Central Congo Basin and Amazonia compared to Southeast Asia, this review covers all three regions to develop a pan-tropical synthesis of peatland ecosystem dynamics and resilience. Table 1 summarises the principle physical, ecological and anthropogenic characteristics of each region.

Region	**Area of peatlands** (km²)	**Below-ground carbon content** (Pg C)	**Earliest reported initiation dates** (Cal. yr BP)	**Dominant peatland form**	**Major peat-forming vegetation types**	**Anthropogenic activities**	
						palaeoanthropocene (pre-200 Cal. yr BP)	**anthropocene** (post-200 Cal. yr BP to present)
Southeast Asia	240,000[1]	68.5[2]	47,800[3]	coastal peat domes	Dipterocarp hardwood swamps	some small-scale clearing of peat swamp forest with use of fire, harvesting of NTFPs[4]	fishing, hunting, foraging for NTFPs*; subsistence & industrial logging, drainage, fire, land use change for agriculture & settlement
Central Congo Basin	145,500[5]	30.6[5]	*c.* 10,500[5]	various ombrotrophic forms and shallow peat domes associated with interfluvial basins[5,6]	hardwood & palm swamps	largely unknown (limited evidence)	no large-scale impacts at present, but future threats from mining, logging, deforestation, oil exploration and palm oil plantations[7]
Peruvian Amazon (PMFB)	35,600[8]	3.14[8]	*c.* 8870[9]	various ombrotrophic & minerotrophic forms associated with basins & old river channels	palm swamps, peatland pole forests, open peatlands	no evidence of past impacts on peatland vegetation suggesting minimal interaction	no large-scale impacts at present, but future threats from oil exploration and spills, oil palm plantations, harvestings of NTFPs[10]

[1](Page et al., 2011), [2](Page et al., 2010), [3](Ruwaimana et al., 2020), [4](Hapsari et al., 2018), [5](Dargie et al., 2017), [6](Davenport et al., 2020), [7](Dargie et al., 2019), [8](Draper et al., 2014), [9](Lähteenoja et al., 2012a), [10](Roucoux et al., 2017)

*NTFPs - non-timber forest products

Table 1 Summary characteristics of each tropical peatland region: Southeast Asia, Central Congo Basin and Peruvian Amazon, specifically the Pastaza-Marañón foreland basin (PMFB), for which data is available.

A

B

C 

Fig. 3 Photographs illustrating one prominent type of peatland ecosystem from each described region: **A)** *Shorea albida* dominated peat swamp forest, in Sumatra, Indonesia; **B**) hardwood dominated swamp forest in the Republic of Congo; and, **C)** *Mauritia flexuosa* dominated palm swamp, locally known as an *aguajál*, in the Peruvian Amazon. (Photo credits: KAH, DH and LESC, respectively.)

2.2 Southeast Asia

Indonesia, Malaysia and Papua New Guinea harbour the largest peatland area of Southeast Asia, at 20.6, 2.6 and 1 Mha, respectively (Page et al., 2011). Peatlands in Brunei, Singapore, the Philippines, Vietnam and Thailand together host the remaining 1% (Page et al., 2011). The average peat thickness ranges from 0.5 m (Susanto et al., 2018) to 7 m (Page et al., 2011), but in Indonesia and Malaysia, thicknesses of up to 20 m have been reported (Page et al., 2011; Ruwaimana et al., 2020). Carbon storage in peatlands across Southeast Asia is estimated at 68.5 Pg C (Page et al., 2011b), although estimates vary according to the methods used (Warren et al., 2017). They typically developed in regions where the wet season lasts for nine to ten months and the mean annual precipitation is ≥ 2500 mm (Rieley and Page, 2016). Most peat-forming ecosystems in the region are forested, ranging from freshwater swamp forests (Fig. 3A), dominated by *Shorea* spp. and other Dipterocarps, to the communities of stunted trees typical of environments with lower nutrient status and thicker peat, found at the centre of peat domes (Anderson, 1964).

2.2.1 Palaeoecological perspective

Peatlands have existed in the interior of Borneo since the late Pleistocene, including some examples that date to 60,000 Cal. yr BP (Anshari et al., 2001; Page et al., 2004; Wüst et al., 2007). The majority of coastal peatlands, however, initiated during the Holocene (Biagioni et al., 2015; Dommain et al., 2011; Hope et al., 2005). Peat accumulation in the coastal plains of Sumatra, Peninsular Malaysia and Borneo was driven by slowing post-glacial sea level rise, which led to the widespread development of mangrove vegetation and consequently the provision of an acidic and flat substrate (Anderson, 1964; Dommain et al., 2011; Horton et al., 2005), and by enhanced precipitation in the middle Holocene (*c*. 8000 - 4000 Cal. yr BP) (e.g., Cole et al., 2015; Neuzil, 1997; Sabiham, 1990; Woodroffe, 2000; Wüst and Bustin, 2004). After the sea level highstand (*c*. 5000 Cal. yr BP), marine regression allowed rapid seaward expansion of peatlands by exposing further suitable land surfaces, i.e., mud flats and sandy coastal plains, which peat swamp forest could colonise (Dommain et al., 2011; Neuzil, 1997).

The development of peatland ecosystems in Southeast Asia was initially assumed to follow the successional pathway of the 'Anderson model'. That is, a coupled evolution of substrate and vegetation from mangrove swamp to mixed swamp forest then mature peat swamp forest, a model confirmed by palaeoecological studies at multiple sites (Cole et al., 2015; Dommain et al., 2015; Sabiham, 1990). Palaeoecological studies at other sites, however, have shown that alternative development pathways exist, for example, where mangrove soil and vegetation are not essential precursors (e.g., Hapsari et al., 2017; Hope et al., 2005; Taylor et al., 2001). Some peatlands started to form in depressions near rivers, under riparian or lowland forests, which then developed into freshwater swamp forests and subsequently peat swamp forests. This type of peatland is mostly located in the interior beyond the influence of marine conditions, or in coastal locations above the Holocene sea level highstand (+5 m a.s.l.) (Hapsari et al., 2017; Neuzil, 1997; Taylor et al., 2001).

2.2.2 Responses to past disturbances

Fire

Fires in Southeast Asian peatlands result from natural (e.g., lightning strikes, Dommain et al., 2015) or anthropogenic causes, or a combination of both (e.g., Anshari et al., 2001; Cole et al., 2019; Hope et al., 2005). Unlike the large-scale fires that now occur annually in some locations (Girkin *et al.*, in progress; Langner & Siegert, 2009; Stolle & Lambin, 2003), however, fire was relatively rare in the past, with a return interval of centuries to millennia (Page & Hooijer, 2016), and probably predominantly ignited by natural sources.

Multiple palaeoecological records suggest that fires did not usually result in the loss of peat (Anshari et al., 2001; Biagioni et al., 2015; Hapsari et al., 2017; Yulianto et al., 2004) or any significant vegetation change. Fires therefore caused limited perturbation to ecosystem function, including carbon accumulation (Anshari et al., 2004, 2001; Biagioni et al., 2015; Cole et al., 2019; Hapsari et al., 2017; Yulianto and Hirakawa, 2006). One exceptional record, from Kutai peatland in Eastern Kalimantan, Indonesia, does provide a rare example of fire-related loss of peat (Hope et al., 2005), akin to the impacts of fire typical of recent decades (Astiani et al., 2018; Page and Hooijer, 2016). Estimations have shown that late Holocene fires (at *c*. 4400, 3900, 1900, and 1400 Cal. yr BP) may have consumed at least the upper 1 m of peat and prevented recolonization by trees at the burnt site, leading to the formation of lakes (van Eijk et al., 2009; Wösten et al., 2006) and the release of ~25 Tg C (between 0.1 to 3.6 Tg C per fire event; Dommain et al., 2014). These severe fires are the only known examples to date in the palaeoanthropocene.

Climatic changes

Climate has served as an important driver of the dynamics of peatlands in Southeast Asia throughout their history (e.g., Anshari et al., 2001, 2004; Hapsari et al., 2017; Page et al., 2009). Multiple studies have shown how moist climates prevalent during the late Pleistocene and Holocene contributed to the initiation and continued accumulation of peat in inland Borneo, Sumatra and Peninsula Malaysia (Anshari et al., 2001; Page et al., 2004; Russell et al., 2014). At some sites, however, increased precipitation in the mid Holocene, coupled with sea level rise, caused high water discharge and frequent flooding, inhibiting peat accumulation or eroding existing peat (Anshari et al., 2001; Hapsari et al., 2017). Palaeoecological and palaeoclimate records illustrate the dynamic relationship between precipitation and peat accumulation and show how other factors, such as relative sea level, can influence this relationship.

Dry conditions are considered unfavorable for Southeast Asian peatland persistence. A lower water table and consequent increased decomposition rate reduces peat accumulation (Anshari et al., 2004; Dommain et al., 2014; Mezbahuddin et al., 2014; Page et al., 2004), and droughts increase the risk of peat fires (Dommain et al., 2014; Page et al., 2002). Palaeoecological studies repeatedly report drought-related fire occurrence, though their impact on peatland vegetation is limited (e.g., Anshari et al., 2001; Biagioni et al., 2015; Cole et al., 2015; Hapsari et al., 2017; Yulianto & Hirakawa, 2006; Yulianto et al., 2004). Evidence exists, however, that climatic changes, such as increases in precipitation, caused shifts in the composition of peatland vegetation communities (e.g., Anshari et al., 2001, 2004; Taylor et al., 2001; Wüst & Bustin, 2004).

Human impact

In Southeast Asian peatlands, prehistoric human activities are often evident in the palaeoecological archives from the presence of elevated charcoal abundance (e.g., Anshari et al., 2001; Hope et al., 2005; Taylor et al., 2001) and changes in peat swamp forest vegetation. Further support is commonly available from contemporaneous archaeological or historical records (e.g., Cole et al., 2019; Hapsari et al., 2017, 2018; Wüst & Bustin, 2004). Although evidence suggests that humans have been present in the Indo-Malayan archipelago since the late Pleistocene, *c*. 35,000 Cal. yr BP (Barker et al., 2017; Bellwood, 1997; Hunt and Premathilake, 2012), their activities were mainly shifting cultivation, hunting and gathering, and apparently limited to forest edges and riversides (rivers being key travel routes) until the last few hundred years.

Indicators of human activity in peatlands across Borneo increase synchronously after 1600 Cal. yr BP (Anshari et al., 2001; Hope et al., 2005; Yulianto et al., 2005), supporting archaeological findings (Krigbaum, 2003; Kusmartono et al., 2017; Kusmartono and Oktrivia, 2019). In Tasek Bera peatland, Peninsular Malaysia, two notable changes in vegetation, at *c.* 2000 Cal. yr BP and over the last 600 years, were attributed to humans, possibly the activities of the Semelai people (Wüst and Bustin, 2004). Meanwhile in Sumatra, very few records of human activities are available for the peatlands during the Holocene (Hapsari et al., 2018, 2017), reflecting the scarcity of people living in and around these densely forested, waterlogged environments before *c*. 200 years ago (Hope et al., 2005).

In Sungai Buluh, Sumatra, a period of peatland forest openness and slower peat accumulation coincided with the occupation period of the Malayu Empire in the vicinity (1000 to 600 Cal. yr BP; Hapsari et al., 2017, 2018; Witrianto, 2014). Palaeoecological data and detailed archaeological and historical records of the dynamics of the Malayu Empire have revealed that its people affected the peatland ecosystem through harvesting timber, forest products and fodder, but not draining the peat, converting the forest or using fire excessively to clear it (Hapsari et al., 2018). The Sungai Buluh peatland started to recover after the people of Malayu Empire abandoned the site, *c*. 600 Cal. yr BP. Its carbon accumulation rate and peat swamp vegetation composition recovered to pre-disturbance states after 60 and 170 years, respectively (Hapsari et al., 2018).

Several records do, however, suggest that people impacted peatlands in this region in irreversibly transformative ways in the late Holocene. A palaeoecological study in Sarawak showed a lack of peat swamp forest recovery within the last *c*. 200 years (Cole et al., 2019), contemporaneous with indicators of anthropogenic activity, including elevated levels of burning, and with historical evidence of human activity in the region (Colombijn, 2005; Kaur, 1995). The decline in peat swamp forest taxa at these sites suggests a loss of peatland ecosystem resilience resulting from the intensity of anthropogenic disturbance that occurred several hundred years ago and/or a lack of opportunity for the vegetation to recover due to ongoing human activity (Cole et al., 2015). The latter explanation was supported at sites where records indicate continuous elevated burning (e.g., Cole et al., 2019).

Present status & future threats to peatlands

Following population and economic growth, Southeast Asian peatlands have undergone rapid land use conversion, primarily into agricultural land (Miettinen et al., 2016, 2012). Since 1990, 3.1 Mha of peat swamp forest has been converted into oil palm plantations annually (Miettinen et al., 2016). In 2015, less than 30% (4.6 Mha) of peatlands throughout Sumatra, Peninsular Malaysia and Borneo remained forested, with only 1 Mha considered to be in a pristine condition (Miettinen et al., 2016). Deforestation has led to irreversible peatland degradation, turning the peat into a dry substrate prone to fire and oxidation, and in turn creating a significant source of atmospheric carbon (e.g., Miettinen et al., 2017; Page & Hooijer, 2016; Vetrita & Cochrane, 2020). This process contrasts with the impact of human activities evidenced in palaeoecological records before 200 years ago, where humans used peatlands in a “resilience-friendly” way, i.e., without clearing the forest with fire or draining the ecosystem (Hapsari et al., 2018).

Under current rates of peatland deforestation/conversion and burning (3.1 and 0.5 Mha yr^{-1}, respectively), driven by factors such as the Indonesian Government’s biofuel and timber production targets (Bassi et al., 2020; Schoneveld et al., 2019; Surahman et al., 2019), all intact peatland ecosystems across Southeast Asia will have disappeared by 2030, if not earlier (Miettinen et al., 2012; Vetrita and Cochrane, 2020). Fortunately, numerous conservation and restoration efforts are underway (e.g., Global Environment Centre, 2021; “Katingan”, 2021; “Rekoforest”, 2021), with long-term leases (60+ years) to peatland sites. The palaeoecological record from Sungai Buluh in Indonesia, suggests that this length of time may be sufficient for degraded peat swamp forests to re-establish their peat formation and carbon sequestration functions, but not to recover previous levels of biodiversity. For this, a longer period of ecosystem recovery, greater than 170 years, may be necessary (Hapsari et al. 2018).

2.3 Central Congo Basin

The largest known peatland complex in tropical latitudes, covering *c*. 145,500 km^2, is in the central Congo basin (Dargie et al., 2017), referred to as the Cuvette Centrale peatland complex. It has only recently been mapped and dated in a single field-based study (Dargie et al., 2017) and there has been little work on peatlands in the wider Congo Basin. Therefore this section is, in parts, necessarily speculative. The peatland complex extends into the east of the Republic of Congo (ROC) (54,700 km^2), and the west of the Democratic Republic of Congo (DRC) (90,800 km^2). At its centre, the peatland occupies a low-lying hydrological drainage basin of the Congo River and its tributaries. The mean peat thickness is 2.2 m ± 1.61 (St. dev.), with a maximum of 5.9 m. The estimated carbon stored below-ground across the entire Congo peatland complex is 30.6 Pg C (95% CI: 6.3 – 46.8), ~29% of the global tropical peatland carbon stock (Dargie et al., 2017).

Annual rainfall in the Central Congo Basin is 1,500 – 2,500 mm yr^{-1}, notably lower than in Amazonia and Southeast Asia (Primack and Corlett, 2005). A range of forest types occur within the peatland complex, though two common peat-forming vegetation communities are the palm-dominated swamp forest (commonly consisting of *Raphia laurentii*) and hardwood swamp forest (dominated by *Uapaca paludosa*, *Carapa procera* and *Xylopia rubescens*) (Fig. 3B). The trees show adaptations to wet conditions, such as stilts, buttresses and aerial roots (Dargie, 2015).

2.3.1 Palaeoecological perspective

Nine basal radiocarbon dates suggest that the peatland began to form between 10,554 to 7137 Cal. yr BP, during the African Humid Period (11,700 – 4000 Cal. yr BP), with an increase in rainfall across western and northern Africa (Aleman and Fayolle, 2020; Dargie et al., 2017; Shanahan et al., 2015). Currently no palaeoecological records exist from within the Cuvette Centrale peatlands studied by Dargie et al. (2017). Outside the peatland complex, the closest comparable record is from Ngamakala swamp, in the Bateke Plateaux region (~220 km to the south). Here, Elenga *et al.* (1994) presented radiocarbon dates from a single core with a peat initiation date of *c.* 24,000 yr BP (uncalibrated). Thus, dates for peat initiation vary significantly across the Congo Basin as a whole, probably dependant on local environmental conditions, e.g., topographic, hydrological, climatic, and on potentially varying mechanisms of formation.

The lack of palaeoecological records from the Cuvette Centrale peatlands means that the environment within which peat began to accumulate has not yet been explored. However, a single record exists from the Congo fan, at the mouth of the Congo River, representing broad vegetation change across West Equatorial Africa (Jahns, 1996) and may provide insights into the environment within which peat initiated. During the Last Glacial Maximum (*c*. 21,000 – 18,000 Cal. yr BP), the climate was cooler and drier, and the Congo fan record is dominated by taxa such as Cyperaceae, Poaceae and *Podocarpus* (Jahns 1996). With the onset of the African Humid period there was an increase in lowland rain forest taxa, such as *Alchornea, Khaya, Pterocarpus, Celtis* and *Uapaca*, in response to the warmer and wetter climate. The Ngamakala swamp record indicates that peat initiated in a "hydromorphous forest" environment, characterised by a dominance of taxa tolerant of wet conditions, including Sapotaceae and *Syzygium*, and an absence of herbaceous taxa (Elenga et al., 1994). An expansion of "hydromorphous forest" was recorded again after 13,000 yr BP (uncalibrated), corresponding to the onset of the African Humid Period.

The mechanism responsible for the initiation of peat within the Cuvette Centrale remains to be established. Peatland formation likely resulted from terrestrialisation, paludification or a combination of the two. A multicore study at one site, Ekolongouma in the northern Republic of

Congo, gives insight into how peat in this region of the Cuvette Centrale expanded laterally following initiation. The oldest (10,555 Cal. yr BP at 3 m depth, 9 km into the peatland) and deepest peat (5.9 m, 17.4 km into the peatland) was recorded towards the centre of the site, with three additional cores taken along a transect showing that the base of the peat becomes progressively younger and shallower towards the peatland margin (Dargie, 2015). Vertical long-term apparent peat accumulation rates also varied (0.36 - 0.21 mm yr^{-1}), becoming slower towards the peatland margin. Five additional cores taken at different sites across the Cuvette Centrale peatlands revealed peat initiation dates in the early Holocene (*c*. 9500 – 7200 Cal. yr BP) and accumulation rates ranging from 0.16 to 0.29 mm yr^{-1} (Dargie et al., 2017).

2.3.2 Responses to past disturbances

Fire

The absence of palaeoecological records from within the Cuvette Centrale peatlands means that the presence and role of fire within this ecosystem remains to be established. The Congo Basin as a whole is one of the most lightning-prone regions on earth (Albrecht et al., 2016) and has a long history of hominin occupation (Crevecoeur et al., 2014) providing possible sources of fire ignition. Studies from outside the Cuvette Centrale peatlands, but within the wider Congo Basin, suggest that fires in the past have apparently occurred in forested regions (including swamp forests) under two scenarios. Firstly, fires occurred during periods of reduced precipitation or drought (Hubau et al., 2015). Secondly, they occurred during periods of increased anthropogenic activity (Brncic et al., 2007; 2009). While these studies provide a palaeoecological view of fire in forested regions within the wider Congo Basin, studies from within the Cuvette Centrale are desperately needed in order to quantify and explore the role of fire within the peatlands in the past.

Climatic changes

Palaeoclimatic records from the Cuvette Centrale peatlands are non-existent, therefore we point to data from marine cores and studies outside the peatlands, which provide evidence for strong climatic changes in central Africa (e.g., Gasse, 2000; Maley and Brenac, 1998; Schefuß et al., 2005; Shanahan et al., 2015; Weijers et al., 2007). Major dry and cool periods during the Last Glacial Maximum (*c*. 21,000 – 18,000 Cal. yr BP) and Younger Dryas (*c*. 12,900 – 11,700 Cal. yr BP), have apparently caused tropical rainforests to contract and form a mosaic with savanna ecosystems (Elenga et al., 1994) or become more open environments (Runge, 1996). Humid and cool environments may have allowed forests to persist with more open canopies, abundant shrubs and herbaceous understorey vegetation (Jahns et al., 1998; Mercader et al., 2000). The onset of the African humid period (11,700 Cal. yr BP) in the Congo Basin was marked by the expansion of forest and a shift to denser forest cover (Mercader et al., 2000). Vincens *et al.* (2005) and Jansen *et al.* (1995) supported this scenario and inferred a general humidification and increase in rainfall at this time across central Africa that promoted the expansion and diversity of rainforest and forested swamp environments. The basal peat radiocarbon dates from the Cuvette Centrale (between 10,554 and 7137 Cal. yr BP) suggest that peatlands were among the ecosystem types that expanded during the African Humid Period (11,700 – 4000 yr BP) (Aleman and Fayolle, 2020; Shanahan et al., 2015). Present day rainfall within the Cuvette Centrale is lower when compared to other tropical peatlands, suggesting to Dargie et al. (2017) that the peatland establishment/expansion was potentially largely climatically driven. Additional palaeoclimatic and palaeoecological records are needed from within the Cuvette Centrale, the Congo Basin and central Africa as a whole, to provide a clearer picture of climatic and vegetation change.

Human impact

The extent to which past societies have used and modified the forests of the Congo Basin is largely undocumented, and no literature exists on the Cuvette Centrale peatlands. However, human populations have been likely active in the region since at least 3,000 years ago. Pits containing pottery sherds and oil palm and *Canarium* nuts, have been found to extend into the equatorial forest interior along the Ubangui River (Phillipson, 2005), with most archaeological evidence for settlement confined to river banks and forest fringes in this and other regions of the wider Congo Basin, e.g., Gabon, Cameroon and Southern Central African Republic (Bostoen et al., 2015). Palynological and climatic evidence, combined with numerous studies on the oral traditions and linguistics of the region, highlight the estimated timing and routes through which Bantu-speaking populations first spread across the Congo Basin. From *c*. 3500 Cal. yr BP, and peaking *c*. 2500 Cal. yr BP, evidence suggests the opening up of forests and the expansion of savannas, created a fragmented forest structure and possible corridors that facilitated Bantu population expansion (Bostoen et al., 2015; de Luna, 2016; Maley, 2002; Maley and Willis, 2010). Bantu speakers likely largely followed familiar environments (e.g., open forest, wooded savannah and grassland), but more recent evidence also showed adaptation to denser forest environments (de Luna, 2017). Although it is clear that there is a long history of human influence on *terra firme* environments within the wider Congo Basin, the history and even present day impacts on the Cuvette Centrale peatlands remains to be explored.

Present status & future threats to peatlands

Currently, the peatlands of the central Congo Basin experience little disturbance and remain largely intact. Dargie *et al.* (2019), however, gave a detailed account of the present threats and conservation priorities for the Congo Basin peatlands. They highlighted changing land use, logging, oil and gas exploration, dam building and infrastructure developments as activities that could transform these ecosystems in the near future. Despite the current low levels of human intervention, ~75 million people reside within the Congo Basin region, 60% of which live in rural areas (Megevand et al., 2013). Peat forests play a role in supporting some of this population, as a source of bushmeat, fuel, fruit and medicines (Dargie et al., 2019). Research is needed to better understand how human populations use and value these peatlands today, and where future threats may arise.

Even if destructive human activities are not currently prevalent in the peatlands, ongoing climatic changes may have significant impact. Annual mean rainfall has declined since 1979, and the length of the boreal summer dry season in the Congo Basin has increased. This trend is related to an amplification of warming over the Sahara, causing what were previously warm and wet conditions in the region to become drier (Cook et al., 2020). Drier conditions could inevitably lead to an increase in peatland fires. While fire frequency is expected to be low in Congolese swamp forest environments, palaeoecological records from the region indicate that past increases in fire activity were associated with periods of increased aridity, the expansion of savanna environments and increased human activity. Therefore, if conditions continue to dry and anthropogenic impacts increase, peatland fires could become a significant threat in the future.

Drier conditions can also lead to a reduction in peat accumulation. In the future, if rainfall reduces and seasonality increases, causing water tables to drop and peatlands to dry, peat accumulation rates could slow, which would reduce the carbon sink capacity of the region. Keeping the peatlands wet and protecting them from intensive and large-scale anthropogenic impact is a conservation priority.

2.4 Amazonia

The majority of Amazonian peatlands are located within the Pastaza-Marañón foreland basin (PMFB) in northern Peru, covering an estimated 35,600 ± 2,133 km^2 (Draper et al., 2014). The low-lying topography of the 100,000 km^2 basin is characterized by high precipitation (2,000 – 3,000 mm yr^1) and frequent flooding, which favours peat formation. Peat accumulates in the PMFB in highly dynamic floodplain settings and in a range of vegetation types, including herbaceous open peatlands, seasonally flooded forest, mixed swamp forest, palm swamp forest (Fig. 3C), and pole forest (Kelly et al., 2017, 2018b; Lähteenoja et al., 2012, 2009; Lähteenoja and Page, 2011; Lawson et al., 2014; Roucoux et al., 2013; Swindles et al., 2018b). Peat depths of up to 7.5 m have been reported in the basin (Lähteenoja and Page, 2011). The most recent estimate of carbon contained within the PMFB is 3.14 (0.44 – 8.15) Pg C (Draper et al., 2014). With addition of the below-ground carbon stocks in other Amazonian peatlands, these ecosystems are an important component of the Amazon basin carbon balance.

A smaller area of peatlands occurs in the meandering belt of the Madre de Dios River in southern Peru, covering 294 km^2 (Householder et al., 2012). Individual peatlands in the Madre de Dios region range in size from 10 to 3,500 ha, and the mean peat depth is estimated at 2.5 m ± 1.8 m, though peat thicknesses of up to 9 m have been reported (Householder *et al*. 2012). The deepest peats are documented in areas that today support dense swamp forest dominated by *Mauritia flexuosa*, whereas more shallow peats (<3.5 m) were documented in areas of open mire vegetation (Householder et al., 2012).

In Brazilian Amazonia, peatlands with varying peat thickness (10 – 210 cm) have been recorded in the middle Negro River basin (Lähteenoja et al., 2013). Shallow peats (≤80 cm depth) have also been reported underlying flooded forests in the upper Negro River basin in northern Amazonia (Dubroeucq and Volkoff, 1998). Farther north still, studies have documented tropical wetlands with abundant peatlands in the lower Orinoco River Delta, Venezuela (Aslan et al., 2003; Vegas-Vilarrúbia et al., 2010). Peat-forming vegetation ranges from palm forests and herbaceous vegetation growing on thicker peat layers (5 to 10 m) (Aslan et al., 2003; Vegas-Vilarrúbia et al., 2010), to swamp forest and shrublands on thinner peats (≤150 cm) (Vegas-Vilarrúbia et al., 2010). Lähteenoja et al. (2013) have suggested that the lesser extent of reported peatlands in central Amazonia, compared with western Amazonia, could be explained by a number of factors, including rainfall and hydrology, tectonic conditions, topography, minerogenic subsoil type and the frequency of fires.

2.4.1 Palaeoecological perspective

Limited palaeoecological studies of peatlands across Amazonia are available, though the number is increasing. The oldest documented extant peatland is the ombrotrophic peat dome at Aucayacu in the PMFB, which has been dated to *c*. 8900 Cal. yr BP. It contains peats up to 7.5 m thick (Lähteenoja and Page, 2011; Swindles et al., 2018b) and is characterised by pole forest today. The palaeoecological record shows that the environment developed from open water wetland, to inundated forest swamp *c*. 6600 Cal. yr BP, to a raised peat dome after *c*. 3900 Cal. yr BP (Swindles et al., 2018b).

Quistococha, a small lake located 120 km north-east of Aucayacu within the PMFB, occupies an abandoned arm of the Amazon River and is today surrounded by a permanently waterlogged closed-canopy palm swamp dominated by *Mauritia flexuosa* and *Mauritiella armata* palms (Räsänen et al., 1991; Roucoux et al., 2013). The swamp contains peat up to 4.9 m thick (Lähteenoja et al., 2009b). The palaeoecological record shows that peat initiated *c*. 2200 Cal. yr BP, after which a marginal fen and/or floating mat with the presence of disturbance and floodplain taxa developed (Lawson et al., 2014; Roucoux et al., 2013). After 2100 Cal. yr BP, the site transitioned into forest vegetation tolerant of deep flooding (Roucoux et al., 2013). When deep flooding ceased after 1000 Cal. yr BP, a palm swamp, dominated by *Mauritia flexuosa*, developed. Despite a general long-term trend of infilling and afforestation at the Quistococha swamp, the palaeoecological record shows times of reversals characterised by short-term increased abundances of open taxa at *c*. 1700 – 1400 Cal. yr BP and 1150 – 1000 Cal. yr BP, possibly caused by either decreased flooding depth or the development of permanent pools with fen and/or floating mat vegetation (Roucoux et al., 2013).

San Jorge, an ombrotrophic peatland located about 20 km southwest of Quistocicha in the PMFB, contains peats of up to 2.4 m thick (Kelly et al., 2018b; Swindles et al., 2018a). The peatland has a domed structure and is characterized by pole forest vegetation. This raised peatland is surrounded by *Mauritia flexuosa*-dominated palm swamp (Kelly et al., 2017; Lähteenoja et al., 2009a). The site may have been located within an active channel of the Amazon *c*. 3,000 years ago, which then moved progressively farther away until the site developed into a floodplain swale or lake (Kelly et al., 2017). Peat initiation occurred *c.* 2290 Cal. yr BP with development of an open-canopy forest and marginal lake-side and/or a floating mat vegetation. After 650 Cal. yr BP, palm-dominated swamp forest was established at San Jorge (Kelly et al., 2017). The pollen and geochemical records show the establishment of pole forest and predominantly rain-fed, ombrotrophic conditions after 200 Cal. yr BP (Kelly et al., 2017).

2.4.2 Responses to past disturbances

Fire

Natural fires are almost non-existent in western Amazonia, as wet conditions of lowland rainforest limit the spread of ignition (Bush et al., 2007). Palaeo-fires in western Amazonia have thus repeatedly been connected to anthropogenic land use, and fossil charcoal has served as a strong indicator of human presence in these landscapes (Bush et al., 2016; Kelly et al., 2018b; McMichael et al., 2012; Urrego et al., 2013). At Aucayacu, studies have identified charcoal fragments in three intervals during the last 4,500 years, inferred to represent anthropogenic activity at these times (Swindles et al., 2018b). Charcoal fragments were rare in the peat profiles retrieved at San Jorge and Quistococha (Kelly et al., 2017; Roucoux et al., 2013). Kelly et al. (2018b) documented them in the lake record in sediments, however, dated to *c*. 2450 Cal. yr BP. These dates are contemporaneous with the oldest archaeological evidence at the site (Rivas Panduro, 2006; Rivas Panduro et al., 2006). Higher abundances of charcoal were found between *c*. 2180 and 90 Cal. yr BP, with lower charcoal concentrations after 90 Cal. yr BP (Kelly et al., 2018b). Although the charcoal record suggests that people were consistently present in the Quistacocha area until the present day, the lake and peat pollen records preserve no evidence for extensive disturbance of the peatland vegetation or deforestation of the local landscape until modern times (Kelly et al., 2018b; Roucoux et al., 2013). Further palaeoecological studies are required to assess the extent to which this is representative of peatlands in the wider region, beyond the pollen catchment of Quistococha.

Climatic changes

Climate change can be difficult to detect in Amazonian peatlands due to the dynamic nature of floodplain settings (Räsänen et al., 1991; Roucoux et al., 2013). Studies have reported direct effects of climate, however, from some palaeoecological sites in the PMFB (e.g., Kelly et al., 2017; Swindles et al., 2018a, 2018b). These effects are mainly evident through alterations in peat accumulation and decomposition rates, linked to climate-induced ecohydrological changes.

Three drought periods are known from the record of the ombrotrophic peat dome at Aucayacu in northern Peru (Swindles et al., 2018b). During the first two periods, drier conditions have apparently increased the peat accumulation rate and caused two different ecohydrological shifts. The first drought, *c*. 6600 – 6100 Cal. yr BP, coincided with a shift from an open water wetland to a forest swamp, whereas the second, *c*. 4900 – 3900 Cal. yr BP, with a shift from a minerotrophic forest swamp to ombrotrophic raised peat dome. The timing of the first two droughts in the Aucayacu record coincided with droughts reported from Lake Sauce in western Amazonia (Bush et al., 2016; Correa-Metrio et al., 2010) and low lake levels from Lake Titicaca in the High Andes (Baker et al., 2005).

The Aucayacu site was influenced by a third drought period, *c*. 1800 – 1100 Cal. yr BP, which led to a cessation of peat accumulation within the ombrotrophic dome and increased peat decomposition, suggested by the presence of a hiatus in the sediment core (Swindles et al., 2018b). A decline in peat accumulation rate is also documented from the peat dome at San Jorge, 200 km to the east, *c*. 1300 – 400 Cal. yr BP (Kelly et al., 2017). The drying climate likely caused the water table to lower, leading to an increased rate of peat and litter decay (Kelly et al., 2017). The transition to ombrotrophic conditions at San Jorge after *c*. 200 Cal. yr BP, is partly explainable by a shift to less precipitation or fluvial influence (Swindles et al., 2018a). This shift apparently occurred at Aucuyacu, when the swamp forest there transitioned to pole forest and the mire became ombrotrophic at a time of climatic drying (Swindles et al., 2018b). At Quistococha, the formation of a palm swamp at *c*. 1000 Cal. yr BP has been linked to reduced flooding depth, which could result from a drier climate. In this case, however, the more parsimonious explanation is a decline in fluvial influence caused by river channel migration (Roucoux et al., 2013).

Human impact

People have inhabited Amazonia for at least 13,000 years (Roosevelt, 2013), with the first evidence of maize cultivation dated to *c*. 6500 Cal. yr BP in Bolivia (Brugger et al., 2016) and *c.* 6320 Cal. yr BP in Peru (Bush et al., 2016). Past human activity in Amazonia caused landscape changes through deforestation (Laurance et al., 2004), burning (Bush et al., 2015), creation of anthropogenic soils (*terra pretas;* Glaser and Woods, 2004; Neves et al., 2004), aquaculture, raised fields (Erickson, 2006), earthworks (Pärssinen et al., 2009), mound building (Rostain, 2012), enrichment of useful species (Clement et al., 2015; Levis et al., 2018, 2017; Roosevelt, 2013), and cultivation (Brugger et al., 2016; Bush et al., 2016; Bush and Colinvaux, 1988). In aseasonal western Amazonia, settlements were often temporally and spatially intermittent compared with more distinct dry season settings. Localized disturbance was strongly influenced by distance from rivers, lakes, seasonal flood-plains, and savannas (Åkesson et al., 2021; Bush et al., 2007; Bush and Colinvaux, 1988; Kelly et al., 2018b; McMichael et al., 2012b, 2012a; McMichael et al., 2015; Roucoux et al., 2013).

For the PMFB region, little evidence suggests prehistoric human impact on peatland vegetation or peat accumulation (Kelly et al., 2018b; Roucoux et al., 2013). Fossil charcoal is only sparsely identified at Aucayacu, Quistococha, and San Jorge, and no cultivars (e.g., maize and manioc) were found in the peat core pollen records. Despite the scarcity of anthropogenic signatures in these palaeoecological records, an archaeological site has been excavated adjacent to Quistococha, revealing fragments of pottery, charcoal, cobs of corn, and phytoliths of palms and grasses dated to two distinct intervals: *c.* 2690 – 2350 Cal. yr BP and *c.* 1880 – 1740 Cal. yr BP (Rivas Panduro, 2006; Rivas Panduro et al., 2006). *Terra pretas* have also been identified in the area. People occupied the Lower and Upper Ucayali River region in the PMFB from at least *c.* 3950 Cal. yr BP to early post-Columbian times and practiced manioc cultivation, experimented with maize cultivation and traded with Andean and Amazonian civilizations (Coomes et al., 2020; Lathrap, 1970; Raymond, 1988).

With European arrival after AD 1492, Amazonia suffered substantial losses in human population (90 – 95% decline) due to warfare, disease, and slavery (Clement, 1999; Dobyns, 2017). Industrialization, demands for raw materials (e.g., rubber, mining, and timber), cattle ranching and agriculture created a surge of settlers to Amazonia. This surge caused extensive deforestation and resource depletion after AD 1850 (e.g., Laurance et al., 2005; Nepstad et al., 1997; Weinstein, 1983).

Present status & future threats to peatlands

The documented peatlands in Amazonia remain largely intact (Roucoux et al., 2017). Contemporary evidence suggests that harvesting of the *Mauritia flexuosa* fruit, known locally as *aguaje*, from peat-forming palm swamps, can be unsustainable where it involves felling of the female, fruit-bearing individuals (Bhomia et al., 2018). Although this harvesting technique is now discouraged where possible, it remains prevalent and problematic (Romulo et al., 2022; Virapongse et al., 2017). Many other subsistence activities taking place in the PMFB peatlands today appear to be more sustainable (e.g., Schulz et al., 2019a, 2019b), and have limited, apparently non-transformative, impacts on the peatlands. Further study of the effects of peatland use (e.g., resource harvesting and hunting) are required, however, to accurately assess the extent to which these apparently low impact activities affect peatland ecosystem function.

Although for the most part, the peatlands of the PMFB today are still hydrologically intact, they remain threatened by several types of anthropogenic activity (Roucoux et al., 2017). Industrial-scale agriculture is currently peripheral to most peatlands, but the availability of new technologies and investment opportunities can put pressure on wetlands to become commercially productive. Pervasive within tropical latitudes, oil palm plantations may be a key driver of habitat loss (Glinskis and Gutiérrez-Vélez, 2019). Increased transport infrastructure also poses threat to this currently isolated, inaccessible region. Plans are underway to extend the road network within the PMFB, cutting through some of the most carbon-rich ecosystems in the Peruvian Amazon (Coronado et al., 2021) and enabling access to forest, which has proven devastating for ecosystems elsewhere in Amazonia (Barber et al., 2014; Gallice et al., 2019). Investigations of the threat of climate change in this region is also underway (Marengo et al., 2018), but more work is needed to understand the effect that predicted changes in seasonal patterns of precipitation and flooding could have on the peatlands, especially given the variety of potential responses evident in palaeoecological records (Kelly et al., 2017; Roucoux et al., 2013; Swindles et al., 2018b). Mining and transportation of oil and gas across remote parts of Amazonia will likely continue to pollute forests and wetlands in at least the near future (e.g., Sierra Praeli, 2020), with as yet unknown consequences for the long-term ecosystem function of peatlands (Baker et al., 2020; Roucoux et al., 2017).

2.5 Synthesis across three tropical peatland regions

Pathways for the development of peatlands share fundamental features across all three continents. The patterns of ecohydrological development and ecological succession involving the colonisation of freshwater anoxic environments are particularly relevant, by flood-tolerant herbs, palms and trees, commonly progressing to vegetation dominated by palms and trees tolerant of low-nutrient, acidic environments as ombrotrophic conditions develop. However, important differences (Fig. 4) also exist. For example, the peatlands in each region, and each peatland within each region, have a unique initiation date (Fig. 4) and development pathway that differs in detail, determined by the local climatic, geological, hydrological and ecological conditions, and history. The development of coastal peat swamp forests in Southeast Asia was closely linked to global sea level changes. The inland peatlands of Central Africa was more directly attributable to local climate and specifically, precipitation. In Amazonia, continual migration and switching of river channels has alternately created and truncated opportunities for peat to accumulate over time. Synthesising examples from across the tropics also demonstrates several universal patterns in ways that people have interacted with peatlands through the Holocene, and in the responses of peatland ecosystems.

Firstly, people have been living in the vicinity of all of these peatlands for much of the Holocene with the presumed palaeoanthropocene extending through the majority of this epoch. As in temperate regions, most historic and pre-historic human activity associated with the tropical peatlands probably happened on their margins, where the peat is shallower and the land more accessible and amenable to exploitation (Page and Baird, 2016).

Secondly, the difference in the effect of fires on peatlands in the deeper palaeoanthropocene versus the more recent anthropocene is stark. In the past, fires were generally rare in these ecosystems whereas today, they are driving significant change, though currently limited to the peatlands in Southeast Asia (Page and Hooijer, 2016). Throughout much of the Holocene, the forest vegetation apparently recovered after periods of burning. Only one study reported a possible effect of fire on the peat substrate itself (from Indonesia, Hope et al., 2005). Burning before *c*. 200 years ago has been associated with both natural and anthropogenic causes (Fig. 4) (Brncic et al., 2009; Hapsari et al., 2018; Hubau et al., 2015; Kelly et al., 2017). But towards the present day, in those peatlands that exemplify contemporary ecosystem changes occurring across tropical forested biomes (e.g., Cole et al., 2019; Malhi et al., 2014), fire events have increased in frequency and are linked to a lack of recovery of peatland vegetation, due to their greater intensity and coupling with deforestation and other disturbances.

One driver of change with still largely unknown directions and consequences, is climate. Across the three tropical peatland areas, climate has fluctuated between wetter and drier periods, equating to more or less favourable conditions for peat accumulation, respectively. In Amazonia, drier conditions have resulted in declines and even hiatuses in peat accumulation (Kelly et al., 2017; Swindles et al., 2018b). In the Central Congo Basin, increased aridity and prolonged drought also apparently caused a hiatus, and to a reduced ability of the peatland ecosystem to recover from burning (Hubau et al., 2015). By contrast, and somewhat counter-intuitively, at Aucayacu in northern Peru, periods of regional climatic drying appear to have encouraged peat accumulation in the flooded forest swamp phase. Later, however, after the transition to ombrotrophy and thus establishment of different ecohydrological conditions, a similar regional drought caused a pronounced slowing of peat accumulation (Swindles et al., 2018b). This pattern illustrates the complexity of peatland responses to climatic and other environmental drivers. Many, likely interacting factors have potential to influence the trajectory of peatland ecohydrological change. It also further highlights the importance of understanding local conditions.

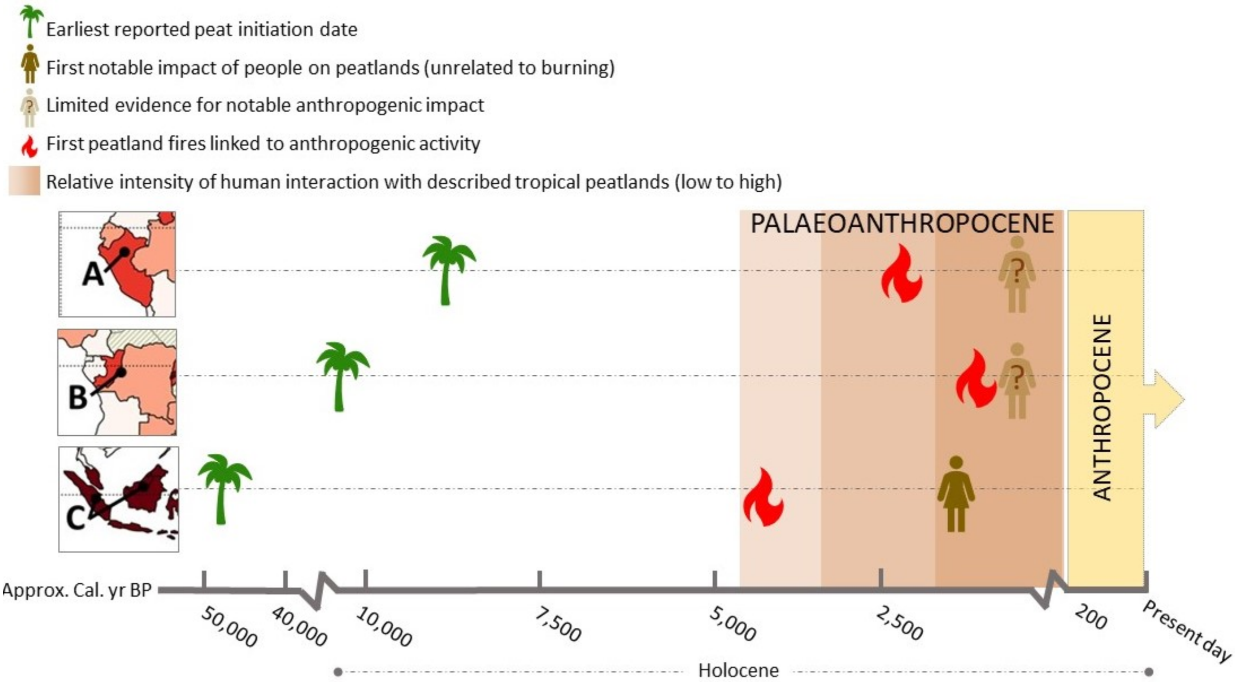

Fig. 4 A timeline of the key events evidenced from the reviewed palaeoecological records from the tropical peatland regions, A – Amazonia (Peru), B – Central Congo Basin (Democratic Republic of Congo, Republic of Congo), and C - Southeast Asia (Indonesia, Malaysia). (For information on the regional images, see Fig. 1.) The timeline demonstrates the approximate temporal placement of the presumed palaeoanthropocene and anthropocene periods, as conceptualised in this review, relative to the Holocene (last *c*. 11,700 years). (See Girkin et al., in progress, for a corresponding review pertaining to the anthropocene.)

3.1 Insights for the anthropocene

The palaeoecological records synthesized in this review demonstrate the temporary nature of the effects of people and of environmental change on tropical peatlands through the palaeoanthropocene. The low intensity of these effects has also enabled the ecosystems to recover. By contrast, notably in Southeast Asia, evidence from human interactions with tropical peatlands in the last *c*. 200 years illustrates an intensification of impacts and a lack of ecosystem recovery (Fig. 5). Can insights from the earlier palaeoanthropocene help to predict how peatlands might respond to anthropogenic perturbations and climate change in the future?

In terms of anthropogenic perturbations, palaeoecological data indicate that tropical peatland vegetation has persisted through periods of human presence in the landscape, including episodes of burning associated with both anthropogenic and natural drivers (Fig. 5). The dynamics of tropical peatlands in the last *c*. 200 years, however, reveal a different story (Girkin *et al.*, in progress). The perturbations observed within this more recent anthropocene period in the tropical peatland region of Southeast Asia, which has undergone the most transformation, apparently differ in two significant ways from those of the palaeoanthropocene. These differences provide important and cautionary insights for understanding how Central African and Amazonian peatlands could respond if exposed to similar perturbations (Lilleskov et al., 2019).

Firstly, the intensity and spatial extent of impacts are larger today. Smaller-scale clearances of peatland vegetation characterised the deforestation practices of the palaeoanthropocene, whereas clear-felling of forest over large areas is common where peatlands are converted to commercial plantations (e.g., Goldstein, 2016). Drainage canals are constructed and maintained, using mechanised vehicles, often in extensive networks (Hooijer et al., 2012; Ritzema et al., 1998). No evidence is available for deliberate peatland drainage before 200 years ago, and certainly not on this scale. Fires have greatly increased in intensity and geographical spread since the 1980s in Southeast Asian peatlands. Their frequency is becoming uncoupled from regional El Niño Southern Oscillation (ENSO) related climatic drying (Gaveau et al., 2014), with extensive burning now taking place annually. The fire regimes of the palaeoanthropocene are characterised by much lower intensity fires with longer return intervals. Consensus is also emerging that the rate of change and predicted elevations in temperature resulting from future anthropogenic global warming are unprecedented for the period in which the tropical peatlands have been extant.

The second major difference is the synchronous and summative nature of contemporary perturbations that rarely occur in isolation (e.g., Loisel et al., 2020; Wijedasa et al., 2017). In many cases, ongoing anthropogenic climate change is the backdrop to large-scale land use change (Fig. 5). Ecosystem conversion disrupts the hydrological and ecological integrity of the peatland unit and its fundamental system of self-regulation (Dommain et al., 2010). Under drier and warmer conditions where sources of ignition are more common in the landscape, peatlands will unlikely recover without significant human intervention (e.g., Graham & Page, 2018; Page et al., 2009).

With respect to the responses of tropical peatlands to climate change, palaeoenvironmental records indicate that future changes in precipitation could cause hiatuses in carbon accumulation. Several records (e.g., Anshari et al., 2001; Hapsari et al., 2017; Swindles et al., 2018b) indicate which climatic and hydrological conditions favour renewed peat accumulation or the development of new peatland sites, i.e., where the water table is at the surface and peat-forming vegetation can grow. These records also demonstrate that the outcome of climatic perturbations on a peatland’s carbon balance, i.e., organic matter accumulation relative to decay, depends on the hydrological regime of the peatland. A dry interval, for example, would affect ombrotrophic (rain-fed) and minerotrophic (river-fed) peatlands differently. For coastal peatlands, sea-level rise may counter potential gains in organic matter accumulation triggered by warmer and wetter conditions through flooding low-lying ecosystems, e.g., in Sarawak, Malaysian Borneo (Hooijer et al., 2015).

Fundamentally, the palaeoenvironmental records reviewed in this paper demonstrate that peatlands can recover from major climatic changes. They can also recover from incidences of human impact and from burning, albeit of much lower intensities of disturbance than are typically experienced by Southeast Asian peatlands today. These records contain scenarios for how people and peatlands can coexist over long timescales, with the potential to illustrate alternative futures for human-peatland interactions in the anthropocene.

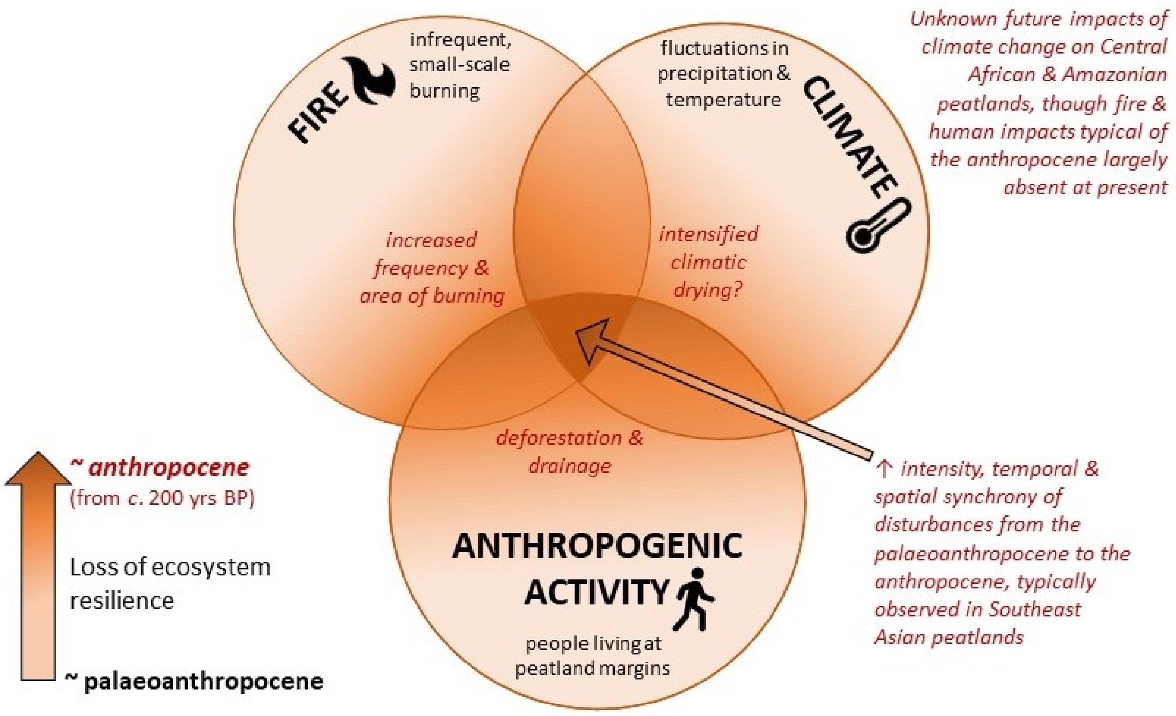

Fig. 5 The three main forms of disturbance to tropical peatlands explored in this review, within the: (i) palaeoanthropocene (black text); and (ii) anthropocene (red text). A loss of resilience of peatland ecosystems in response to the differing intensities and combinations of disturbances in the last *c*. 200 years compared to those observed prior to this, in the palaeoanthropocene, is illustrated by many peatlands in Southeast Asia.

3.2 Research Priorities

Palaeoecology provides multiple 'natural experiments' in which the variables of ecology, hydrology, climate, and human activity come together in different combinations at different times, and at different sites. The resulting effects on ecosystem functions, such as carbon sequestration, are measurable. These measurements can contribute to our understanding of how peatlands will respond to future, primarily anthropogenic, environmental changes by contextualising the effects of natural versus anthropogenic processes on tropical peatlands. High resolution palaeoecological records provide information on how long peatlands took to recover from different kinds of disturbance in the past and on the details of ecological recovery. In addition, high resolution radiocarbon dating reveals past patterns of carbon sequestration and carbon emissions from tropical peatlands. This is important because limited knowledge is available of where, when and how peatlands in the past transitioned from serving as a carbon sink to a carbon source (Hooijer et al., 2010; Wang et al., 2018), making it difficult to judge the relative contribution of natural versus anthropogenic factors to these shifts. Although it is well understood that climatic drying can cause a peatland's water table to fall below the surface for significant parts of the year, a situation unconducive for peat accumulation, our ability to predict exactly how ongoing anthropogenic climate change will influence carbon sequestration across tropical peatlands in the near future remains limited (Loisel et al., 2020). The results of both natural and computer-simulated experiments exploring the carbon cycle, where palaeoecological data are useful to parameterize models, are of increasing importance as every nation is encouraged to account for and minimise their greenhouse gas emissions. Peatlands are a significant, if as yet poorly quantified contributor to or mitigator of these emissions (Ekardt et al., 2020; Kumar et al., 2020).

Tropical peatlands have demonstrated resilience to perturbations, such as climatic changes, throughout prehistory, but they are also quickly degraded by more intense, short-lived disturbances caused by human activities. Significant gaps remain in our knowledge of peatland processes, particularly around positive and negative feedbacks that act to destabilise or stabilise the system (Page and Baird, 2016). An urgent need exists to understand more about the dynamics and resilience of peatlands, including the most likely drivers that lead to the loss of their peat-forming potential.

Another priority of tropical peatland research is to engage with communities who live in and around these ecosystems and use them for their livelihoods in ways that might have much in common with palaeoanthropocene human-peatland interactions (as in tropical forests, i.e., Roberts et al., 2021, 2018). Engagement with local people is necessary to address socio-ecological, political and economic issues, in addition to scientific questions. More effort is required to understand how to protect and restore peatland ecosystems with respect to not only the engineering challenges, but also the challenges of securing support from all peatland stakeholders. Peatland conservation and restoration may require: measures to protect, or explore collaboratively, alternative local livelihoods; monitoring and regulation of agribusinesses engaged in peatland use and management; and resources, training, legislation and partnerships to enable implementation of the above (Carmenta et al., 2020; Harrison et al., 2020). For effective conservation and restoration, understanding how societies value and care for peatlands is essential (Byg et al., 2020, 2017), in a relationship that may extend deep into prehistory, and the socio-economic and political context in which peatland management decisions are currently made (Dohong et al., 2017) and resolved on the ground (O'Reilly et al., 2020).

4.1 Conclusion

Review and synthesis of the literature on tropical peatlands provide insights that address the three questions posed in this paper.

Firstly, prior to transformative human activity, the majority of peatlands across lowland Southeast Asia, the Central Congo Basin and Amazonia, shared a common ecology and development trajectory: of forest vegetation in waterlogged conditions resulting in the accumulation of peat carbon. Specific regional and local peatland dynamics differed, for example, the timing of peat initiation and hydrological and vegetation development pathways, determined by the local climatic, geological, hydrological and ecological conditions, and history.

Secondly, palaeoecological records indicate that tropical peat swamp forest ecosystems have persisted through a variety of disturbances: episodes of climatic drying and drought, relatively low-intensity and intermittent burning, and incidences of localised and short-term anthropogenic forest clearance, with the dynamics of disturbance and recovery specific to each locality. Several studies have demonstrated hiatuses in peat accumulation linked to past climatic changes, followed by evidence of renewed peat accumulation (e.g., Anshari et al., 2004; Hubau et al., 2015; Kelly et al., 2017).

Thirdly, peatland ecosystem resilience is not evident where anthropogenic activity has become more intensive, more frequent, and larger in scale in the last *c*. 200 years (e.g., Cole et al., 2015), demonstrating the onset of transformative human impacts on these ecosystems. More extensive movement of people into, and intensive use of, peatland areas, along with the use of fire and drainage to manipulate these ecosystems, have led to significant losses of vegetation and carbon, primarily in Indonesia and Malaysia (Girkin *et al.*, in progress). In line with observations from the palaeoanthropocene, however, regional idiosyncrasies still dominate. No one universal type of anthropogenic impact affects all tropical peatlands. This is exemplified by the persistence of largely intact peatlands in the Central Congo and Amazon basins.

Tropical peatlands have accumulated carbon over millenia as a result of waterlogged conditions. These conditions pose challenges for local communities, yet palaeoecological studies indicate that people have interacted with these landscapes throughout the Holocene, and that tropical peatlands have responded dynamically to low-level prehistoric, palaeoanthropocene human activity. Contemporary studies demonstrate the loss of ecosystem function and extent of transformation that is possible in tropical peatlands since industrialised land use conversion began. If these ecosystems, rich in resources of local to global value and vulnerable to irreversible transformation, are to persist, more careful consideration is necessary on how we interact with them, perhaps learning from the deeper palaeoanthropocene period.

Several areas of future research are suggested to address outstanding gaps in knowledge. Firstly, acquisition and analysis of high resolution palaeoecological and palaeoenvironmental records from the under-researched tropical peatland localities, coupled with high resolution radiocarbon dating, will enable us to understand more about natural and anthropogenic processes, and their interactions, in these ecosystems. Secondly, feeding these data into models of peatland ecosystems will help to fill vital knowledge gaps, namely around carbon sequestration and emission dynamics through time. Thirdly, future research should prioritise working collaboratively with people living in and around tropical peatlands, to understand their livelihood needs and aspirations, and explore pathways for sustainable interaction with these invaluable ecosystems.

~

Note

This article is the first of a two-part review of *Tropical peatlands in the anthropocene*. The articles have been written together to provide complementary reviews of the past, present and future interactions of people with tropical peatlands, focusing on those in Southeast Asia, Central Africa and Amazonia. *Tropical peatlands in the anthropocene: lessons from the past* (herein) explores: (i) the state of knowledge on tropical peatland development and ecosystem responses to anthropogenic disturbance in the palaeoanthropocene (the period following the earliest evidence for human presence), using evidence from palaeoecology, and (ii) how past disturbances compare with contemporary levels of anthropogenic disturbance and the insights they provide for predicting future responses and ecosystem resilience. *Tropical peatlands in the anthropocene: the present and the future* (the second article; Girkin et al., in progress) describes: (i) the patterns of human interaction with tropical peatlands in the 20th and early 21st centuries, and (ii) how these impacts could be mitigated in the future. The articles cross-reference each other to indicate where the reader can learn more on themes that are covered more fully in the other.

Author contributions

LESC and NTG conceived the article. KAH, DH, CMÅ and KHR wrote the first draft. All authors contributed to subsequent revisions of the article.

Acknowledgements

We would like to thank the anonymous reviewers of this article for their valuable comments, and the Editors, for their support and patience during the completion of this series of papers. We also thank Dr Ian Lawson for reviewing and proof-reading sections of the text, and assisting in the creation of Fig. 1. We are grateful to the German Research Foundation (BE 2116/32-1) for funding KAH; to NERC for funding DH, via the CongoPeat project (NE/R016860/1, awarded to Prof Simon Lewis), and CMÅ and part-funding KHR (NE/R000751/1); to the Newton-Paulet Institutional Links Grant (Grant ref. 220-2018) for part-funding KHR and LESC, and to the Leverhulme Trust for part-funding LESC (Research Grant RPG-2018-306).

References

Åkesson, C.M., McMichael, C.N.H., Raczka, M.F., Huisman, S.N., Palmeira, M., Vogel, J., Neill, D., Veizaj, J., Bush, M.B., 2021. Long-term ecological legacies in western Amazonia. J. Ecol. 109, 432–446. https://doi.org/10.1111/1365-2745.13501

Albrecht, R.I., Goodman, S.J., Buechler, D.E., Blakeslee, R.J., Christian, H.J., 2016. Where Are the Lightning Hotspots on Earth? Bull. Am. Meteorol. Soc. 97, 2051–2068. https://doi.org/10.1175/BAMS-D-14-00193.1

Aleman, J.C., Fayolle, A., 2020. Long-Term Vegetation Change in Central Africa: The Need for an Integrated Management Framework for Forests and Savannas 281–315. https://doi.org/10.1007/978-981-15-4458-3_9

Anderson, J.A.R., 1964. The Structure and Development of the Peat Swamps of Sarawak and Brunei. J. Trop. Geogr. 18, 7–16.

Anshari, G., Peter Kershaw, A., Van Der Kaars, S., 2001. A Late Pleistocene and Holocene pollen and charcoal record from peat swamp forest, Lake Sentarum wildlife reserve, West Kalimantan, Indonesia. Palaeogeogr. Palaeoclimatol. Palaeoecol. 171, 213–228. https://doi.org/10.1016/S0031-0182(01)00246-2

Anshari, G., Peter Kershaw, A., Van Der Kaars, S., Jacobsen, G., 2004. Environmental change and peatland forest dynamics in the Lake Sentarum area, West Kalimantan, Indonesia. J. Quat. Sci. 19, 637–655. https://doi.org/10.1002/jqs.879

Aslan, A., White, W.A., Warne, A.G., Guevara, E.H., 2003. Holocene evolution of the western Orinoco Delta, Venezuela. GSA Bull. 115, 479–498. https://doi.org/10.1130/0016-7606(2003)115<0479:HEOTWO>2.0.CO;2

Astiani, D., Curran, L.M., Burhanuddin, Taherzadeh, M., Mujiman, Hatta, M., Pamungkas, W., Gusmayanti, E., 2018. FIRE-DRIVEN BIOMASS AND PEAT CARBON LOSSES AND POST-FIRE SOIL CO₂ EMISSION IN A WEST KALIMANTAN PEATLAND FOREST. J. Trop. For. Sci. 30, 570–575.

Baker, P.A., Fritz, S.C., Garland, J., Ekdahl, E., 2005. Holocene hydrologic variation at Lake Titicaca, Bolivia/Peru, and its relationship to North Atlantic climate variation. J. Quat. Sci. 20, 655–662. https://doi.org/https://doi.org/10.1002/jqs.987

Baker, T.R., Del Castillo Torres, D., Honorio Coronado, E., Lawson, I.T., Martín Brañas, M., Montoya, M., Roucoux, K.H., 2020. The challenges for achieving conservation and sustainable development within the wetlands of the Pastaza - Marañon basin, Peru, in: Chirif Tirado, A. (Ed.), Peru: Deforestation in Times of Climate Change. IWGIA, 2019, Lima, pp. 155–174.

Barber, C.P., Cochrane, M.A., Souza, C.M., Laurance, W.F., 2014. Roads, deforestation, and the mitigating effect of protected areas in the Amazon. Biol. Conserv. 177, 203–209. https://doi.org/10.1016/j.biocon.2014.07.004

Barker, G., Hunt, C., Barton, H., Gosden, C., Jones, S., Lloyd-Smith, L., Farr, L., Nyirí, B., O'Donnell, S., 2017. The 'cultured rainforests' of Borneo. Quat. Int. 448, 44–61. https://doi.org/10.1016/j.quaint.2016.08.018

Bellwood, P., 1997. Prehistory of the Indo-Malaysian Archipelago. ANU Press.

Bennett, K.D., Willis, K.J., 2001. Pollen, in: Tracking Environmental Change Using Lake Sediments. Kluwer Academic Publishers, Dordrecht, pp. 5–32. https://doi.org/10.1007/0-306-47668-1_2

Bhomia, R.K., van Lent, J., Rios, J.M.G., Hergoualc'h, K., Coronado, E.N.H., Murdiyarso, D., 2018. Impacts of Mauritia flexuosa degradation on the carbon stocks of freshwater peatlands in the Pastaza-Marañón river basin of the Peruvian Amazon. Mitig. Adapt. Strateg. Glob. Chang. 1–24. https://doi.org/10.1007/s11027-018-9809-9

Biagioni, S., Krashevska, V., Achnopha, Y., Saad, A., Sabiham, S., Behling, H., 2015. 8000years of vegetation dynamics and environmental changes of a unique inland peat ecosystem of the Jambi Province in Central Sumatra, Indonesia. Palaeogeogr. Palaeoclimatol. Palaeoecol. 440, 813–829. https://doi.org/10.1016/j.palaeo.2015.09.048

Birks, H.J.B., 2008. Paleoecology, in: Encyclopedia of Ecology, Five-Volume Set. Elsevier Inc., pp. 2623–2634. https://doi.org/10.1016/B978-008045405-4.00525-5

Bostoen, K., Clist, B., Doumenge, C., Grollemund, R., Hombert, J.M., Muluwa, J.K., Maley, J., 2015. Middle to late holocene paleoclimatic change and the early bantu expansion in the rain forests of Western Central Africa. Curr. Anthropol. 56, 354–384. https://doi.org/10.1086/681436

Brncic, T.M., Willis, K.J., Harris, D.J., Telfer, M.W., Bailey, R.M., 2009. Fire and climate change impacts on lowland forest composition in northern Congo during the last 2580 years from palaeoecological analyses of a seasonally flooded swamp. The Holocene 19, 79–89. https://doi.org/10.1177/0959683608098954

Brugger, S.O., Gobet, E., van Leeuwen, J.F.N., Ledru, M.P., Colombaroli, D., van der Knaap, W.O., Lombardo, U., Escobar-Torrez, K., Finsinger, W., Rodrigues, L., Giesche, A., Zarate, M., Veit, H., Tinner, W., 2016. Long-term man-environment interactions in the Bolivian Amazon: 8000 years of vegetation dynamics. Quat. Sci. Rev. 132, 114–128. https://doi.org/10.1016/j.quascirev.2015.11.001

Bush, M.B., Colinvaux, P.A., 1988. A 7000-year pollen record from the Amazon lowlands, Ecuador. Vegetatio 76, 141–154. https://doi.org/10.1007/BF00045475

Bush, M.B., Correa-Metrio, A., McMichael, C.H., Sully, S., Shadik, C.R., Valencia, B.G., Guilderson, T., Steinitz-Kannan, M., Overpeck, J.T., 2016. A 6900-year history of landscape modification by humans in lowland Amazonia. Quat. Sci. Rev. 141, 52–64. https://doi.org/https://doi.org/10.1016/j.quascirev.2016.03.022

Bush, M.B., McMichael, C.H., Piperno, D.R., Silman, M.R., Barlow, J., Peres, C.A., Power, M., Palace, M.W., 2015. Anthropogenic influence on Amazonian forests in pre-history: An ecological perspective. J. Biogeogr. 42, 2277–2288. https://doi.org/10.1111/jbi.12638

Bush, M.B., Silman, M.R., Listopad, C.M.C.S., 2007. A Regional Study of Holocene Climate Change and Human Occupation in Peruvian Amazonia. J. Biogeogr. 34, 1342–1356.

Byg, A., Martin-Ortega, J., Glenk, K., Novo, P., 2017. Conservation in the face of ambivalent public perceptions – The case of peatlands as 'the good, the bad and the ugly.' Biol. Conserv. 206, 181–189. https://doi.org/10.1016/J.BIOCON.2016.12.022

Byg, A., Novo, P., Kyle, C., 2020. Caring for Cinderella—Perceptions and experiences of peatland restoration in Scotland. People Nat. pan3.10141. https://doi.org/10.1002/pan3.10141

Carmenta, R., Zabala, A., Trihadmojo, B., Gaveau, D., Salim, M.A., Phelps, J., 2020. Evaluating bundles of interventions to prevent peat-fires in Indonesia. Glob. Environ. Chang. 102154. https://doi.org/10.1016/j.gloenvcha.2020.102154

Clement, C.R., 1999. 1492 and the loss of amazonian crop genetic resources. I. The relation between domestication and human population decline. Econ. Bot. 53, 188–202. https://doi.org/10.1007/BF02866498

Clement, C.R., Denevan, W.M., Heckenberger, M.J., Junqueira, A.B., Neves, E.G., Teixeira, W.G., Woods, W.I., 2015. The domestication of amazonia before european conquest. Proc. R. Soc. B Biol. Sci. https://doi.org/10.1098/rspb.2015.0813

Clement, S., Standish, R.J., 2018. Novel ecosystems: Governance and conservation in the age of the Anthropocene. J. Environ. Manage. 208, 36–45. https://doi.org/10.1016/J.JENVMAN.2017.12.013

Cole, L.E.S., Bhagwat, S.A., Willis, K.J., 2019. Fire in the Swamp Forest: Palaeoecological Insights Into Natural and Human-Induced Burning in Intact Tropical Peatlands. Front. For. Glob. Chang. 2, 48. https://doi.org/10.3389/ffgc.2019.00048

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. https://doi.org/10.1111/1365-2745.12329

Cole, L.E.S., Bhagwat, S.A., Willis, K.J., 2014. Recovery and resilience of tropical forests after disturbance. Nat. Commun. 5. https://doi.org/10.1038/ncomms4906

Colombijn, F., 2005. A Moving History of Middle Sumatra, 1600-1870. Mod. Asian Stud. 39, 1–38.

Cook, K.H., Liu, Y., Vizy, E.K., 2020. Congo Basin drying associated with poleward shifts of the African thermal lows. Clim. Dyn. 54, 863–883. https://doi.org/10.1007/s00382-019-05033-3

Coomes, O.T., Takasaki, Y., Abizaid, C., 2020. Impoverishment of local wild resources in western Amazonia: a large-scale community survey of local ecological knowledge. Environ. Res. Lett. 15, 74016. https://doi.org/10.1088/1748-9326/ab83ad

Cooper, D.J., Sueltenfuss, J., Oyague, E., Yager, K., Slayback, D., Caballero, E.M.C., Argollo, J., Mark, B.G., 2019. Drivers of peatland water table dynamics in the central Andes, Bolivia and Peru. Hydrol. Process. 33, 1913–1925. https://doi.org/https://doi.org/10.1002/hyp.13446

Corlett, R.T., 2015. The Anthropocene concept in ecology and conservation. Trends Ecol. Evol. 30, 36–41. https://doi.org/10.1016/J.TREE.2014.10.007

Coronado, E.N.H., Hastie, A., Reyna, J., Flores, G., Grández, J., Lähteenoja, O., Draper, F.C., Åkesson, C.M., Baker, T.R., Bhomia, R.K., Cole, L.E.S., Dávila, N., Águila, J. Del, Águila, M. Del, Torres, D.D.C., Lawson, I.T., Brañas, M.M., Mitchard, E.T.A., Monteagudo, A., Phillips, O.L., Ramírez, E., Ríos, M., Ríos, S., Rodriguez, L., Roucoux, K.H., Casapia, X.T., Vasquez, R., Wheeler, C.E., Montoya, M., 2021. Intensive field sampling increases the known extent of carbon-rich Amazonian peatland pole forests. Environ. Res. Lett. 16, 074048. https://doi.org/10.1088/1748-9326/AC0E65

Correa-Metrio, A., Cabrera, K.R., Bush, M.B., 2010. Quantifying ecological change through discriminant analysis: a paleoecological example from the Peruvian Amazon. J. Veg. Sci. 21, 695–704.

Crevecoeur, I., Skinner, M.M., Bailey, S.E., Gunz, P., Bortoluzzi, S., Brooks, A.S., Burlet, C., Cornelissen, E., De Clerck, N., Maureille, B., Semal, P., Vanbrabant, Y., Wood, B., 2014. First Early Hominin from Central Africa (Ishango, Democratic Republic of Congo). PLoS One 9, e84652. https://doi.org/10.1371/JOURNAL.PONE.0084652

Dargie, G.C., 2015. Quantifying and Understanding the Tropical Peatlands of the Central Congo Basin.

Dargie, G.C., Lawson, I.T., Rayden, T.J., Miles, L., Mitchard, E.T.A., Page, S.E., Bocko, Y.E., Ifo, S.A., Lewis, S.L., 2019. Congo Basin peatlands: threats and conservation priorities. Mitig. Adapt. Strateg. Glob. Chang. 24, 669–686. https://doi.org/10.1007/s11027-017-9774-8

Dargie, G.C., Lewis, S.L., Lawson, I.T., Mitchard, E.T.A., Page, S.E., Bocko, Y.E., Ifo, S.A., 2017. Age, extent and carbon storage of the central Congo Basin peatland complex. Nature 542, 86–90.

https://doi.org/10.1038/nature21048

Davenport, I.J., McNicol, I., Mitchard, E.T.A., Dargie, G., Suspense, I., Milongo, B., Bocko, Y.E., Hawthorne, D., Lawson, I., Baird, A.J., Page, S., Lewis, S.L., 2020. First Evidence of Peat Domes in the Congo Basin using LiDAR from a Fixed-Wing Drone. Remote Sens. 12, 2196. https://doi.org/10.3390/rs12142196

Davies, A.L., Streeter, R., Lawson, I.T., Roucoux, K.H., Hiles, W., 2018. The application of resilience concepts in palaeoecology. Holocene. https://doi.org/10.1177/0959683618777077

de Luna, K.M., 2017. Conceptualizing vegetation in the Bantu Expansion: Reflections on linguistics in central African history. Quat. Int. 448, 158–168. https://doi.org/10.1016/j.quaint.2016.08.016

de Luna, K.M., 2016. Collecting food, cultivating people: Subsistence and society in Central Africa. Yale University Press.

Dobyns, H.F., 2017. Estimating aboriginal American population: An appraisal of techniques with a New Hemispheric estimate, in: The Atlantic Slave Trade: Volume I Origins-1600. Taylor and Francis, pp. 163–186. https://doi.org/10.4324/9781351147682-8

Dohong, A., Aziz, A.A., Dargusch, P., 2017. A review of the drivers of tropical peatland degradation in South-East Asia. Land use policy 69, 349–360. https://doi.org/10.1016/j.landusepol.2017.09.035

Dommain, R., Cobb, A.R., Joosten, H., Glaser, P.H., Chua, A.F.L., Gandois, L., Kai, F.-M., Noren, A., Salim, K.A., Su'ut, N.S.H., Harvey, C.F., 2015. Forest dynamics and tip-up pools drive pulses of high carbon accumulation rates in a tropical peat dome in Borneo (Southeast Asia). J. Geophys. Res. Biogeosciences 120, 617–640. https://doi.org/10.1002/2014JG002796

Dommain, R., Couwenberg, J., Glaser, P.H., Joosten, H., Suryadiputra, I.N.N., 2014. Carbon storage and release in Indonesian peatlands since the last deglaciation. Quat. Sci. Rev. 97, 1–32. https://doi.org/10.1016/j.quascirev.2014.05.002

Dommain, R., Couwenberg, J., Joosten, H., 2011. Development and carbon sequestration of tropical peat domes in south-east Asia: Links to post-glacial sea-level changes and Holocene climate variability. Quat. Sci. Rev. 30, 999–1010. https://doi.org/10.1016/j.quascirev.2011.01.018

Dommain, R., Couwenberg, J., Joosten, H., 2010. Hydrological self-regulation of domed peatlands in south-east Asia and consequences for conservation and restoration.

Draper, F.C., Honorio Coronado, E.N., Roucoux, K.H., Lawson, I.T., A. Pitman, N.C., A. Fine, P. V., Phillips, O.L., Torres Montenegro, L.A., Valderrama Sandoval, E., Mesones, I., García-Villacorta, R., Arévalo, F.R.R., Baker, T.R., 2018. Peatland forests are the least diverse tree communities documented in Amazonia, but contribute to high regional beta-diversity. Ecography (Cop.). 41, 1256–1269. https://doi.org/10.1111/ecog.03126

Draper, F.C., Roucoux, K.H., Lawson, I.T., Mitchard, E.T.A., Honorio Coronado, E.N., Lähteenoja, O., Torres Montenegro, L., Valderrama Sandoval, E., Zaráte, R., Baker, T.R., 2014. The distribution and amount of carbon in the largest peatland complex in Amazonia. Environ. Res. Lett. 9, 124017. https://doi.org/10.1088/1748-9326/9/12/124017

Dubroeucq, D., Volkoff, B., 1998. From Oxisols to Spodosols and Histosols: evolution of the soil mantles in the Rio Negro basin (Amazonia). Catena 32, 245–280.

Ekardt, F., Jacobs, B., Stubenrauch, J., Garske, B., 2020. Peatland Governance: The Problem of Depicting in Sustainability Governance, Regulatory Law, and Economic Instruments. Land 9, 83. https://doi.org/10.3390/land9030083

Elenga, H., Schwartz, D., Vincens, A., 1994. Pollen evidence of late Quaternary vegetation and inferred climate changes in Congo. Palaeogeogr. Palaeoclimatol. Palaeoecol. 109, 345–356. https://doi.org/10.1016/0031-0182(94)90184-8

Ellis, E.C., Goldewijk, K.K., Siebert, S., Lightman, D., Ramankutty, N., 2010. Anthropogenic transformation of the biomes, 1700 to 2000. Glob. Ecol. Biogeogr. 19, 589–606. https://doi.org/10.1111/J.1466-8238.2010.00540.X

Erickson, C.L., 2006. The Domesticated Landscapes of the Bolivian Amazon.

Foley, S.F., Gronenborn, D., Andreae, M.O., Kadereit, J.W., Esper, J., Scholz, D., Pöschl, U., Jacob, D.E., Schöne, B.R., Schreg, R., Vött, A., Jordan, D., Lelieveld, J., Weller, C.G., Alt, K.W., Gaudzinski-Windheuser, S., Bruhn, K.C., Tost, H., Sirocko, F., Crutzen, P.J., 2013. The Palaeoanthropocene - The beginnings of anthropogenic environmental change. Anthropocene 3, 83–88. https://doi.org/10.1016/j.ancene.2013.11.002

Folke, C., Polasky, S., Rockström, J., Galaz, V., Westley, F., Lamont, M., Scheffer, M., Österblom, H., Carpenter, S.R., Chapin, F.S., Seto, K.C., Weber, E.U., Crona, B.I., Daily, G.C., Dasgupta, P., Gaffney, O., Gordon, L.J., Hoff, H., Levin, S.A., Lubchenco, J., Steffen, W., Walker, B.H., 2021. Our future in the Anthropocene biosphere. Ambio 50, 834–869. https://doi.org/10.1007/S13280-021-01544-8/FIGURES/12

Fonkén, M.S.M., 2014. An introduction to the bofedales of the Peruvian High Andes. Mires Peat 15, 1–13.

Froyd, C.A., Willis, K.J., 2008. Emerging issues in biodiversity & conservation management: The need for a palaeoecological perspective. Quat. Sci. Rev. 27, 1723–1732. https://doi.org/10.1016/J.QUASCIREV.2008.06.006

Gallice, G.R., Larrea-Gallegos, G., Vázquez-Rowe, I., 2019. The threat of road expansion in the Peruvian Amazon. ORYX 53, 284–292. https://doi.org/10.1017/S0030605317000412

Gasse, F., 2000. Hydrological changes in the African tropics since the Last Glacial Maximum. Quat. Sci. Rev. 19, 189–211. https://doi.org/10.1016/S0277-3791(99)00061-X

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, 1–7. https://doi.org/10.1038/srep06112

Githumbi, E., Marchant, R., Olago, D., 2020. Using the Past to Inform a Sustainable Future: Palaeoecological Insights from East Africa. Springer, Cham, pp. 187–195. https://doi.org/10.1007/978-3-030-14857-7_18

Glaser, B., Woods, W.I., 2004. Amazonian Dark Earths: Explorations in Space and Time, Amazonian Dark Earths: Explorations in Space and Time. Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-662-05683-7

Glinskis, E.A., Gutiérrez-Vélez, V.H., 2019. Quantifying and understanding land cover changes by large and small oil palm expansion regimes in the Peruvian Amazon. Land use policy 80, 95–106. https://doi.org/10.1016/J.LANDUSEPOL.2018.09.032

Global Environment Centre, 2021. No Title [WWW Document]. URL https://www.gec.org.my/index.cfm?&menuid=334

Goldstein, J., 2016. Carbon Bomb: Indonesia's Failed Mega Rice Project [WWW Document]. Environ. Soc. Portal. URL http://www.environmentandsociety.org/arcadia/carbon-bomb-indonesias-failed-mega-rice-project (accessed 1.12.21).

Graham, L.L.B., Page, S.E., 2018. A limited seed bank in both natural and degraded tropical peat swamp forest: the implications for restoration. Mires Peat 22, 1–13. https://doi.org/10.19189/MaP.2017.OMB.302

Hajdas, I., 2008. Radiocarbon dating and its applications in Quaternary studies. E&G Quat. Sci. J. 57, 2–24. https://doi.org/10.3285/eg.57.1-2.1

Hapsari, K.A., Biagioni, S., Jennerjahn, T.C., Reimer, P.M., Saad, A., Achnopha, Y., Sabiham, S., Behling, H., 2017. Environmental dynamics and carbon accumulation rate of a tropical peatland in Central Sumatra, Indonesia. Quat. Sci. Rev. 169, 173–187. https://doi.org/10.1016/j.quascirev.2017.05.026

Hapsari, K.A., Siria Biagioni, |, Jennerjahn, T.C., Reimer, | Peter, Saad, A., Sabiham, S., Behling, H., 2018. Resilience of a peatland in Central Sumatra , Indonesia to past anthropogenic disturbance : Improving conservation and restoration designs using palaeoecology. J. Ecol. 1–18. https://doi.org/10.1111/1365-2745.13000

Harrison, M.E., Ottay, J.B., D'Arcy, L.J., Cheyne, S.M., Anggodo, Belcher, C., Cole, L., Dohong, A., Ermiasi, Y., Feldpausch, T., Gallego-Sala, A., Gunawan, A., Höing, A., Husson, S.J., Kulu, I.P., Soebagio, S.M., Mang, S., Mercado, L., Morrogh-Bernard, H.C., Page, S.E., Priyanto, R., Ripoll Capilla, B., Rowland, L., Santos, E.M., Schreer, V., Sudyana, I.N., Taman, S.B.B., Thornton, S.A., Upton, C., Wich, S.A., Veen, F.J.F., 2020. Tropical forest and peatland conservation in Indonesia: Challenges and directions. People Nat. 2, 4–28. https://doi.org/10.1002/pan3.10060

Hobbs, R.J., Higgs, E., Hall, C.M., Bridgewater, P., Chapin, F.S., Ellis, E.C., Ewel, J.J., Hallett, L.M., Harris, J., Hulvey, K.B., Jackson, S.T., Kennedy, P.L., Kueffer, C., Lach, L., Lantz, T.C., Lugo, A.E., Mascaro, J., Murphy, S.D., Nelson, C.R., Perring, M.P., Richardson, D.M., Seastedt, T.R., Standish, R.J., Starzomski, B.M., Suding, K.N., Tognetti, P.M., Yakob, L., Yung, L., 2014. Managing the whole landscape: historical, hybrid, and novel ecosystems. Front. Ecol. Environ. 12, 557–564. https://doi.org/10.1890/130300

Hooijer, A., Page, S., Canadell, J.G., Silvius, M., Kwadijk, J., Wösten, H., Jauhiainen, J., 2010. Current and future CO_2 emissions from drained peatlands in Southeast Asia Current and future CO_2 emissions from drained peatlands in Southeast Asia. Biogeosciences 7, 1505–1514. https://doi.org/10.5194/bgd-6-7207-2009

Hooijer, A., Page, S., Jauhiainen, J., Lee, W.A., Lu, X.X., Idris, A., Anshari, G., 2012. Subsidence and carbon loss in drained tropical peatlands. Biogeosciences 9, 1053–1071. https://doi.org/10.5194/bg-9-1053-2012

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.

Hope, G., Chokkalingam, U., Anwar, S., 2005. The stratigraphy and fire history of the Kutai Peatlands, Kalimantan, Indonesia. Quat. Res. 64, 407–417. https://doi.org/10.1016/j.yqres.2005.08.009

Horton, B.P., Gibbard, P.L., Milne, G.M., Morley, R.J., Purintavaragul, C., Stargardt, J.M., 2005. Holocene sea levels and palaeoenvironments, Malay-Thai Peninsula, southeast Asia. Holocene 15, 1199–1213. https://doi.org/10.1191/0959683605hl891rp

Householder, E.J., Janovec, J.P., Tobler, M.W., Page, S., Lähteenoja, O., 2012. Peatlands of the madre de dios river of peru: Distribution, geomorphology, and habitat diversity. Wetlands 32, 359–368. https://doi.org/10.1007/s13157-012-0271-2

Hubau, W., Van den Bulcke, J., Van Acker, J., Beeckman, H., 2015. Charcoal-inferred Holocene fire and vegetation history linked to drought periods in the Democratic Republic of Congo. Glob. Chang. Biol. 21, 2296–2308. https://doi.org/10.1111/gcb.12844

Hunt, C.O., Premathilake, R., 2012. Early Holocene vegetation, human activity and climate from Sarawak, Malaysian Borneo. Quat. Int. 249, 105–119. https://doi.org/10.1016/j.quaint.2011.04.027

Jahns, S., 1996. Vegetation history and climate changes in West Equatorial Africa during the Late Pleistocene and Holocene, based on a marine pollen diagram from the Congo fan. Veg. Hist. Archaeobotany 1996 53 5, 207–213. https://doi.org/10.1007/BF00217498

Jahns, S., Hüls, M., Sarnthein, M., 1998. Vegetation and climate history of west equatorial Africa based on a marine pollen record off Liberia (site GIK 16776) covering the last 400,000 years. Rev. Palaeobot. Palynol. 102, 277–288. https://doi.org/10.1016/s0034-6667(98)80010-9

Jansen, F., Ufkes', E., Khelifa, L. Ben, 1995. The Younger Dryas in Equatorial and Southern Africa and in the Southeast Atlantic Ocean.

Katingan [WWW Document], 2021. URL https://katinganproject.com/impacts/1/climate

Kaur, A., 1995. The Babbling Brookes: Economic Change in Sarawak 1841-1941. Mod. Asian Stud. 29, 65–109. https://doi.org/10.1017/S0026749X00012634

Kelly, T.J., Lawson, I.T., Cole, L.E.S., 2018a. Peat. Springer, Cham, pp. 1197–1200. https://doi.org/10.1007/978-3-319-39312-4_187

Kelly, T.J., Lawson, I.T., Roucoux, K.H., Baker, T.R., Honorio-Coronado, E.N., Jones, T.D., Rivas Panduro, S., 2018b. Continuous human presence without extensive reductions in forest cover over the past 2500 years in an aseasonal Amazonian rainforest. J. Quat. Sci. 33, 369–379. https://doi.org/https://doi.org/10.1002/jqs.3019

Kelly, T.J., Lawson, I.T., Roucoux, K.H., Baker, T.R., Jones, T.D., Sanderson, N.K., 2017. The vegetation history of an Amazonian domed peatland. Palaeogeogr. Palaeoclimatol. Palaeoecol. https://doi.org/10.1016/j.palaeo.2016.11.039

Koh, L.P., Miettinen, J., Liew, S.C., Ghazoul, J., 2011. Remotely sensed evidence of tropical peatland conversion to oil palm. Proc. Natl. Acad. Sci. U. S. A. 108, 5127–5132. https://doi.org/10.1073/pnas.1018776108

Krigbaum, J., 2003. Neolithic subsistence patterns in northern Borneo reconstructed with stable carbon isotopes of enamel. J. Anthropol. Archaeol. 22, 292–304. https://doi.org/10.1016/S0278-4165(03)00041-2

Kumar, P., Adelodun, A.A., Khan, M.F., Krisnawati, H., Garcia-Menendez, F., 2020. Towards an improved understanding of greenhouse gas emissions and fluxes in tropical peatlands of Southeast Asia. Sustain. Cities Soc. https://doi.org/10.1016/j.scs.2019.101881

Kusmartono, V.P.R., Hindarto, I., Herwanto, E., 2017. Late Pleistocene to recent: Human activities in the deep interior equatorial rainforest of Kalimantan, Indonesian Borneo. Quat. Int. 448, 82–94. https://doi.org/10.1016/j.quaint.2016.09.025

Kusmartono, V.P.R., Oktrivia, U., 2019. Neolithic Occupations on the Southern Slope of the Müller Mountains: Nanga Balang and Muara Joloi (Okupasi Neolitik Di Lereng Selatan Pegunungan Müller: Nanga Balang Dan Muara Joloi). Kindai Etam J. Penelit. Arkeol. 4. https://doi.org/10.24832/ke.v4i1.37

Lähteenoja, O., Flores, B., Nelson, B., 2013. Tropical Peat Accumulation in Central Amazonia. Wetlands 33, 495–503. https://doi.org/10.1007/s13157-013-0406-0

Lähteenoja, O., Page, S., 2011. High diversity of tropical peatland ecosystem types in the Pastaza-Marañón basin, Peruvian Amazonia. J. Geophys. Res. 116, G02025. https://doi.org/10.1029/2010JG001508

Lähteenoja, O., Reátegui, Y.R., Räsänen, M., Torres, D.D.C., Oinonen, M., Page, S., 2012a. The large Amazonian peatland carbon sink in the subsiding Pastaza-Marañón foreland basin, Peru. Glob. Chang. Biol. 18, 164–178. https://doi.org/10.1111/j.1365-2486.2011.02504.x

Lähteenoja, O., Reátegui, Y.R., Räsänen, M., Torres, D.D.C., Oinonen, M., Page, S., 2012b. The large Amazonian peatland carbon sink in the subsiding Pastaza-Marañón foreland basin, Peru. Glob. Chang. Biol. 18, 164–178. https://doi.org/10.1111/j.1365-2486.2011.02504.x

Lähteenoja, O., Ruokolainen, K., Schulman, L., Alvarez, J., 2009a. Amazonian floodplains harbour minerotrophic and ombrotrophic peatlands. CATENA 79, 140–145. https://doi.org/10.1016/J.CATENA.2009.06.006

Lähteenoja, O., Ruokolainen, K., Schulman, L., Oinonen, M., 2009b. Amazonian peatlands: An ignored C sink and potential source. Glob. Chang. Biol. 15, 2311–2320. https://doi.org/10.1111/j.1365-2486.2009.01920.x

Langan, C., Farmer, J., Rivington, M., Novo, P., Smith, J.U., 2019. A wetland ecosystem service assessment tool; Development and application in a tropical peatland in Uganda. Ecol. Indic. 103, 434–445. https://doi.org/10.1016/j.ecolind.2019.04.019

Langner, A., Siegert, F., 2009. Spatiotemporal fire occurrence in Borneo over a period of 10 years. Glob. Chang. Biol. 15, 48–62. https://doi.org/10.1111/j.1365-2486.2008.01828.x

Lathrap, D.W., 1970. The Upper Amazon. Praeger Publishers, New York.

Laurance, W.F., Albernaz, A.K., Fearnside, P.M., Vasconcelos, H.L., Ferreira, L.V., 2004. Deforestation in Amazonia. Science (80-.). 304, 1109b-1111b. https://doi.org/10.1126/science.304.5674.1109b

Laurance, W.F., Bergen, S., Cochrane, M., Fearnside, P.M. Delamônica, P., D'Angelo, S., Barber, C., Fernandes, T., 2005. The future of the Amazon, in: Bermingham, C.D., Moritz, C. (Eds.), Tropical Rainforests: Past, Present, and Future. University of Chicago Press, Chicago, Illinois, USA, p. 1004.

Lawson, I.T., Jones, T.D., Kelly, T.J., Coronado, E.N.H., Roucoux, K.H., 2014. The Geochemistry of Amazonian Peats. Wetlands. https://doi.org/10.1007/s13157-014-0552-z

Lawson, I.T., Kelly, T.J., Aplin, P., Boom, A., Dargie, G., Draper, F.C.H., Hassan, P.N.Z.B.P., Hoyos-

Santillan, J., Kaduk, J., Large, D., Murphy, W., Page, S.E., Roucoux, K.H., Sjögersten, S., Tansey, K., Waldram, M., Wedeux, B.M.M., Wheeler, J., 2015. Improving estimates of tropical peatland area, carbon storage, and greenhouse gas fluxes. Wetl. Ecol. Manag. https://doi.org/10.1007/s11273-014-9402-2

Leifeld, J., Menichetti, L., 2018. The underappreciated potential of peatlands in global climate change mitigation strategies /704/47/4113 /704/106/47 article. Nat. Commun. 9, 1–7. https://doi.org/10.1038/s41467-018-03406-6

Levis, C., Costa, F.R.C., Bongers, F., Peña-Claros, M., Clement, C.R., Junqueira, A.B., Neves, E.G., Tamanaha, E.K., Figueiredo, F.O.G., Salomão, R.P., Castilho, C. V., Magnusson, W.E., Phillips, O.L., Guevara, J.E., Sabatier, D., Molino, J.F., Cárdenas López, D., Mendoza, A.M., Pitman, N.C.A., Duque, A., Núñez Vargas, P., Zartman, C.E., Vasquez, R., Andrade, A., Camargo, J.L., Feldpausch, T.R., Laurance, S.G.W., Laurance, W.F., Killeen, T.J., Mendonça Nascimento, H.E., Montero, J.C., Mostacedo, B., Amaral, I.L., Guimarães Vieira, I.C., Brienen, R., Castellanos, H., Terborgh, J., De Jesus Veiga Carim, M., Da Silva Guimarães, J.R., De Souza Coelho, L., De Almeida Matos, F.D., Wittmann, F., Mogollón, H.F., Damasco, G., Dávila, N., García-Villacorta, R., Coronado, E.N.H., Emilio, T., De Andrade Lima Filho, D., Schietti, J., Souza, P., Targhetta, N., Comiskey, J.A., Marimon, B.S., Marimon, B.H., Neill, D., Alonso, A., Arroyo, L., Carvalho, F.A., De Souza, F.C., Dallmeier, F., Pansonato, M.P., Duivenvoorden, J.F., Fine, P.V.A., Stevenson, P.R., Araujo-Murakami, A., Aymard, C.G.A., Baraloto, C., Do Amaral, D.D., Engel, J., Henkel, T.W., Maas, P., Petronelli, P., Cardenas Revilla, J.D., Stropp, J., Daly, D., Gribel, R., Ríos Paredes, M., Silveira, M., Thomas-Caesar, R., Baker, T.R., Da Silva, N.F., Ferreira, L. V., Peres, C.A., Silman, M.R., Cerón, C., Valverde, F.C., Di Fiore, A., Jimenez, E.M., Peñuela Mora, M.C., Toledo, M., Barbosa, E.M., De Matos Bonates, L.C., Arboleda, N.C., De Sousa Farias, E., Fuentes, A., Guillaumet, J.L., Møller Jørgensen, P., Malhi, Y., De Andrade Miranda, I.P., Phillips, J.F., Prieto, A., Rudas, A., Ruschel, A.R., Silva, N., Von Hildebrand, P., Vos, V.A., Zent, E.L., Zent, S., Cintra, B.B.L., Nascimento, M.T., Oliveira, A.A., Ramirez-Angulo, H., Ramos, J.F., Rivas, G., Schöngart, J., Sierra, R., Tirado, M., Van Der Heijden, G., Torre, E. V., Wang, O., Young, K.R., Baider, C., Cano, A., Farfan-Rios, W., Ferreira, C., Hoffman, B., Mendoza, C., Mesones, I., Torres-Lezama, A., Medina, M.N.U., Van Andel, T.R., Villarroel, D., Zagt, R., Alexiades, M.N., Balslev, H., Garcia-Cabrera, K., Gonzales, T., Hernandez, L., Huamantupa-Chuquimaco, I., Manzatto, A.G., Milliken, W., Cuenca, W.P., Pansini, S., Pauletto, D., Arevalo, F.R., Costa Reis, N.F., Sampaio, A.F., Urrego Giraldo, L.E., Valderrama Sandoval, E.H., Valenzuela Gamarra, L., Vela, C.I.A., Ter Steege, H., 2017. Persistent effects of pre-Columbian plant domestication on Amazonian forest composition. Science (80-.). 355, 925–931. https://doi.org/10.1126/science.aal0157

Levis, C., Flores, B.M., Moreira, P.A., Luize, B.G., Alves, R.P., Franco-Moraes, J., Lins, J., Konings, E., Peña-Claros, M., Bongers, F., Costa, F.R.C., Clement, C.R., 2018. How people domesticated Amazonian forests. Front. Ecol. Evol. 5, 171. https://doi.org/10.3389/fevo.2017.00171

Lewis, S.L., Maslin, M.A., 2015. Defining the Anthropocene. Nature. https://doi.org/10.1038/nature14258

Lilleskov, E., McCullough, K., Hergoualc'h, K., del Castillo Torres, D., Chimner, R., Murdiyarso, D., Kolka, R., Bourgeau-Chavez, L., Hribljan, J., del Aguila Pasquel, J., Wayson, C., 2019. Is Indonesian peatland loss a cautionary tale for Peru? A two-country comparison of the magnitude and causes of tropical peatland degradation. Mitig. Adapt. Strateg. Glob. Chang. 24, 591–623. https://doi.org/10.1007/s11027-018-9790-3

Loisel, J., Gallego-Sala, A., Amesbury, M., Magnan, G., Anshari, G., Beilman, D., Benavides, J., Blewett, J., Camill, P., Charman, D., Chawchai, S., Hedgpeth, A., Kleinen, T., Korhola, A., Large, D., Mansilla, C., Müller, J., van Bellen, S., West, J., Yu, Z., Bubier, J., Garneau, M., Moore, T., Sannel, A., Page, S., Väliranta, M., Bechtold, M., Brovkin, V., Cole, L., Chanton, J., Christensen, T., Davies, M., De Vleeschouwer, F., Finkelstein, S., Frolking, S., Galka, M., Gandois, L., Girkin, N., Harris, L., Heinemeyer, A., Hoyt, A., Jones, M., Joos, F., Juutinen, S., Kaiser, K., Lacourse, T., Lamentowicz, M., Larmola, T., Leifeld, J., Lohila, A., Milner, A., Minkkinen, K., Moss, P., Naafs, B., Nichols, J., O'Donnell, J., Payne, R., Philben, M., Piilo, S., Quillet, A., Ratnayake, A., Roland, T., Sjögersten, S., Sonnentag, O., Swindles, G., Swinnen, W., Talbot, J., Treat, C., Valach, A., Wu, J., 2020. Expert assessment of future vulnerability of the global peatland carbon sink. Nat. Clim. Chang. 2020 111 11, 70–77. https://doi.org/10.1038/s41558-020-00944-0

Maley, J., 2002. A Catastrophic Destruction of African Forests about 2,500 Years Ago Still Exerts a Major Influence on Present Vegetation Formations. IDS Bull. 33, 13–30.

Maley, J., Brenac, P., 1998. Vegetation dynamics, palaeoenvironments and climatic changes in the forests of western Cameroon during the last 28,000 years B.P. Rev. Palaeobot. Palynol. 99, 157–187. https://doi.org/10.1016/S0034-6667(97)00047-X

Maley, J., Willis, K., 2010. Did a savanna corridor open up across the Central African forests 2500 years ago [WWW Document]. CoForChange.

Malhi, Y., Gardner, T.A., Goldsmith, G.R., Silman, M.R., Zelazowski, P., 2014. Tropical Forests in the Anthropocene. http://dx.doi.org/10.1146/annurev-environ-030713-155141 39, 125–159. https://doi.org/10.1146/ANNUREV-ENVIRON-030713-155141

Marcello Bassi, A., Kieft, J., Boer, E., Mahfuzh Aufar Kari, T., Wulanddri, E., Forslund, L., 2020. Applying Systems Analysis to Evaluate Options for Sustainable Use of Peatlands in Central Kalimantan in Indonesia, in: Land Use Change and Sustainability. IntechOpen. https://doi.org/10.5772/intechopen.85677

Marengo, J.A., Souza, C.M., Thonicke, K., Burton, C., Halladay, K., Betts, R.A., Alves, L.M., Soares, W.R., 2018. Changes in Climate and Land Use Over the Amazon Region: Current and Future Variability and Trends. Front. Earth Sci. 6, 228. https://doi.org/10.3389/feart.2018.00228

McMichael, C.H., Correa-Metrio, A., Bush, M., 2012a. Pre-Columbian fire regimes in lowland tropical rainforests of southeastern Peru. Palaeogeogr. Palaeoclimatol. Palaeoecol. 342, 73–83.

McMichael, C.H., Piperno, D.R., Bush, M.B., Silman, M.R., Zimmerman, A.R., Raczka, M.F., Lobato, L.C., 2012b. Sparse pre-Columbian human habitation in Western Amazonia. Science (80-.). 336, 1429–1431. https://doi.org/10.1126/science.1219982

McMichael, C.H., Piperno, D.R., Neves, E.G., Bush, M.B., Almeida, F.O., Mongeló, G., Eyjolfsdottir, M.B., 2015. Phytolith Assemblages Along a Gradient of Ancient Human Disturbance in Western Amazonia. Front. Ecol. Evol. 3, 141. https://doi.org/10.3389/fevo.2015.00141

Megevand, C., Mosnier, A., Hourticq, J., Sanders, K., Doetinchem, N., Streck, C., 2013. Deforestation Trends in the Congo Basin. The World Bank. https://doi.org/10.1596/978-0-8213-9742-8

Mercader, J., Runge, F., Vrydaghs, L., Doutrelepont, H., Ewango, C.E.N., Juan-Tresseras, J., 2000. Phytoliths from archaeological sites in the tropical forest of Ituri, democratic Republic of Congo. Quat. Res. 54, 102–112. https://doi.org/10.1006/qres.2000.2150

Mezbahuddin, M., Grant, R.F., Hirano, T., 2014. Modelling effects of seasonal variation in water table depth on net ecosystem CO2 exchange of a tropical peatland. Biogeosciences 11, 577–599. https://doi.org/10.5194/bg-11-577-2014

Miettinen, J., Hooijer, A., Vernimmen, R., Liew, S.C., Page, S.E., 2017. From carbon sink to carbon source: extensive peat oxidation in insular Southeast Asia since 1990. Environ. Res. Lett. 12, 024014. https://doi.org/10.1088/1748-9326/aa5b6f

Miettinen, J., Hooijer, A., Wang, J., Shi, C., Liew, S.C., 2012. Peatland degradation and conversion sequences and interrelations in Sumatra. Reg. Environ. Chang. 12, 729–737. https://doi.org/10.1007/s10113-012-0290-9

Miettinen, J., Shi, C., Liew, S.C., 2016. Land cover distribution in the peatlands of Peninsular Malaysia, Sumatra and Borneo in 2015 with changes since 1990. Glob. Ecol. Conserv. 6, 67–78. https://doi.org/10.1016/j.gecco.2016.02.004

Mumbi, C.T., Marchant, R., Lane, P., 2014. Vegetation Response to Climate Change and Human Impacts in the Usambara Mountains. ISRN For. 2014, 1–12. https://doi.org/10.1155/2014/240510

Murdiyarso, D., Lilleskov, E., Kolka, R., 2019. Tropical peatlands under siege: the need for evidence-based policies and strategies. Mitig. Adapt. Strateg. Glob. Chang. 24, 493–505.

https://doi.org/10.1007/s11027-019-9844-1
Nepstad, D.C., Kunk, C.A., Uhl3, C., Vieira, I.C., Leflbvre, P., Pedlowski, M., Matricardi, E., Negreiros, G., Brown, I.F., Amaral', E., Homma, A., Jj, R.W., 1997. Land-use in Amazonia and the Cerrado of Brazil. Ciência e Cultura, São Paulo, v. 49, n. 1/2, p. 73-86, 1997.
Neuzil, S.G., 1997. Onset and Rate of Peat and Carbon Accumulation in Four Domed Ombrogenous Peat Deposits, Indonesia. Proc. Int. Symp. Biodiversity, Environ. Importance Sustain. Trop. Peat Peatlands 55–72.
Neves, E.G., Petersen, J.B., Bartone, R.N., Heckenberger, M.J., 2004. The Timing of Terra Preta Formation in the Central Amazon: Archaeological Data from Three Sites, in: Amazonian Dark Earths: Explorations in Space and Time. Springer Berlin Heidelberg, pp. 125–134. https://doi.org/10.1007/978-3-662-05683-7_9
O'Reilly, P., Anshari, G., Sancho, J.J., Jaya, A., Antang, E., Antang, C., Evers, S., Evans, C., Wilson, P., Crout, N., Sjorgesten, S., Upton, C., Page, S., 2020. Oil palm governance at the grassroots: How assemblage links oil palm, livelihoods and local administration in an indonesian village. University of Leicester.
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. https://doi.org/10.1007/s10021-008-9216-2
Page, S., Wüst, R., Banks, C., 2010. Past and present carbon accumulation and loss in Southeast Asian peatlands. PAGES news 18, 25–27. https://doi.org/10.22498/pages.18.1.25
Page, S.E., Baird, A.J., 2016. Peatlands and Global Change: Response and Resilience. Annu. Rev. Environ. Resour. 41, 35–57. https://doi.org/10.1146/annurev-environ-110615-085520
Page, S.E., Hooijer, A., 2016. In the line of fire: the peatlands of Southeast Asia. Philos. Trans. R. Soc. B Biol. Sci. 371, 20150176. https://doi.org/10.1098/rstb.2015.0176
Page, S.E., Rieley, J.O., Banks, C.J., 2011. Global and regional importance of the tropical peatland carbon pool. Glob. Chang. Biol. 17, 798–818. https://doi.org/10.1111/j.1365-2486.2010.02279.x
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 during 1997. Nature 420, 61–65. https://doi.org/10.1038/nature01131
Page, S.E., Wust, 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. https://doi.org/10.1002/jqs.884
Pärssinen, M., Schaan, D., Ranzi, A., 2009. Pre-Columbian geometric earthworks in the upper Purús: A complex society in western Amazonia. Antiquity 83, 1084–1095. https://doi.org/10.1017/S0003598X00099373
Phillips, S., Rouse, G.E., Bustin, R.M., 1997. Vegetation zones and diagnostic pollen profiles of a coastal peat swamp, Bocas del Toro, Panama. Palaeogeogr. Palaeoclimatol. Palaeoecol. 128, 301–338. https://doi.org/10.1016/S0031-0182(97)81129-7
Phillipson, D.W., 2005. African Archaeology . Cambridge University Press.
Posa, M.R.C., Wijedasa, L.S., Corlett, R.T., 2011. Biodiversity and Conservation of Tropical Peat Swamp Forests. Bioscience 61, 49–57. https://doi.org/10.1525/bio.2011.61.1.10
Primack, R.B., Corlett, R., 2005. Tropical rain forests: an ecological and biogeographical comparison. Blackwell Pub.
Räsänen, M.E., Salo, J.S., Jungner, H., 1991. Holocene floodplain lake sediments in the Amazon: 14C dating and palaeoecological use. Quat. Sci. Rev. 10, 363–372. https://doi.org/https://doi.org/10.1016/0277-3791(91)90037-U
Raymond, J.S., 1988. A View from the Tropical Forest., in: Keatinge, R.W. (Ed.), Peruvian Prehistory: An Overview of Pre-Inca and Inca Society . Cambridge University Press, Cambridge, pp. 279–

300.

Rekoforest [WWW Document], 2021. . Restor. Ekosist. Riau. URL https://www.rekoforest.org/

Ribeiro, K., Pacheco, F.S., Ferreira, J.W., Sousa-Neto, E.R., Hastie, A., Krieger Filho, G.C., Alvalá, P.C., Forti, M.C., Ometto, J.P., 2021. Tropical peatlands and their contribution to the global carbon cycle and climate change. Glob. Chang. Biol. 27, 489–505. https://doi.org/10.1111/gcb.15408

Rieley, J., Page, S.E., 2016. Tropical Peatland of the World, in: Osaki, M., Tsuji, N. (Eds.), Tropical Peatland Ecosystems. Springer Japan, Tokyo.

Ritzema, H.P., Mat Hassan, A.M., Moens, R.P., 1998. A new approach to water management of tropical peatlands: A case study from Malaysia. Irrig. Drain. Syst. 12, 123–139. https://doi.org/10.1023/A:1005976928479

Rivas Panduro, S., 2006. Proyecto de Investigación: Excavaciones Arqueológicas en Quistococha, Loreto-Amazonia Peruana, RNA No. CR. ed. Lima.

Rivas Panduro, S., Panaifo Texeira, M., Oyuela-Caycedo, A., Al., E., 2006. Informe preliminar sobre los hallazgos en el sitio archeológico de Quistococha, Amazonía peruana. Bol. Estud. Amaz. 1, 79–98.

Roberts, P., Boivin, N., Kaplan, J.O., 2018. Finding the anthropocene in tropical forests. Anthropocene 23, 5–16. https://doi.org/10.1016/J.ANCENE.2018.07.002

Roberts, P., Buhrich, A., Caetano-Andrade, V., Cosgrove, R., Fairbairn, A., Florin, S.A., Vanwezer, N., Boivin, N., Hunter, B., Mosquito, D., Turpin, G., Ferrier, Å., 2021. Reimagining the relationship between Gondwanan forests and Aboriginal land management in Australia's "Wet Tropics." iScience 24, 102190. https://doi.org/10.1016/J.ISCI.2021.102190

Romulo, C.L., Kennedy, C.J., Gilmore, M.P., Endress, B.A., 2022. Sustainable harvest training in a common pool resource setting in the Peruvian Amazon: Limitations and opportunities. Trees, For. People 7, 100185. https://doi.org/10.1016/J.TFP.2021.100185

Roosevelt, A.C., 2013. The Amazon and the Anthropocene: 13,000 years of human influence in a tropical rainforest. Anthropocene 4, 69–87. https://doi.org/10.1016/j.ancene.2014.05.001

Rostain, S., 2012. Between Sierra and Selva: Landscape transformations in upper Ecuadorian Amazonia. Quat. Int. 249, 31–42. https://doi.org/10.1016/j.quaint.2011.08.031

Roucoux, K.H., Lawson, I.T., Baker, T.R., Del Castillo Torres, D., Draper, F.C., Lähteenoja, O., Gilmore, M.P., Honorio Coronado, E.N., Kelly, T.J., Mitchard, E.T.A., Vriesendorp, C.F., 2017. Threats to intact tropical peatlands and opportunities for their conservation. Conserv. Biol. 31, 1283–1292. https://doi.org/10.1111/cobi.12925

Roucoux, K.H., Lawson, I.T., Jones, T.D., Baker, T.R., Coronado, E.N.H., Gosling, W.D., Lähteenoja, O., 2013. Vegetation development in an Amazonian peatland. Palaeogeogr. Palaeoclimatol. Palaeoecol. 374, 242–255. https://doi.org/10.1016/J.PALAEO.2013.01.023

Runge, J., 1996. Palaeoenvironmental interpretation of geomorphological and pedological studies in the rain forest "core-areas" of eastern zaire (central africa). South African Geogr. J. 78, 91–97. https://doi.org/10.1080/03736245.1996.9713613

Russell, J.M., Vogel, H., Konecky, B.L., Bijaksana, S., Huang, Y., Melles, M., Wattrus, N., Costa, K., King, J.W., 2014. Glacial forcing of central Indonesian hydroclimate since 60,000 y B.P. Proc. Natl. Acad. Sci. U. S. A. 111, 5100–5105. https://doi.org/10.1073/pnas.1402373111

Ruwaimana, M., Anshari, G.Z., Silva, L.C.R., Gavin, D.G., 2020. The oldest extant tropical peatland in the world: a major carbon reservoir for at least 47 000 years. Environ. Res. Lett. 15, 114027. https://doi.org/10.1088/1748-9326/abb853

Saatchi, S.S., Harris, N.L., Brown, S., Lefsky, M., Mitchard, E.T.A., Salas, W., Zutta, B.R., Buermann, W., Lewis, S.L., Hagen, S., Petrova, S., White, L., Silman, M., Morel, A., 2011. Benchmark map of forest carbon stocks in tropical regions across three continents. Proc. Natl. Acad. Sci. U. S. A. 108, 9899–9904. https://doi.org/10.1073/pnas.1019576108

Sabiham, S., 1990. Studies on peat in the coastal plains of Sumatra and Borneo. Part IV: a study of the floral composition of peat in coastal plain of Brunei, Borneo. Southeast Asian Stud. 27, 461–484.

Schefuß, E., Schouten, S., Schneider, R.R., 2005. Climatic controls on central African hydrology during the past 20,000 years. Nat. 2005 4377061 437, 1003–1006. https://doi.org/10.1038/nature03945
Schoneveld, G.C., Ekowati, D., Andrianto, A., Van Der Haar, S., 2019. Modeling peat- and forestland conversion by oil palm smallholders in Indonesian Borneo. Environ. Res. Lett. 14. https://doi.org/10.1088/1748-9326/aaf044
Schulz, C., Martín Brañas, M., Núñez Pérez, C., Del Aguila Villacorta, M., Laurie, N., Lawson, I.T., Roucoux, K.H., 2019a. Peatland and wetland ecosystems in Peruvian Amazonia: indigenous classifications and perspectives. Ecol. Soc. 24. https://doi.org/10.5751/ES-10886-240212
Schulz, C., Martín Brañas, M., Núñez Pérez, C., Del Aguila Villacorta, M., Laurie, N., Lawson, I.T., Roucoux, K.H., 2019b. Uses, cultural significance, and management of peatlands in the Peruvian Amazon: Implications for conservation. Biol. Conserv. 235, 189–198. https://doi.org/10.1016/j.biocon.2019.04.005
Seddon, A.W.R., Mackay, A.W., Baker, A.G., Birks, H.J.B., Breman, E., Buck, C.E., Ellis, E.C., Froyd, C.A., Gill, J.L., Gillson, L., Johnson, E.A., Jones, V.J., Juggins, S., Macias-Fauria, M., Mills, K., Morris, J.L., Nogués-Bravo, D., Punyasena, S.W., Roland, T.P., Tanentzap, A.J., Willis, K.J., Aberhan, M., van Asperen, E.N., Austin, W.E.N., Battarbee, R.W., Bhagwat, S., Belanger, C.L., Bennett, K.D., Birks, H.H., Bronk Ramsey, C., Brooks, S.J., de Bruyn, M., Butler, P.G., Chambers, F.M., Clarke, S.J., Davies, A.L., Dearing, J.A., Ezard, T.H.G., Feurdean, A., Flower, R.J., Gell, P., Hausmann, S., Hogan, E.J., Hopkins, M.J., Jeffers, E.S., Korhola, A.A., Marchant, R., Kiefer, T., Lamentowicz, M., Larocque-Tobler, I., López-Merino, L., Liow, L.H., Mcgowan, S., Miller, J.H., Montoya, E., Morton, O., Nogué, S., Onoufriou, C., Boush, L.P., Rodriguez-Sanchez, F., Rose, N.L., Sayer, C.D., Shaw, H.E., Payne, R., Simpson, G., Sohar, K., Whitehouse, N.J., Williams, J.W., Witkowski, A., 2014. Looking forward through the past: Identification of 50 priority research questions in palaeoecology. J. Ecol. 102, 256–267. https://doi.org/10.1111/1365-2745.12195
Shanahan, T.M., Mckay, N.P., Hughen, K.A., Overpeck, J.T., Otto-Bliesner, B., Heil, C.W., King, J., Scholz, C.A., Peck, J., 2015. The time-transgressive termination of the African humid period. Nat. Geosci. 8, 140–144. https://doi.org/10.1038/ngeo2329
Sierra Praeli, Y., 2020. More than 470 oil spills in the Peruvian Amazon since 2000: Report [WWW Document]. Mongabay. URL https://news.mongabay.com/2020/10/more-than-470-oil-spills-in-the-peruvian-amazon-since-2000-report/ (accessed 1.10.21).
Sjögersten, S., Black, C.R., Evers, S., Hoyos-Santillan, J., Wright, E.L., Turner, B.L., 2014. Tropical wetlands: A missing link in the global carbon cycle? Global Biogeochem. Cycles 28, 1371–1386. https://doi.org/10.1002/2014GB004844
Smith, B.D., Zeder, M.A., 2013. The onset of the Anthropocene. Anthropocene 4, 8–13. https://doi.org/10.1016/j.ancene.2013.05.001
Stolle, F., Lambin, E.F., 2003. Interprovincial and interannual differences in the causes of land-use fires in Sumatra, Indonesia. Environ. Conserv. 30, 375–387.
Streeter, R., Dugmore, A.J., Lawson, I.T., Erlendsson, E., Edwards, K.J., 2015. The onset of the palaeoanthropocene in Iceland: Changes in complex natural systems. The Holocene 25, 1662–1675. https://doi.org/10.1177/0959683615594468
Surahman, A., Shivakoti, G.P., Soni, P., 2019. Climate change mitigation through sustainable degraded peatlands management in central Kalimantan, Indonesia. Int. J. Commons 13, 859–866. https://doi.org/10.5334/ijc.893
Susanto, D.M., Giska, P., Marlianasari, P., 2018. Buku Panduan Karakteristik Lahan Gambut .
Swindles, G.T., Kelly, T.J., Roucoux, K.H., Lawson, I.T., 2018a. Response of testate amoebae to a late Holocene ecosystem shift in an Amazonian peatland. Eur. J. Protistol. 64, 13–19. https://doi.org/https://doi.org/10.1016/j.ejop.2018.03.002
Swindles, G.T., Morris, P.J., Whitney, B., Galloway, J.M., Gałka, M., Gallego-Sala, A., Macumber, A.L., Mullan, D., Smith, M.W., Amesbury, M.J., Roland, T.P., Sanei, H., Patterson, R.T., Sanderson, N., Parry, L., Charman, D.J., Lopez, O., Valderamma, E., Watson, E.J., Ivanovic, R.F., Valdes, P.J.,

Turner, T.E., Lähteenoja, O., 2018b. Ecosystem state shifts during long-term development of an Amazonian peatland. Glob. Chang. Biol. 24, 738–757. https://doi.org/10.1111/gcb.13950

Taylor, D., Yen, O.H., Sanderson, P.G., Dodson, J., 2001. Late quaternary peat formation and vegetation dynamics in a lowland tropical swamp; Nee Soon, Singapore. Palaeogeogr. Palaeoclimatol. Palaeoecol. 171, 269–287. https://doi.org/10.1016/S0031-0182(01)00249-8

Thornton, S.A., Dudin, Page, S.E., Upton, C., Harrison, M.E., 2018. Peatland fish of Sebangau, Borneo: Diversity, monitoring and conservation. Mires Peat 22. https://doi.org/10.19189/MaP.2017.OMB.313

Thornton, S.A., Setiana, E., Yoyo, K., Dudin, Yulintine, Harrison, M.E., Page, S.E., Upton, C., 2020. Towards biocultural approaches to peatland conservation: The case for fish and livelihoods in Indonesia. Environ. Sci. Policy 114, 341–351. https://doi.org/10.1016/j.envsci.2020.08.018

Urrego, D.H., Bush, M.B., Silman, M.R., Niccum, B.A., De La Rosa, P., McMichael, C.H., Hagen, S., Palace, M., 2013. Holocene fires, forest stability and human occupation in south-western Amazonia. J. Biogeogr. 40, 521–533. https://doi.org/https://doi.org/10.1111/jbi.12016

van Eijk, P., Leenman, P., Wibisono, I.T.C., Giesen, W., 2009. Regeneration and restoration of degraded peat swamp forest in Berbak NP, Jambi, Sumatra, Indonesia. Malayan Nat. J. 61, 223–241.

Vegas-Vilarrúbia, T., Baritto, F., López, P., Meleán, G., Ponce, M.E., Mora, L., Gómez, O., 2010. Tropical Histosols of the lower Orinoco Delta, features and preliminary quantification of their carbon storage. Geoderma 155, 280–288. https://doi.org/https://doi.org/10.1016/j.geoderma.2009.12.011

Vetrita, Y., Cochrane, M.A., 2020. Fire frequency and related land-use and land-cover changes in Indonesia’s Peatlands. Remote Sens. 12. https://doi.org/10.3390/RS12010005

Vincens, A., Buchet, G., Williamson, D., Taieb, M., 2005. A 23,000 yr pollen record from Lake Rukwa (8°S, SW Tanzania): New data on vegetation dynamics and climate in Central Eastern Africa. Rev. Palaeobot. Palynol. 137, 147–162. https://doi.org/10.1016/j.revpalbo.2005.06.001

Virapongse, A., Endress, B.A., Gilmore, M.P., Horn, C., Romulo, C., 2017. Ecology, livelihoods, and management of the Mauritia flexuosa palm in South America. Glob. Ecol. Conserv. https://doi.org/10.1016/j.gecco.2016.12.005

Walker, M., Johnsen, S., Rasmussen, S.O., Popp, T., Steffensen, J.P., Gibbard, P., Hoek, W., Lowe, J., Andrews, J., Björck, S., Cwynar, L.C., Hughen, K., Kershaw, P., Kromer, B., Litt, T., Lowe, D.J., Nakagawa, T., Newnham, R., Schwander, J., 2009. Formal definition and dating of the GSSP (Global Stratotype Section and Point) for the base of the Holocene using the Greenland NGRIP ice core, and selected auxiliary records. J. Quat. Sci. 24, 3–17. https://doi.org/10.1002/JQS.1227

Wang, S., Zhuang, Q., Lähteenoja, O., Draper, F.C., Cadillo-Quiroz, H., 2018. Potential shift from a carbon sink to a source in Amazonian peatlands under a changing climate. Proc. Natl. Acad. Sci. U. S. A. 115, 12407–12412. https://doi.org/10.1073/pnas.1801317115

Warren, M., Hergoualc’h, K., Kauffman, J.B., Murdiyarso, D., Kolka, R., 2017. An appraisal of Indonesia’s immense peat carbon stock using national peatland maps: Uncertainties and potential losses from conversion. Carbon Balance Manag. https://doi.org/10.1186/s13021-017-0080-2

Weijers, J.W.H., Schefuß, E., Schouten, S., Damsté, J.S.S., 2007. Coupled thermal and hydrological evolution of tropical Africa over the last deglaciation. Science (80-.). 315, 1701–1704. https://doi.org/10.1126/SCIENCE.1138131/SUPPL_FILE/WEIJERS.SOM.PDF

Weinstein, B., 1983. The Amazon rubber boom, 1850-1920. Stanford University Press.

Whitlock, C., Larsen, C., 2002. Charcoal as a Fire Proxy. Springer, Dordrecht, pp. 75–97. https://doi.org/10.1007/0-306-47668-1_5

Wijedasa, L.S., Jauhiainen, J., Könönen, M., Lampela, M., Vasander, H., Leblanc, M.-C., Evers, S., Smith, T.E.L., Yule, C.M., Varkkey, H., Lupascu, M., Parish, F., Singleton, I., Clements, G.R., Aziz, S.A., Harrison, M.E., Cheyne, S., Anshari, G.Z., Meijaard, E., Goldstein, J.E., Waldron, S., Hergoualc'h, K., Dommain, R., Frolking, S., Evans, C.D., Posa, M.R.C., Glaser, P.H., Suryadiputra, N., Lubis, R., Santika, T., Padfield, R., Kurnianto, S., Hadisiswoyo, P., Lim, T.W., Page, S.E., Gauci, V., Van Der Meer, P.J., Buckland, H., Garnier, F., Samuel, M.K., Choo, L.N.L.K., O'Reilly, P., Warren, M., Suksuwan, S., Sumarga, E., Jain, A., Laurance, W.F., Couwenberg, J., Joosten, H., Vernimmen, R., Hooijer, A., Malins, C., Cochrane, M.A., Perumal, B., Siegert, F., Peh, K.S.-H., Comeau, L.-P., Verchot, L., Harvey, C.F., Cobb, A., Jaafar, Z., Wösten, H., Manuri, S., Müller, M., Giesen, W., Phelps, J., Yong, D.L., Silvius, M., Wedeux, B.M.M., Hoyt, A., Osaki, M., Hirano, T., Takahashi, H., Kohyama, T.S., Haraguchi, A., Nugroho, N.P., Coomes, D.A., Quoi, L.P., Dohong, A., Gunawan, H., Gaveau, D.L.A., Langner, A., Lim, F.K.S., Edwards, D.P., Giam, X., Van Der Werf, G., Carmenta, R., Verwer, C.C., Gibson, L., Gandois, L., Graham, L.L.B., Regalino, J., Wich, S.A., Rieley, J., Kettridge, N., Brown, C., Pirard, R., Moore, S., Capilla, B.R., Ballhorn, U., Ho, H.C., Hoscilo, A., Lohberger, S., Evans, T.A., Yulianti, N., Blackham, G., Onrizal, Husson, S., Murdiyarso, D., Pangala, S., Cole, L.E.S., Tacconi, L., Segah, H., Tonoto, P., Lee, J.S.H., Schmilewski, G., Wulffraat, S., Putra, E.I., Cattau, M.E., Clymo, R.S., Morrison, R., Mujahid, A., Miettinen, J., Liew, S.C., Valpola, S., Wilson, D., D'Arcy, L., Gerding, M., Sundari, S., Thornton, S.A., Kalisz, B., Chapman, S.J., Su, A.S.M., Basuki, I., Itoh, M., Traeholt, C., Sloan, S., Sayok, A.K., Andersen, R., 2017. Denial of long-term issues with agriculture on tropical peatlands will have devastating consequences. Glob. Chang. Biol. 23. https://doi.org/10.1111/gcb.13516

Wijedasa, L.S., Sloan, S., Page, S.E., Clements, G.R., Lupascu, M., Evans, T.A., 2018. Carbon emissions from South-East Asian peatlands will increase despite emission-reduction schemes. Glob. Chang. Biol. 24, 4598–4613. https://doi.org/10.1111/gcb.14340

Willis, K.J., Bailey, R.M., Bhagwat, S.A., Birks, H.J.B., 2010. Biodiversity baselines, thresholds and resilience: Testing predictions and assumptions using palaeoecological data. Trends Ecol. Evol. https://doi.org/10.1016/j.tree.2010.07.006

Witrianto, 2014. Potensi sejarah dan purbakala DAS Batanghari. Anal. Sej. 5, 68–79.

Woodroffe, C.D., 2000. Deltaic and estuarine environments and their Late Quaternary dynamics on the Sunda and Sahul shelves, in: Journal of Asian Earth Sciences. Pergamon, pp. 393–413. https://doi.org/10.1016/S1367-9120(99)00074-7

Wösten, H., Hooijer, A., Siderius, C., Rais, D.S., Idris, A., Rieley, J., 2006. Tropical peatland water management modelling of the air hitam laut catchment in indonesia. Int. J. River Basin Manag. 4, 233–244. https://doi.org/10.1080/15715124.2006.9635293

Wüst, R., Rieley, J., Page, S., van der Kaars, S., Wang, W.-M., Jacobsen, G., Smith, A., 2007. Peatland evolution in Southeast Asia during the last 35,000 cal years: implications for evaluating their carbon storage potential. Trop. Peatl. 27–29.

Wüst, R.A.J., Bustin, R.M., 2004. Late Pleistocene and Holocene development of the interior peat-accumulating basin of tropical Tasek Bera, Peninsular Malaysia. Palaeogeogr. Palaeoclimatol. Palaeoecol. 211, 241–270. https://doi.org/10.1016/j.palaeo.2004.05.009

Yulianto, E., Hirakawa, K., 2006. Vegetation and environmental change in the early-Middle holocene at a tropical peat swamp forest, Central Kalimantan, Indonesia. Tropics 15, 65–73. https://doi.org/10.3759/tropics.15.65

Yulianto, E., Hirakawa, K., TSUJI, H., 2004. Charcoal and organic geochemical properties as an evidence of Holocene fires in tropical peatland, Central Kalimantan, Indonesia. Tropics 14, 55–63. https://doi.org/10.3759/tropics.14.55

Yulianto, E., Rahardjo, A.T., Noeradi, D., Siregar, D.A., Hirakawa, K., 2005. A Holocene pollen record of vegetation and coastal environmental changes in the coastal swamp forest at Batulicin, South Kalimantan, Indonesia. J. Asian Earth Sci. 25, 1–8. https://doi.org/10.1016/j.jseaes.2004.01.005