

**DISTURBANCE, RECOVERY & RESILIENCE IN TROPICAL FORESTS:
A FOCUS ON THE COASTAL PEAT SWAMP FORESTS OF
MALAYSIAN BORNEO.**

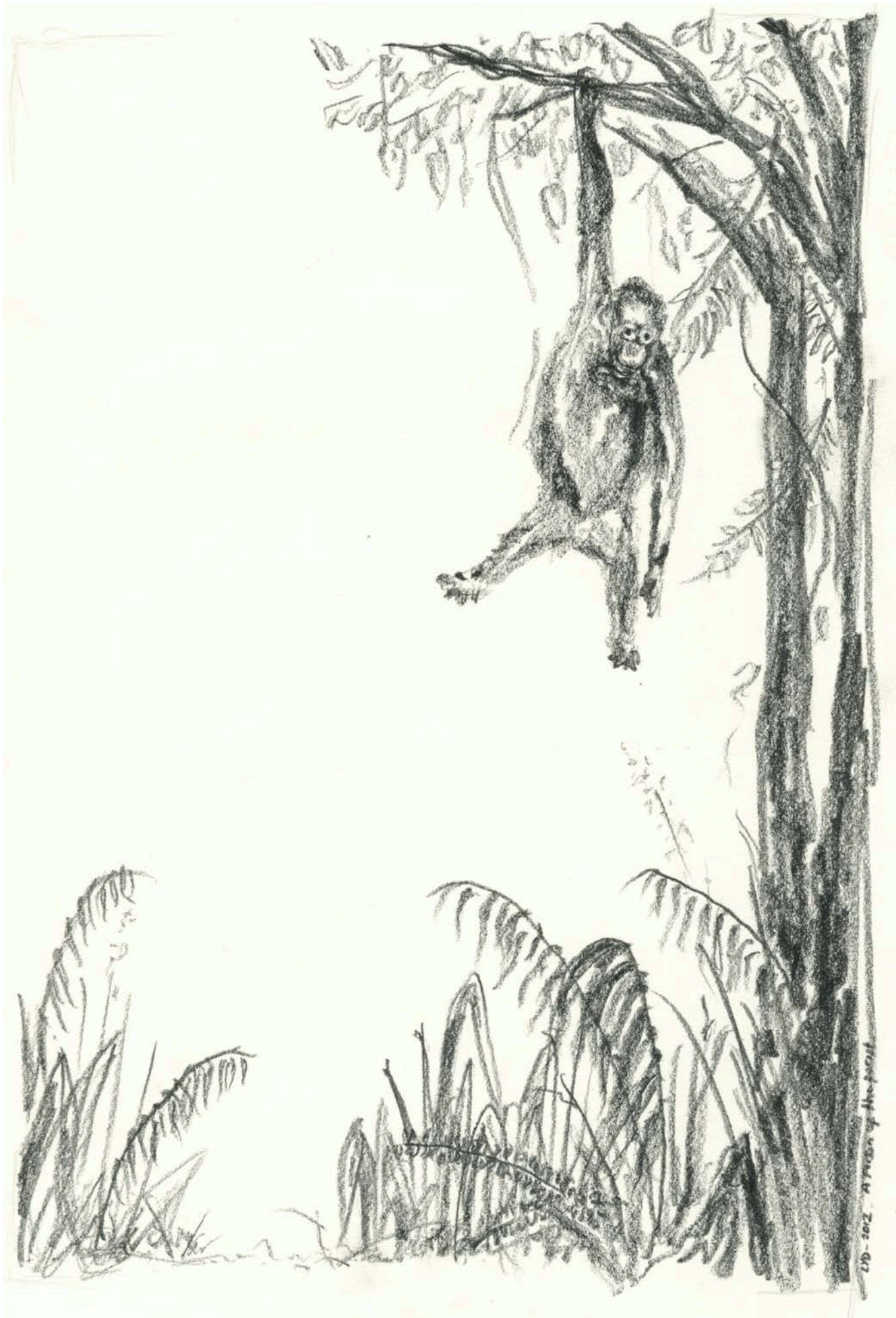
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Lydia Cole
Green Templeton College





Disturbance, Recovery and Resilience in Tropical Forests: A Focus on the Coastal Peat Swamp Forests of Malaysian Borneo.

Lydia E. S. Cole, Green Templeton College, D.Phil., Trinity Term 2012

ABSTRACT

Tropical forests have existed for up to one hundred million years, and today provide many ecosystem services vital for human well-being. They also harbour great biodiversity, which, in addition to its intrinsic value, plays a key role in the functioning of these ecosystems. Despite their local to global significance, there are still many knowledge gaps concerning the dynamic processes that govern the functioning of tropical forests. Rapid rates of deforestation and landscape conversion, predominantly for logging and industrial agriculture, are limiting the time and opportunity available to collect the information needed to fill these gaps. This research aims to shed light on the long-term ecological functioning of tropical forests, specifically investigating the history of disturbance in these ecosystems and the response of forest vegetation to past perturbations. The carbon-rich tropical peat swamp forests found along the coast of Sarawak, Malaysian Borneo, are a central focus of this study. For these forests in particular, a large deficit of knowledge surrounding their history and unique ecological functioning is coupled with some of the highest conversion rates of all tropical forest ecosystems across the world. In this thesis, palaeoecological data has been used to reconstruct temporal variability in forest vegetation coincident with external perturbations in order to identify changes in the resilience of these ecosystems through time, via indicators such as slowing rates of recovery and reduced regeneration of forest vegetation. Results suggest that tropical forest ecosystems have, for the most part, shown resilience to natural disturbances in the past, ranging from instantaneous localised tree-fall to longer-term regional climatic change; but that recent anthropogenic disturbances, of novel forms and greater intensities, are jeopardizing the potential for forest recovery and thus compromising ecosystem resilience. These findings enhance our understanding of the ecology of tropical peat swamp forests, and tropical forests more broadly. They also provide a context for contemporary tropical forest management, allowing for predictions on future responses to disturbance and enabling more ecologically sustainable landscape planning.

Acknowledgements

Over the last few months, I've started to realise quite how lucky I am. I've just spent four years learning about and working in one of the places I always wanted to go to and been ever intrigued by: the mystical tropical forests of Borneo. Perhaps I should start my thanks then, with an acknowledgement to NERC, who gave me some money four years ago and never asked for more from me than to spend it. And I have....and much of it on a far off, magical and mosquitoey island!

There is one person for whose help I am entirely indebted, and indeed, for whose presence gave me the opportunity to treat the peat swamps of Borneo as my "field sites". The freshly Dr Kho Lip Khoon has spent so many hours taking me around his country, helping me to find peat, dig peat and send peat home to England, over the last four years. And my great thanks extend also to his kind family and fun friends, who made my trips difficult to come back from! Kelvin Egay will get a special mention, for his time and his teachings. And for introducing me to some of the spirits of the forest (i.e. tuak).

Back on this slightly chillier island, I am very lucky to be part of the hugely interesting and interested research group that is the ever-expanding Long-term Ecology Lab. In addition to babies, the team frequently produces all sorts of interesting work and in a very warm and welcoming environment. And there's always someone around to help. I'd like to thank El in particular, for patiently teaching me so much and in such good humour. And thanks go to Ambroise for his cheeriness, Caro for her thoughtfulness, Marc for saving me from going grey waiting for the computer to remember it *is* still alive, and Jake for being so enthusiastic, especially with all things oil palm!

And at the top of this tower of academic inspiration are my supervisors. I am constantly in awe of them, and even after four years, can't claim to understand how they manage to achieve what they do and be who they are. I have learnt SO much from them over this time, and for that I owe them great thanks. But equally, I'd like to thank them for being so patient and supportive, and for always having faith in me despite the many times I didn't. I hope I might be as wise as them one day....and be able to create extra hours in the day, as they somehow seem to!

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Oh, there are so many people I'd like to thank. Ben P. and sister George have taught me much about the art of concise and scientific writing whilst editing my thesis – which was above-and-beyond the call of duty, even for a little sister. For her, I will be ever cautious of my future use of commas. The writing of this peat book itself would not have been half as pleasant if I wasn't welcomed everyday into Green Templeton College by the cheery Porters and beautiful gardens. I am very grateful that they've let me hang around for so many years.

And then to my friends. I think I'd just like to thank all of the wonderful people who have drifted into and out of my life in Oxford over the last four years, bringing magic and opening my eyes to new wonder. And magic definitely does exist. The bustle of BCMs that I had the privilege of doing my Masters with, will always have a special place in my Oxford, as well as Pink Man, of course. And the many others that came after. I'd like to thank Oxford, actually, for managing to find two successive jobs to attract one of my closest friends, Miss Bloom, here every day, and to cause so many others to travel through and stay for a while in this special city....oh, and to let me live with them (Ms. Massey). And a quick thank you to Maan, for being Maan, and for the almond

croissants. This paragraph hasn't done justice to the many wonderful friends in my life who have made my DPhil years a wonderful affair.

But my life didn't start or will now end with pollen and peat, however. It all started in one of the most beautiful places of...anywhere. I spent my childhood in the New Forest (though I think that the "New" needs some further palaeoecological investigation), running between forest and farm as and when I pleased. And I have always had three great comrades to run around with, whether playing or fighting! Thank you, sisters, for being part of a blessed home. None of any of this, none of me, none of Oxford, would have been possible without the two most inspiring and truly wonderful people I have ever met. To my Mum and Dad, I can never give enough thanks. But I hope this collection of words might make them proud and make them appreciate how their support has made so much possible. I wish they had taught me how better to say "no" to things though! But there are many worse things than being born into a cake-fuelled "yes" family!

So, after many months of Woman's Hour-sponsored microscope marathons, and approximately 103,012 pollen grains.... I am a professional Soil Detective. What will come of this, I'm not sure. But one of the important things the last four years have taught me is just how important it is to look to and learn from history, or indeed, pre-history, when deciding how to deal with the present. I was brought up in an environment where responsibility was valued, both towards people, and crucially, towards the environment: "leave only footprints" is something that resonates. Though I know the plight of tropical peat swamps is driven by a slew of complex things, jumbled up into the chimney that is capitalism.... And I appreciate that these rich and vital ecosystems have a limited shelf-life under these conditions (as Prof Peat, Hans Joosten, confirmed), I am never-the-less hugely grateful and somewhat proud to have studied these landscapes over the last four years. And I will continue to advocate for their conservation and 'sustainable' management. They are, in some ways, the perfect example of the perfect storm that we are creating with our heavy footprints.

But there is always hope, and as I've found out, *forests* can recover.

Lydia

Oxford, 21st September 2012.

Preface

This thesis is structured around six papers, which are manuscripts in preparation for submission to the journals detailed below, and thus broadly formatted accordingly. References are both listed with each manuscript and combined in the Bibliography (page 281), except for those used solely in the meta-analyses (see Appendix of Chapter 2 & 7). Supplementary Material is found at the end of each chapter. Statements of contribution to these papers by the additional authors are included on page 297-298.

PAPER 1: Cole, L.E.S., Bhagwat, S.A. and K.J. Willis (2012) Resilience and recovery rates of tropical forests through time.

Manuscript in preparation for *Nature*.

PAPER 2: Cole, L.E.S., Bhagwat, S.A. and K.J. Willis (2012) Disturbance, ecology and resilience in a tropical peat swamp forest.

Manuscript in preparation for *Biotropica*.

PAPER 3: Cole, L.E.S., Bhagwat, S.A. and K.J. Willis (2012) Sensitivity of tropical peat swamp forests to Holocene ENSO activity and anthropogenic impact.

Manuscript in preparation for *Bioscience*.

PAPER 4: Cole, L.E.S., Bhagwat, S.A. and K.J. Willis (2012) Flaming peat: synergistic effects of fire and forest clearance on tropical peat swamp forests.

Manuscript in preparation for *Ecology Letters*.

PAPER 5: Cole, L.E.S., Bhagwat, S.A. and K.J. Willis (2012) Long-term disturbance dynamics, recovery and resilience of tropical peat swamp forests in Malaysian Borneo.

Manuscript in preparation for *Global Change Biology*.

PAPER 6: Cole, L.E.S., K.J. Willis and S.A. Bhagwat (2012) Challenges and opportunities for the *sustainable* management of tropical peat swamp forests.

Manuscript in preparation for *Global Environmental Change – Human Policy Dimensions*.

Glossary

acrotelm	upper-most peat layer
APMI	ASEAN Peatland Management Initiative
ASEAN	Association of Southeast Asian Nations
CA	Capitalists
CBD	Convention on Biological Diversity
comp	used to describe a fossil pollen grain when it is almost certainly the same as the reference taxon (Benninghoff & Kapp, 1962)
CPL	Converted Peatland study site
CSPO	Certified Sustainable Palm Oil
CV	coastal vegetation ecological group
CV%	relative percentage of coastal vegetation in the total pollen sum
DP	degraded peat ecological group
DP%	relative percentage of degraded peat vegetation in the total pollen sum
DPL	Deforested Peatland study site
ENSO	El Niño Southern Oscillation
ES	Estate Managers
FELCRA	Federal Land Consolidation and Rehabilitation Authority
GO	Government
highstand	point at which the sea-level reaches its maximum height
IPWP	Indo-Pacific Warm Pool
IPCC	Intergovernmental Panel on Climate Change
ITCZ	Inter-Tropical Convergence Zone
MPOB	Malaysian Palm Oil Board
NERC	Natural Environment Research Council
NGO	Non-governmental organisation
OF	other forest ecological group
OF%	relative percentage of open forest vegetation in the total pollen sum
OV	open vegetation ecological group
PSF	Peat Swamp Fragment study site (context specific)
PSF	peat swamp forest (mature forest taxa) ecological group (context specific)
PSF%	relative percentage of mature peat swamp forest taxa in the total pollen sum
PSF+	peat swamp forest (pioneer taxa) ecological group
PSF+%	relative percentage of pioneer peat swamp forest taxa in the total pollen sum
PSF+%:PSF%	ratio of pioneer to mature peat swamp forest components of total pollen sum
SCORE	Sarawak Corridor of Renewable Energy (www.sarawakscore.com.my/)
SH	Smallholders
sim	used to describe a fossil pollen grain when it is more similar to the reference taxon than any other known reference taxa, but there is less certainty in the association than if allocated comp tag (Benninghoff & Kapp, 1962)
ST	Scientists
REDD	Reducing Emissions from Deforestation and Forest Degradation
REDD+	Reducing Emissions from Deforestation and Forest Degradation with the addition of the co-benefits of conservation, sustainable management of forests and enhancement of forest carbon stocks
RSPO	Round Table on Sustainable Palm Oil
SUERC	Scottish Universities Environmental Research Centre
TotPSF	total peat swamp forest vegetation component, i.e. sum of PSF and PSF+ groups
TotPSF%	relative percentage of all peat swamp forest taxa in the total pollen sum
type	used to describe a fossil pollen grain when it is identified as corresponding with one morphology within a polymorphic taxonomic unit (Benninghoff & Kapp, 1962)

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Chapter 1

INTRODUCTION

“[We want] to see the jungle falling left and right and people settled over what are now lonely wastes and turning them into cultivated land.”

- Charles Brooke, Second Raj of Sarawak, 1867.

In the face of pressure from expanding human populations and industrial agriculture, “jungle”, i.e. tropical forest, is often seen as unproductive wasteland by capitalists, governments and farmers, with little value intact, but immense value in a converted state. Thus forest conversion has been rife over the last *c.* 200 years across the Tropics. How such anthropogenic landscape change fits into the context of past disturbance in this biome, how rapidly tropical forest vegetation can recover from a multitude of drivers of perturbation, and how resilient they are to such disturbance over time, are the key questions this thesis aims to investigate.

In addition to being considered of little use in their intact state, arguments for permanently converting tropical forests into agricultural land and other forms of development focus on research findings that demonstrate the biodiversity deficit in secondary compared to primary forests (Barlow *et al.*, 2007; Gibson *et al.*, 2011), or, perhaps counterintuitively, the apparent resilience of vegetation to the many ways we disturb them today, as illustrated by rapid rates of forest recovery (for example Jones and Schmitz, 2009; Cole *et al.*, *in prep*, see Chapter 2).

Different stakeholders adopt the standpoint that best asserts their land management aspirations (Lindenmayer & Laurance, 2012). But there is limited evidence to support these viewpoints and for very few tropical forests do we know enough to decipher what has shaped the environments we see today; instead assumptions of wider landscape history are often being

drawn from inaccurate extrapolations of the small proportion of landscapes that have been studied (Barlow *et al.*, 2012). This lack of knowledge is especially true in the case of the highly-threatened peat swamp forests that line the coasts of Southeast Asia (Phillips, 1998); an ecosystem that is often described as “wasteland” (Sawal, 2003). There is much still unknown about the characteristics of tropical forests’ response to different drivers of disturbance in the past, notably their rate of recovery, and how ‘natural’ these ecosystems are, or indeed what role humans have played in shaping them in the past (Willis *et al.*, 2004; Brncic *et al.*, 2007). In order to make more reasoned judgements on how to manage these landscapes for persistence today, we need to understand their ecology, history and vitally, their resilience. Palaeoecology, the study of relationships between animals, plants and their environment in the past (Birks, 1986), offers a method for addressing these gaps in knowledge, and exploring time scales over which ecological responses to environmental change *are* measurable (Rull, 2010). This thesis employs a palaeoecological approach to question how “pristine” and resilient these tropical ecosystems truly are.

Tropical forests & disturbance

Tropical forests form the world’s most biodiverse ecosystems. They also harbour the greatest terrestrial stores of carbon on Earth (FAO, 2006; Midgley *et al.*, 2010), assisting in global carbon cycling and the regulation of atmospheric climate (Mahli, 2012). Locally, these habitats provide innumerable resources for people, ranging from products, such as food, fibres and medicinal plants, to services, including water provision and regulation, nutrient cycling and pollination (Ricketts, 2004). Contrary to previous thought, tropical forests are dynamic ecosystems that have been subjected to and recovered from multiple disturbances through time (Cole *et al.*, *in prep*, see Chapter 2), including those caused by humans (for example van Gemerden *et al.*, 2003; Willis *et al.*, 2004; Heckenberger *et al.*, 2007; Barlow *et al.*, 2012).

Drivers of disturbance have varied through both time and space. Temporally, major disturbances have generally coincided with periods of rapid climatic change, such as the Little Ice Age (Lozano-Garcia *et al.*, 2010), approximately 100 – 600 years ago (Grießinger *et al.*, 2011). Spatially, perturbations can result from localised events, such as tree-fall (Mwavu & Witkowski, 2008), land-slides (Dalling & Tanner, 1995) and forest-wide drought (Lewis *et al.*, 2011). The evidence for their continued persistence illustrates that tropical forests have responded to such perturbation, maintaining the ecological capacity for regeneration throughout the last 10,000 years and far beyond (Bush *et al.*, 2011).

Contemporary disturbance, however, appears to manifest over different spatial and temporal scales to those seen in the past, and is mostly associated with anthropogenic land-use change. Various studies have documented evidence for pre-historic human clearance of tropical forest to create space for agriculture, whether employing the practice of shifting cultivation (Morley, 1982; Arroyo-Kalin, 2012), or for the establishment of rice cultivation (Hunt & Rushworth, 2005), or simply burning areas to aid in the pursuit of wild meat (Bustos-Schindler *et al.*, 2010). The majority of these practices proved sustainable, at the relatively low human population densities of the past and with the adoption of sufficiently long rotation periods, developing through experience to ensure forest re-growth between clearance cycles. Today, however, such modest disturbance has turned into large-scale and permanent deforestation, predominantly to secure land for the development of monoculture agricultural plantations in Southeast Asia (for example Koh *et al.*, 2011, Miettinen *et al.*, 2012a), and vast cattle ranches in South America (Geist and Lambin, 2002), functioning at high profit under economies of scale. Apart from agricultural expansion, responding to the increasing volumes of resources required to feed a growing and increasingly urban-based human population, in conjunction with unprecedented growth in consumption rates, there are numerous other contemporary

drivers of disturbance in tropical forest ecosystems (Geist & Lambin, 2002). The most important ones include logging (Asner *et al.*, 2009), clearance of areas for mining (for example in Tanzania (Senzota & Mbago, 2010)), infrastructure and settlement for activities such as tourism (for example in Cambodia (Gaughan *et al.*, 2009)), and potentially changes in atmospheric composition, i.e. CO₂ enrichment, linked to climatic change (Phillips *et al.*, 2008; Lewis *et al.*, 2009), though the exact contribution and impact of this latter driver is yet unknown. Increases in atmospheric CO₂ may in fact be increasing plant productivity in the Amazon (Phillips *et al.*, 2008) and Africa (Lewis *et al.*, 2009; Muller-Landau, 2009), although simultaneous changes in weather patterns, notably atmospheric moisture, coupled with human land-use change, may limit the realisation of this potential. Over 40 million hectares of the world's primary forests have been converted to other land-uses since 2000 (FRA, 2010), and this figure is set to rise as human population size increases (UNPD, 2011), coupled with a rising demand for more, and more varied commodities (Koh & Lee, 2012), and in addition, for the production of biofuels (Koh *et al.*, 2011), which has recently become a hugely political and contentious issue (for example see The Guardian, 2008). Currently in many tropical landscapes, the revenue generated by such industry exceeds that attainable from the standing forests (Fisher *et al.*, 2011; though see Martin Persson (2012) for a pan-tropical analysis where findings differ), especially those stood in the path of potential oil palm plantation development (Morel & Morel, 2012), thus providing little incentive for their conservation.

Tropical peat swamp forests

One type of tropical forest that is particularly threatened, yet valuable and under-valued, is the peat swamp forest of the Tropics (Fig. 1). These unique ecosystems cover approximately 3% of the Earth's terrestrial surface, yet contain approximately 30% of its soil carbon (Parish *et al.*, 2008).

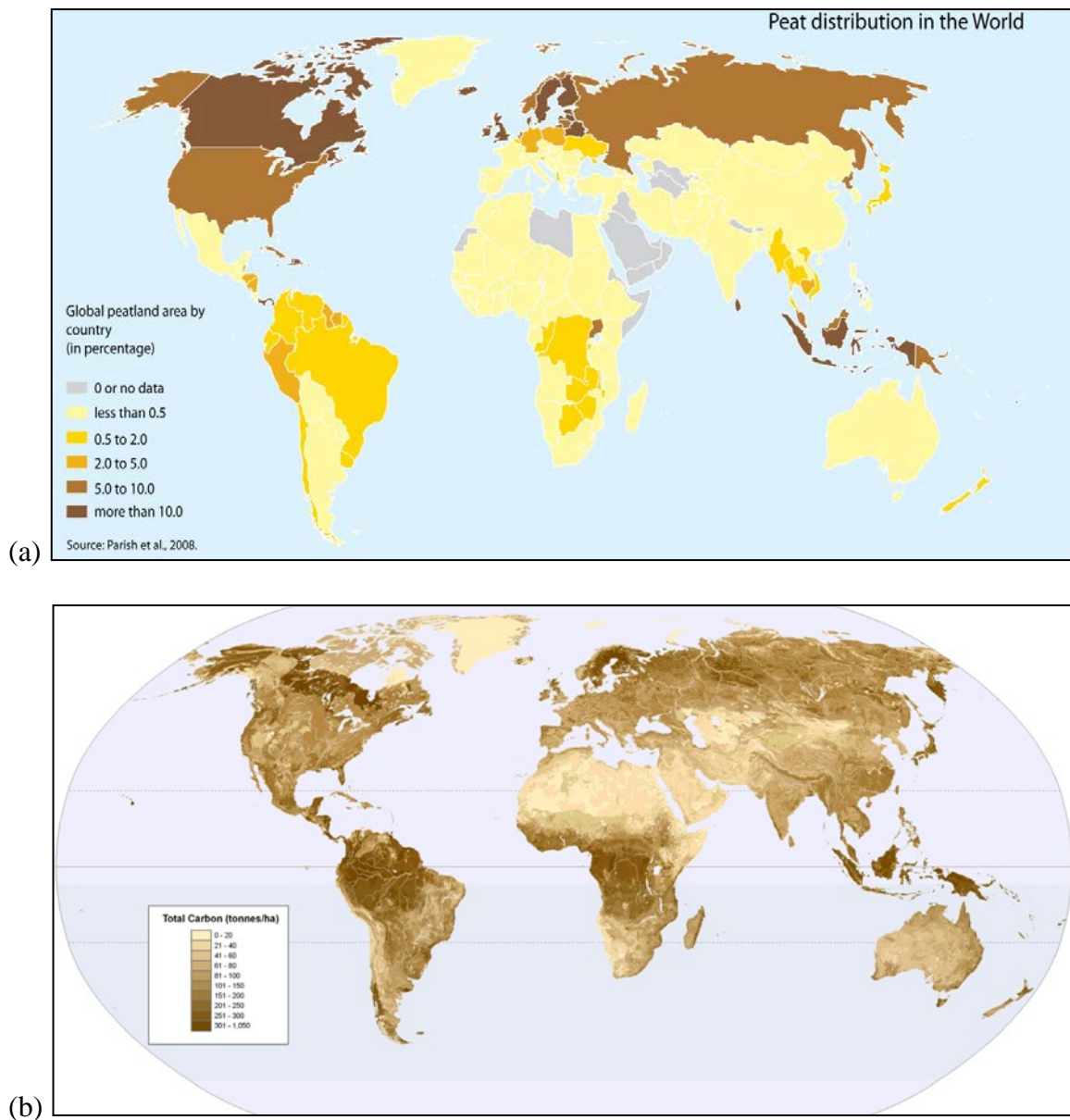


Fig. 1 Maps showing the location of (a) global peatland area by country, and (b) terrestrial carbon stores, illustrating the coincidence of high carbon with peatland ecosystems, especially in the Tropics. (Maps courtesy of (a) Parish *et al.*, 2008, and (b) Scharlemann *et al.*, 2011.)

Peat swamp forests are formed in environments where water-logged conditions develop, mostly as a result of impermeable underlying substrates, or often between river channels or behind coastal habitats, such as mangroves, which prevent the easy drainage of water from an area (Liong & Siong, 1979; Andriess, 1988). Waterlogging creates an anaerobic environment, in which limited decomposition, i.e. the respiration of dead organic matter, can occur, and thus layers of leaves and branches from the resident vegetation accumulate. The plants, in turn,

contribute to the hydrological self-regulation of the peat swamp, through adaptations such as buttress roots, which reduce the hydraulic conductivity of the peat, whilst increasing its water-holding capacity (Dommain *et al.*, 2010). This helps to ensure the peat is permanently wet, even in drier seasons, since even a small amount of drying will result in the oxidation of the carbon-rich substrate, leading to degradation and subsidence (Hooijer *et al.*, 2011). This tight interrelationship between peat development, hydrology and vegetation is especially important on the periphery of coastal peat domes, where the sloping edges increase the gravitational pull of water.

Coastal peat domes are common across Southeast Asia (Dommain *et al.*, 2011). Their development is thought to have started *c.* 5000 Cal. yr BP, after the mid-Holocene sea-level highstand, prior to sea-level fall and coastal progradation (Dommain *et al.*, 2011). Over 55% of tropical peatlands are found in Southeast Asia, some 250,000 km² (Page *et al.*, 2011). These peat swamp forests provide multiple ecosystem services to many different communities. At a global level, these coastal peat swamps are hugely important for their carbon storage and sequestration potential; the peat swamp forests of Malaysia store 9.1 Gtonnes of carbon, *c.* 2% of the volume globally stored in peat despite comprising <1% of the global area (Page *et al.*, 2011), and have been sequestering it for thousands of years (Dommain *et al.*, 2011; see Page *et al.*, 2004, for Indonesian data). With much of the remaining lowland forest habitat on mineral soil in these areas having already been converted into agriculture or other uses, the peat swamp forests act as a refuge for a vast array of flora and fauna (Yule, 2010). In terms of endemics, there are numerous species of fish adapted to the blackwaters found in peat swamps (Posa *et al.*, 2011), including the commercially important catfish (*Clarias* spp.), and many others which are highly threatened by current peatland development, especially in Central Kalimantan (Giam *et al.*, 2012). In addition, there is a suite of trees adapted to the waterlogged, acidic and low

nutrient (oligotrophic) environment, with Jongkong (*Dactylocladus stenostachys*) being one example (Phillips, 1998). There are also many species which are no longer found in abundance elsewhere, such as black-banded langur (*Presbytis melalophos*) (Phillips, 1998) and the conservation icon, the orang-utan (*Pongo* spp.) (Morrogh-Bernard *et al.*, 2003; Meijaard *et al.*, 2012). As with any ‘healthy’ tropical forest, this faunal component contributes to the maintenance of regeneration (Melo *et al.*, 2010), and thus without it, in so-called “silent forests” (<http://www.silentforests.net/>), ecosystem functioning is severely impacted.

On a local scale, these coastal peat swamp forest ecosystems perform several important services for communities living in their vicinity, the main one being water supply and management (Phillips, 1998). On the coast they prevent salt water from infiltrating into inland agricultural areas, and can protect against storm surges and flooding during monsoonal months, as well as secure a water supply across the drier seasons via their high water-storage capacity (Liong & Siong, 1979; Silvius & Giesen, 1996; Phillips, 1998). Provision of resources from peat swamp forest includes food from a multitude of fruit trees, medicinal plants, and materials for the construction of houses and equipment (Silvius & Giesen, 1996), such as from the ubiquitous and highly valuable rattan (Whitmore, 1998, p188), mostly of the genus *Calamus*.

Peat swamp forests of Sarawak

The aforementioned range of products and services are offered by the peat swamp forests of Sarawak, northern Borneo. This Malaysian State accommodates the greatest proportion of the nation’s peat soils, some 60% (FAO, 2012), covering approximately 13% of its land area (Wetlands International, 2010) (Fig. 2).

Fifty years ago, much of the coast was dominated by these wetland forests, and all of the biodiversity they contained. Though described in the past as “marginal wasteland” (Sawal, 2003), some communities used these ecosystems for hunting fish, for example in the areas around Sri Aman Division (Egay, personal communication), for subsistence agriculture in shallow peat swamps at the edges of rivers, and for hunting (Wetlands International, 2010). However, there is no evidence for significant human impact in these humid forests prior to the late 20th century, with scientific studies focusing on ecological structure and change in these forests, both in Sarawak (Anderson, 1964; Anderson & Muller, 1975; Miettinen *et al.*, 2011a) and elsewhere in Borneo (Anshari *et al.*, 2001; Anshari *et al.*, 2004; Page *et al.*, 1999; Koh *et al.*, 2011). From the early 1950s, however, with the increase in technology and resources and consequently the ability to overcome the challenges of using these flooded environments, in addition to rising international market demand, logging of economically valuable timber, such as ramin, *Gonystylus bancanus*, started (Sawal, 2003). Peat swamp forests became increasingly deforested and degraded. Following from this, plantation development started, and by 2010, 0.9 million ha of Sarawak’s 1.6 million ha of peat swamp forests had already been logged and drained (SarVision, 2011), predominantly for the establishment of plantations of the exotic palm, *Elaeis guineensis* (Corley & Tinker, 2003), for the production of palm oil. Today, oil palm plantation coverage is approaching 10% of the peatland area of the State (Koh *et al.*, 2011), with rubber plantations and mixed horticulture occupying further converted peat swamp forests (Wetlands International, 2010). With much of Sarawak’s lowland mineral soils already planted on, in line with much of the rest of Borneo, even within protected areas (Curran *et al.*, 2004; Miettinen *et al.*, 2011), and other land too steep for agriculture, or too steeped in historical land rights issues to be commandeered by plantation companies, the peatlands are now seen as the “last frontier of an important arable land” (Dolmat, 2005). As a result, few

peat domes remain undisturbed, and government subsidies are currently available to encourage smallholders and plantation companies alike, to embark on developing the remaining areas.

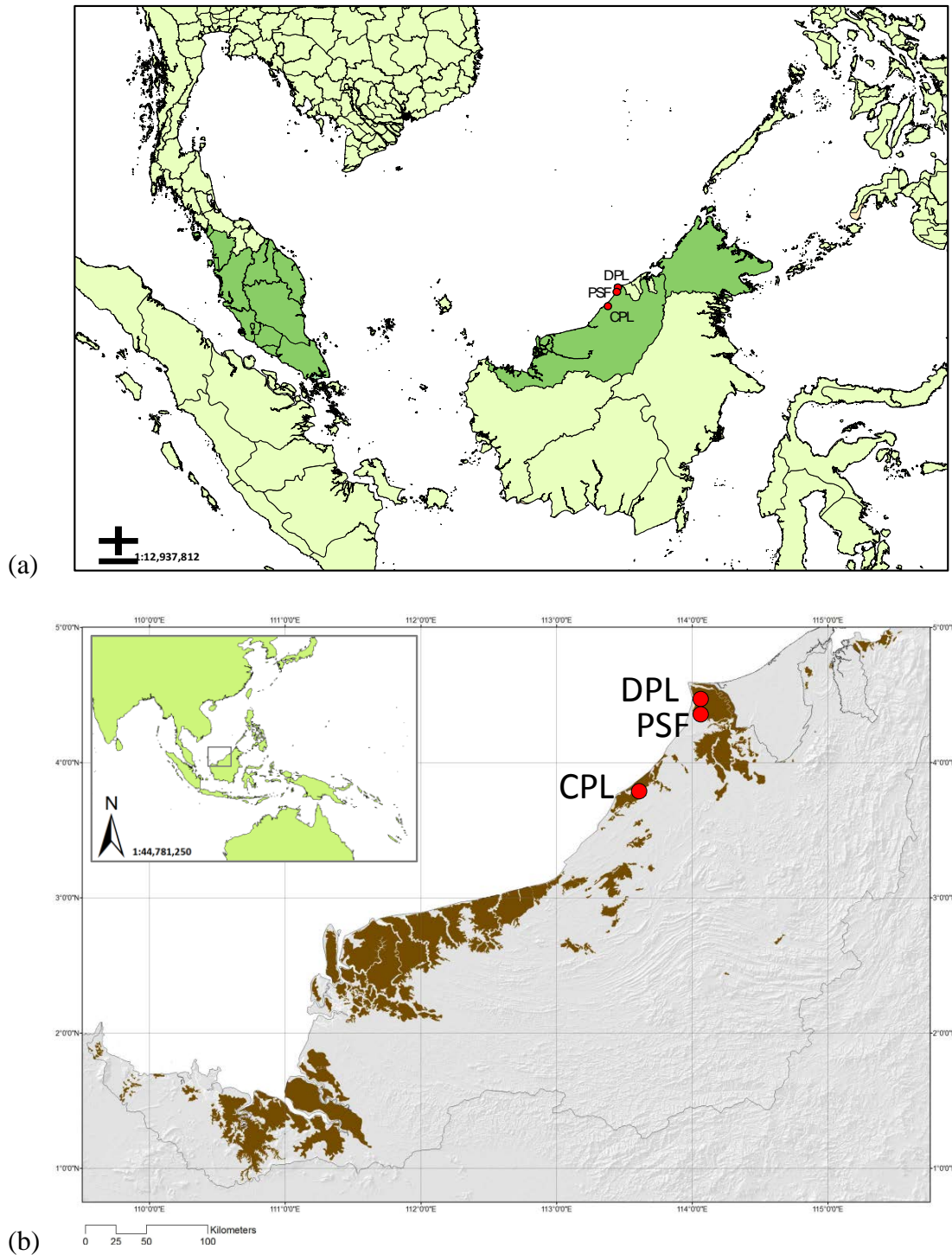


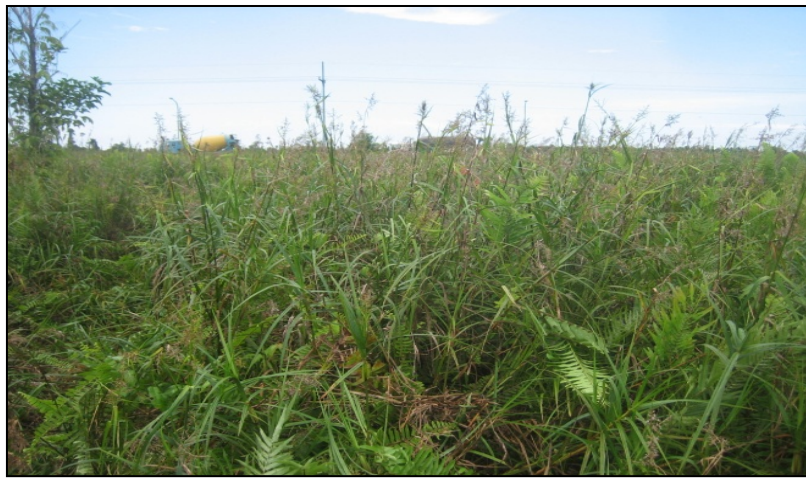
Fig. 2 Maps showing (a) the position of Malaysia and Borneo island within insular Southeast Asia, and (b) the State of Sarawak within Southeast Asia (inset) and the location of its peatland areas (brown). The three studied sites have been marked by a red dot on each map: CPL, Converted Peatland; PSF, Peat Swamp Fragment, and DPL, Deforested Peatland. ((b) Courtesy of SarVision, 2011.)

Ecosystem resilience

Although some level of disturbance is a natural component of all ecosystems, these contemporary disturbances are considered unnatural, predominantly because forest regeneration has not occurred after the disturbance has ended, and thus the characteristics of the ecosystem have changed. Such ecological transformation can be described as manifesting due to a loss of resilience, i.e. the ecosystem has not maintained its structure and function post-disturbance (Holling, 1973), but diverged into a different state, defined by different parameters (Carpenter *et al.*, 2011). Interest in the resilience of ecosystems has increased enormously over the last 40 years as they have been visibly impacted by the intensification of anthropogenic land-use change (Zalasiewicz *et al.*, 2011), especially in the Tropics (Laurance *et al.*, 2012), hindering the natural process of regeneration and thus putting into question the recovery and continued function of these habitats (Fig. 3). In order to prevent the shift into an alternative state concomitant with a loss in resilience, knowledge of the threshold level of disturbance which promotes such change must be gained. Various quantitative methods have been developed more recently to track changes in key ecosystem variables, such as measuring autocorrelation and critical slowing down (Dakos *et al.*, 2012), that would signal the approach to a threshold. Rates of recovery post-disturbance (Veraart *et al.*, 2012) and fluctuations in ecosystem structure and function (Carpenter & Brock, 2006), can also act as indicators of a loss of resilience. In order to understand more comprehensively the ecological functioning of an ecosystem, including its capacity to respond to disturbance, and thus its dynamics of resilience, it is important to consider a wide range of ecosystem variables and indicators (Boyd, 2012), and critically, in a long-term context (Willis & Bhagwat, 2010).



(a)



(b)



(c)

Fig. 3 Photographs taken of three peatland environments in Sarawak: (a) a secondary peat swamp forest, with relatively intact hydrology and vegetation, (b) a highly disturbed peatland (see vehicles travelling by road in the background), and (c) a young oil palm plantation established on the former site of a peat swamp forest. In (b) and (c), logging, establishment of drains and burning have eliminated forest cover and potentially shifted the ecosystems into an alternative state, associated with a loss of peat swamp forest resilience. (Images by L.E.S.C.)

Measuring resilience

Without knowledge of the basic structure, composition and abundance of the different components in an ecosystem, i.e. its baseline condition, and its behaviour in response to perturbations of varying intensities from various drivers in the past, assessments of resilience cannot be made (Ludwig *et al.*, 1997). Palaeoecological analysis offers a powerful tool for investigating such ecosystem characteristics and placing variation in resilience indicators within a broader ecological context (Willis *et al.*, 2010a). Palaeoecology is the discipline that studies the long-term ecological interactions between plants, animals and their environment over varying time-scales in the past, from tens to tens of millions of years (Birks, 1986); it vastly extends the scope of contemporary ecological science and thus improves the information available from which to make key insights on ecosystem functioning (Rull, 2010).

Palaeoecological methods employ various proxies stored in different chronologically-constrained sediments, to reconstruct past environmental change: fossil pollen is used to gain evidence on plant communities of the past, fossil charcoal for information on past fire regimes, and different stable chemical isotopes to measure soil nutrient changes, to name but a few of the potential variables (for a full review of techniques see Berglund, 1986). In conservation science, palaeoecological data is invaluable for making more reasoned predictions about how the biological component of ecosystems may respond to future perturbations (Meadows, 2012), for example climatic changes (Willis *et al.*, 2010b), invasive species (Gillson *et al.*, 2008), and varying levels of human impact (Brncic *et al.*, 2007). Fundamentally, it also allows for an assessment of how *natural* an ecosystem actually is (Willis & Birks, 2006), and thus what role humans may play in it within the context of more sustainable landscape management.

Knowledge gaps

Before such sustainable tropical forest management is possible, there are still many outstanding questions to answer on the history of these ecosystems, notably their baseline biotic composition and dynamics, as well as interactions with past disturbances that have shaped their current state and would affect their future response to perturbations.

The following comprise key questions for which answers are required in order to assess the resilience of tropical forest ecosystems. What is the disturbance regime of these forests? How quickly do they recover from disturbance? Consequently, how resilient are they to different forms and magnitudes of disturbance? And are there universal factors that affect forest resilience? For inferring the resilience and strategies for the sustainable management of the oft-quoted “fragile” tropical peat swamp forests (DID, 2001) in particular, there are further outstanding questions. What is the history of disturbance in these ecosystems? How do they respond to different disturbances? What does this tell us about their unique ecology? What are the current direct and indirect threats to these peat swamp forests? And how are the forests valued by the different key stakeholders? Answers to these questions will contribute to vital knowledge on the ecological functioning and the resilience of these ecosystems to disturbance; information required for their conservation and sustainable use into the future.

Aims & objectives

Given these research needs, the main aim of this study is to investigate the responses of tropical forest ecosystems to disturbances through the Holocene, and make scientifically informed inferences on their resilience to disturbance, past and present.

The six central research questions addressed in this thesis, each constituting a chapter, are as follows:

- (i) How rapidly do tropical forests recover from disturbance, and are there factors that affect their recovery rates and resilience? (Cole *et al.*, *in prep*, see Chapter 2.)
- (ii) What factors caused disturbance in a tropical peat swamp forest in Sarawak, Malaysian Borneo, in the past, and how did the vegetation respond? (Study focuses on Peat Swamp Fragment, Fig. 2) (Cole *et al.*, *in prep*, see Chapter 3.)
- (iii) Is ENSO-induced climatic change linked to burning incidence in tropical peat swamp forests and what impact does it have on forest vegetation change? (Study focuses on Converted Peatland, Fig. 2) (Cole *et al.*, *in prep*, see Chapter 4.)
- (iv) What is the burning regime in three tropical peat swamp forests and what role does fire play in driving vegetation dynamics through time? (Study focuses on three sites, Fig. 2) (Cole *et al.*, *in prep*, see Chapter 5.)
- (v) How and why has the vegetation changed through time in the coastal peat swamp forests of Sarawak, and are their implications for ecosystem resilience? (Study focuses on three sites, Fig. 2) (Cole *et al.*, *in prep*, see Chapter 6.)
- (vi) What are the key challenges and opportunities for managing these peat swamp forests more sustainably under contemporary human disturbance? (Cole *et al.*, *in prep*, see Chapter 7.)

Methodological approach

A mixed-methods approach was employed in order to answer the inter-disciplinary research questions posed in this thesis. To address the first component, a literature review and meta-analysis were performed, collecting and collating published data on incidences of disturbance and rates of recovery of tropical forests across the world. The following four questions

employed a range of techniques to collect and analyse data. Field techniques included qualitative vegetation surveys and peat sediment extraction using a hand-held coring device, from three coastal peatlands in north-east Sarawak, Malaysian Borneo (Fig. 2). Laboratory techniques were used to sub-sample from each of the collected sediment archives at regular intervals, in order to isolate and measure fluctuations in fossil pollen grains and spores, and fossil charcoal, which served as proxies for past vegetation and environmental change through time in each site. Radiocarbon dating techniques were used to obtain age-depth estimates and construct profiles of peat sediment accumulation through time. Analyses carried out on the resultant data ranged from rate of change to Principal Components Analysis, employing techniques that enabled the exploration of relationships between vegetation and environmental change, and potential disturbance indicators through time. Finally, to complement the long-term ecological component of the study, an assessment of the contemporary human drivers of change in these ecosystems was made using social science methods. A series of stakeholder interviews were performed to explore the values and management challenges associated with the tropical peat swamp forests of Sarawak.

Thesis outline

The first study, included as Chapter 2, employs a meta-analysis approach to analyse data gathered from 71 pollen diagrams, of published palaeoecological research from across the tropical forests of the World, focusing on rates of tropical forest recovery after 283 different disturbance events, and analyses how trends in responses across time and space may elucidate factors affecting ecosystem resilience.

Chapters 3 to 6 form a focused investigation into the long-term ecology and disturbance history of the tropical peat swamp forests of Sarawak, with consideration of their resilience to

perturbation spanning the last 7000 years. Palaeoecological research is performed on three peat cores extracted from three sites in the Miri administrative district of the Malaysian State of Sarawak, in northern Borneo, in order to gather proxies from which to reconstruct past vegetation, fire and environmental change over the late Holocene.

The final component of this interdisciplinary study, Chapter 7, uses key informant and stakeholder interviews, in addition to a literature review, to explore the contemporary barriers to the sustainable management of Sarawak's peat swamp forests. With any conservation-based research that investigates ecosystem change in human-influenced landscapes, exploring the human component is central to understanding processes and developing solutions. Data collected in this study will provide some context to the current situation of unimpeded forest conversion, and allow for informed recommendations on future conservation strategies for these important ecosystems.



CHAPTER 2

Paper 1: RESILIENCE AND RECOVERY RATES OF TROPICAL FORESTS THROUGH TIME

Lydia E.S. Cole*‡, Shonil A. Bhagwat*†‡ and Katherine J. Willis*‡

*Oxford Long-term Ecology Laboratory, Department of Zoology, University of Oxford,
Oxford, United Kingdom

†School of Geography and the Environment, University of Oxford, Oxford, United Kingdom

‡Biodiversity Institute, Oxford Martin School, Department of Zoology, University of Oxford,
Oxford, United Kingdom

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ABSTRACT

The time that it takes for forested tropical ecosystems to recover from disturbance is of widespread interest to conservationists, forestry managers and carbon-traders alike. Yet to date there has been no biome-wide synthesis to determine these rates of recovery. Here we present results from a meta-analysis of published palaeoecological records from South and Central American, African and Asian tropical rainforests that report 283 forest recovery events from disturbances occurring over the past 20,000 years. We demonstrate that forests in Central America and Africa have generally recovered faster from past disturbances than those in South America and Asia. Forest regrowth after climatic change and human impact has occurred more slowly than recovery after natural large infrequent disturbances. Contrary to expectation, increasing numbers and frequency of disturbance events at a site through time do not slow down recovery, indicating a degree of resilience in tropical forests to frequent past disturbance. These findings are important for managing tropical forests, especially for intensity of use, determining potential carbon budgets within the ecosystem and the time allocated for forest regrowth.

INTRODUCTION

Tropical forests are recognised globally for the important ecosystem services that they provide. They also represent an ecosystem that, in some regions, has undergone significant disturbance and has recovered. Knowledge of recovery rates and responses of tropical forest to past forms of disturbance is critical to our understanding of the capacity of these ecosystems to respond to present and future disturbances. Although it is generally accepted that if left long enough, tropical rainforest will recover (McNamara *et al.*, 2012), there is much debate about the nature of forest regrowth and the time taken for it, with full recovery to pre-disturbance vegetation levels typically reported at <50 years (for example Chazdon *et al.*, 2007; D'Oliveira *et al.*,

2011; Cole *et al.*, 2012). There is also the assumption that ecosystems that have undergone greater or more frequent disturbances in the past will be less resilient to disturbance events and consequently demonstrate a slower recovery rate or no recovery (transition to an alternative state) (Egbert & Scheffer, 2007).

The aim of this project was to determine the factors that may affect responses of tropical forest ecosystems to disturbance through time, by examining recovery rates from 283 past intervals of disturbance reported in palaeoecological records. We addressed three fundamental questions: (i) How quickly have forests recovered from disturbances in the past? (ii) Are there factors that affect recovery rates, i.e. disturbance type, geographical location, frequency of disturbance events in time? (iii) How have recovery rates changed through time?

METHODS

To determine trends in recovery rates of tropical forests, we conducted a meta-analysis of 71 published fossil pollen records from the tropics (Figure 1), focusing on the four regions of Asia, Africa, and Central and South America. These datasets were selected based on their location (within 23°N and 23°S), evidence of disturbance events over the past 20,000 years and good chronological control (¹⁴C dating) (see Supplementary Information). Within these 71 fossil pollen records, a total of 283 disturbance events were analysed with a quarter of studies demonstrating five or more disturbance events and associated recovery. Data from the published pollen diagrams were extracted using Datathief III (Tummers, 2006).

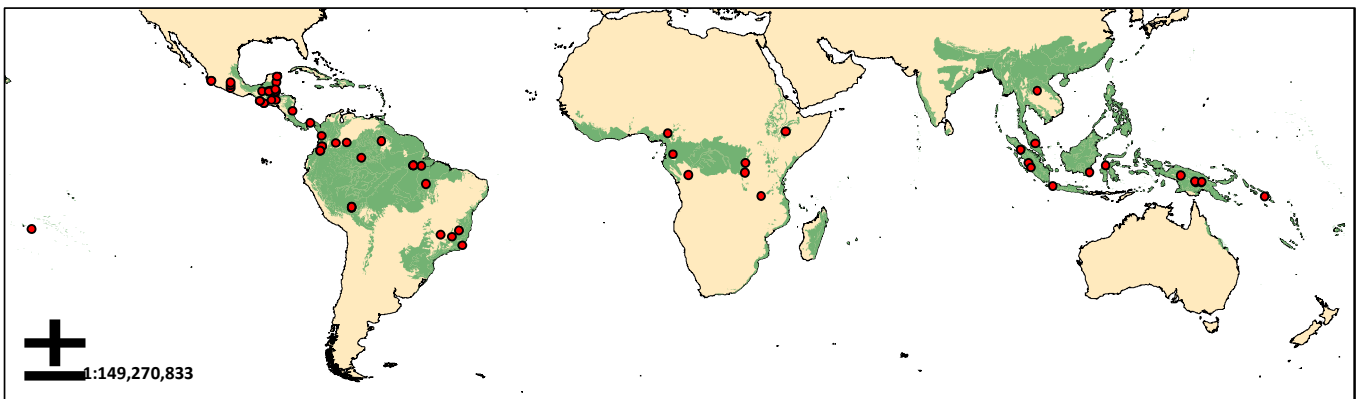


Fig. 1 A map highlighting the World's tropical forest ecosystems, illustrating the location of all studies included in this meta-analysis. (The WWF Biome of *Tropical and Subtropical Moist Broadleaf Forests* is shown in green (Olson *et al.*, 2001).)

The type of disturbance at each event was classified from information on the published pollen diagrams and in the associated text. All forms of *anthropogenic* disturbance were broadly classified as forest clearing (FC), though various categories were recorded (see Supplementary Information): burning, shifting cultivation, agriculture or combinations of these (Table 1). Within *natural* disturbances, climatic changes (C), including climatic drying, increased precipitation and sea level change, and large infrequent disturbances (LI), encompassing hurricanes, landslides, fire events and volcanic eruptions, were all recorded (Table 1). If both natural and anthropogenic disturbances were simultaneously discussed in the text in relation to a disturbance event, it was assigned an *unclear* (U) cause.

Table 1 Disturbance types and indicators, i.e. proxies, used to identify them, extracted either from published pollen diagrams or from the associated text. Abbreviations for the different disturbance types are shown in brackets. (See Supplementary Information for full record of disturbance types referred to here.)

Disturbance source	Disturbance type	Proxy
NATURAL	Climate (C)	Oxygen isotopes, fire (low levels, not linked to human presence), magnetic susceptibility, lithology
	Precipitation (CP)	Rainfall, monsoon strength variation, climate drying (CD)
	Sea-level rise (CS)	Sea level
	Large infrequent (LI)	Hurricane (LI-H), landslide (LI-L), fire (LI-F), volcano (volcanic ash) (LI-V)
HUMAN	Burning (B)	Microfossil & macrofossil charcoal
	Forest clearing (FC)	Temporary, predominantly resulting from shifting cultivation (SC), or more permanent, generally selective clearing, or not described (FC) signified by e.g. fruit trees, <i>Poaceae</i> , & disturbance indicators/secondary forest taxa, e.g. <i>Arenga</i> and <i>Macaranga</i> , or magnetic susceptibility
	Agriculture (Ag)	Agricultural indicators, e.g. fruit trees - <i>Ficus</i> , crops – <i>Poaceae</i>
Unclear	(U)	Disturbance indicators present but specific type not clarified

The main variables extracted from published pollen diagrams for recovery rate (RR) calculations are presented in Table 2 (see also Supplementary Information). Kruskal-Wallis Analysis of Ranks, with the assumption of independent samples, was used to look for significant differences between RR across different grouped variables: (i) disturbance type, and (ii) geographical location, and (iii) between the standardised rate of disturbance events (SRD), i.e. a measure of perturbation frequency at each site through time, and geographical location. SRD was calculated by dividing the number of disturbances in a site by the approximate time over which they occurred, to give a rate per 1000 years. Correlation analysis was performed, using Spearman's Rank Correlation Coefficient, to test for significant relationships between the RR and the following variables: i) the SRD; ii) the sequential number of disturbance events at a site, and (iii) the time of onset of forest decline at each disturbance event (see Supplementary Information).

Table 2 Main features in and variables extracted from published pollen diagrams for recovery rate calculations. (See Supplementary Fig. 1 (Supplementary Information) for an example of how data were extracted from diagrams.) Forest recovery is described as the maximum increase in percentage of forest pollen after a decline, prior to a stabilising point or further decline. (*Forest cover* is used as a crude descriptor of past vegetation extent reconstructed from fossil pollen, but is not representative of a quantifiable forest area.) (n = number of disturbance events)

Variable	Description	Notation
INDEPENDENT VARIABLES		
Disturbance type	Factor causing impact on forest vegetation, shown on pollen diagram or referred to in the text	See Table 1 for categories
Geographical attributes	Potential influencers of forest ecology/disturbance response	location, altitude, latitude, longitude
Standardised rate of disturbance events (SRD)	Average number of disturbance events in a site per 1000 yrs	$SRD = \frac{n}{(T_{1,pre} - T_{n,max})} * 1000$
RESPONSE VARIABLE & MEASUREMENTS		
Recovery Rate (RR)	Rate of forest recovery relative to degree of disturbance-induced forest cover change, i.e. % increase in forest cover per year in relation to pre-disturbance level	$RR = \frac{((F_{max} - F_{min}) / (F_{pre} - F_{min})) * 100}{T_{rec}}$
Forest cover maximum pre-disturbance (%)	Percentage of forest pollen at maximum point pre-decline (i.e. baseline forest cover percentage)	F_{pre}
Forest cover minimum at disturbance (%)	Percentage of forest pollen at minimum point during disturbance event	F_{min}
Forest cover at maximum recovery (%)	Percentage of forest pollen at point of maximum recovery (prior to a stabilising point or further decline)	F_{max}
Time period of recovery (yrs)	Time period from maximum reduction to maximum recovery	T_{rec}

RESULTS

Results demonstrate that the majority of past disturbance was caused by forest clearing, followed by climatic changes and large infrequent events ($n = 166$, $n = 87$ and $n = 13$, respectively). For the majority of disturbance events, forest regrowth stopped before 100%

recovery, with median recovery reaching 95.5% (to 3 s.f.) ($n = 283$), either due to the onset of another disturbance event, or due to the establishment of a lower forest proportion in the landscape. Across disturbance types, recovery rates varied greatly, with projected times to 95.5% forest recovery from the pre-disturbance baseline ranging from 1 to 6846 years ($n = 283$), while the estimated median time was 210 years (to the nearest year) ($n = 283$) (Fig. 2). As an indication of the span of recovery rates, the average time for 95.5% recovery was 503 years (to the nearest year) (Standard Deviation = 768.159, $n = 283$).

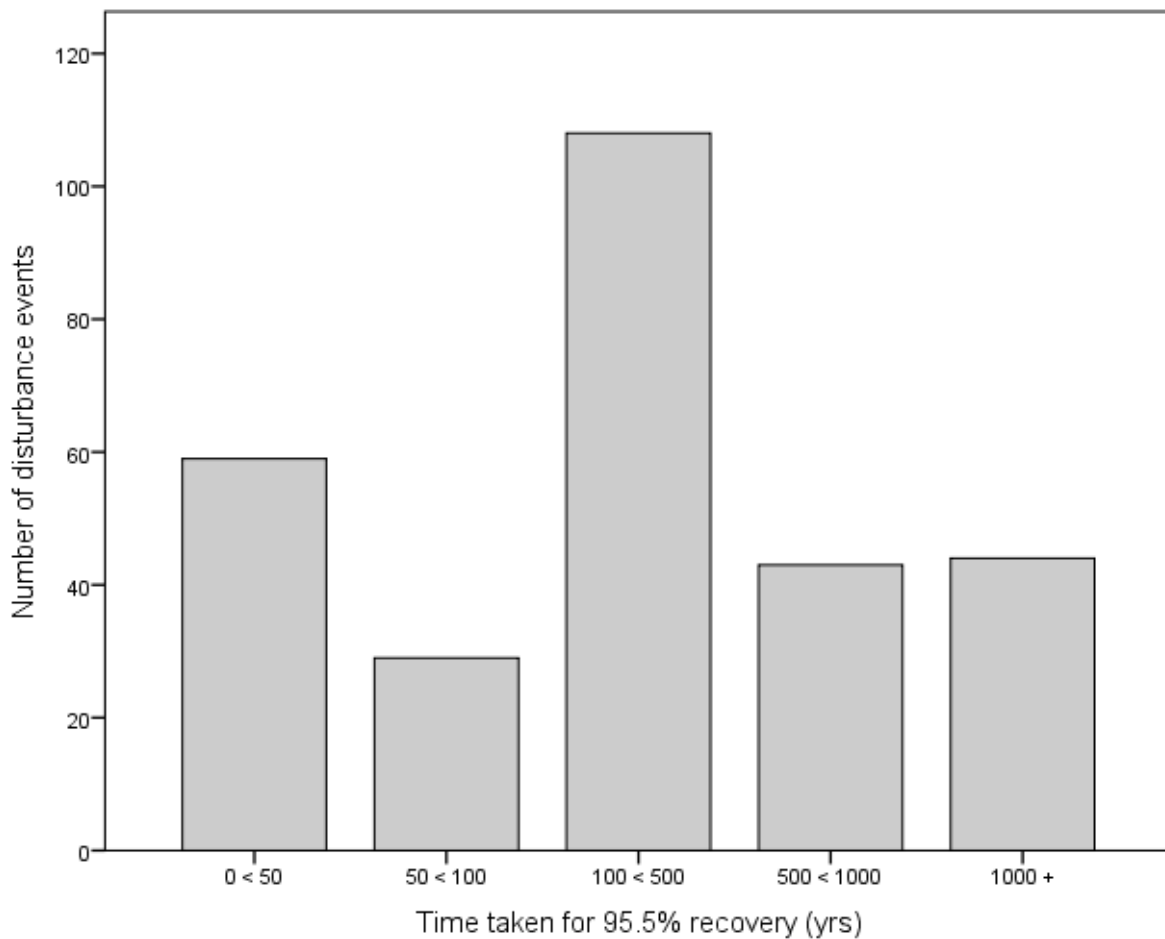


Fig. 2 Percentage of disturbance events to take different numbers of years for 95.5% recovery to pre-disturbance forest cover baseline at each event ($n = 283$). Recovery rates were used to calculate the time taken to a projected 95.5% recovery, i.e. the median extent of recovery for the dataset.

Significant differences were present between response rates of tropical forest to different natural versus anthropogenic disturbances (Independent Samples Kruskal-Wallis One-way ANOVA p value = 0.004, $n = 283$) (Fig. 3a). RR were fastest after large infrequent disturbances (LI) (median = 2.836% relative recovery per year (see Table 2 for details of RR calculation and Supplementary Fig. 1 (Supplementary Information) for data extraction), $n = 13$) and slowest after climatic changes (C) (median = 0.412% relative recovery per year, $n = 87$) and human-induced disturbances (FC) (median = 0.410% relative recovery per year, $n = 166$). The broad geographical region in which the forest resides also affects the RR of forest (Independent Samples Kruskal-Wallis Test p value = 0.007, $n = 283$) (Fig. 3b). In general, forest ecosystems from the Central American tropics recovered more rapidly and those from Asia the slowest, with median times for 95.5% recovery of 141 years ($n = 111$) & 415 years ($n = 58$) (to the nearest year), respectively. Other geographical co-variables support this finding: there is a significant positive correlation between RR and latitude of the sample (Spearman's rho Correlation Coefficient = 0.124, p value = 0.002 in 2-tailed test at 95% confidence level, $n = 283$), and a significant negative correlation with longitude (Spearman's rho Correlation Coefficient = -0.231, p value < 0.001 in 2-tailed test at 95% confidence level), i.e. samples above the equator and to the geographical West recover more quickly than those below the equator and towards the East. The altitudinal setting of the forest does not correlate with its recovery, however.

The standardised rate of disturbance events, SRD, allows further investigation of the potential reasons for the relationship between RR and geographical location. The geographical location is not significantly related to the SRD (Independent Samples Kruskal-Wallis Test p value = 0.140, $n = 71$) (Fig. 3c). However, there is a significant relationship between this metric and the RR (Spearman's rho Correlation Coefficient = 0.540, p value < 0.001 in 2-tailed test at 95%

confidence level, $n = 283$) (Fig. 3d), indicating that the higher the frequency of disturbance events at a site, the more rapid is the forest recovery.

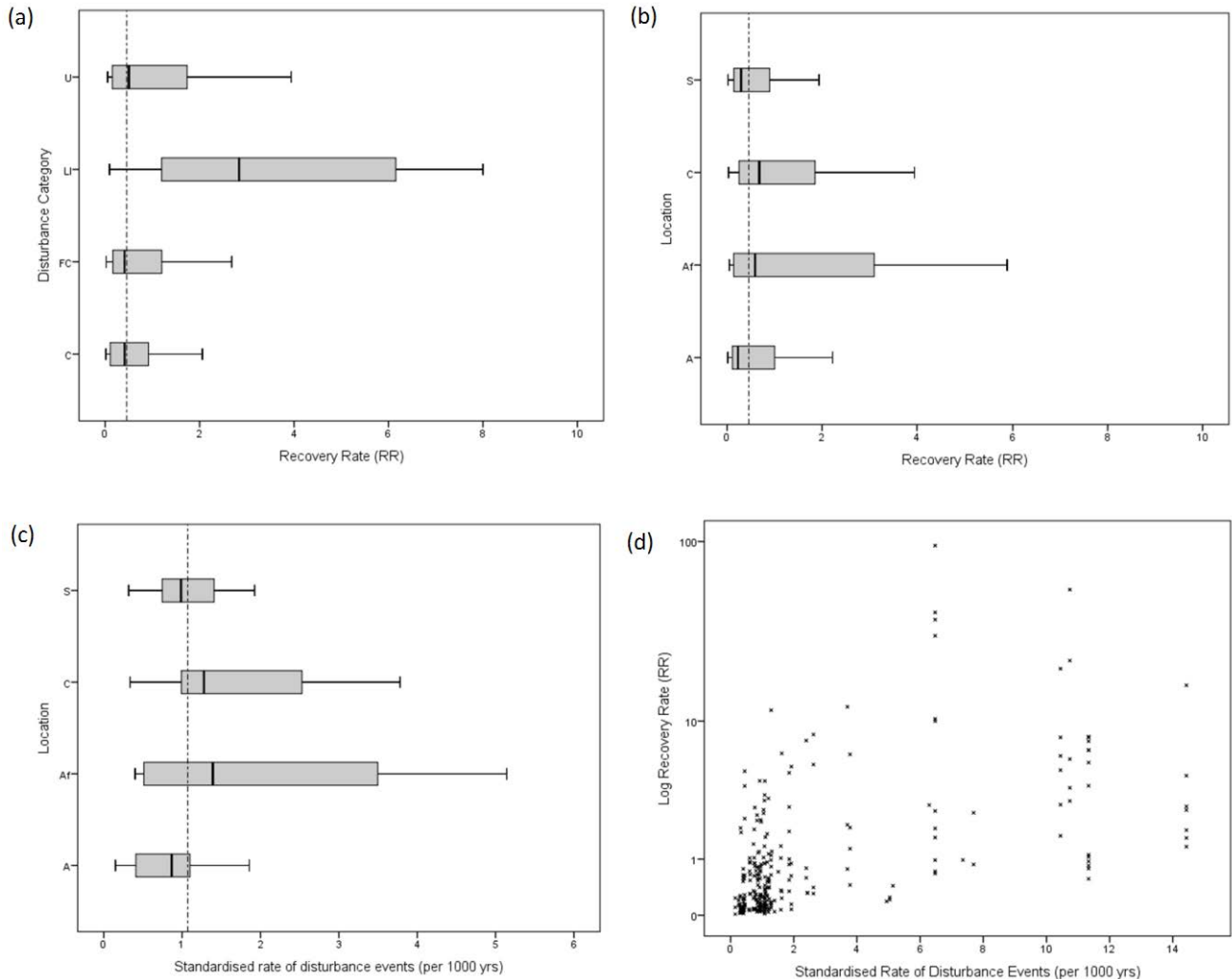


Fig. 3 Composite figure of (a) recovery rates (RR) across disturbance category, (b) RR across geographical locations, (c) the standardised rate of disturbance events (SRD) across geographical locations, and (d) the relationship between SRD and RR. (a) Box plot of RR for grouped disturbance categories. C, climate-related factors ($n = 87$); FC, anthropogenic forest clearance, grouping FC, SC, B, Ag and combinations of these ($n = 166$); LI, natural large infrequent events ($n = 13$); U, cause of disturbance unclear ($n = 17$). (b) Box plot of RR for different location groups. S, South America ($n = 85$); C, Central America ($n = 111$); Af, Africa ($n = 29$); A, Asia ($n = 85$). (c) Box plot of SRD across different location groups. The vertical line in (a) and (b) represents the median RR for the entire data set, i.e. 0.455% relative recovery per year, and in (c) the median SRD, i.e. 1.072 disturbance events per 1000 yrs. Shaded areas on (a), (b) and (c) represent the interquartile range and the whisker lines the 95% confidence intervals for each category. (d) Scatter plot illustrating the relationship between the SRD and RR (plotted on a log-linear scale to accommodate the variability in the dataset).

Analysis of the relationship between RR and the number of disturbance events allows investigation of changes in tropical forest resilience through time. Contrary to expectation, there is positive correlation between RR and the sequential number of the disturbance event (Spearman's rho Correlation Coefficient = 0.170, p value = 0.004 in 2-tailed test at 95% confidence level, $n = 283$) (Fig. 4a), i.e. the speed of recovery increases after successive disturbances. When testing whether RR, and by inference resilience, have changed through time (Fig. 4b), results show there is a significant negative relationship between RR and the approximate time of onset of the disturbance event (Spearman's rho Correlation Coefficient = -0.452, p value = 0.000 in 2-tailed test at 95% confidence level, $n = 283$), with RR increasing with time to the present day.

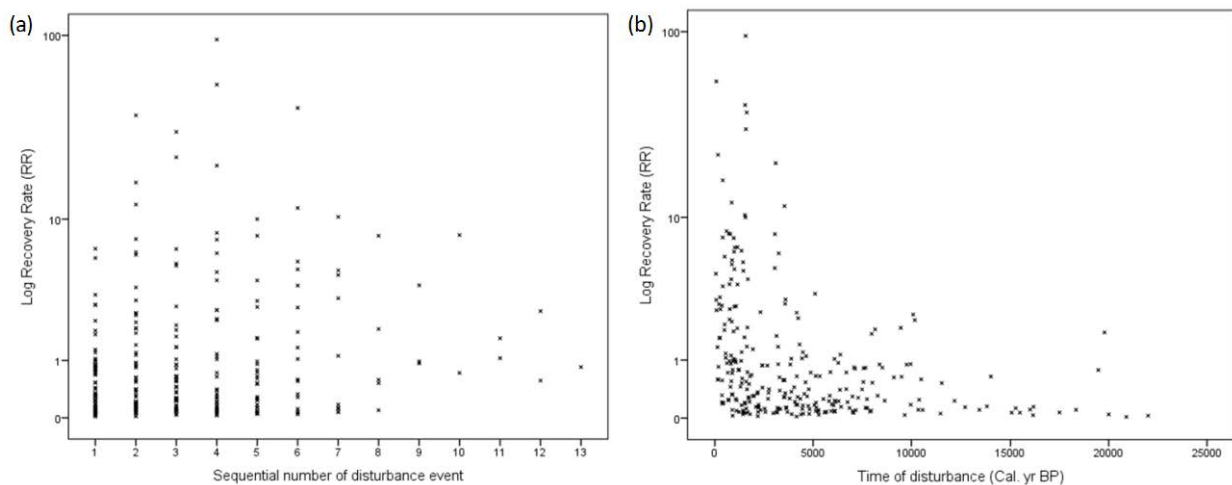


Fig. 4 Changes in resilience of tropical forests through time. The log of RR is plotted against: (a) the sequential number of disturbance events (Spearman's rho Correlation Coefficient = 0.170, p value = 0.004 in 2-tailed test at 95% confidence level, $n = 283$), and (b) approximate time of the onset of the disturbance event (Spearman's rho Correlation Coefficient = -0.452, p value < 0.001 in 2-tailed test at 95% confidence level, $n = 283$). RR is plotted on a logarithmic scale to accommodate the variability in the dataset.

DISCUSSION

(i) How quickly have forests recovered from disturbances in the past?

Tropical forests have been disturbed by a variety of factors over the Late Glacial and Holocene periods, and recovery has proceeded to varying degrees. Contrary to findings reported elsewhere (Jones & Schmitz, 2009), our analyses indicate that for most tropical forest ecosystems, the length of time taken to re-establish forest cover to values *c.* 95% of former arboreal cover takes >150 years. Only after approximately 20% of disturbance events did the forest recover within the 42 years reported as the average for complete recovery in tropical and boreal forests across the world (Jones and Schmitz, 2009). Length of time is an important distinction to make because while there are a number of studies that suggest that any form of disturbed (often referred to as secondary) forest has less ecological value than primary forests (Barlow *et al.*, 2007; Gibson *et al.*, 2011), few of these have examined forests that have been recovering for >150 years and therefore are unlikely to be comparing like-with-like but rather a forest ecosystem in the early stages of succession. This relatively long length of time required for recovery is relevant for contemporary forestry management where periods allocated for forest re-growth post-logging are rarely ecologically suitable (Asner *et al.*, 2006) and practices underpinned by inadequate and biased knowledge (Lindenmayer & Laurance, 2012).

Incorporating a longer rotation period into forest management plans, to allow for enhanced regeneration, may improve forest productivity. However, the fact that following 50% of the disturbance events the forest returned to less than 95.5% of former abundance (as recorded by fossil pollen from forest taxa), suggests that once disturbed, the canopy rarely recovers fully. Determining whether there are specific species and/or common traits in trees that do not return post-disturbance, would be a valuable area for future research.

(ii) *Are there factors that affect recovery rates, i.e. disturbance type, geographical location, perturbation frequency?*

Significant differences in recovery rates suggest that in the management of tropical forests certain factors will influence the effectiveness of restoration. The result that recovery is fastest following natural infrequent disturbances is in many ways unsurprising; this is a process that has been occurring throughout the earth's history and considered to play an important role in ecosystem dynamics (Connell, 1978), though to varying extents (Bongers *et al.*, 2009). In terms of management, this result implies that designing anthropogenic forest disturbances that more closely mimic natural disturbance regimes, especially large infrequent ones such as wind-falls, will result in a lesser decline in the abundance of forest trees in the landscape, and may dramatically reduce the time required and resources needed for forest regeneration. The slow recovery rates recorded following burning are of particular concern, given that this is the favoured mode of clearance for agriculture in tropical forests; it is also sometimes practised by conservation managers to create increased diversity through invoking a particular disturbance regime (Burrows, 2008), albeit one that is ecologically misplaced in some cases (Morrison *et al.*, 1996).

The slower recovery rate apparent in Asia and South America compared to Central America and Africa is an interesting finding. Suggested causes for this difference include factors related to current biotic controls such as vegetation life histories (Chazdon *et al.*, 2007) and tree species diversity (Hector *et al.*, 2011), abiotic controls such as soil fertility and climate (Quesada *et al.*, 2012), and to past disturbance events (Muller-Landau, 2009). A working hypothesis related to the latter factor is that regions which demonstrate faster recovery rates have undergone greater disturbance (in particular frequency of events) in the past. As a consequence of this history of perturbation, such as human disturbance resulting from large-

scale forest-based ancient civilisations, for example the Maya society of Guatemala (Mueller *et al.*, 2010; Turner & Sabloff, 2012) and Mexico (see Heckenberger *et al.* (2003) for insights on the later expansion of human societies in the Amazon), and extreme weather events, for example the extensive historical droughts of Central Africa (van Gemerden *et al.*, 2003) and frequent hurricanes of Central America (Vandermeer & Granzow De La Cerda, 2004), the forest vegetation might have evolved adaptations to enable dynamic responses to disturbance.

(iii) How have recovery rates, i.e. forest resilience, changed through time?

As a preliminary answer to this question, results from this study provide interesting insights. Increasing rates of recovery with successive disturbance events at a site (Fig. 4a), with time towards present (Fig. 4b), and with higher frequency of disturbance (Fig. 3d), strongly suggest that these tropical forest ecosystems are responding dynamically to heightened perturbation, with their vegetation components evolving adaptations that promote ecosystem resilience through time. This finding runs counter to recent studies modelling ecosystem resilience to contemporary forms and intensities of disturbance over short time scales. For example, Dakos *et al.* (2011) and Veraart *et al.* (2012) identify slowing recovery rates with increasing disturbance as a robust indicator of a loss of resilience in different systems. However, patterns of tropical forest recovery from contemporary disturbances, which, to a great extent, are far from mimicking natural disturbance regimes (Barlow *et al.*, 2012; Lindenmayer & Laurance, 2012), may diverge from those of the long-term recovery dynamics observed here. Accounting for both hypotheses on resilience may require careful consideration of the temporal and spatial context of the ecosystem and the associated disturbance and recovery dynamics, and crucially the adoption of a long-term view in analysis.

METHODS SUMMARY

Chronological calibration

Various procedures were used to date the published diagrams. Where age-depth models were not present in the published study, the dating programme, *clam* (Blaauw, 2010), in R (R Core Team, 2012), was used to construct the best-fitting age-depth model for the reported ages. Similarly, *clam* was used to calibrate dates reported in ^{14}C radiocarbon years. Where data were not available in the reference for surface dates, a default of -55 Cal. yr BP, with error 1, was used, in line with conventional dating of modern samples (Taylor, 1987). In the absence of age uncertainties for a radiocarbon date, an average of the value for dates on either side was used, or in the case of basal samples, the youngest date reported. If no age uncertainties were reported, a default of 50 years was used, for example in Deevey *et al.* (1979). IntCal04 and SHCal04 curves were used for Northern and Southern Hemisphere age-depth model construction and calibrations, respectively, except where the latter had dates older than 10522 ^{14}C radiocarbon years, in which case the IntCal04 curve was used. Calibrated ages are reported as the average of the 95.4% two sigma (2σ) calibrated age range that obtains the greatest relative area under the probability distribution curve.

Measurements, metrics and notation

(See Tables 1 and 2)

Data acquisition and analysis

Tests for normality and variance were performed on the RR data. Q-Q plots demonstrated that the dataset differed significantly from a normal distribution, thus non-parametric analyses were used to investigate the relationship between independent and response factors. The highly variable and, in some cases, small sample sizes, as well as limited prior knowledge of the data

set contributed to this choice of analysis. To test for the possibility of pseudoreplication, variance components analysis was carried out. The estimate of the variance in RR *within groups*, represented as random variation within individual studies ($\text{var}_{\text{error}} = 54.661$), was significantly greater than the variance *between groups* ($\text{var}_{\text{cases}} = 6.649$) (ANOVA F-score = 1.463, p value = 0.021, d.f.(numerator/denominator) = 70/213). This significant result allows for each individual disturbance event to be treated as an independent replicate despite the majority of events belonging to the same case (i.e. one fossil pollen record).

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AUTHOR CONTRIBUTIONS

LESC, SB and KJW designed the study; LESL collected and analysed the data; LESL, SB and KJW wrote the manuscript.

AUTHOR INFORMATION

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Correspondence and requests for materials should be addressed to L.E.S.C. (e-mail: lydia.cole@zoo.ox.ac.uk, lyd@cantab.net).

SUPPLEMENTARY INFORMATION

SI 1 Supplementary Table 1 Data and references of studies included in meta-analysis.

SI 2 Supplementary Fig. 1 Example of a published pollen diagram from which data has been extracted.

Supplementary Table 1 All published studies from which data were extracted, and variables recorded from diagrams.

Reference	Country	Location	Latitude	Longitude	Altitude (m)	Site	No. recoveries	Vegetation ID	Disturbance Category	Disturbance Type	Tpre (Cal. yr BP)	Tmin (Cal. yr BP)	Tmax (Cal. yr BP)	Trec (yrs)	Fpre (%)	Fmin (%)	Fmax (%)	FD (%)	RR (%)
Morley (1982)	Indonesia	A	-2.0197	101.375	950	swamp adjoining Lake Padang	5	Primary forest trees	FC	SC	5593	*	*	520	93	69	78	25.8	0.072
									FC	SC	5069	*	*	296	78	52	65	33.3	0.169
									FC	SC	3897	*	*	325	62	38	67	38.7	0.372
									FC	SC	2539.5	*	*	325	78	39	54	50.0	0.118
									FC	SC	1391	*	*	285	54	36	67	33.3	0.604
Maloney (1985/80)	Indonesia	A	2.3306	98.8333	1450	Pea Sim-sim swamp	1	Forest	FC	FC	4452.5	*	*	630	95	41	80	56.8	0.115
Newsome (1985)	Indonesia	A	-1.0667	100.7667	1535	Lake di-Atas swamp	3	Forest	FC	FC	0	13141	11435	1706	81	60	84	25.9	0.067
									FC	FC	11435	9303	7957	1346	84	34	71	59.5	0.055
									FC	FC	7957	7163	6155	1008	86	56	84	34.9	0.093
Powell <i>et al.</i> (1975)	Papua New Guinea	A	-5.8667	144.2167	1885	Draepi Swamp	1	Forest	LI	LI-V	1100	*	*	741	79	32	64	59.5	0.092
Maloney (1981)	Indonesia	A	2.3333	98.8333	1445	Tao Sippinggan	1	Forest	FC	Ag	1038.5	*	*	100	80	45	80	43.8	1.000
van Zeist <i>et al.</i> (1979)	Indonesia	A	-6.8333	106.9167	1000	Situ Gunung	4	arboreal pollen	FC	FC	8015	7657	7494	163	82	68	80	17.1	0.526
									FC	FC	7494	7292	7100	192	80	66	77	17.5	0.409
									FC	FC	6301	6085	5675	410	75	14	70	81.3	0.224
									C	CD	5675	4995	4745	250	70	5	18	92.9	0.080
Morley (1981)	Malaysia	A	3.8167	102.4167	lowland	Tasek Bera Kuin (swamp)	4	Forest taxa	U	N	4615	*	*	125	92	80	88	13.0	0.533
									U	N	1527.5	*	*	515	96	52	94	45.8	0.185
									FC	SC	797	*	*	49	94	58	66	38.3	0.454
									FC	SC	548.5	*	*	129	66	42	78	36.4	1.163
Urquhart (2009)	Nicaragua	S	12.0345	-83.9276	lowland	Neotropical swamp	6	Non-disturbance forest taxa	LI	LI-H	3574.5	*	*	40	56	44	58	21.4	2.917
									LI	LI-F	3253	*	*	15	58	32	56	44.8	6.154
									LI	LI-F	3135.5	*	*	15	56	48	50	14.3	1.667
									LI	LI-F	3094.5	*	*	20	60	54	78	10.0	20.000
									LI	LI-F	3057	*	*	10	78	68	76	12.8	8.000
									LI	LI-F	3050	*	*	10	76	68	72	10.5	5.000
Mueller <i>et al.</i> (2009)	Guatemala	S	17	-89.9167	lowland	Lake Peten Itza	1	Tropical forest taxa	C	CD	4500	*	*	800	69	9	35	87.0	0.054

Colinvaux <i>et al.</i> (1996)	Brazil	S	0.26667	-66.6833	lowland	Lake Pata	4	Arboreal	C	C	17492.5	11262.5	9465.5	1797	81	73	83	9.9	0.070									
									U	U	9465.5	7358.5	7294	64.5	83	75	85	9.6	1.938									
									U	U	7294	6727.5	6099	628.5	85	74	93	12.9	0.275									
									U	U	6099	5783.5	4879	904.5	93	80	90	14.0	0.085									
Elenga <i>et al.</i> (1994)	Congo	Af	-4.075	15.3833	400	Ngamakala Pond	7	Arboreal	C	CD	16165	*	*	516	67	55	64	17.9	0.145									
									C	CD	15261.5	*	*	3027	64	54	92	15.6	0.126									
									C	C	9501	*	*	46	92	75	80	18.5	0.639									
									C	C	4240.5	*	*	58	80	68	84	15.0	2.299									
									C	CD	3620	*	*	166	66	31	39	53.0	0.138									
									U	U	1152.5	*	*	118.5	40	37	51	7.5	3.938									
Piperno & Jones (2003)	Panama	C	9.0333	-79.5167	10	crater lake	3	Arboreal	FC	FC	7056	6586	5888	947	64	50	59	21.9	0.068									
									FC	FC	3489	2770	2015	621.5	27	18	50	33.3	0.572									
									FC	FC	886	540	96	544.8	36	27	32	25.0	0.102									
Vincens <i>et al.</i> (2003)	Tanzania	Af	-9.3333	33.75	770	crater lake	6	Zambeziian arboreal pollen	C	CD	3582	2966	2673	274	33	15	32	54.5	0.345									
									C	C	2673	2490	2271	200.6	32	28	35	12.5	0.872									
									C	CP	1595	1522	1456	59.4	47	10	22	78.7	0.546									
									C	CP	1456	1373	1326	41.6	22	17	27	22.7	4.808									
									C	CP	1082	1023	951	35.6	9	5	9	44.4	2.809									
Behling & Lima da Costa (2000)	Brazil	S	-1.75	-51.5	lowland	small river (with tidal influence)	1	Trees, shrubs, climbers & epiphytes	C	CS	7893.5	*	*	1392	74.7	48	77	35.7	0.079									
									Maley (2002)	Cameroon	Af	-4.6667	9.4	300	crater lake	7	Trees	C	C	20000	*	*	1334	82	40	65	51.2	0.045
																		C	CD	18333	*	*	800	65	36	60	44.6	0.103
																		C	CD	16000	*	*	1000	62	30	64	51.6	0.106
																		C	CD	14000	*	*	200	64	50	68	21.9	0.643
																		C	CP	11500	*	*	300	68	50	78	26.5	0.519
C	CD	10500	*	*	300	78	61	91	21.8	0.588																		
C	CP	3333	*	*	666	98	60	89	38.8	0.115																		
Wooller <i>et al.</i> (2004)	Belize	C	16.8333	-88.1	0	Twin Cays	3	Mangrove	LI	LI-H	7135	7070	6938	132	83	34	86	59.0	0.804									
									LI	LI-H	4480	4251	4224	27	86	18	40	79.1	1.198									
									LI	LI-H	4171	4094	3829	265	33	12	48	63.6	0.647									
Umer <i>et al.</i> (2007)	Ethiopia	Af	6.8667	39.8167	3950	Garba Guracha	1	trees & shrubs	FC	Ag	2197	1266	468	1266	68	41	67	39.7	0.076									

Bonnefille & Riollet (1988)	Burundi	Af	-3.4667	29.5667	2103	Kashiru Swamp	2	arboreal pollen	FC	FC	1437	793	439.5	353.5	29	23	24	20.7	0.047
									FC	FC	439.5	168	0	168	24	15	18	37.5	0.198
Wooler <i>et al.</i> (2007)	Belize	C	16.8333	-88.1	0	Twin Cays	9	Mangrove	U	U	7982	7923	7827	96	99	65	100	24.4	1.736
									C	CS	6370	6214	5924	290	86	32	95	62.8	0.402
									C	CS	5924	5496	5146	350	95	82	86	13.7	0.088
									C	CS	5146	4944	4356	588	86	76	88	11.6	0.204
									C	CS	4356	4120	3938	182	88	69	78	21.6	0.260
									C	CS	3545	3322	3197	125	70	53	59	24.3	0.282
									C	CS	3197	2620	1370	1250	59	48	66	18.6	0.131
									C	CS	1370	913	617	296	66	53	73	19.7	0.520
Berrio <i>et al.</i> (2006)	Mexico	C	17.75	-99.4667	1430	Lake Huitziltepec	12	dry deciduous & mesophylous forest	FC	Ag	1869	1836	1729	107	59.00	30	51	49.2	0.677
									FC	Ag	1621	1599	1595	4	43.00	35	47	18.6	37.500
									FC	Ag	1579	1572	1568	4	39.00	30	41	23.1	30.556
									FC	Ag	1568	1564	1560	4	41.00	36	55	12.2	95.000
									FC	Ag	1560	1549	1545	4	55.00	25	37	54.5	10.000
									FC	Ag	1541	1537	1530	7	36.00	28	51	22.2	41.071
									FC	Ag	1530	1522	1518	4	51.00	34	41	33.3	10.294
									FC	FC	1137	1053	923	130	29.00	21	41	27.6	1.923
									FC	FC	923	875	661	214	41.00	30	53	26.8	0.977
									FC	FC	661	598	459	139	53.00	31	53	41.5	0.719
									FC	Ag	263	144	82	62	59.00	47	59	20.3	1.613
FC	Ag	82	49	16	33	59.00	44	57	25.4	2.626									
Berrio <i>et al.</i> (2000)	Colombia	S	5.8	-76.7	50	Laguna Jotaordo	1	trees, shrubs, climbers & epiphytes	FC	Ag	1334	1266	1198	68	80.00	62	74	22.5	0.980
Berrio <i>et al.</i> (2002)	Colombia	S	4.0833	-70.35	150	Laguna Chenevo	3	forest, gallery forest, shrubs & trees	FC	FC	6103	5687	4313.5	1373.5	67.00	62	78	7.5	0.233
									FC	FC	4313.5	2823.5	2729	94.5	78.00	72	80	7.7	1.411
									FC	FC	2729	2329	1975.5	353.5	80.00	72	82	10.0	0.354
Berrio <i>et al.</i> (2002)	Colombia	S	3.9667	-73.05	175	Laguna Mozambique	1	forest, gallery forest, shrubs & trees	FC	Ag	382.5	299	180	119	93.00	57	65	38.7	0.187
Berrio <i>et al.</i> (2002)	Colombia	S	3.1	-76.5167	1020	Quilichao	2	dry forest	FC	Ag	2415	2346	2322	24	77.00	34	43	55.8	0.872
									FC	Ag	2322	2299	2155	144	43.00	34	67	20.9	2.546

Berrio <i>et al.</i> (2002)	Colombia	S	3.0833	-76.5333	1020	La Teta	3	dry forest	FC	Ag	2215.5	1492	1228	264	61.00	22	37	63.9	0.146
									FC	Ag	1228	1193.5	866	327.5	36.00	12	18	66.7	0.076
									FC	Ag	866	741	657	84	18.00	11	42	38.9	5.272
Marchant & Taylor (1998)	Uganda	Af	-1.0833	29.75	2150	Mubwindi Swamp	5	montane forest	FC	FC	501	424	407	17	74.00	64	74	13.5	5.882
									FC	FC	407	386.5	375	11.5	74.00	49	60	33.8	3.826
									FC	FC	161	220.5	217.5	3	61.00	52	58	14.8	22.222
									FC	FC	77.5	75	71.5	3.5	62.00	50	73	19.4	54.762
									FC	FC	71.5	71	35.5	35.5	73.00	63	74	13.7	3.099
Bush <i>et al.</i> (2007)	Peru	S	-12.177	-69.0978	230	lake	5	arboreal	FC	B	5165	5023	4752	271	83	58	67	30.1	0.133
									FC	B	4752	4417	4035	382	67	57	63	14.9	0.157
									FC	Ag	4035	3661	3305	356	63	51	70	19.0	0.445
									FC	AgB	3305	2860	2319	541	70	61	80	12.9	0.390
									FC	AgB	834	666	566	100	81	77	94	4.9	4.250
Bush <i>et al.</i> (2007)	Peru	S	-12.083	-69	230	lake	1	arboreal	FC	B	1364	860	597	263	62	49	90	21.0	1.199
Bush <i>et al.</i> (2007)	Peru	S	-12.083	-69	230	lake	1	arboreal	FC	B	884	428	222	206	84	69	91	17.9	0.712
Bush <i>et al.</i> (2007)	Peru	S	-12.083	-69	230	lake	2	arboreal	FC	Ag	2411	994	865	129	44	29	46	34.1	0.879
									FC	B	865	497	350	147	46	30	81	34.8	2.168
Bush <i>et al.</i> (2007)	Brazil	S	-1.6469	-53.5956	25	lake	6	arboreal	FC	Ag	8381	8286	8152	134	96	86	98	10.4	0.896
									FC	B	7086	6895	6762	133	98	89	99	9.2	0.835
									FC	B	5524	4857	4552	305	87	78	85	10.3	0.255
									FC	AgB	4552	4038	3790	248	85	79	84	7.1	0.336
									FC	AgB	1429	1219	990	229	91	79	81	13.2	0.073
									FC	AgB	990	667	552	115	81	76	92	6.2	2.783
Bush <i>et al.</i> (2007)	Brazil	S	-1.6469	-53.5956	25	lake	8	arboreal	FC	Ag	8528	8030	7671	359	41	14	94	65.9	0.825
									FC	B	7671	6954	6427	527	94	81	90	13.8	0.131
									FC	AgB	6427	5172	4881	291	90	47	65	47.8	0.144
									FC	AgB	4881	4456	4211	245	65	35	88	46.2	0.721
									FC	AgB	4211	3630	3223	407	88	53	94	39.8	0.288
									FC	AgB	3223	2889	2222	667	94	57	85	39.4	0.113
									FC	Ag	2222	1815	1449	366	85	52	73	38.8	0.174
									FC	Ag	1449	1059	112	947	73	61	72	16.4	0.097

Bush <i>et al.</i> (2007)	Brazil	S	-1.6469	-53.5956	25	lake	5	arboreal	FC	B	8286	7866	7561	305	90	74	89	17.8	0.307
									FC	AgB	7561	7141	6797	344	89	82	95	7.9	0.540
									FC	AgB	5136	5021	4792	229	80	76	82	5.0	0.655
									FC	AgB	1928	1279	1069	210	87	71	81	18.4	0.298
									FC	AgB	821	630	191	439	81	79	87	2.5	0.911
Velez <i>et al.</i> (2005)	Colombia	S	2.0333	-77	760	Patia 1	5	dry forest	FC	B	7005	6609	6138	471	69.00	43	79	37.7	0.294
									FC	B	6138	5709	5257	452	79.00	52	78	34.2	0.213
									FC	B	5257	5053	4353	700	78.00	51	66	34.6	0.079
									FC	B	3512	3220	2899	321	49.00	36	48	26.5	0.288
									FC	B	1660	881	773	108	41.00	22	37	46.3	0.731
Velez <i>et al.</i> (2005)	Colombia	S	2.0333	-77	760	Patia 2	4	dry forest	FC	FC	4690.5	3424.5	3173	251.5	81.00	38	70	53.1	0.296
									FC	FC	3173	2073	1710	363	70.00	24	36	65.7	0.072
									FC	FC	1710	1051.5	749.5	302	36.00	15	32	58.3	0.268
									FC	FC	749.5	582.5	486	96.5	32.00	26	39	18.8	2.245
Montoya <i>et al.</i> (2011)	Venezuela	S	4.4667	-61.5833	910	peat bog	3	dryland forest post recovery	FC	B	5607	4805	4479	326	64	42	47	34.4	0.070
									FC	B	4479	3855	3499	356	47	35	42	25.5	0.164
									FC	B	3499	2608	2088	520	42	33	60	21.4	0.577
Zogning <i>et al.</i> (2001)	Cameroon	Af	6.47	10.31	1000	lake	1	trees	C	CD	2423.5	2307	2229	78	48	10	23	79.2	0.439
Mueller <i>et al.</i> (2010)	Guatemala	C	16.917	-89.8333	lowland	Lake Peten Itza	2	tropical lowland forest	FC	FC	870	754	366	388	79	39	89	50.6	0.322
									FC	FC	366	292	48	244	89	72	85	19.1	0.313
Figueroa-Rangel <i>et al.</i> (2010)	Mexico	C	19.592	-104.282	1820-1890	SMBR	3	highly diverse cloud forest	C	CD	1198	984	882	102	68	40	62	41.2	0.770
									C	CD	856	833	767	66	62	60	76	3.2	12.121
									C	CD	499	425	387	38	66	43	61	34.8	2.059
Parkes <i>et al.</i> (1992)	Tahiti	A	-17.667	-149.45	470	Lake Vaihiria	7	mid & high altitude hygrophile forest	LI	LI	487	445	402	43	46	31	43	32.6	1.860
									LI	LI	404	382	362	20	43	34	63	20.9	16.111
									LI	LI	362	321	280	41	63	20	70	68.3	2.836
									FC	FC	280	259	232	27	70	45	63	35.7	2.667
									FC	FC	233	208	131	77	63	37	69	41.3	1.598
									FC	FC	132	81	56	25	69	42	51	39.1	1.333
FC	FC	57	30	2	28	51	20	60	60.8	4.608									

Piperno <i>et al.</i> (2007)	Mexico	C	18.35	-99.483	740	Laguna Tuxpan	4	seasonally dry tropical forest	C	CD	1936	1903	1854	49	50	34	44	32.0	1.276
									C	CD	1662	1568	1512	56	40	8	43	80.0	1.953
									C	CD	1306	1254	1163	91	45	16	28	64.4	0.455
									FC	Ag	979	940	878	62	31	21	60	32.3	6.290
Giovana Parizzi <i>et al.</i> (1998)	Brazil	S	-19.633	-43.9	740	Lagoa Santa	4	cerrado semideciduous mosaic	C	CP	5100	4631	4162	469	14	13	29	7.1	3.412
									C	CP	4162	3740	3224	516	29	19	20	34.5	0.019
									C	CP	3224	2849	2333	516	20	17	31	15.0	0.904
									C	CP	2333	1863	1394	469	31	16	23	48.4	0.100
Haberle <i>et al.</i> (1991)	Indonesia	A	-4.083	138.933	1420	Kelela Swamp	6	montane & sub-alpine forest	FC	FC	5850	5261	4826	435	83	65	89	21.7	0.307
									FC	FC	4826	4226	3645	581	89	75	84	15.7	0.111
									FC	FC	3645	2781	2091	690	84	55	80	34.5	0.125
									FC	FC	2091	1854	1488	366	80	59	70	26.3	0.143
									FC	FC	1509	1186	909	277	69	67	76	2.9	1.625
									FC	FC	900	638	393	245	76	55	72	27.6	0.330
Haberle (1996)	Solomon Islands	A	-9.5	160.083	20	Laukutu Swamp	1	inland swamp	FC	FC	1605	904	441	463	47	17	34	63.8	0.122
Haberle (1998)	Papua New Guinea	A	-5.833	142.833	1650	Haeapugua Basin	3	variable lower montane	C	C	20896	16134	13410	2724	68	18	37	73.5	0.014
									C	C	13410	12805	8960	3845	37	27	67	27.0	0.104
									FC	FC	1113	953	683	270	59	23	46	61.0	0.237
Haberle (1998)	Papua New Guinea	A	-5.667	142.583	2300	Tugupugua Basin	4	variable lower montane	U	U	13801	13257	12690	567	56	49	55	12.5	0.151
									U	U	12690	11974	11332	642	55	45	54	18.2	0.140
									FC	FC	7744	6705	6235	470	83	67	86	19.3	0.253
									FC	FC	908	555	-20	575	70	33	39	52.9	0.028
Denham <i>et al.</i> (2003)	Papua New Guinea	A	-5.783	144.333	1560	Kuk Swamp	6	intermontane valley	FC	FC	10181	10137	10092	45	47	36	47	23.4	2.222
									FC	FC	10092	10011	9965	46	47	23	50	51.1	2.446
									FC	Ag	7572	6849	6751	98	22	2	18	90.9	0.816
									FC	Ag	6751	6545	6216	329	18	5	14	72.2	0.210
									FC	Ag	5335	4849	4387	462	15	9	27	40.0	0.649
									FC	Ag	4387	3929	3021	908	27	12	18	55.6	0.044

Neff <i>et al.</i> (2006)	Guatemala	C	13.933	-91.15	lowland	Sipacate - SIP99E	2	"arboreal"	FC	Ag	3839	3721	3288	433	16	7	42	56.3	0.898
									FC	Ag	3288	3150	2796	354	42	9	82	78.6	0.625
Neff <i>et al.</i> (2006)	Guatemala	C	13.933	-91.15	lowland	Sipacate - SIP014	1	"arboreal"	FC	Ag	5289	5251	4452	799	35	7	16	80.0	0.040
Neff <i>et al.</i> (2006)	Guatemala	C	14.483	-92.117	lowland	Manchon - MAN015	5	"arboreal"	C	CD	5882	5414	5320	94	28	12	23	57.1	0.731
									FC	Ag	4781	4734	4605	129	29	12	21	58.6	0.410
									FC	Ag	3914	2743	2438	305	38	4	9	89.5	0.048
									FC	Ag	1677	1291	1056	235	14	13	23	7.1	4.255
FC	Ag	1056	717	459	258	23	11	19	52.2	0.258									
Neff <i>et al.</i> (2006)	Guatemala	C	14.5	-92.167	lowland	Tilipia - TIL016	4	"arboreal"	FC	Ag	4435	4296	4188	108	28	20	29	28.6	1.042
									FC	Ag	4168	4064	3851	213	29	21	64	27.6	2.523
									FC	Ag	3808	3425	2947	478	64	30	73	53.1	0.265
									FC	Ag	764	648	606	42	38	30	39	21.1	2.679
Neff <i>et al.</i> (2006)	Guatemala	C	14.5	-92.167	lowland	Tilipia - OC001	3	"arboreal"	FC	FC	2161	1524	1359	165	28	12	21	57.1	0.341
									FC	FC	1359	1041	947	94	21	19	31	9.5	6.383
									FC	FC	711	546	310	236	31	22	27	29.0	0.235
Hermanowski <i>et al.</i> (2012)	Brazil	S	-6.352	-50.394	740	Pantano da Mauritia	5	"tropical forest"	C	CD	10396	10104	9971	133	78	32	47	59.0	0.245
									C	CD	9971	9971	9764	207	47	33	38	29.8	0.173
									C	CD	9764	9715	9667	48	38	31	34	18.4	0.893
									C	CD	9667	8937	6854	2083	34	10	29	70.6	0.038
									C	CD	6854	6306	5722	584	29	13	25	55.2	0.128
Figueroa-Rangel <i>et al.</i> (2012)	Mexico	C	19.593	-104.279	1880-2100	Sierra de Manantlan B.R.	13	"cloud forest"	C	CD	1152	1097	1069	28	46	30	60	34.8	6.696
									C	CD	1072	1043	1018	25	60	5	18	91.7	0.945
									C	CD	1018	994	964	30	18	12	24	33.3	6.667
									C	CD	964	940	911	29	24	19	30	20.8	7.586
									C	CD	911	893	861	32	30	18	21	40.0	0.781
									C	CD	877	860	837	23	21	7	25	66.7	5.590
									C	CD	827	811	796	15	24	12	14	50.0	1.111
									C	CD	785	770	745	25	14	10	18	28.6	8.000
									C	CD	746	726	707	19	18	10	16	44.4	3.947
									C	CD	707	691	639	52	16	11	32	31.3	8.077
FC	FC	558	464	374	90	43	24	42	44.2	1.053									

									FC	FC	374	280	184	96	42	20	32	52.4	0.568
									FC	FC	184	96	5	91	32	19	29	40.6	0.845
Lozano-Garcia <i>et al.</i> (2005)	Mexico	C	19.167	-99.533	2570	Lake Chignahuapan	7	"Trees"	C	CD	22003	20722.5	19753	969.5	71	43	51	39.4	0.029
									C	CD	19781.5	19188.5	18234	954.5	51	49	83	3.9	1.781
									C	CD	16149.5	14695	11408.5	3286.5	71	25	80	64.8	0.036
									C	CD	10579	9865	8505.5	1359.5	86	59	96	31.4	0.101
									U	U	4803.5	4527.5	3686.5	841	88	74	80	15.9	0.051
									FC	FC	3686.5	3239	1671.5	1567.5	80	47	86	41.3	0.075
									FC	FC	1671.5	1432	1099.5	332.5	86	61	67	29.1	0.072
da Luz <i>et al.</i> (2011)	Brazil	S	-21.75	-41.333	lowland	Lagoa de Cima	6	arboreal pollen	C	CD	7673	7334	7178	156	45	17	53	62.2	0.824
									C	CD	7178	6857	6040	817	53	21	47	60.4	0.099
									C	CD	6040	5090	4648	442	47	10	37	78.7	0.165
									C	CD	4648	4449	4206	243	37	34	42	8.1	1.097
									C	CD	4206	4052	3544	508	42	34	41	19.0	0.172
									C	CD	3544	3000	2990	10	41	22	44	46.3	11.579
Dominguez- Vazquez & Islebe (2008)	Mexico	C	16.991	-91.592	800	Laguna Naja	3	LMRF	C	CD	1237	719	578	141	40	13	43	67.5	0.788
									FC	Ag	403	265	180	85	44	42	55	4.5	7.647
									FC	Ag	180	102	-16	118	55	42	51	23.6	0.587
Carrillo-Bastos <i>et al.</i> (2010)	Mexico	C	19.297	-88.07	lowland	Lake Tzib	5	tropical forest	C	CD	6091	4722	4079	643	94	55	78	41.5	0.092
									C	CD	4079	3827	3548	279	78	73	76	6.4	0.215
									C	CD	3548	3184	2709	475	76	69	88	9.2	0.571
									FC	Both	2709	2430	1787	643	88	79	94	10.2	0.259
									C	CD	1787	1032	753	279	94	79	81	16.0	0.048
Rue (1987)	Honduras	C	14.75	-88.083	635	Lake Yojoa	5	Arboreal Pollen	FC	FC	5273	4900	4714	186	37	16	20	56.8	0.102
									FC	Ag	3594	3445	3221	224	27	25	39	7.4	3.125
									FC	Ag	3221	2848	2662	186	39	35	45	10.3	1.344
									FC	Ag	1766	1953	1542	411	67	26	62	61.2	0.214
									FC	Ag	1542	1244	610	634	62	26	40	58.1	0.061
Rue (1987)	Honduras	C	14.75	-89.1333	700	Petapilla Swamp	2	Arboreal Pollen	FC	FC	681	656	519	596	63	38	75	39.7	0.248
									FC	Ag	362	331	284	301	62	51	58	17.7	0.211
Deevey <i>et al.</i> (1979)	Guatemala	C	17.067	-89.417	lowland	Lake Yaxha	4	Grassland arboreal + arboreal	FC	Ag	1998	1885	1715	170	52	31	42	40.4	0.308

									FC	Ag	1632	1557.5	1435.5	122	42	18	30	57.1	0.410
									FC	Ag	1435.5	1354.5	1287	67.5	30	24	46	20.0	5.432
									FC	Ag	604	497.5	474	23.5	53	30	75	43.4	8.326
Deevey <i>et al.</i> (1979)	Guatemala	C	17.067	-89.367	lowland	Lake Sacnab	5	Grassland arboreal + arboreal	FC	Ag	4136.5	2727	2230	497	85	42	79	50.6	0.173
									FC	Ag	2230	1973.5	1784	189.5	79	51	58	35.4	0.132
									FC	Ag	1784	1463.5	1360	103.5	58	25	47	56.9	0.644
									FC	Ag	1360	1232	744	488	47	31	44	34.0	0.166
									FC	Ag	744	476.5	225.5	251	44	22	76	50.0	0.978
Leyden <i>et al.</i> (1998)	Mexico	C	20.667	-87.833	lowland	Lake Coba	4	trees & shrubs sum	FC	Ag	3131	2436	2195	241	76	29	37	61.8	0.071
									FC	Ag	2195	1903	1628	275	37	33	37	10.8	0.364
									FC	Ag	1628	1244	964	280	37	28	62	24.3	1.349
									FC	Ag	964	795	623	172	62	45	75	27.4	1.026
Penny <i>et al.</i> (1996)	Thailand	A	17.133	103.017	lowland	Nong Han Kumphawapi	2	trees & shrubs sum	FC	B	5954	3292	2188	1104	23	11	35	52.2	0.181
									FC	B	2188	1551	1067	484	35	17	19	51.4	0.023
Ledru (1993)	Brazil	S	-19	-46.767	1050	Salitre de Minas	6	arboreal pollen	C	CD	19469	15199	15058.5	140.5	47	25	49	46.8	0.776
									C	C	15058.5	14726	13369.5	1356.5	49	39	48	20.4	0.066
									C	CD	12150	12170	10354.5	1815.5	21	8	62	61.9	0.229
									C	CD	10354.5	9607.5	8644	963.5	62	46	62	25.8	0.104
									C	CD	8644	7986	7043	943	62	51	75	17.7	0.231
									C	CD	7043	5271.5	4486	785.5	75	10	43	86.7	0.065
Flenley & Butler (2001)	Indonesia	A	-2.25	101.5	1100	Sikijang Swamp	7	forest taxa	C	C	9963	9167	9114	53	93	68	80	26.9	0.906
									C	C	9114	8556	8343	213	80	62	86	22.5	0.626
									FC	B	8157	7659	7606	53	83	52	83	37.3	1.887
									FC	FC	7024	6398	5137	1261	82	56	85	31.7	0.088
									FC	B	5137	4491	3887	604	85	70	78	17.6	0.088
									FC	B	3887	3251	2573	678	78	76	90	2.6	1.032
									FC	B	2573	1948	623	1325	90	67	90	25.6	0.075
Curtis <i>et al.</i> (1998)	Guatemala	C	16.917	-89.833	110	Lake Peten-Itza	4	high forest	FC	FC	6692	6335	6281	54	82	59	68	28.0	0.725
									FC	FC	6281	6217	6091	126	68	51	71	25.0	0.934
									FC	FC	6091	6045	5892	153	71	64	75	9.9	1.027
									FC	FC	2976	1810	64	1746	58	13	61	77.6	0.061

Yulianto <i>et al.</i> (2005)	Indonesia	A	-3.317	116.117	lowland	Batulicin swamp	2	mangrove	C	CS	7761	7322	6334	988	47	12	56	74.5	0.127
									FC	FC	1535	980	-55	1035	45	29	63	35.6	0.205
Kirleis <i>et al.</i> (2011)	Indonesia	A	-1.654	120.189	1331	Bariri Tower	1	trees and palms	FC	FC	210	74	51	23	29	8	22	72.4	2.899
Enters <i>et al.</i> (2010)	Brazil	S	-17.988	-42.119	600	Lago Aleixo	2	forest trees/shrubs	C	C	5813	5495	4890	605	78	61	84	21.8	0.224
									C	C	1726	1600	1272	328	82	66	81	19.5	0.286
Monacci <i>et al.</i> (2011)	Belize	C	17.421	-88.272	lowland	SR-63	8	mangroves	U	U	6687	6534	6386	148	78	60	71	23.1	0.413
									U	U	6386	6248	6086	162	71	65	76	8.5	1.132
									U	U	6086	5755	4737	1018	76	65	74	14.5	0.080
									C	C	2758	2277	1739	538	44	30	61	31.8	0.412
									U	U	1739	1273	838	435	61	50	74	18.0	0.502
									C	CD	838	453	265	188	74	49	75	33.8	0.553
									U	U	265	211	144	67	75	69	82	8.0	3.234
U	U	144	114	25	89	82	55	69	32.9	0.583									

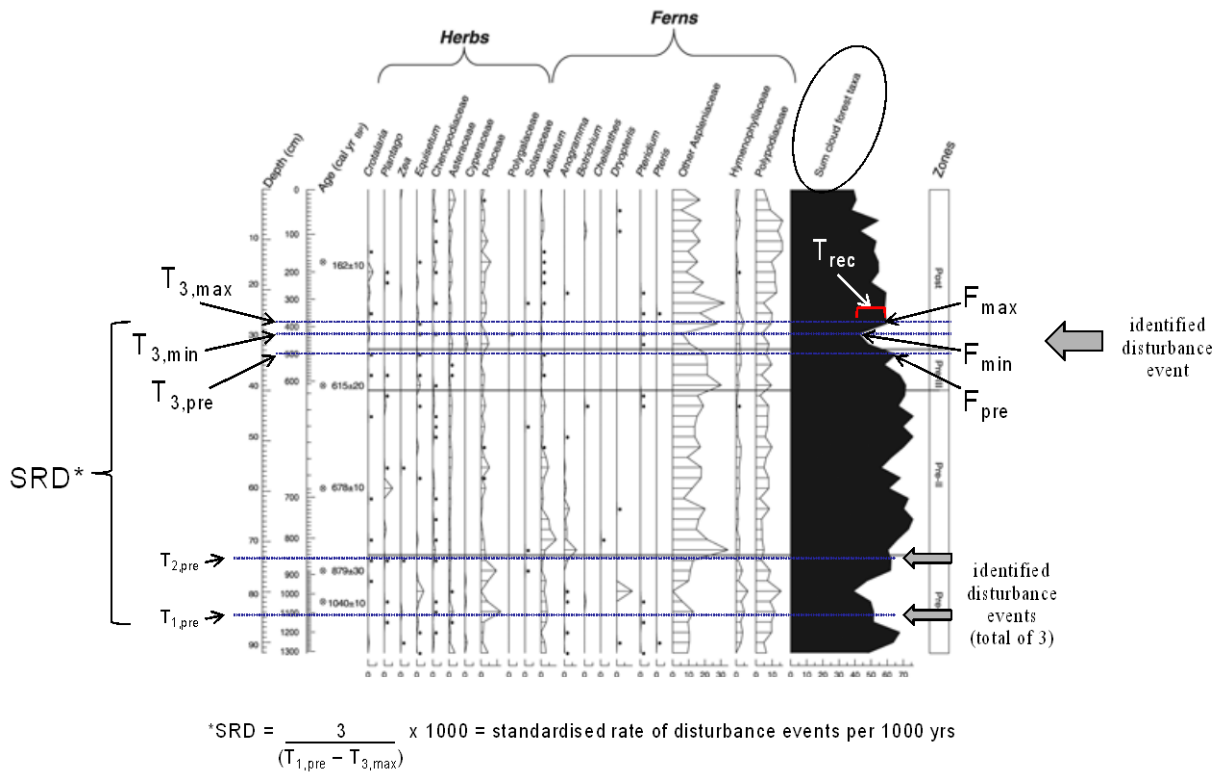
*Variables not recorded – T_{rec} measured directly from diagram.

Associated Reference List

(formatting does not follow the style of the article & references below are not all included in Bibliography, page 281)

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Supplementary Fig. 1 An example of a published pollen diagram from which data were extracted, with annotations to describe the measurements made and the SRD metric calculated. (See SI 1 for specific details of the disturbance event shown, and Table 2 for a description of acronyms. T_{pre} , T_{min} and T_{max} represent the time at the point of maximum forest cover prior to disturbance, minimum forest cover during disturbance event and maximum forest recovery, respectively.)

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Paper 2: DISTURBANCE, ECOLOGY AND RESILIENCE IN A TROPICAL PEAT SWAMP FOREST

Cole, L.E.S.¹, S.A. Bhagwat.² and Willis, K.J.³

¹Oxford Long-term Ecology Laboratory, Department of Zoology, University of Oxford, Oxford, United Kingdom

²School of Geography and the Environment, University of Oxford, Oxford, United Kingdom

³Biodiversity Institute, Oxford Martin School, Department of Zoology, University of Oxford, Oxford, United Kingdom

Corresponding author: Lydia Cole, tel: 01865 281321, fax: 01865 271249,

lydia.cole@zoo.ox.ac.uk

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ABSTRACT

Tropical peat swamp forests in SE Asia are rapidly undergoing conversion for agricultural development. In an intact state, these wetland forests provide a huge range of services for both local and global communities. Yet on-going degradation is threatening future provision from these “fragile” ecosystems. In order to understand what level of perturbation these forests can tolerate, knowledge of their ecological response to past disturbances is required. This study investigates the long-term ecology of a tropical peat swamp forest (identified as Peat Swamp Fragment site) in Sarawak, Malaysian Borneo, focusing on changes in plant communities after different disturbance events and discussing the implications for the resilience of this ecosystem. By reconstructing past vegetation change using fossil pollen and charcoal records obtained from a peat core extracted in northern Borneo, we indicate that there have been four major periods of disturbance over the past 4000 years. Probable drivers range from intensified El Niño Southern Oscillation (ENSO) to elevated fire and human impact. Results also indicate that the peat swamp forest community responds dynamically to disturbances prior to 300 Cal. yr BP. However, after this period, with the onset of anthropogenic land-use change in the locality, regeneration of forest vegetation is less-apparent, indicating a loss of resilience in the more recent past. These results support the existence of a unique ecology in peat swamp forests, notably the peat-water-vegetation interrelationship that is fundamental for their self-regulation. For the persistence of tropical peatlands, consideration of their hydrological integrity is key, and the development of sustainable management practices must consider the potential to limit disturbances to ‘natural’ levels.

Key words peat swamp forest, long-term ecology, disturbance, regeneration, resilience, fire, human land-use change

INTRODUCTION

Disturbance is a common component of all ecosystems, influencing their temporal and spatial dynamics (Turner, 2010). In tropical forest environments, externally-driven perturbations promote species turnover, through triggering the onset of succession; one of the factors thought to contribute in this ecosystem to the maintenance of some of the highest levels of diversity found anywhere on earth (Connell, 1978). The magnitude of disturbance can vary over space and time, ranging from spontaneous localised disruptions, such as land-slides and hurricanes in Puerto Rico (Lugo & Scatena, 1996), to large-scale ongoing climatic changes, for example in the Amazon (Feeley *et al.*, 2012). Information on the frequency of occurrence, intensity and, fundamentally, impact of disturbance events on tropical forest ecosystems through time is limited but vital for understanding the ecology of these ecosystems and predicting their responses to future external drivers. Knowledge is particularly sparse for the tropical peat swamp forests of the coasts of Southeast Asia; regarded as “fragile” (DID, 2001) and “unusual” (Yule, 2010) ecosystems in their functioning, they are thought to have experienced little disturbance since their development in the mid-Holocene (Dommain *et al.*, 2011).

These coastal peat swamp forests are undergoing rapid change (Miettinen & Liew, 2010; Koh *et al.*, 2011), with over 50% having been deforested between 2000 to 2010, at rates twice as fast as those of lowland evergreen forest in the region during this period (Miettinen *et al.*, 2012b). In Sarawak, one of the two east Malaysian States in northern Borneo, such logging and conversion of peat swamp forests is particularly rife: the rate of deforestation over the last 10 years has been 12 times greater than the average rate for forests across Asia (SarVision, 2011), and 25% greater than the lowland dipterocarp forests of the island (Langner *et al.*, 2007; Miettinen *et al.*, 2011). Unlike the natural disturbances of the past, contemporary change is predominantly driven by humans, mostly with the aim of establishing plantations (Miettinen *et al.*, 2012a), notably for pulpwood and palm oil production (Murdiyarso *et al.*, 2010; Miettinen *et al.*, 2012a).

Aside from their value as agricultural frontiers (Koh *et al.*, 2011), tropical peat swamp forests provide many other services to both local and global communities. People living in the proximity of these wetland ecosystems benefit from the year-round provision of water and stabilisation against periodic flooding (Phillips, 1998); from access to food, timber, fish and other products of the forests, and from the prevention of intrusion by saline water into coastal areas (Silvius & Giesen, 1996). Globally, they perform as the Earth's most spatially-efficient terrestrial ecosystem for carbon sequestration over millennial time scales (Dommain *et al.*, 2011). In particular, SE Asian peatlands store 11-14% of the global peat carbon pool whilst covering only approximately 6% of the global peat-covered surface (Page *et al.*, 2011). Residing within the Sundaland Biodiversity Hotspot (CI, 2012), much of SE Asia's peat swamp forests act as an important refuge for a great diversity of species (Yule, 2010), ranging from fish, highly-adapted to the acidic blackwaters, such as the swamp Gourami *Parosphromenus paludicola* (Ng *et al.*, 1994), to highly-threatened primates, notably the iconic orangutan, *Pongo* spp. (Morrogh-Bernard *et al.*, 2003; Meijaard *et al.*, 2012).

The conversion of peat swamp forest essentially exchanges the provision of this multitude of ecosystem services for just one: that of monoculture production. This process involves the removal of all forest vegetation, often over large areas, and the establishment of drains to remove excess water. In an undisturbed system, peat accumulation occurs under waterlogged conditions, where anaerobic respiration greatly hinders the decomposition of dead organic matter (DOA, 2003; Staub & Gastaldo, 2003; Dommain *et al.*, 2010). The vegetation creating this build-up of carbon-rich substrate grows into the peat, contributing to the upper-most peat layer. This layer, referred to as the acrotelm (Page *et al.*, 1999), comprises the peat swamp forest floor and the lower part of the above-ground vegetation, including the buttress roots of canopy trees (an adaptation to the oligotrophic waterlogged environment). It is vital for maintaining the microtopographical landscape of hummocks and hollows that enables hydrological self-regulation within the peat dome, and ensures that the substrate is permanently waterlogged (Dommain *et al.*, 2010), especially at the sloping edges

of the coastal peat dome, where the hydraulic conductivity is highest. Such architecture is central to maintaining the permanent water-saturated anaerobic environment in which peat swamp ecosystems persist (Dommain *et al.*, 2010). Thus each component, i.e. peat, water and vegetation, is vital. When these areas are logged and drained, the hydrological self-regulation is disrupted (Dommain *et al.*, 2010), which is thought to trigger irreversible degradation within the peat swamp forest ecosystem, and the emission of vast amounts of carbon (Jauhiainen *et al.*, 2008), even once the disturbance factor has been removed. Yet, information testing this hypothesis is lacking since such conversion for large-scale agricultural use has been ecologically recent. Therefore exploring the response of forest vegetation to past disturbances within these coastal peat swamps will contribute to knowledge on the recovery dynamics of this ecosystem, and fundamentally its resilience.

Resilience is defined as the capacity of an ecosystem to maintain structural and functional integrity in the face of disturbance (Holling, 1973). When an ecosystem loses its resilience, it is described as having crossed a threshold, shifting into an alternative state (Ficetola & Denöel, 2009), from which recovery to the previous system is prevented due to extreme physical or ecological change (Scheffer & Carpenter, 2003). Understanding what forms and magnitude of disturbance may cause such a shift in tropical peat swamp forests is vital for preventing the loss of ecosystem function and, subsequently, the provision of its many ecosystem services. More fundamentally, knowledge on the ecological functioning of this unique ecosystem and the characteristics of the baseline vegetation, referred to here as the peat swamp forest composition prior to large disturbances, are required in order to model responses to disturbance.

Palaeoecology, the branch of ecology that studies the relationships between plants, animals and their environment in the past, provides an invaluable tool for deciphering peat swamp forest vegetation baselines and investigating the behaviour of ecosystems in response to disturbances through time (Willis *et al.*, 2010). Analysing fossil elements preserved in

sediments enables the long-term biotic-physical environment interactions to be deciphered, and temporal changes in them to be identified.

This study aimed to determine the disturbance history, ecological response and resilience of a coastal peat swamp forest in Sarawak, Malaysian Borneo, using palaeoecological techniques. Specifically, it aimed to address the following questions: (1) What is the baseline vegetation of this coastal peat swamp forest?; (2) What factors caused disturbance in this ecosystem in the past, and how did the vegetation respond?; and (3) How resilient is this peat swamp forest to disturbance?

METHODS

Study Site

This investigation is based on a core taken from a partially-degraded peat swamp forest fragment (henceforth Peat Swamp Fragment) in the Sungai Dua Forest Reserve (04°21'24''N, 114°0'21''E), a small patch of peat swamp forest on the outskirts of the town of Miri, in the Miri Division of Sarawak, northern Borneo (Fig. 1). This region is described as having a tropical ever-wet climate (Morley & Flenley, 1987), with an average temperature of 25°C and average rainfall exceeding 370 cm yr⁻¹, mostly falling during the Southern Hemisphere Summer Monsoon, between November to April (Haberle *et al.*, 2001). A core of 382 cm, the depth at which minerogenic content exceeded organic, of continuous overlapping 50 cm sequences, was extracted using a Russian corer, in October 2009. Each section was then carefully wrapped and transported back to the Oxford Long-term Ecology Laboratory for analysis.

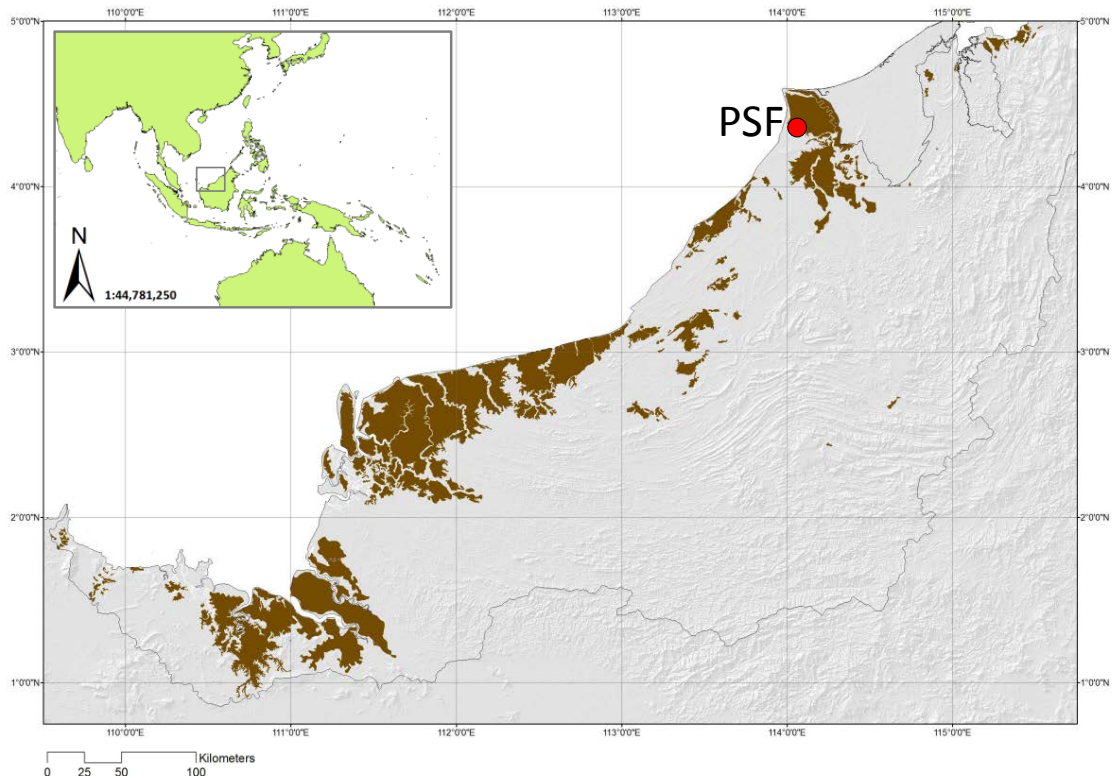


Fig. 1 Map showing the geographical location of Sarawak, Malaysian Borneo (inner box), within SE Asia, and the Peat Swamp Fragment study site (PSF) within Sarawak’s peatlands. (Peatlands shown in brown. Image courtesy of SarVision, 2011.)

Data Collection

Prior to extraction of samples for palaeoecological analysis, the lithology of each section of core was described according to the Troels-Smith classification system (Troels-Smith, 1955), and the magnetic susceptibility recorded. Magnetic susceptibility readings are a measure of the relative composition of iron oxides in the sediment with depth (Gubbins & Bervera, 2008), and can be used as a proxy for climatic change through reflecting soil-water content, erosion events and the sediment regime (Balsam *et al.*, 2011). In general, smaller and more negative values indicate greater soil-moisture (Grimley *et al.*, 2008) and organic matter content (Hamilton *et al.*, 1986), both materials being diamagnetic (Hunt and Premathilake, 2012).

Palaeoecological analysis was performed on 52 samples prepared according to standard techniques (Bennett and Willis, 2001). Pollen preparations were made of 1 cm³ samples at 4 cm intervals for the majority of the core, and 6 cm and 8 cm intervals towards

the top. A Meiji microscope, at 400× magnification, was then used to count a minimum of 300 fossil pollen grains per sampling level, excluding indeterminate pollen (i.e. grains that were deformed, obscured or unidentified). Both a reference collection, compiled from various sources, and published plates (Huang, 1972; Anderson & Muller, 1975; Stuijts, 1993) were used to aid the identification of pollen grains. Due to the diversity of species in the peat swamp flora and differing levels of pollen production amongst them, taxa identified through pollen counting were allocated to ecological groups (Table 1, and Appendix S3) to aid interpretation of the palaeo-plant communities (for example as performed by Muller, 1963) using various publications from the region (Anderson, 1964, 1980; Anshari *et al.*, 2001, 2004; Coode *et al.*, 1996; Stuijts, 1993). A pollen sum was then calculated and used to estimate the relative abundance of each taxon and each ecological group, giving them a percentage score, e.g. PSF%. Open vegetation taxa, i.e. those that produce unusually large volumes of pollen per plant which can bias the interpretation of the vegetation composition of the landscape, for example Poaceae (Bush, 2002), were excluded from the pollen sum. The relevant groups in this study are the peat swamp forest mature (PSF) and pioneer (PSF+) communities (Table 1), the sum of which equals TotPSF%, and open vegetation, which we use as a proxy for human-induced disturbance.

Macrocharcoal particles in each 1 cm³ sample were counted using a light microscope, and microcharcoal concentration measured according to Clark's point count method (Clark, 1982), at corresponding intervals with fossil pollen, to broadly reconstruct local and regional fire events (Clark, 1988), respectively. Significant pollen assemblage zones were constructed using an optimal splitting by information content technique on all pollen data, after assessing the number of zones that were significant via a broken stick modelling approach across different data analyses (Bennett, 1996). *Psimpoll* version 4.26 (developed by Bennett, 1994) was used to display all pollen, spore and charcoal counts and other ecological variables (Fig. 2 & 3), and to compute the Palynological Richness. This represents the change in diversity of fossil pollen taxa between each sample through time (Birks & Line, 1992), and is calculated

by computing the temporal change in rarefied PSF taxonomic richness, measured in $E(T_n)$ units (estimated taxonomic richness in a sample of n individuals (Birks & Line, 1992)), using the minimum count for individuals from the PSF ecological group in the Peat Swamp Fragment core, i.e. across all temporal samples a minimum of 15 pollen grains from the PSF ecological group (comprising PSF and PSF+ taxa) was recorded in the sample at -75 Cal. yr BP, to standardize the data and account for differing sample sizes.

Table 1 Definition of ecological groups, acronyms used and major plant taxa associated with each. (See Appendix S3 for full list of key plant taxa associated with each ecological group.)

Ecological Group	Name	Explanation	Major plant taxa
PSF	peat swamp forest – mature	if taxa present in peat swamp forest, assumed to grow in old-growth forest	* <i>Combretocarpus</i> (Anisophyllaceae), <i>Shorea</i> (Dipterocarpaceae), <i>Stemonurus</i> (Icacinaeae)
PSF+	peat swamp forest – pioneers	if taxa increase in abundance in pollen diagram, indicates early successional plant community of secondary peat swamp forest	* <i>Elaeocarpus</i> (Elaeocarpaceae), <i>Macaranga</i> (Euphorbiaceae), <i>Syzygium</i> (Myrtaceae), <i>Ficus</i> (Moraceae)
TotPSF	total peat swamp forest	All taxa of peat swamp forest origin, i.e. both mature and pioneer taxa	See above*
DP	degraded peat	taxa found in highly disturbed and open-canopied peat areas, generally where natural hydrology has been disrupted	<i>Dillenia</i> (Dilleniaceae), <i>Melastoma</i> (Melastomataceae), <i>Poikilospermum</i> (Urticaceae)
CV	coastal vegetation	coastal vegetation associated with succession to peat from mangrove/littoral habitat type	<i>Oncosperma</i> (Arecaceae), <i>Quassia</i> (Simaroubiaceae)
OF	other forest	other forest (non-peat swamp forest taxa), e.g. swamp forest or forest on mineral soils	<i>Terminalia</i> (Combretaceae), <i>Rubus</i> (Rosaceae)
OV	open vegetation	disturbance tolerant vegetation indicative of open environments greater than tree-fall gaps, not included in pollen sum	Monoletes, Triletes, Poaceae, Cyperaceae

AMS Radiocarbon dating and analysis of five sediment samples, spanning the length of the core, was performed at both the ¹⁴Chrono Centre in the Archaeology and Palaeoecology Department, at Queen’s University Belfast, and the SUERC AMS Laboratory, at the NERC Radiocarbon Facility. The coding package *Clam* (Blaauw, 2010), in the statistical software, R

(R Project, 2012), with a Northern Hemisphere correction, i.e. the IntCal04 curve, was used to calibrate the conventional radiocarbon dates and construct the best-fitting age-depth model (see Appendix S1 and S2).

Several proxies for disturbance have been measured in order to investigate the timing and intensity of potential external drivers of perturbation in this ecosystem. Various ecological response indicators have also been computed to demonstrate when significant changes in the recorded vegetation occur, and identify ecological responses. See Table 2 for descriptions of both sets of indicators.

Table 2 Disturbance proxies and ecological response indicators used to investigate the factors driving vegetation change through time in the Peat Swamp Fragment site.

	Factor represented	Description of trend
<i>Disturbance proxy</i>		
Troel-Smith stratigraphy	Depositional environment	Change in sediment accumulation environment
Magnetic susceptibility	Peat moisture levels	Change in soil environment and moisture levels
Microcharcoal	Regional fire	Incidence of fire in the landscape
Macrocharcoal	Local fire	Incidence of fire in the peat swamp forest
Open vegetation	Open areas (non-forested)	Human forest clearance causing canopy opening
ENSO events	Climatic change	Episodes of intensified ENSO regionally
<i>Ecological Response indicator</i>		
PSF+:%:PSF% ratio	Ratio of pioneer to mature PSF taxa	Internal peat swamp forest regeneration
Palynological Richness	TotPSF taxonomic diversity	Change in taxonomic richness in peat swamp forest (i.e. PSF+ and PSF taxa)
Vegetation zonation	Major landscape vegetation change	Location of significantly different vegetation communities within the temporal pattern of pollen counted

Analysis

Multivariate analysis was performed in order to investigate the changes in (i) *all* taxa (giving an indication of fluctuations in the PSF community relative to those in the degraded peat, other forest and coastal vegetation groups), and (ii) PSF taxa within the peat swamp forest ecosystem (internal peat swamp forest change), through time. Principal Components Analysis (henceforth PCA) was performed in CANOCO (ter Braak & Šmilauer, 2002), in order to identify distinct groups of plant taxa, both internal and external to the peat swamp forest, and time-specific samples, as well as the temporal relationship between plant

communities. Data were square-root transformed and species scores were divided by standard deviations and scaled according to inter-species correlations.

Finally, in order to investigate whether there was a change in the resilience of this peat swamp forest through time, the rate of recovery of the TotPSF% was measured and plotted against time. Recovery is defined as any increase in TotPSF% after a decline, whether the cause of the disturbance can be inferred through disturbance proxies or not. The non-parametric test for correlation, Spearman's Rank Correlation Coefficient (Spearman's rho) (used to increase statistical accuracy when dealing with the small sample size of this study), was calculated in SPSS, to statistically test whether the rate changes both towards the present day and with increasing incidences of TotPSF% decline.

RESULTS

Peat swamp forest baseline vegetation

Throughout the past, PSF has formed the major vegetation type in this landscape, with a contribution to the pollen sum fluctuating around *c.* 90% (Fig. 2). However, the main taxa forming this peat swamp forest have varied through time (see Appendix S4 for full pollen diagram), as has the relative contribution of pioneer versus mature PSF types. After the onset of peat swamp development at approximately 3800 Cal. yr BP, as illustrated by the transition from clay to peat on the Troels-Smith profile and the sharp reduction in magnetic susceptibility values, the ratio of PSF pioneer to mature taxa increases. For the following 1000 years, pioneer taxa, such as *Macaranga* (Euphorbiaceae), *Syzygium* (Myrtaceae) and *Ficus* (Moraceae), have relative pollen abundances some three times greater than mature taxa, of which *Uncaria* (Rubiaceae), *Blumeodendron* (Euphorbiaceae) and *Shorea* (Dipterocarpaceae) form major genera. The vegetation characteristics of this period, from approximately 3800 to 1700 Cal. yr BP, are referred to as the baseline peat swamp forest vegetation in this study. Only one event appears to interrupt this baseline at approximately 2800 Cal. yr BP (described subsequently). Within the so-called baseline landscape

community, degraded peat taxa fluctuate around 5% of the pollen sum, and other forest, predominantly comprising *Poikilospermum* (Urticaceae), and coastal vegetation groups are also present. Both zonation divisions on the pollen diagram (Fig. 2) and the patterns of clustering amongst temporal samples in both PCA diagrams (Fig. 3) support the presence of this baseline community: the majority of samples outside of the clusters are those from the basal 2000 years after the onset of peat accumulation. The palynological richness during this time is also relatively stable, reducing only at *c.* 1700 Cal. yr BP., at the transition between Zone 1 and 2.

Major disturbance events & peat swamp forest vegetation response

3800 Cal. yr BP - The first apparent major disturbance event occurs at the base of the core, *c.* 3800 Cal. yr BP, where the core stratigraphy details a transition in sedimentary environment from clay to peat. Magnetic susceptibility readings decrease significantly at this point, reflecting a reduction in minerogenic input and probably also a reduction in charcoal, and an increase in peat-moisture levels. There is a coincident decrease in microcharcoal levels, which, along with macrocharcoal levels, then remain relatively low for the first half of the baseline period, until approximately 3000 Cal. yr BP. As the peat starts to accumulate during this disturbance event, pioneer PSF taxa, such as *Macaranga*, rise in relative proportion, causing the ratio of pioneer to mature PSF vegetation to increase. The pollen accumulation rate also notably increases during this peat-clay transition zone. Prior to this point, the vegetation associated with the peat swamp forest ecosystem was historically unique, forming an isolated cluster with Dipterocarpaceae as a major taxa (Fig. 3), after which there is a general similarity of vegetation in the peat swamp forest and wider landscape until the proceeding disturbance event.

2200-2800 Cal. yr BP – Following a period of approximately 1000 years of relatively stable peat swamp forest, evidence suggests the presence of another disturbance event at *c.* 2800

Cal. yr BP. Although Troels-Smith and magnetic susceptibility results show no major changes, both micro- and macrocharcoal experience peaks in concentration. PCA clusters suggest the vegetation remained disturbed until 2380 Cal. yr BP at the earliest, with distinct vegetation communities both within the peat swamp forest and wider landscape (Fig. 3). The ratio of pioneer to mature PSF taxa declines, along with the rate of pollen accumulation (Fig. 2), and much of the vegetation comprises the mature-forest indicator, *Stemonurus* (Icacinaceae). Towards the end of the period, at c. 2100 Cal. yr BP, there is a somewhat anomalous peak in open vegetation, coinciding with an increase in the percentage of pioneer taxa within the peat swamp forest.

1400-1700 Cal. yr BP - Various ecological response indicators suggest the presence of a third disturbance event at approximately 1700 Cal. yr BP, despite there being no notable changes in any of the disturbance proxies. These indicators include a slight increase in the contribution of PSF taxa to the pollen count, coinciding with the lowest value for mature PSF taxa across the core (less than 10% of the pollen sum), and thus the highest value of the PSF+%:PSF% ratio, with pioneer taxa, such as *Macaranga*, dominating. Palynological richness also declines to some of the lowest recorded levels.

300 Cal. yr BP onwards – The palynological richness reaches similar low levels from c. 200 Cal. yr BP, coinciding with increased levels of macrocharcoal and several rapid episodes of PSF decline, signalling a final disturbance period within the peat swamp forest. At this point, open vegetation increases significantly, and remains high until the present day.

Simultaneously, there is a distinct vegetation community both within the PSF and amongst all taxa (Fig. 3.), with *Stemonurus*, *Pandanus* (Pandanaeae) and *Trema* (Ulmaceae) forming significant contributions. Pollen from other ecological groups also contribute more to the pollen sum, with other forest taxa, such as *Poikilospermum* (Urticaceae), rising to >50% of the pollen sum at points within the last 200 years.

Key to sediment stratigraphy

- Dark peat
- Peat-clay transition
- Clay

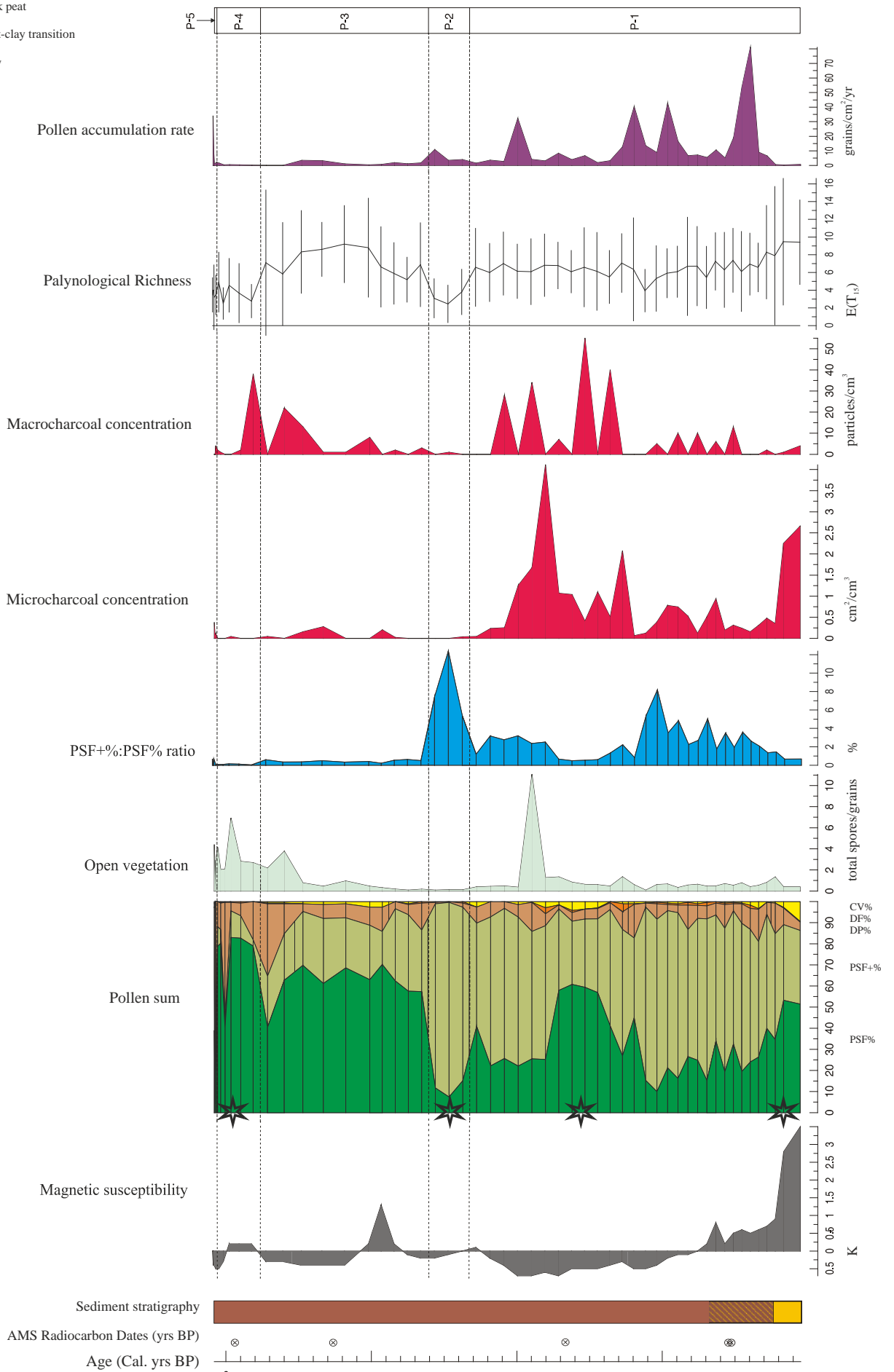
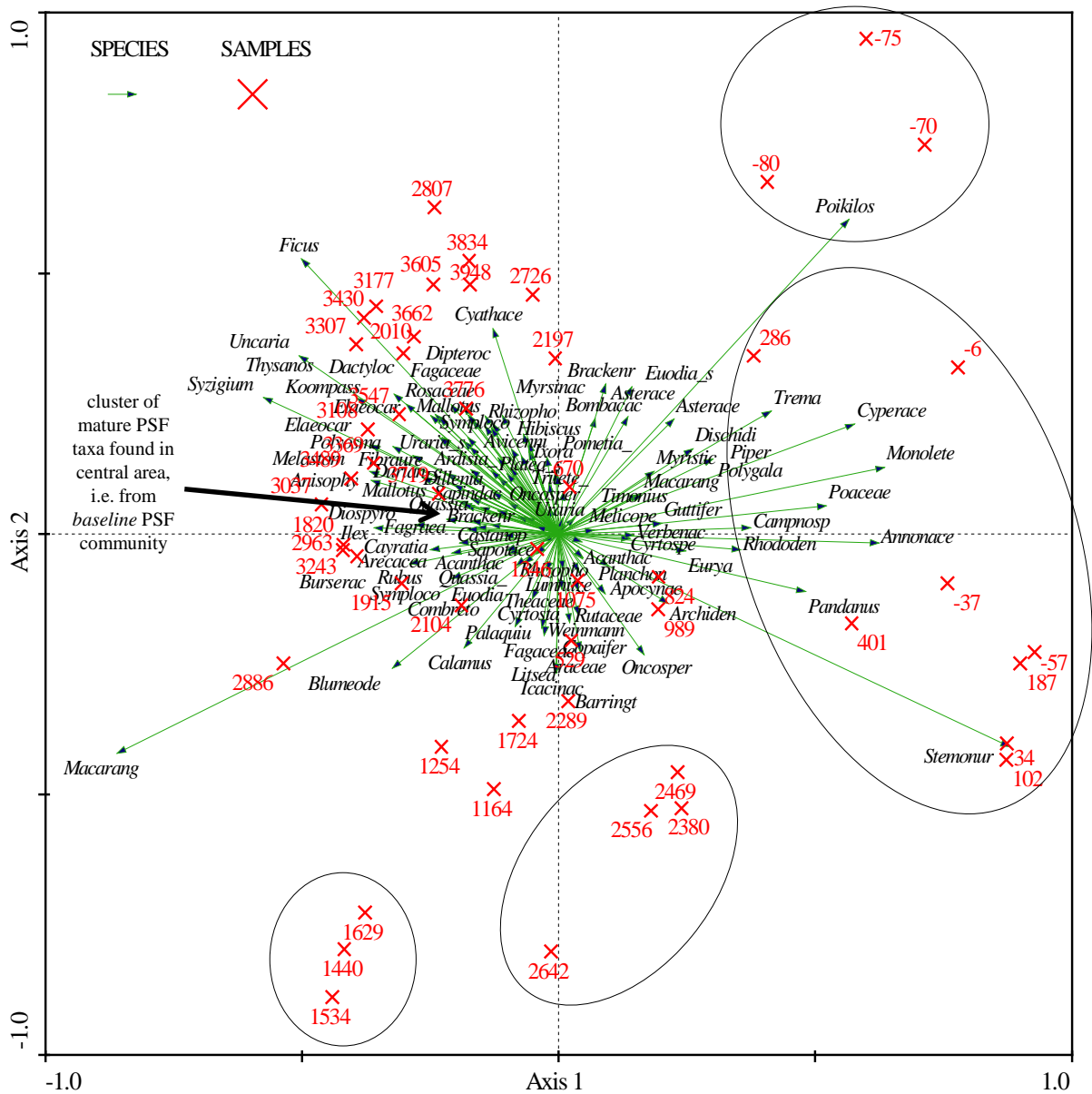


Fig. 2 Summary diagram of the Peat Swamp Fragment, displaying sediment stratigraphy results (see Key for description of colours), pollen percentage data for the five ecological groups (PSF – dark green, PSF+ – light-green, DP – brown, OF – orange, CV – yellow), open vegetation (light grey), PSF+:%:PSF% ratio (blue), macrocharcoal and microcharcoal concentrations (red), palynological richness of TotPSF (line with confidence intervals), pollen accumulation rate (purple), and major pollen zones. (Partially decomposed organic matter is found in all stratigraphic layers, but most common within *Dark peat* and least within the *Clay* layer.) The broad location of major disturbance and recovery events referred to in Fig. 3 are marked with a star.

(a)



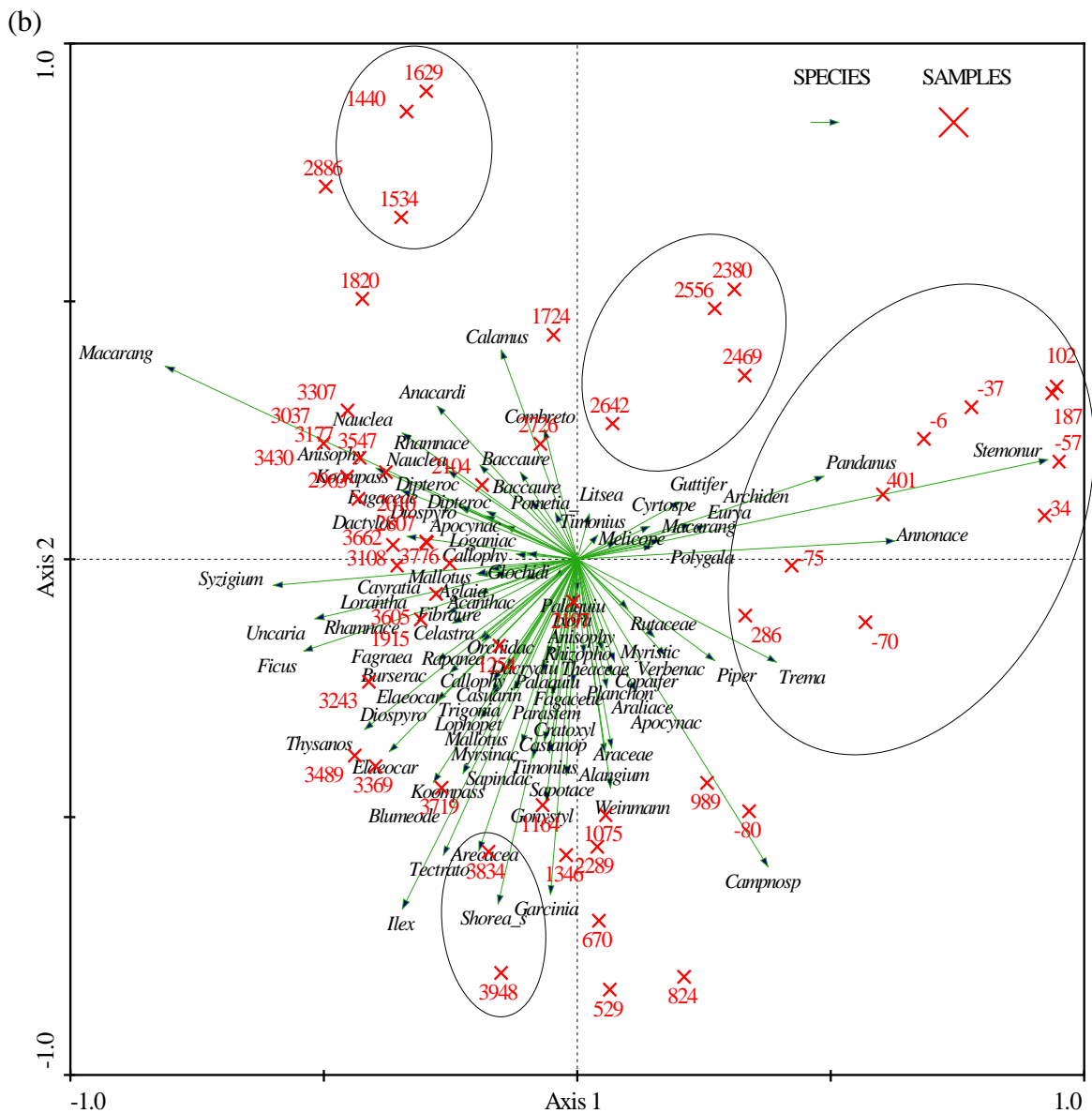


Fig. 3 PCA results of (a) *all* taxa and (b) *TotPSF* taxa counted in the core taken from Peat Swamp Fragment site. In (a) the 1st axis of the ordination explains 31.2% of the variance in the distribution of taxa across temporal samples and the 2nd axis, 10.3%; in (b), 35% and 11.2% of the variance is attributed to the 1st and 2nd axes respectively. Circles illustrate major clusters of samples through time, in some cases corresponding with pollen zones. (Where necessary, in order to reduce overlap and make key taxa more visible, plant names have been removed from their original computed location and a summary label added. Genus names are used, where such distinction was possible during the identification process, and all names restricted to the first eight characters. See Table S2 in Appendix S3, for full names of taxa.)

Peat swamp forest ecological change & resilience

The variable chosen in this study for investigating potential changes in resilience over the last 4000 years, the rate of TotPSF% recovery post-disturbance, has slowed significantly between 4000 - 300 Cal. yr BP when intensified human impact started, both with time to present

(Spearman's $\rho = 0.895$, $p = 0.000$ (two-tailed), $n = 12$) and with number of disturbance events (Spearman's $\rho = 0.895$, $p < 0.001$ (two-tailed), $n = 12$) (Fig. 4). However, post-300 Cal. yr BP, after which human disturbance is thought to have intensified, the recovery rates have increased dramatically, albeit coinciding with some of the lowest levels of palynological richness seen through the core. From 400 Cal. yr BP, Open Vegetation, the key indicator of human disturbance in the peat swamp forest, reached levels over twice as large as those seen throughout the past (with the exception of the somewhat anomalous peak at *c.* 2100 Cal. yr BP) (Fig. 3). During this period, the PSF+%:PSF% ratio reaches its lowest level, indicating greatly elevated numbers of mature PSF pollen taxa in the sum relative to pioneer taxa (Fig. 3).

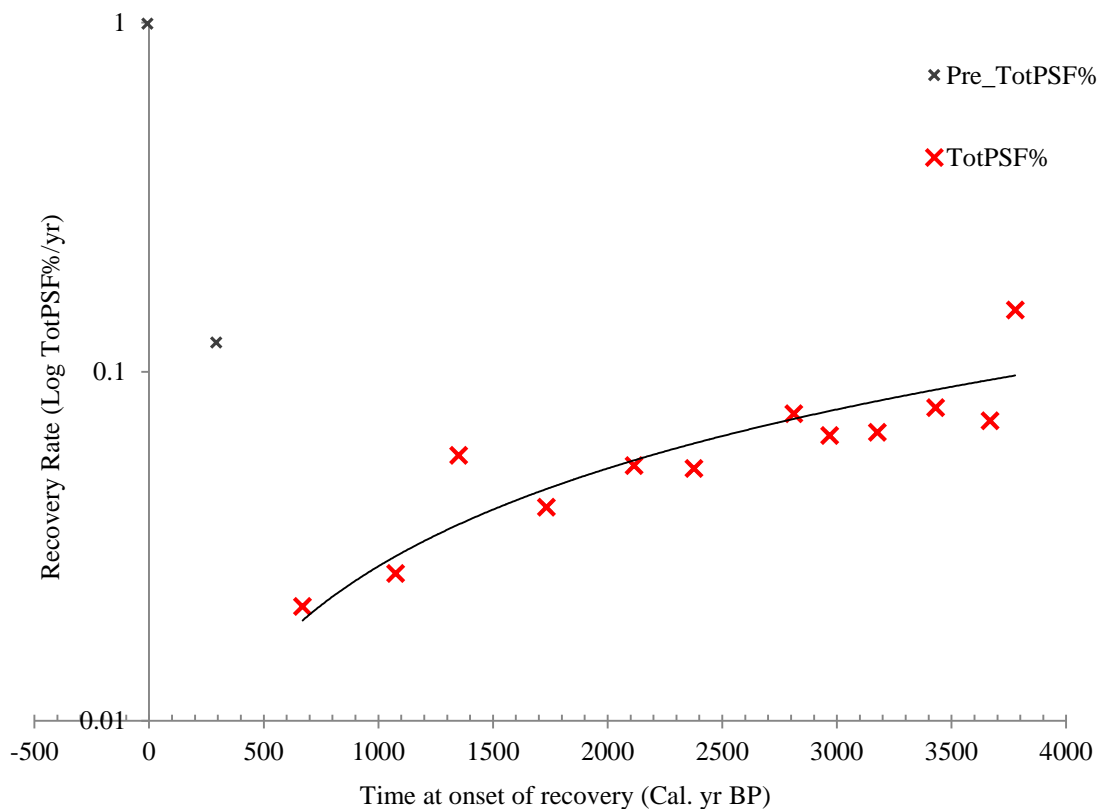


Fig. 4 A log-normal plot showing the relationship between the recovery rate of the total PSF, after incidences of decline, and time, measured in percentage change in TotPSF% per year. The line of best fit is included for illustration. Spearman's Rank Correlation Coefficient values show there is a significant positive relationship between recovery rates of the PSF community and time (Spearman's $\rho = 0.895$, $p = 0.000$ (two-tailed), $n = 12$) and significant negative relationship with number of disturbance events (Spearman's $\rho = -0.895$, $p = 0.000$ (2-tailed), $n = 12$), prior to *c.* 300 Cal. yr BP, after which the relationship changes with the onset of more intense anthropogenic disturbance and a fundamental change in the behaviour of the system (data points labelled *Pre_TotPSF%*).

DISCUSSION

The coastal peat swamp forest in Sarawak, Malaysia, investigated in this study, shows different ecological responses to different drivers of disturbance through time.

Peat swamp forest baseline vegetation

This peat swamp forest ecosystem has been a relatively stable component of the landscape since the onset of peat accumulation, with fluctuations between mature and pioneer taxa indicating an internal dynamism, predominantly in response to local fire and other disturbances, as described in more detail below. Evidence suggests that the majority of the coastal peat swamp forests of Borneo developed after 5000 years ago, as a result of sea-level fall and coastline progradation post-mid-Holocene highstand (Dommain *et al.*, 2011). Once accumulation started, there is little recorded evidence of disturbance in the region's coastal peat development, except for that caused by a reduction in climatic humidity linked to intensified Late Holocene El Niño Southern Oscillation (henceforth ENSO) variability (Dommain *et al.*, 2011). The data from this core demonstrates stability in peat accumulation, which necessarily corresponds with a stable peat swamp forest baseline (Dommain *et al.*, 2010). One exception to this stability is shown in an increase in the rate of accumulation towards the present day, which might reflect post-retrieval disturbance of the peat core rather than the true accumulation rate. The presence of components from the other ecological groups, notably degraded peat taxa, is likely to represent periods where the peat swamp forest canopy was more open *locally* rather than illustrating changes in the landscape composition beyond the boundaries of the peat swamp, since in these closed-canopy environments there tends to be an over-representation of pollen grains from vegetation growing *in situ* (Maloney, 1985).

Major disturbance events & peat swamp forest vegetation response

There have been various major disturbance events over the last *c.* 3800 years, identified through the measurement of various proxies (Table 2) and comparison with the baseline ecosystem state mentioned above. The development of the baseline forest ecosystem coincides with the onset of peat accumulation at approximately 3800 Cal. yr BP. A rising dominance of pioneer taxa and a large increase in the pollen accumulation rate supports the rapid growth of peat swamp forest in this locality. There is likely to have been peat swamp forest within the broader landscape given the relative proportion of mature PSF taxa in the pollen count prior to this. However, the presence of clay at the base of the core does not support the *local* existence of swamp vegetation. As mentioned previously, several studies (for example Taylor *et al.*, 2001; Burn *et al.*, 2010) emphasize that when interpreting pollen diagrams of densely forested ecosystems, as are abundant in the Tropics, it is important to consider the nature of the ecosystem in which the pollen has been deposited, since a closed canopy will restrict the influx of regional pollen and bias the relative pollen composition towards very local producers. The presence of mature PSF taxa at the base of this core may illustrate such an interpretational challenge: a relatively open canopy, prior to the development of peat swamp forest at this site, may have enabled vegetation influx from extra-local habitats where peat swamp forest was already established. As the canopy becomes closed at the Peat Swamp Fragment site, the pollen rain then represents a much more localised signal. Similarly, microcharcoal levels fall sharply, suggestive of either a significant reduction in regional fire, or of a closing canopy reducing the potential of regional proxies reaching the site of deposition. Reduced regional biomass burning may be an indirect consequence of wetter climatic conditions ensuing during a period where ENSO intensity was lower (Woodroffe *et al.*, 2003). The development of peat swamp forest at this point in time represents an active response to environmental change, with vegetation adapted to the altered physical conditions establishing in these coastal areas.

The first major disturbance to this vegetation occurred between approximately 2800 - 2200 Cal. yr BP. Increased local fire prevalence during this period, as indicated by elevated macrocharcoal levels in particular, may have hindered regeneration within the peat swamp forest for a period of approximately 300 years prior to 2400 Cal. yr BP, when macrocharcoal levels again decline. The increase in mature relative to pioneer PSF taxa and the low pollen accumulation rate between approximately 2800 Cal. yr BP and 2400 Cal. yr BP supports the hypothesis that there was limited regeneration during this period. Another suggestion is that climatic change, specifically an increase in the intensity and frequency of ENSO events (Gagan *et al.*, 2004; Woodroffe *et al.*, 2003), which are strongly linked to regional climatic drying (Clement *et al.*, 1999; van der Kaars *et al.*, 2010), may have been responsible for such a disturbance. However, there does not appear to be a clear link between such climatic change and elevated fire in peat swamp forest ecosystems (Cole *et al.*, *in prep*, see Chapter 4). Whatever the indirect driver of this apparent fire-induced disturbance, it is evident that the community composition of the peat swamp forest changed, with a lower composition of pioneer relative to mature forest taxa suggestive of limited regeneration within the peat swamp community. At the end of this period, a peak in open vegetation and microcharcoal may suggest a greater opening of the peat swamp forest canopy, allowing a higher influx of particles from the wider landscape, and elevated fire within it, encouraging more Poaceae and fern-dominated communities. Shortly afterwards, from *c.* 2300 Cal. yr BP, when fire prevalence reduces, pioneer PSF taxa again increase and there is a peak in the pollen accumulation rate, suggestive of the re-establishment of forest regeneration.

At approximately 1700 Cal. yr BP, a significant increase in pioneer taxa suggests another disruption to the peat swamp forest baseline community. There are two potential reasons for this change. Firstly, this marks the end of a period of relatively intense fire, both locally and regionally, and thus major regeneration may have occurred as a response to reduced disturbance, as documented in contemporary studies (for example Chave *et al.* (2008) in Amazonian rainforests; Muller-Landau (2009) in African tropical forests). The

second potential driver of the observed vegetation change is the intensification of ENSO events, reported from *c.* 1700 Cal. yr BP by Woodroffe *et al.* (2003) from climate-proxy data derived from coral microatolls on Christmas Island, less than 2000 km south of Borneo in the equatorial Pacific. A coincident increase in magnetic susceptibility readings may reflect a decrease in peat moisture levels, in support of this hypothesis. Although there is no discernible impact on the vegetation, a peak in magnetic susceptibility readings at *c.* 1200 Cal. yr BP, may indicate further ENSO-related rapid climatic drying (Woodroffe *et al.*, 2003). This suggests some inherent resilience within the peat swamp forest to these natural climatic events.

After the preceding disturbance episode until approximately 500 Cal. yr BP, the baseline vegetation community does not return, with the relative contribution of mature PSF taxa higher and pollen accumulation at lower rates to those measured previously, suggesting reduced peat swamp forest regeneration. However, the palynological richness of the peat swamp forest is marginally greater than that seen during the baseline vegetation period, possibly reflecting a slight increase in disturbance and a manifestation of the Intermediate Disturbance Hypothesis (Connell, 1979; Wilkinson, 1999), wherein at moderate levels of ecosystem perturbation, species diversity reaches maximum levels. Given the close similarity to the palynological richness of the baseline period, and the principles involved in diversity-stability relationships and the “insurance hypothesis” (Yachi & Loreau, 1999) (explored in Allison, 2004), the functionality of this recent ecosystem is likely to be comparable. Since the measured disturbance proxies, notably fire, especially of regional origin, and open vegetation are at insignificant levels, climatic drying resulting from amplified ENSO (Woodroffe *et al.*, 2003) may be implicated in this ecosystem disturbance. By contrast, disturbance proxies become significantly more obvious during the final recorded period of disturbance, from *c.* 300 Cal. yr BP, and are thought to reflect the onset of anthropogenic disturbance in these coastal peat swamp forests. An increase in levels of macrocharcoal, indicating local burning, is the key indicator of human presence here, as

shown in other studies (for example Bush *et al.*, 2007; Bhagwat *et al.*, 2012). In conjunction with charcoal, raised levels of disturbance taxa are observed, notably the shrubby plants of Ulmaceae, i.e. *Trema*, which is associated with the creation of gaps within peat swamp forests larger than those resulting from local disturbances (Flenley & Butler, 2001), and *Pandanus* (Pandanaeae), which is linked to the onset of peat swamp forest development in some areas (Hope *et al.*, 2005). Open vegetation taxa, especially spores from monolet ferns, which are common on unmanaged degraded tropical peatlands (Miettinen & Liew, 2010; Hoscilo *et al.*, 2011), and a relatively sharp reduction in palynological richness are also suggestive of human landscape modification at this time (Fig. 4). Flenley & Butler (2001) found a similar reduction, albeit slight, in diversity with increased disturbance in a core taken from Rawang Sikijang in the Rift Valley of Sumatra. Low ratios of pioneer to mature PSF taxa, along with reduced palynological richness, reflect reduced regeneration during this most recent phase of disturbance. This is likely to result from anthropogenic land-use change, thought to have started approximately 200 years ago in these coastal peat swamp forests (Sawal, 2003; Cole *et al.*, *in prep*, see Chapter 7), predominantly for the purposes of subsistence agriculture (Cramb, 2009).

Peat swamp forest ecological change & resilience

Results from this study demonstrate a general decline in recovery rates of the peat swamp forest community with increasing disturbance events through time. This slowing of recovery is indicative of an ecosystem approaching a loss of resilience (Veraart *et al.*, 2012), with each cumulative perturbation event further reducing the ability of the vegetation to respond dynamically. The *intensity* of disturbance is thought to be a key factor in determining the resilience of ecosystems to perturbation (Turner, 2010). In this study, intensity is defined according to two components: magnitude and frequency. We present an ecological model of peat swamp forest responses to different intensities of disturbance to illustrate this (Fig. 5). When a disturbance regime, i.e. the sum of all disturbances affecting an ecosystem (White &

Jentsch, 2001), reaches an intensity such that it exceeds the relative regeneration rate of the ecosystem, preventing sufficient recovery between perturbation events, there will be a loss of resilience in the system. Intensity manifests over both space and time. Spatially, the geographical extent and degree of perturbation to the system translates into the magnitude of disturbance; temporally, the length of time between events represents the frequency. As the analysis of recovery rates demonstrates, this peat swamp forest ecosystem recovers more slowly with increasing numbers of disturbance events, suggesting a reduced capacity to respond to the perturbations. (The impact of the temporal *rate* of disturbance on the speed of recovery has not been investigated here due to the limitation in the analysis of a small sample size.) This slowing may result from increasingly truncated regeneration with each event, or accumulating physical disturbance to the tight peat-water-vegetation system vital for peat accumulation (Dommain *et al.*, 2010). Haberle *et al.* (2001) observed that with increasing disturbance in various wetland sites across Malesia, pollen from grasses and disturbance-tolerant taxa gradually increase and forest pollen decrease, thus suggesting a reduction in resilience. Similarly, Nishimura *et al.* (2007) report limited species turnover from a peat swamp forest system in Central Kalimantan affected by severe drought during the ENSO event of 1997, but suggest that increased frequencies of such drought will elevate the drought-induced mortality of canopy trees, changing the species diversity and encouraging more degraded peat species to colonise.

However, within the last 300 years in this site, the pattern of slowing recovery appears to have altered, and recovery rates have increased dramatically. To interpret this counter-intuitive result it is necessary to examine both the different aspects of the disturbance events during this period (Miller *et al.*, 2012) and the composition of plant species in the recovering forest, particularly novel species or associations which have the potential to alter ecosystem dynamics (Hobbs *et al.*, 2009).

Results here, in conjunction with studies performed in other tropical coastal peat swamp forest ecosystems, indicate that broadly, two types of disturbances can be identified in

this ecological profile through time (Fig. 5), which are characterised by both frequency and magnitude components. These comprise small disturbances, which are defined as those of a low intensity, i.e. with a sufficiently low magnitude and frequency such that the peat swamp forest vegetation can recover in between perturbations; and high intensity disturbances, that occur too frequently or with too high a magnitude to allow for peat swamp forest regeneration between each event, reducing the capacity of the ecosystem to respond and thus its resilience. From the disturbance events proposed in this study, and vegetation responses reported here and elsewhere (for example Nishimura *et al.*, 2007; Saharjo and Nurhayati, 2006), results suggest that a key factor determining the threshold of resilience in this ecosystem, i.e. the level of perturbation beyond which regeneration does not occur, is the impact that disturbance has on the upper-most peat layer. Small disturbances, such as the creation of wind-throw gaps (Anderson, 1964) or short-term drought or fire, do not disrupt this hummock-hollow architecture, but stimulate a nuanced response within the peat swamp forest community (Fig. 5). After both tree-fall and local drought, the gap created by the death of the large canopy trees generates an opportunity for the understory vegetation community, comprising a cohort of pioneer taxa and seedlings and saplings of primary and secondary peat swamp forest species, to regenerate. After intense droughts, such as those associated with ENSO years and proposed as a potential driver of disturbance in Peat Swamp Fragment at c.1700 Cal. yr BP, canopy trees, growing on the less nutrient-poor hummocks, tend to die off due to lack of water coupled with an intolerance of excessive drying (Nishimura *et al.*, 2007). This opens up the canopy allowing light to reach the peat floor and trigger the regeneration of the predominantly pioneer species. Over time, the secondary, and then primary peat swamp forest plants will re-grow and re-create the forest canopy, as occurred towards 1400 Cal. yr BP in Peat Swamp Fragment.

Fire events provoke a different response as a result of their differing impact of disturbance. Saharjo and Nurhayati (2007) report that fires within peat swamp forest generally destroy the understory but leave the canopy relatively intact, as appears to have

been the case in the Peat Swamp Fragment described here between *c.*2800 – 2400 Cal. yr BP. Regeneration then re-started once the seed sources had re-established in the disrupted uppermost peat layer. As observed in this study, small-scale disturbances are considered important for maintaining high-diversity tropical ecosystems, through providing an opportunity for different species to colonize and adaptations to develop appropriate for the post-disturbance conditions (Connell, 1978; Haberle *et al.*, 2001; Flenley & Butler, 2001). According to the typology proposed here (Fig. 5), results from this study and elsewhere (Cole *et al.*, *in prep*, see Chapters 4 and 6) also suggest that climatic perturbation acts as a small disturbance. As mentioned, work by Nishimura *et al.* (2007) has shown resilience in a peat swamp forest to one such drought event, but authors suggest that recurrent excessive drying of the peat, associated with ENSO (Takahashi *et al.*, 2002; Dommain *et al.*, 2011), will disrupt its regeneration. Intensified local burning, often associated with agriculture (Wooster *et al.*, 2012), or a combination of fire and drought, is likely to have the same impact. Opportunistic species of the degraded peat communities will colonise, as well as ferns and Cyperaceae (Flenley & Butler, 2001), common to unmanaged degraded peatlands (Miettinen & Liew, 2010), and in some cases, Poaceae, especially under conditions of recurrent fire (Fig. 5).

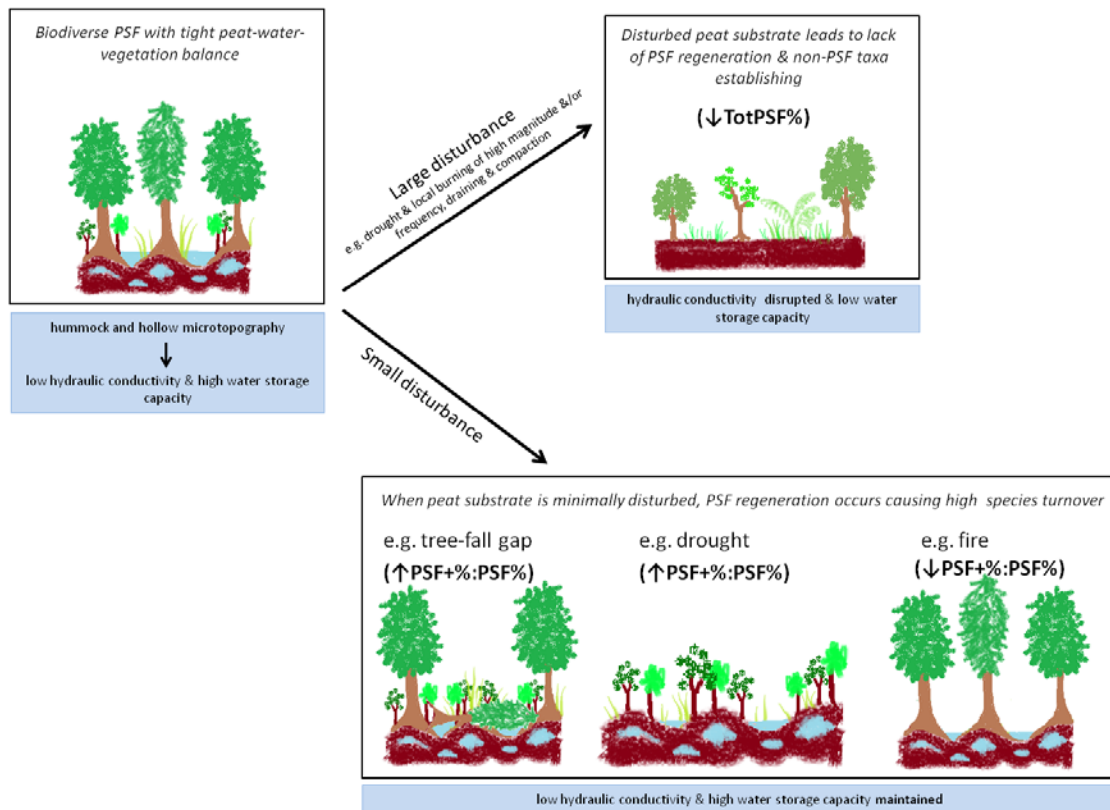


Fig. 5 Cartoon illustrating the impact of different magnitudes of disturbance on peat swamp forest ecology. The impact of disturbance on the ratio of PSF+%;PSF% in the subsequent period is shown in brackets for comparison with the results in Fig. 2.

Implications for management

Results from this study suggest that peat swamp forest has shown resilience in the face of a range of disturbances in the past, mostly of natural origin and of relatively low intensity, in comparison to factors causing large change in these ecosystems within the last several hundred years. The situation emerging in this peat swamp forest is by no means unique for forested ecosystems: a study of forests in north-east Queensland, Australia, showed how dynamically the ecosystem responded to climatic change, fire-related disturbance and activities of native peoples (i.e. Aborigines), but how, post-European settlement, disturbance has intensified and there is no evidence yet that the forest will be resilient to such heightened impacts (Haberle *et al.*, 2006). One key finding of this study, is the distinction between different types of disturbance, as illustrated by the threshold of ecological response and regeneration within the peat swamp forest. Palaeoecological data from this study provides important insights into the baseline vegetation and long-term ecological functioning of this

now rapidly changing and unique coastal ecosystem, highlighting both its resilience to natural disturbance, and likely gradual loss of such to anthropogenic land-use change.

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Tables, Figures Legends & Figures

(These have been left in the body of the text to ease the reading of the manuscript.)

Appendix

Appendix S1 **Table S1** AMS radiocarbon dates for Peat Swamp Fragment core.

Appendix S2 **Fig. S1** Age-depth profile.

Appendix S3 **Table S2** Ecological groups, with key plant taxa.

Appendix S4 **Fig. S2** Summary pollen diagram of Peat Swamp Fragment site.

Appendix S1

Table S1 Accelerator mass spectrometry (AMS) ^{14}C ages along with calibrated ages for radiocarbon dated samples from Peat Swamp Fragment core, calculated using Calib 601. (An age of 50 Cal. yr BP was given to the PSF sample taken at 30 cm depth, to approximate a *modern* date.)

Lab Code	Core	Depth (cm)	^{14}C yr BP	$\delta^{13}\text{C}$ (‰)	Calibrated ages (cal yr BP)	Dated material
SUERC-35240	PSF	30	modern	-29.9	50	peat
UBA-15749	PSF	100	841 +/- 25	-32.4	741.5 ± 48.5	peat
SUERC-35241	PSF	155	2275+/-37	-30.2	2209.5 ± 52.5	peat
SUERC-35242	PSF	200	3270+/-35	-30.7	3506 ± 70	peat
UBA-15129	PSF	240	3242 ±22	-31.6	3441 ± 46	peat

Appendix S2

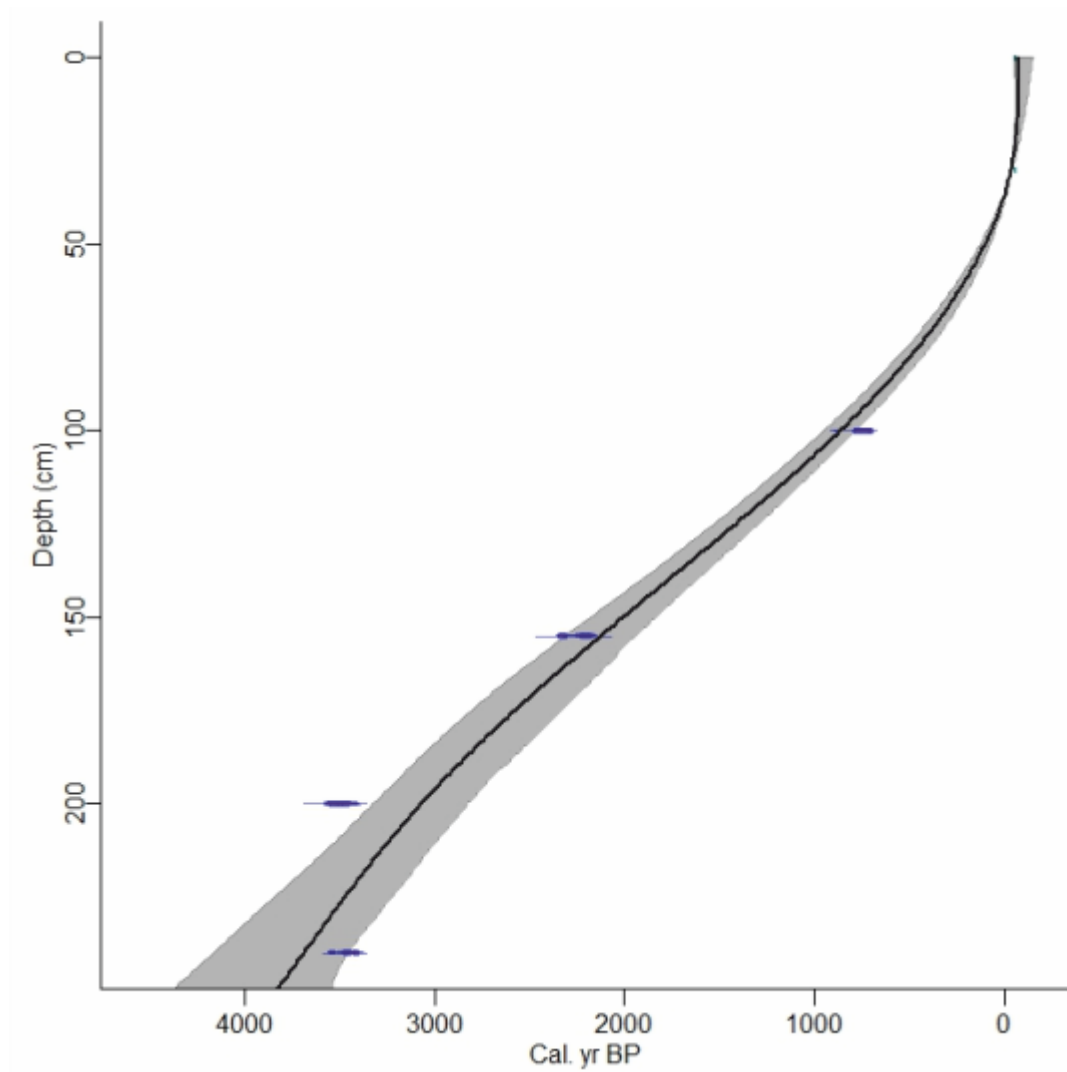


Fig. S1 Age-depth profile of Peat Swamp Fragment core. Smoothing spline proved the best-fitting model, with extrapolated basal points and surface (0 cm) age set at -55years.

Appendix S3

Table S2 Ecological groupings of plant types identified through fossil pollen analysis, comprising key families and specific taxa for past vegetation reconstruction (i.e. those that constituted >0.05% of the total pollen sum in any one sample in any core). The system of notation developed by Benninghoff and Kapp (1962) has been used to reflect the level of certainty in fossil pollen identifications made: ‘comp’ indicates a grain that is almost certainly the same as the reference taxon; ‘sim’, one that is more similar to the reference taxon than any other known reference taxa, but there is less certainty in the association; and ‘type’, a grain corresponds with one morphology within a polymorphic taxonomic unit. (For a complete list of fossil pollen grains and spores counted, see Table S1, Appendix 1 in Chapter 6, page 208.)

Plant family	Pollen taxon
PEAT SWAMP FOREST (PSF)	
Araceae	
Arecaceae	<i>Calamus</i>
Anacardiaceae	<i>Camptosperma</i> sim
Anisophyllaceae/Rhizophoraceae	<i>Combretocarpus</i>
Aquifoliaceae	<i>Ilex</i>
Casuarinaceae	<i>Casuarina</i>
Crypteroniaceae	<i>Dactylocladus</i>
Dipterocarpaceae	<i>Shorea</i> sim
	Dipterocarpaceae type
	Dipterocarpaceae Fagaceae type
	Dipterocarpaceae Menispermaceae type
Euphorbiaceae	<i>Blumeodendron</i>
	Euphorbiaceae type
Fabaceae	<i>Koompassia</i>
	<i>Koompassia</i> sim
Fagaceae	<i>Castanopsis</i>
Guttiferae	<i>Garcinia</i>
	Guttiferae Cratoxylon Theaceae type
Icacinaceae	<i>Stemonurus</i>
Meliaceae	<i>Aglaia</i> sim
Pandanaceae	<i>Pandanus</i>
Rhizophoraceae	Rhizophoraceae type
Rubiaceae	<i>Nauclea</i>
	<i>Thysanospermum</i>
	<i>Uncaria</i>
Sapotaceae	<i>Palaquium</i> comp
Theaceae	<i>Eurya</i>
PEAT SWAMP FOREST – pioneers (PSF+)	
Elaeocarpaceae	<i>Elaeocarpus</i>
	<i>Elaeocarpus</i> sim
Euphorbiaceae	<i>Baccaurea</i>
	<i>Macaranga</i>
	<i>Macaranga</i> sim
	<i>Mallotus</i>
Menispermaceae	<i>Fibraurea</i>
Moraceae	<i>Ficus</i>
Myrtaceae	<i>Syzygium</i>
Piperaceae	<i>Piper</i>
Sapindaceae	<i>Pometia</i> comp
Ulmaceae	<i>Trema</i>

DEGRADED PEAT (DP)	
Asteraceae	Asteraceae type
Celastraceae	<i>Bhesa</i> sim
Dilleniaceae	<i>Dillenia</i>
Melastomataceae	<i>Melastoma</i>
Urticaceae	<i>Poikilospermum</i>
OTHER FOREST (OF)	
(no types exceeded minimum presence values)	
COASTAL VEGETATION (CV)	
Areaceae	<i>Cyrtostachys</i>
	<i>Oncosperma</i>
	<i>Oncosperma</i> sim
Ochnaceae	<i>Brackenridgea</i> sim
Rhizophoraceae	<i>Ceriops</i> sim
	<i>Rhizophora</i>
Sonneratiaceae	<i>Sonneratia</i>
OPEN VEGETATION (not included in pollen sum)	
Poaceae	
Cyperaceae	
Monolete	
Lycopodiaceae	<i>Lycopodium cernuum</i>
	<i>Lycopodium phlegmaria</i>
Lygodiaceae	
Cyathaceae	
Trilete	

Appendix S4

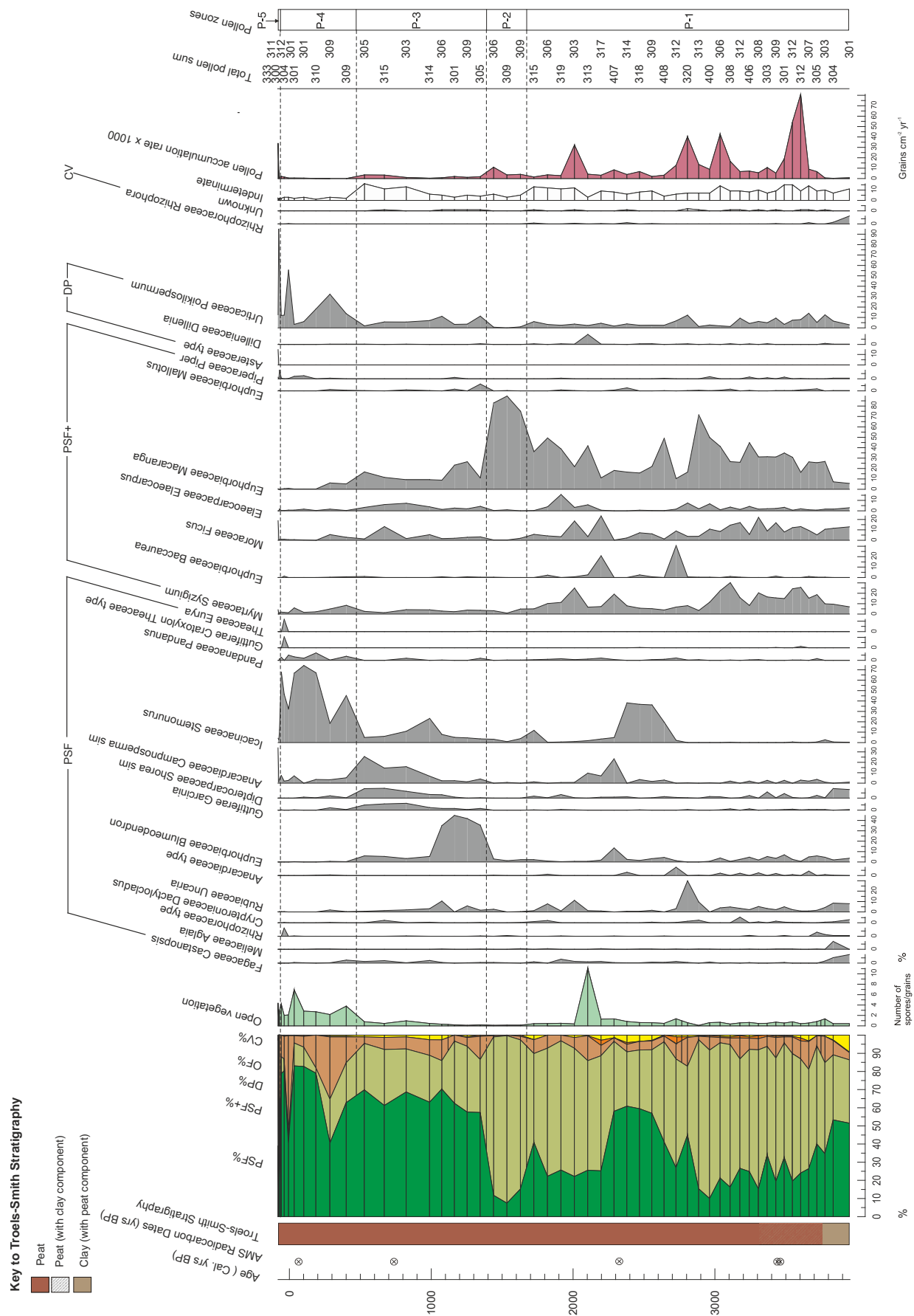


Fig. S2 Summary pollen diagram of Peat Swamp Fragment. Only pollen taxa that contribute > 0.05% to the pollen sum, at any one level, are included.



Paper 3: SENSITIVITY OF TROPICAL PEAT SWAMP FORESTS TO HOLOCENE ENSO

ACTIVITY AND ANTHROPOGENIC IMPACT

Cole, L.E.S.¹, S.A. Bhagwat.² and Willis, K.J.³

¹Oxford Long-term Ecology Laboratory, Department of Zoology, University of Oxford,
Oxford, United Kingdom

²School of Geography and the Environment, University of Oxford, Oxford, United Kingdom

³Biodiversity Institute, Oxford Martin School, Department of Zoology, University of Oxford,
Oxford, United Kingdom

Corresponding author: Lydia Cole, tel: 01865 281321, fax: 01865 271249,

lydia.cole@zoo.ox.ac.uk

Key words peat swamp forest, long-term ecology, ENSO, vegetation change, fire

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ABSTRACT

The forested peat swamps of Southeast Asia contain over 10% of the World's peatland carbon pool. During recent climatically-dry periods, these peat swamps have become more vulnerable to fire and vast areas have burnt uncontrollably, releasing large amounts of the stored carbon. Such regional drying is often caused by intensified El Niño effects, manifesting in the phenomenon known as the El Niño Southern Oscillation (ENSO), which has been amplifying over the late Holocene. Whether ENSO has impacted on the extensive coastal peat swamp forests of northern Borneo over the last 5000 years is largely unknown. This study investigates the presence of a climatic signal in a coastal peat swamp forest in Sarawak, Malaysian Borneo. Changes in fossil pollen and charcoal are assessed in relation to periods of intense ENSO activity. Results suggest that ENSO has played a role in the internal regeneration dynamics of these forests, though likely mediated via drought and not fire disturbance.

INTRODUCTION

The current warming of the climate, and coupled intensification of extreme weather events, is becoming an increasing concern for many nations, predominantly due to its potential impact on ecosystems and thus, on people. One such climatic phenomenon that has been intensifying over the last 5000 years (Haberle, 1996; Gagan *et al.*, 2004), unrelated to anthropogenic forcing, is the El Niño Southern Oscillation, henceforth ENSO. El Niño events form the dominant driver of climatic change in the Tropics (Clement *et al.*, 1999), causing precipitation and temperature extremes (Neukom and Gergis, 2012) for between nine months and two years (NOAA, 2012). They occur with a periodicity of approximately two to seven years (Clement *et al.*, 1999), averaging four years between events (Woodroffe *et al.*, 2003), though this latter figure varies between studies. ENSO describes the phenomenon where the El Niño climatic fluctuation interacts with the Southern Oscillation pattern of

atmospheric pressure and temperature over the Pacific Ocean, causing extreme weather events on both its eastern and western margins. During these events, the Earth experiences large redistributions of heat and moisture (Mayewski *et al.*, 2004), with precipitation in Insular Southeast Asia shifting from the land to the ocean due to an interruption of the air flow of the Inter-Tropical Convergence Zone (ITCZ) (Stott *et al.*, 2002). This shift of the convective system away from the Southeast Asian land masses manifests in a delayed monsoon and early onset of the dry season, which, given that monsoon winds primarily govern the climate of Southeast Asia (Whitmore, 1984), can have significant effects, predominantly via this extreme regional drying (Clement *et al.*, 1999; van der Kaars *et al.*, 2010). Although ENSO events, in some form, are likely to have existed throughout the Quaternary Period (Stott *et al.*, 2002), their intensity has been increasing over the latter half of the Holocene (Moy *et al.*, 2002; Gagan *et al.*, 2004), in part due to the effects of orbital forcing: changes in the precession of the Earth's orbit from the mid-Holocene have altered the seasonal cycle of solar radiation, thus altering the planet's air circulation systems. This resulted in a southward shift in the ITCZ, and associated movement of the Indo-Pacific Warm Pool (IPWP) (a large body of water, with a mean sea surface temperature exceeding 28°C, stretching from the Pacific to the Indian Ocean) and weakening of the Asian summer monsoon (Abram *et al.*, 2009), causing regional to global climatic changes (Clement *et al.*, 2000; Mayewski *et al.*, 2004; Partin *et al.*, 2007). Despite this knowledge, there is much debate about ENSO activity during the Holocene (for example Moy *et al.*, 2002; Woodroffe *et al.*, 2003) and about the impacts its activity has had on ecosystems throughout this time. In the last quarter century however, there is clear evidence of devastating widespread impacts of ENSO events (Siegert *et al.*, 2001; Page *et al.*, 2002; Phua *et al.*, 2007). For example, in 1997-98, coincident with the most recent major El Niño episode, there were widespread fires in forests across Southeast Asia, and Page *et al.* (2002) calculated that approximately 30% of a 2.5 million hectare area in Central Kalimantan burned, over 90% of which was peatland. By extrapolating estimates of the carbon released from such burning, they reported that

between 0.81 – 2.57 Gt carbon emissions were generated in Indonesia in conjunction with this climatic episode (Page *et al.*, 2002), with the upper estimate equating to 40% of the mean annual global carbon emissions. Concurrently in East Kalimantan, supporting Page *et al.*'s extrapolations, over 300,000 ha of peat swamp forest burnt (Siegert *et al.*, 2001), adding to the resultant far-reaching pollution and human-health problems (Aiken, 2004). Although exact sources of ignition often remain unknown, it is highly probable that the prevailing ENSO-related dry conditions made the environment more vulnerable to burning (Hope *et al.*, 2005).

There is significant evidence for a relationship between ENSO events and fire in insular Southeast Asia (van der Kaars *et al.*, 2010), as well as increased fire during periods of rapid climate change (Haberle and Ledru, 2001) and precipitation variability (Gagan *et al.*, 2004). ENSO-related inter-annual changes in the regional moisture supply have initiated droughts across large areas of Southeast Asia (Goldammer & Seibert, 1989), through reducing the levels of soil moisture, which in turn increases the vulnerability of the forests to fire (Haberle *et al.*, 2001). In terms of impacts on vegetation, intense ENSO events, through their association with fire and drought-stress, have the potential to act as a significant source of disruption to tropical forest communities (Haberle *et al.*, 2001; Gagan *et al.*, 2004).

However, such disturbance is thought to be one of the pivotal drivers for the maintenance of diversity in these tropical ecosystems (Connell, 1978) (though see Bongers *et al.*, 2009, for a critique of the intermediate disturbance hypothesis). Through the creation of forest gaps during drier or fire-prevalent periods, opportunities arise for the regeneration of forest taxa spanning successional groups, and diversification via the evolution of new adaptations in these communities (Haberle & Ledru, 2001). During the periods of high climatic variability and high charcoal occurrence associated with ENSO events, Haberle *et al.* (2001) reported an increase in the rate of vegetation change and community turnover, i.e. change in species diversity, potentially causing positive feedback in the system and encouraging the

development of fire-susceptible forest ecosystems. Whether these changes, linked to the intensification of ENSO events, are also apparent in Southeast Asia's peat swamp forest ecosystems is unknown.

These unique forests, predominantly fringing the coasts of Indonesia and Malaysia, though also found across Southeast Asia (APFI, 2011), are of global importance. They are repositories of approximately 20% of the World's terrestrial carbon (Gopal, 2012), and habitats for a wide diversity of flora and fauna (Ewel, 2010; Yule, 2010), including many threatened species (Phillips, 1998; Posa *et al.*, 2011). The development of coastal peat swamp forests started with the onset of sea level fall, after the post-Glacial highstand approximately 5000 years ago (Dommain *et al.*, 2011). The exposure of the previously submerged coastal zones, coupled with continued sedimentation, provided waterlogged conditions in which vegetation could grow and the resulting partially-decomposed organic matter accumulate (Dommain *et al.*, 2011). Permanent high peat soil water content is thus vital for the maintenance of peat swamps (Dommain *et al.*, 2010), and for their continued carbon sequestration potential. In addition to their ecological value, they provide a variety of products and services for local communities, from building materials and fish, to the prevention of saline water intrusion and inter-seasonal water stabilisation (Silvius & Giesen, 1996; Phillips, 1998). Over 80% of Malaysia's peat swamp forests, more than 1.2 million ha (Wetlands International, 2010), lie in Sarawak, one of the two East Malaysian States in northern Borneo (Fig. 1). These swamps act as palaeoarchives, providing key information on past responses of the biota to external drivers of disturbance (Dommain *et al.*, 2011), such as ENSO events, and insights into future responses.

However, there are limited studies that investigate the impact of ENSO events on peat swamp forests in particular (see Anshari *et al.* (2001) for a discussion of the stress caused by ENSO climate variability 3000 yrs ago on peat swamp forests in Western Kalimantan), with the

majority of insights coming from forests that differ substantially in their characteristics. For example, Haberle *et al.* (2001) report of a period of high regional charcoal frequency and rapid vegetation changes from the mid to late Holocene (5000 yr BP to present) in cores from high altitude swamps and low altitude lakes across Indonesia and Papua New Guinea, when El Niño-related climate variability intensified; van der Kaars *et al.* (2010) and Haberle & Ledru (2001) similarly found evidence for greater fires during late Holocene dry periods and those of rapid climate change and high climate variability, respectively; and Gagan *et al.* (2004) observed increased ecosystem disturbance from *c.* 5000 years ago when looking at studies across the tropical Pacific.

Peat swamp forests, because of their water-logged nature, may prove less susceptible to ENSO-related increases in fire incidence, and more to the effects of atmospheric drying and the desiccation of organic matter that may result from that (Goldammer & Seibert, 1989). In Borneo at present, intensified ENSO events are reported to have a significant control on the magnitude of fire activity, with the fire itself resulting predominantly from sources of human ignition linked to land-use change and agriculture (Wooster *et al.*, 2012), and indeed opportunistic burning during ENSO-induced dry periods (Anshari *et al.*, 2001). However, this relationship is yet to be tested and the relative roles of ENSO and human impact in driving fire dynamics, determined.

This study thus aims to identify how sensitive the coastal peat swamp forests of northern Borneo have been to intensified ENSO events over the latter half of the Holocene. It also aims to decipher the relative timing and intensity of disturbance caused by human activity in this ecosystem, and whether elevated local and regional fire can be attributed to climatic or anthropogenic impacts, or a combination of the two. In particular, we address the following three hypotheses: (i) that increased ENSO activity is linked to increased fire and thus burning within the peat swamp forest, due to ENSO-induced drought; (ii) that increased disturbance,

linked to ENSO activity, results in greater community turnover and vegetation change in the peat swamp forest; and (iii) that human disturbance in the peat swamp forest, via burning regimes, is amplifying fire incidence caused by intensified ENSO events in the recent past, disrupting the baseline vegetation and ecological response. In order to address these hypotheses, we adopted a palaeoecological approach: fossil pollen and charcoal, in a peat core extracted from Sarawak, northern Borneo, were analysed in conjunction with independent palaeoclimate records. The overall objectives were to determine the impact of ENSO events on this ecosystem, and how recent intensified climatic and human disturbance may be contributing to its degradation, thus providing insights for the mitigation of such effects.

METHODS

Study Site

This study is based on a core taken from an agricultural plot, adjacent to forest fragments and an oil palm plantation, in a peat area of the Batu Niah District of Sarawak. The site, henceforth named Converted Peatland (03°52'4''N, 113°42'43''E), is approximately 10 km from the coast, 1 km from the Niah river, and currently under smallholder agriculture. The region, Northern Borneo, is described as having a tropical ever-wet climate (Morley & Flenley, 1987), with an average temperature of 25°C and average rainfall of greater than 370 cm yr⁻¹, mostly falling during the Southern Hemisphere Summer Monsoon, between November to April (Haberle *et al.*, 2001). A sedimentary core of 318 cm, the depth at which minerogenic content exceeded organic, was extracted using a hand-held coring device.

Data Collection

Prior to extraction of samples for palaeoecological analysis, the lithology of each section of the sediment core was described according to the Troels-Smith classification system (Troels-Smith, 1955), and the magnetic susceptibility recorded. Magnetic susceptibility readings are

a measure of the relative composition of iron oxides in the sediment with depth (Gubbins & Bervera, 2008), and can be used as a proxy for climatic change through reflecting soil-water content (Balsam *et al.*, 2011). In general, smaller and more negative results indicate greater soil-moisture (Grimley *et al.*, 2008) and organic matter content (Hamilton *et al.*, 1986), both materials being diamagnetic (Hunt and Premathilake, 2012). Samples for palaeoecological analysis were prepared according to standard techniques (Bennett and Willis, 2001). Both a reference collection, compiled from various sources, and published plates (Huang, 1972; Anderson & Muller, 1975; Stuijts, 1993) were used to aid the identification of fossil pollen grains contained in the sediment core.

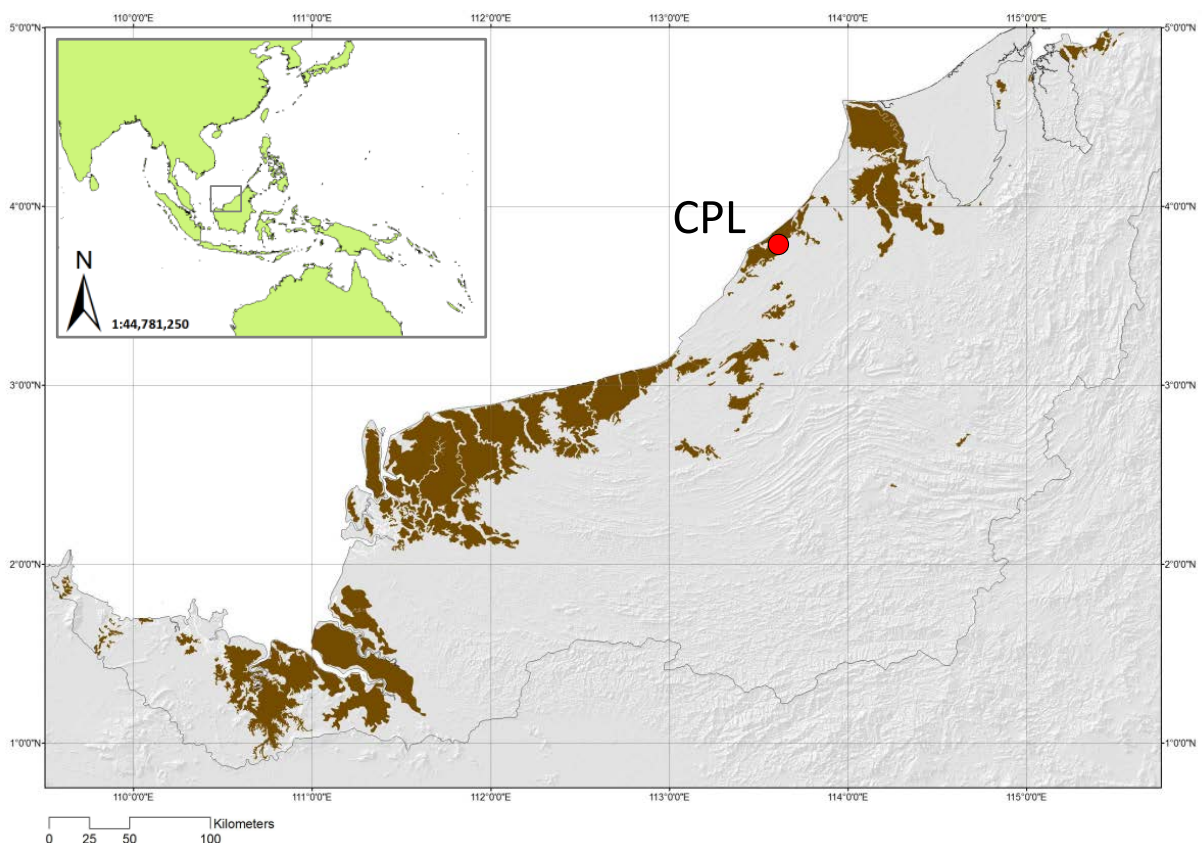


Fig. 1 Map showing the geographical location of Sarawak, Malaysian Borneo (inner box), within Southeast Asia, and the Converted Peatland study site (CPL) within Sarawak's peatlands. (Peatlands shown in brown. Image courtesy of SarVision, 2011.)

Due to the diversity of species in the peat swamp flora and differing levels of pollen production, taxa identified through pollen counting were allocated to ecological groups (Table 1) to aid interpretation of the palaeo-plant communities (for example as performed by Muller, 1963) using various publications from the region (Anderson, 1964; 1980; Stuijts, 1993; Coode *et al.*, 1996; Anshari *et al.*, 2001; 2004). A pollen sum was then calculated and used to estimate the relative abundance of each taxon and each ecological group, giving a percentage score, e.g. PSF%. Open vegetation types, i.e. those that produce unusually large volumes of pollen per plant which can bias the interpretation of the vegetation composition of the landscape, for example Poaceae (Bush, 2002), were excluded from the pollen sum. The relevant groups in this study are the PSF and PSF+ communities, the sum of which equals the total PSF community, i.e. TotPSF%, and open vegetation, which we use as a proxy for human-induced disturbance (Table 1). Macrocharcoal particles in each 1 cm³ sample were counted using a light microscope, and microcharcoal concentration measured according to Clark's point count method (Clark, 1982), at simultaneous intervals as fossil pollen, to broadly reconstruct local and regional fire events (Clark, 1988), respectively. Significant pollen assemblage zones (Z-1 to Z-4, Fig. 3) were constructed using an optimal splitting by information content technique on all pollen data, after assessing the number of zones that were significant via a broken stick modelling approach across different data analyses (Bennett, 1996). *Psimpoll* version 4.26 (developed by Bennett, 1994) was used to display all pollen, spore and charcoal counts and other ecological variables (Fig. 2 & 3).

Table 1 Definition of ecological groups, acronyms used and major plant taxa associated with each.

Ecological Group	Name	Explanation	Major plant taxa
PSF	peat swamp forest	if taxa present in peat swamp forest, assumed to grow in old-growth forest	<i>Combretocarpus</i> (Anisophyllaceae), <i>Shorea</i> (Dipterocarpaceae), <i>Stemonurus</i> (Icacinaeae)
PSF+	peat swamp forest – pioneers	if taxa increase in abundance in pollen diagram, indicates early successional plant community of secondary peat swamp forest	<i>Elaeocarpus</i> (Elaeocarpaceae), <i>Macaranga</i> (Euphorbiaceae), <i>Syzygium</i> (Myrtaceae), <i>Ficus</i> (Moraceae)
DP	degraded peat	taxa found in highly disturbed and open-canopied peat areas, generally where natural hydrology has been disrupted	<i>Dillenia</i> (Dilleniaceae), <i>Melastoma</i> (Melastomataceae), <i>Poikilospermum</i> (Urticaceae)
CV	coastal vegetation	coastal vegetation associated with succession to peat from mangrove/littoral habitat type	<i>Oncosperma</i> (Arecaceae), <i>Quassia</i> (Simaroubiaceae)
OF	other forest	other forest (non-peat swamp forest taxa), e.g. swamp forest or forest on mineral soils	<i>Terminalia</i> (Combretaceae), <i>Rubus</i> (Rosaceae)
OV	open vegetation	disturbance tolerant vegetation indicative of open environments greater than tree-fall gaps, not included in pollen sum	Monoletes, Triletes, Poaceae, Cyperaceae

Chronology

AMS Radiocarbon dating and analysis of five sediment samples, spanning the length of the core, were performed at either the ¹⁴C Chrono Centre in the Archaeology and Palaeoecology Department, at Queen’s University Belfast, or the SUERC AMS Laboratory, at the NERC Radiocarbon Facility. The coding package *Clam* (Blaauw, 2010), in the statistical software, R (R Core Team, 2012), with a Northern Hemisphere correction, i.e. the IntCal04 curve, was used to calibrate the conventional radiocarbon dates (see Table S1, Appendix 1) and construct the best-fitting age-depth model (Fig. 2).

ENSO-related climate variability profile

A literature search was performed in order to construct a profile of climatic change through the Holocene, with a focus on ENSO variability. Periods of major change in ENSO intensity

in Southeast Asia were identified and a simplified profile made from which to compare ecological variables (Fig. 3; Table 2). Several papers provided key information for the construction of the profile (Haberle *et al.*, 2001; Moy *et al.*, 2002; Woodroffe *et al.*, 2003; Gagan *et al.*, 2004; Mayewski *et al.*, 2004; Abram *et al.*, 2007; Partin *et al.*, 2007; Grießinger *et al.*, 2011; Selvaraj *et al.*, 2011). For each time point at which fossil pollen was sampled, an ENSO score was assigned, such that the relationship between ENSO intensity and ecological change could be statistically explored.

Table 2 Major periods of ENSO-related climatic change, the score of relative intensity awarded to each and references used to construct them.

ENSO Time Period (Cal. yr BP)	ENSO-related characteristics of period	Score	References (in order of characteristics)
0 – 100	Intensified ENSO	2	Gagan <i>et al.</i> (2004)
100 – 600	Little Ice Age; declining ENSO frequency	1	Grießinger <i>et al.</i> (2011); Moy <i>et al.</i> (2002)
600 – 1700	Amplification of ENSO	3	Woodroffe <i>et al.</i> (2003)
1700 – 3000	Abrupt increase in ENSO magnitude & Holocene maximum	2	Gagan <i>et al.</i> (2004); Woodroffe <i>et al.</i> (2003)
3000 - 3800	Reduced ENSO intensity	1	Woodroffe <i>et al.</i> (2003)
3800 - 5000	Onset of modern ENSO variability; reductions in Summer East Asia Monsoon; series of periods of tropical aridity; drought in New Guinea	2	Gagan <i>et al.</i> (2004); Selvaraj <i>et al.</i> (2011); Mayewski <i>et al.</i> (2004); Haberle <i>et al.</i> (2001)
5000 - 7000+	Relatively high precipitation in northern Borneo, & a relatively stable climate regionally; Summer Monsoon dominant & ENSO weak	0	Partin <i>et al.</i> (2007); Haberle <i>et al.</i> (2001); Abram <i>et al.</i> (2007); Moy <i>et al.</i> (2002)

Analysis

In order to explore the relationships between periods of intensified ENSO, other recorded environmental variables, i.e. macrocharcoal, microcharcoal, magnetic susceptibility and open vegetation, and (i) internal peat swamp forest dynamics, i.e. PSF vegetation change, and (ii) external landscape dynamics, i.e. community turnover, multivariate statistics were also performed. Principal Components Analysis (henceforth PCA) was performed in CANOCO (ter Braak & Šmilauer, 2002), to graphically illustrate the nature of such associations. Data were square-root transformed, and species scores divided by standard deviations and scaled

according to inter-species correlations. Internal dynamics are represented by relative changes in PSF% and PSF+% changes, and external by changes in the four key ecological groups in the landscape, i.e. TotPSF%, DP%, OF% and CV% (Table 1). To analyse the strength of the correlation between the vegetation and firstly, ENSO periods, and secondly, all environmental variables, Monte Carlo Permutation Tests were done, using 999 restricted permutations by sample to account for the data being composed of a time-series.

In order to look at changes in the diversity of pollen taxa recorded between each sample through time, and the rate at which this diversity changes, the palynological richness (Birks & Line, 1992) and rate of change of the total PSF (TotPSF%), respectively, were calculated.

The palynological richness is calculated in *Psimpoll* by computing the temporal change in rarefied PSF taxonomic richness, measured in $E(T_n)$ units (estimated taxonomic richness in a sample of n individuals (Birks & Line 1992)), using the minimum count for total PSF taxa in the Converted Peatland core after the onset of peat swamp forest development (marked by the transition between Zones 1 and 2), i.e. 83 grains recorded at the sampling point representing 2647 Cal. yr BP, to standardize the data and account for differing sample sizes. The rate of change of the total PSF% (TotPSF%) was calculated in Excel, using the following equation:

$$\text{Rate of change of TotPSF\%} = \frac{\text{TotPSF\%}_{t2} - \text{TotPSF\%}_{t1}}{|T_2 - T_1|}$$

where T_2 represents the younger date. A negative result for the rate of change of the total PSF% (TotPSF%) indicates a period of PSF decline and a positive result growth; a greater value in either direction represents a more rapid speed of change in the extent of the PSF group, and increasing fluctuation suggests instability in the environment (Carpenter & Brock, 2006; Dakos *et al.*, 2012; Veraart *et al.* 2012).

RESULTS

ENSO and peat swamp forest

The age-depth profile illustrates that this core covers a period of over 7000 years, encompassing the latter half of the Holocene, in which ENSO activity intensified. Indeed, there is a visible change in the sedimentation rate at approximately 5000 Cal. yr BP (Fig. 2), coinciding with the onset of modern ENSO variability (Table 2). At this point, the sediment accumulation rate decreases by approximately three fold from the period before 5000 Cal. yr BP. Such a change in accumulation is reflected by the Troels-Smith profile: there is a transition from a lighter, more clay-dominated sediment type to a darker one, containing more peat, but maintaining some finer clay grains throughout. Laminations, suggestive of specific depositional periods and/or flooding events, occur in sections throughout the core (Fig. 2), although they are more frequent in the period prior to 5000 Cal. yr BP., where wetter and warmer climatic conditions were prevalent. Other sections where greater banding of sediment is seen approximately coincide with transition points in ENSO intensity at 5000 Cal. yr BP, 1700 Cal. yr BP and 700 Cal. yr BP. Fragments of woody material and other partially-decomposed organic matter are present throughout the profile. In the last 250 years, the sediment becomes darker and comprises more peat, linked with a slight increase in the accumulation rate.

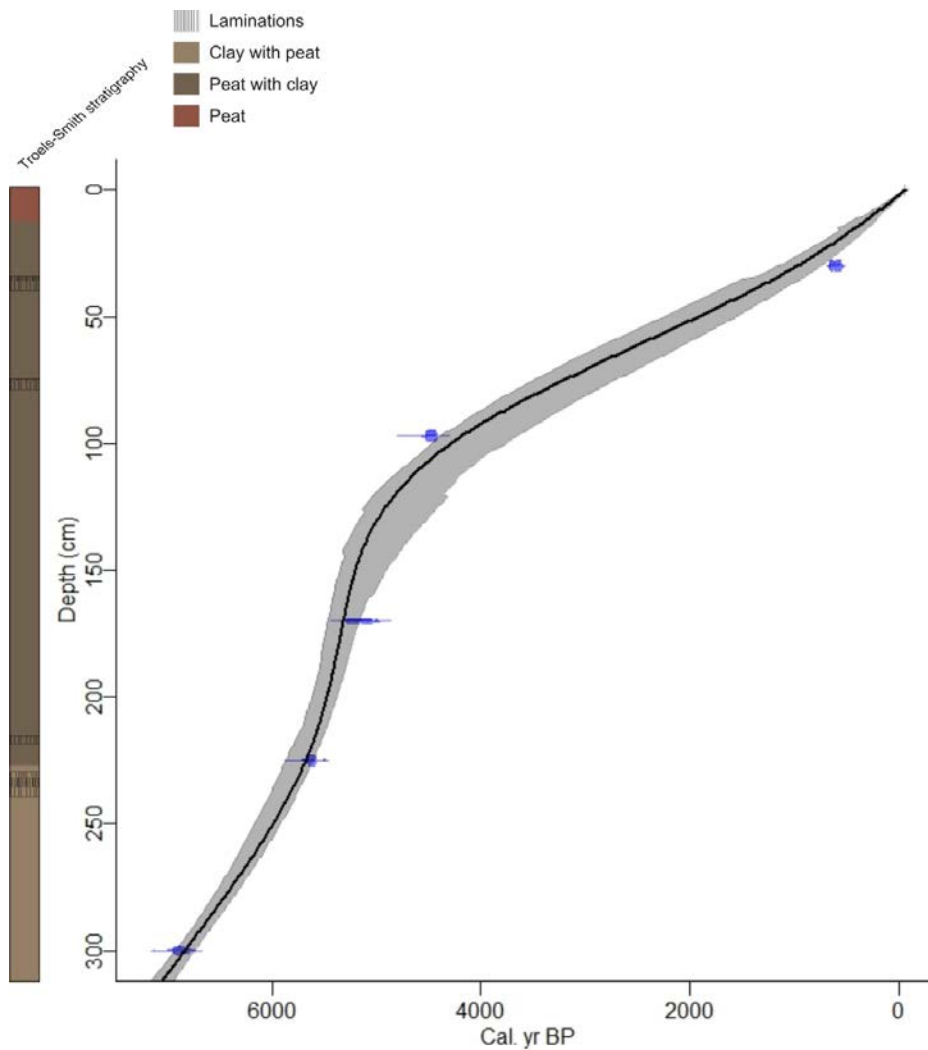


Fig. 2 Age-depth and temporally-aligned Troels-Smith stratigraphic profile, along with a key to the colour scheme. Smoothing spline proved the best-fitting model for the Converted Peatland core, with extrapolated basal points and a surface (0 cm) age set at -55 years.

Magnetic susceptibility results (Fig. 3) demonstrate that after 5000 Cal. yr BP organic-matter and soil moisture content increased, suggesting the presence of a waterlogged environment. This is also reflected in the lithology of the sedimentary profile (Fig. 2). Values (κ) remain low until approximately 1700 Cal. yr BP, coincident with the onset of the most intense ENSO period, when extreme values indicate low soil moisture content. A peak in magnetic susceptibility *c.* 2500 Cal. yr BP co-occurs with peaks in micro- and macrocharcoal, suggesting the former may be a result of raised levels of charcoal, a magnetic material, in the sediment. Magnetic susceptibility then decreases again in the latter half of the 20th Century,

possibly coinciding with the timing of the Little Ice Age climatic event (Lozano-Garcia *et al.*, 2010), and the sediment becomes darker, indicative of higher peat content.

The pollen summary diagram demonstrates that PSF has dominated this landscape since *c.* 2800 Cal. yr BP, forming the baseline ecological community in this site for the last three millennia (Fig. 3). Prior to this, the pollen rain was dominated by Rhizophoraceae's *Rhizophora*, a genus associated with mangroves. Therefore, during the latter half of the Holocene, the ecosystem appears to have changed considerably: from an estuarine-based vegetation community, where sediment accumulated comparatively rapidly as a result of both riverine and tidal sediment transport and low rates of organic matter decomposition, to a more diverse forested landscape under which peat soils started to develop.





After 3000 Cal. yr BP, reflecting this transition to a peat swamp ecosystem, pioneer taxa, such as *Macaranga* and *Syzygium*, started to increase, in conjunction with mature PSF taxa and the general palynological richness of the developing community. This vegetation change coincides with a transition in ENSO conditions, from a period of reduced to greater ENSO strength, and with the boundary between vegetation zones Z-1 and Z-2. At this point there are also several peaks in the rate of change of the total PSF%, suggesting greater forest fluctuation towards the end of this period of reduced ENSO intensity. Proceeding this, pioneer and disturbance taxa both within (PSF+) and outside of the peat swamp forest (degraded peat (DP) and open vegetation) significantly increase, with genera such as Urticaceae's *Poikilospermum* contributing more to the pollen sum, and ferns, Poaceae and Cyperaceae becoming more present in the landscape. Dipterocarpaceae pollen types similarly show an increase after this point, indicating drier conditions. The transition between vegetation zones Z-2 and Z-3, coinciding with the onset of a period of amplified ENSO around 1700 Cal. yr BP, marks the decline of the PSF and replacement with degraded peatland (DP) taxa.

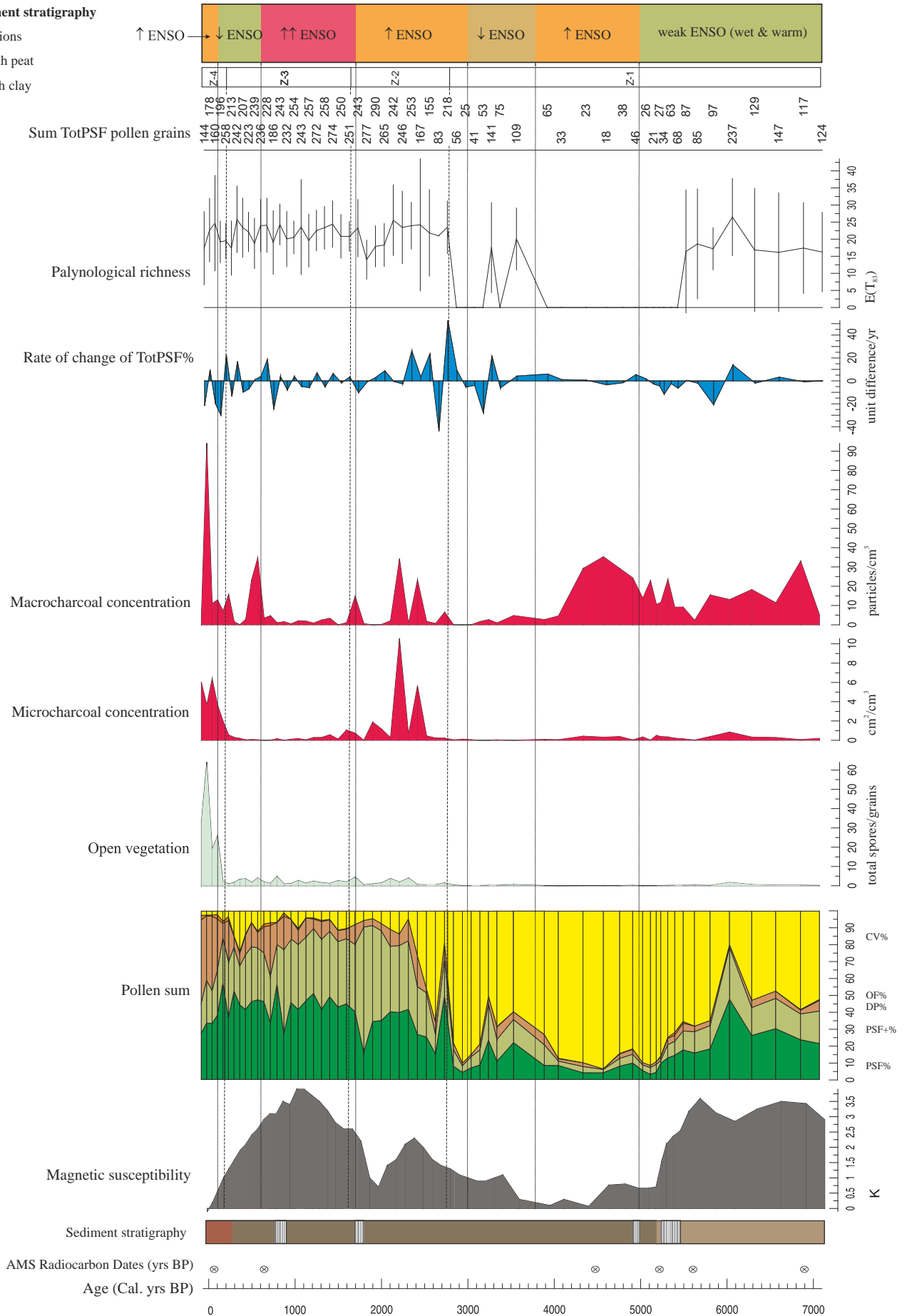
The greatest period of peat swamp forest decline and increase in disturbance and open vegetation taxa is seen in the last millennium, and in particular the last two centuries, detailed in vegetation zone Z-4. This coincides with the final period of intensified ENSO. The rate of change of the total PSF% also increases during this recent period (Fig. 3), after demonstrating more elevated levels from approximately 3000 Cal. yr BP.

Results of the ordination analysis (Table 3 and Fig. 4 for illustration) reveal that there is no significant relationship between ENSO peaks and the total PSF% (TotPSF% representing *External* PSF dynamics), despite ENSO-related change proving to have the most influence of all recorded environmental variables on landscape ecological conditions. Similarly, ENSO does not play a significant role in internal PSF dynamics, though increases in ENSO peaks are loosely coupled with increases in mature and pioneer PSF taxa (Fig. 4).

Fig. 3 Summary pollen diagram, showing sediment (Troels-Smith) stratigraphy (see Key), magnetic susceptibility (grey), five ecological groups (with TotPSF% represented by the boundary between PSF+ and DP groups, and each group coloured as follows: PSF dark green, PSF+ light green, DP brown, OF orange and CV yellow), open vegetation counts (light grey), micro- and macro-charcoal concentrations (red), rate of change of TotPSF% (blue), palynological richness (with 95% confidence intervals), the sum of the TotPSF pollen grains at each sampling level, significant pollen zones (marked Z) and the approximate timing of changes in ENSO intensity (the direction and number of arrows attached to the ENSO label describe the relative intensity of ENSO in comparison to its activity pre-5000 Cal. yr BP). Acronyms are explained in Table 1. (Samples were taken for pollen analysis at 2 cm intervals for the majority of the core, and 4 cm, 8 cm and 16 cm intervals towards the base.)

Key to sediment stratigraphy

-  Laminations
-  Clay with peat
-  Peat with clay
-  Peat



Charcoal and peat swamp forest

Macrocharcoal levels, and by proxy local fire, do not appear to be associated with the dynamics of either mature or pioneer PSF taxa, or any other ecological group (Fig. 4a).

There are no outstanding associations between local fire and other ecological groups.

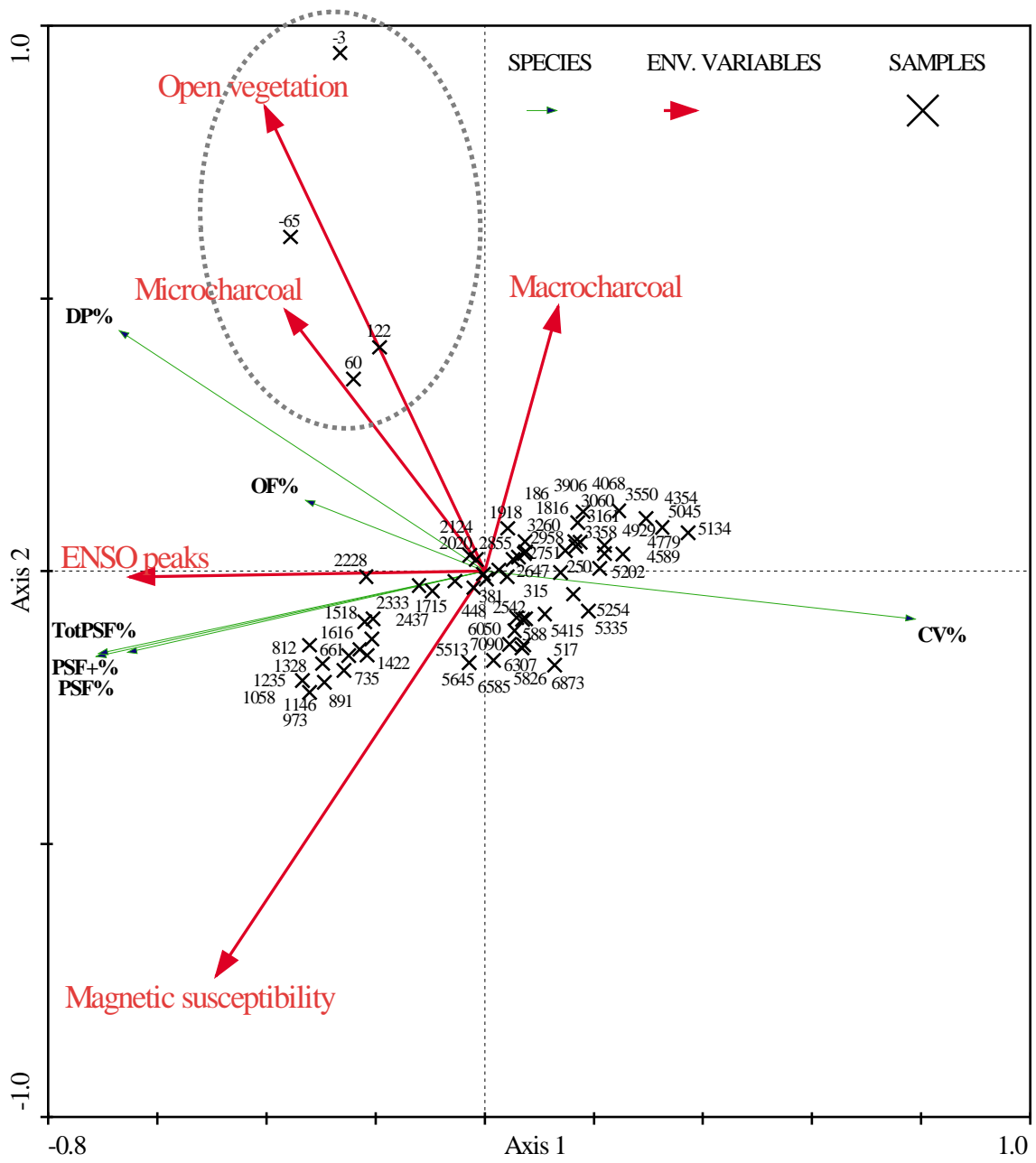
However, increases in microcharcoal appear to be weakly associated with increases in degraded peat (DP) and other forest (OF) ecological groups. Regional fire is also correlated with open vegetation, and both environmental variables with pollen samples of the last two centuries (circled cluster in Fig. 4a).

Table 3 Monte Carlo Permutation Test results, performed to analyse the strength of the relationship in Converted Peatland between (a) ENSO, and (b) the other recorded environmental variables, i.e. macrocharcoal, microcharcoal, magnetic susceptibility and open vegetation (the variable with the greatest influence on the distribution of the vegetation data is displayed with its associated *F*-statistic), and (i) internal PSF dynamics, i.e. most significant recorded factors associated with PSF% and PSF+% dynamics, and (ii) external landscape dynamics, i.e. factors most strongly linked with changes in all ecological groups in the landscape (TotPSF%, DP%, OF% and CV%). (999 restricted permutations by sample (allowing for time-series analysis) were used to calculate *F*-statistics and *p* values.)

CPL	Environmental variables	<i>F</i> -statistic	<i>p</i> value	Degrees of freedom [†]	Eigenvalue (1 st axis)	Sum of all canonical eigenvalues
(i) Internal	(a) ENSO	13.29	0.570	116	0.184	0.498
	(b) magnetic susceptibility	15.59	0.262	116	0.488	
(ii) External	(a) ENSO	18.81	0.518	236	0.242	0.594
	(b) ENSO	18.81	0.518	236	0.559	

[†]Number of sampled sediment levels was 61.

(a)



(b)

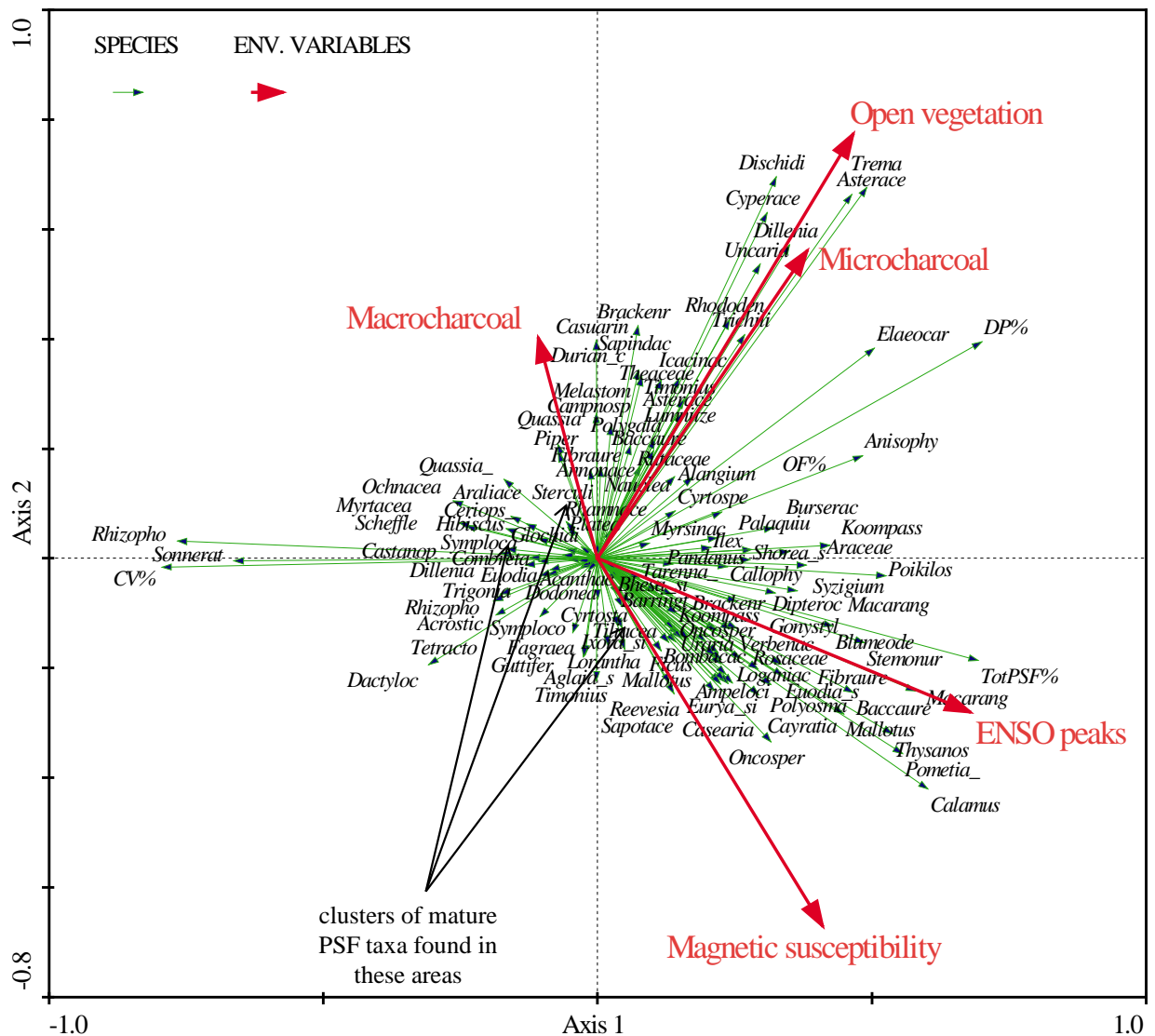


Fig. 4 Ordination diagrams showing the relationship between ENSO and other recorded environmental variables and (a) internal PSF dynamics, i.e. changes in PSF% and PSF+%, and external landscape change, i.e. changes in the ecological groups TotPSF%, DP%, OF% and CV%, through time, and (b) these external ecological changes in addition to the trends in all recorded taxa (with sample dates excluded). In (a), the 1st axis of the ordination explains 53.3% of the variance in the distribution of the ecological groups and the 2nd axis, 3.1%; with the inclusion of environmental variables, this percentage variance accounted for by the 1st and 2nd axes becomes 93.6% and 5.5%, respectively. In (b), 35.8% variance is attributed to the 1st axis and 4.9% to the 2nd axis, with the explained variance increasing to 81.6% and 11.1%, respectively, when environmental variables are accounted for in the assessment of directional distribution of taxa. (Where necessary, in order to reduce overlap and make key taxa more visible, plant names have been moved and mature PSF taxa removed from their original computed location in (b), and summary labels added. Genus names are used, where such distinction was possible during the identification process, and all names restricted to the first eight characters. See Fig. S1 Appendix 3, for full names of taxa.)

Open vegetation/human impact and peat swamp forest

As mentioned, fluctuations in open vegetation, the proxy for anthropogenic disturbance, do show a correlation, albeit insignificant, with community turnover within the wider peat swamp forest landscape. Open vegetation does not appear to have any relationship with internal peat swamp forest vegetation change, however.

ENSO, humans and peat swamp forest

ENSO intensity correlates most strongly, though insignificantly, with internal peat swamp forest vegetation dynamics, whereas changes in community turnover in the wider landscape are associated with those of open vegetation, i.e. human disturbance, with the greatest coupling occurring in the last 200 years (see Fig. 3 and cluster in Fig. 4a). However, coincident increases in fire and open vegetation with decreases in total PSF and elevated fluctuations in the rate of change of the total PSF% in the last several hundred years (Fig. 3), suggest that human and fire disturbance may have had a greater interaction with the peat swamp forest in the recent past.

DISCUSSION

This study tested three hypotheses related to climate-human-fire dynamics during the last 7000 years, in the peat swamp forests of Southeast Asia. In particular, it illuminated the relationship between the regional changes in ENSO intensity over the late Holocene, and the relative impact of such climatic fluctuations and human impact on the vegetation of this coastal peat swamp forest.

The first hypothesis tested the predicted relationship between increased intensity of ENSO-related drought events and increased fires within peat swamp forests. Evidence from this

study indicates that within the surveyed peatland, no relationship is apparent between intervals of intensified ENSO and burning, prior to human disturbance. Thus the baseline PSF community at this site appears to have been remarkably resilient to ENSO-induced droughts, which did not promote a greater incidence of forest fires. In fact, the slight negative correlation with macrocharcoal suggests that local fire may have decreased during periods of intense ENSO. This finding is in direct contrast to recent studies equating large-scale fires in peat swamp forests in Borneo over the last 20 years with ENSO events (Page *et al.*, 2002; Phua *et al.*, 2012). Rather than fire, soil moisture may be the primary mode of ENSO-related disturbance within peat swamp forest ecosystems, as suggested by Nishimura *et al.* (2007), though further testing of this hypothesis is required.

The second hypothesis tested whether increased intensity and variability of ENSO events creates greater disturbance in the peat swamp forest, as evidenced by greater vegetation change within the peat swamp forest and community turnover in the wider landscape.

Evidence from this study supports this hypothesis and indicates that the greatest and most rapid changes in peat swamp forest composition and proportion occur post-3000 Cal. yr BP, coinciding with the period in which ENSO events reached a Holocene maximum (Woodroffe *et al.*, 2003). There is a correlation, albeit weak, shown between periods of greater ENSO intensity and PSF change, especially between approximately 700 and 3000 Cal. yr BP, coinciding with the two periods where regional ENSO was most amplified. At this point there is a notable increase in the pioneer and mature vegetation of the PSF, reflected in changes in the palynological richness of this group, suggesting development of the ecosystem. Several mature PSF taxa, for example Dipterocarps, remain stable components during this period, or in fact show increases in relative abundance, e.g. *Shorea* sp., especially during the last 1,700 years, coinciding with more intense ENSO events; a trend that has also

been observed in a study from Maluku, Indonesia (van der Kaars *et al.*, 2010). Dipterocarpaceae trees are known to be drought-sensitive, undergoing mass flowering, followed by mast fruiting, during water-stressed years (Ashton *et al.*, 1988). In conjunction with these compositional shifts in the last 3000 years, the rate of change of the entire PSF increased, with larger and more frequent fluctuations than observed in the earlier Holocene. For the peat swamp ecosystem studied here, results therefore suggest that despite a lack of influence from burning, ENSO events may have played a role in shaping internal PSF dynamics, i.e. through creating disturbance events that generated opportunities for species turnover. Drier soil-moisture conditions may have been responsible for the apparent ENSO-induced disturbances, promoting local succession within these coastal forests. The coincidence of magnetic susceptibility peaks with periods of more intense ENSO events supports this interpretation through providing a proxy that indicates changes in soil moisture content (Grimley *et al.*, 2008; Balsam *et al.*, 2011). A similar relationship has also been observed in a study investigating the link between climate, human impact and lowland forest dynamics in Sarawak (Hunt and Premathilake, 2012). In summary, rather than increased ENSO events being a negative influence on the peat swamp forest, results from this study appear to suggest that the amplification of ENSO events over the latter half of the Holocene has acted to promote regeneration and diversity within this coastal peat swamp forest and thus can be seen as a positive influence on the ecosystem.

The third hypothesis addressed by this study was that in recent decades, human impact has had a far greater influence on burning dynamics than ENSO-related climatic change in this coastal peat swamp forest. There are various pieces of evidence that support this hypothesis. Firstly, there is a correlation (though weak) between open vegetation peaks and an increase in degraded peat vegetation in the landscape, which also coincides with high levels of regional

burning. This suggests that human activity within the last 200 years, predominantly via biomass burning, has impacted on this peat swamp forest ecosystem. Dramatic increases in open vegetation and degraded peat taxa and declines in total PSF% are apparent in the last two centuries, coupled with burning events of a higher intensity than seen in the last 2000 years, or indeed throughout the last 7000 years in the case of local fires. Other studies support our findings, indicating the recent elevated and significant influence of humans in these coastal peat swamp forests (Liong & Siong, 1979; Sawal, 2003; Cole *et al.*, *in prep*, see Chapter 7). In addition, a study looking at fire occurrence across a range of forest types in Borneo between 1997 and 2006, showed that, although peat swamp forests were the most impacted by ENSO-related drought, it was human-induced fire, often exacerbated by ENSO-related drying, that was the major driver of vegetation change in this ecosystem (Langner and Siegert, 2009). Across Borneo today, human activities, often linked to land-use policies, are predominantly responsible for episodes where burning elevates above background levels (Langner and Siegert, 2009; Carlson *et al.*, 2012).

The results presented here provide one of the first insights into the relative impact of ENSO on a tropical coastal peat swamp forest. This study suggests that past periods of intense ENSO events have played a role in promoting regeneration within coastal peat swamp forests, predominantly via the drying of the peat soil environment, and not via fire. These ENSO-related changes would have directly affected the hydrology of the peat swamps, an integral characteristic of these ecosystems (Dommain *et al.*, 2011). Nishimura *et al.* (2007) reported ENSO drying as predominantly altering the water availability to the hummocks of the hummock-hollow structure that is important for maintaining low hydraulic conductivity and high water storage capacity within peat swamp forest, causing mortality of canopy species growing there. This drying is unlikely to disrupt the microtopography however

(Nishimura *et al.*, 2007) and our results, recording change through time, indicate that regeneration can continue (Cole *et al.*, *in prep*, see Chapter 3), and in the longer term, such drought events contribute to the enhancement of species diversity.

In addition, there appears to have been no significant impact of burning on the vegetation at this site over the majority of the last 7000 years, suggesting that fire has not played a role as a major driver of disturbance during the past, forming a natural component of the landscape. However, within the last few centuries, fire and human disturbance have become more interrelated, and more implicated in a decline in the peat swamp forest, obscuring the signal from changes in ENSO intensity alone, as observed in other ecosystems (Cosgrove *et al.*, 2007; Haberle, 2005; Haberle *et al.*, 2006). Whether these forests can maintain resilience in the face of these elevated and synergistic levels of contemporary disturbance is questionable (Haberle *et al.*, 2006). Increased intensity and frequency of fires, coupled with draining of the peatlands, which fundamentally changes the peat soil structure and thus influences hydrology and vegetation simultaneously (Dommain *et al.*, 2010; Page *et al.*, 1999), may jeopardize the ability of the forest to continue to respond dynamically to climatic and fire disturbance. Recent studies have demonstrated the link between such elevated biomass burning and human-activity (Goldammer, 2007; Langner *et al.*, 2007; Field *et al.*, 2009) and discussed the importance of identifying the reasons for such burning in order to reduce the destruction it causes (Carlson *et al.* 2012). This, in turn, would enhance the capacity of the forest to withstand the impacts of intense ENSO events.

Overall, this study has demonstrated a dynamic response of peat swamp forest to both ENSO-related drying and, potentially, fire disturbance in the past. However, the maintenance of such resilience today is less certain. Contemporary disturbances, predominantly mediated

through anthropogenic activities, which have increased rapidly in the region's peatlands in the last two decades (Miettinen & Liew, 2010), appear to be larger than these ecosystems have previously experienced. In conjunction with the predicted tropical precipitation shifts (Van Der Werf *et al.*, 2008), future reductions of rainfall during the dry seasons (Li *et al.*, 2007), the increasing frequency of severe droughts (Nishimua *et al.*, 2007) (analogous to ENSO effects), and current gaps in our understanding of the interaction of tropical climate systems in the IPWP region (Abram *et al.*, 2007; 2009), recent and accumulating disturbances may cause novel and more intense impacts within these increasingly stressed ecosystems. Unlike in the past, recent ENSO events have been strongly linked to enhanced CO₂ emissions (Page *et al.*, 2002; Hirano *et al.*, 2007) and widespread destructive fires (Wooster *et al.*, 2012), most likely because of the vulnerable state these ecosystems are left in post-human disturbance. If trends in anthropogenic climate change (IPCC, 2007) and human population growth (UNDP, 2012) continue, the impacts of intense ENSO years on peat swamp forests may amplify yet further, and force the ecosystem beyond the threshold at which it can respond dynamically and recover. The forecasting of such events (Wooster *et al.*, 2012), and the restoration of degraded peatlands, fundamentally via re-wetting (Dommain *et al.*, 2010), may prove key components of their proactive management. Increasing the resilience of these systems to external perturbation, predominantly through limiting the degrading impacts of human land-use, will help to prevent extensive fires and the resultant carbon emissions, and to conserve this unique ecosystem.

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SUPPLEMENTARY MATERIAL

Appendix 1 **Table S1** AMS radiocarbon dates.

Appendix 2 Details of pollen preparation.

Appendix 3 **Fig. S1** Summary pollen diagram of Converted Peatland core, and corresponding ENSO activity.

APPENDIX 1

Table S1 Accelerator mass spectrometry (AMS) ^{14}C ages along with calibrated ages for radiocarbon dated samples from Converted Peatland core, calculated using Calib 601.

Lab Code	Core	Depth (cm)	^{14}C yr BP	$\delta^{13}\text{C}$ (‰)	Calibrated ages (cal yr BP)	Dated material
SUERC-35243	CPL	30	618 +/-35	-30.2	603 +/-56	soil
UBA-14322	CPL	97	4018 +/-26	-32.8	4475 +/-54	soil
SUERC-35244	CPL	170	4486 +/-35	-29.4	5166 +/-129	soil
SUERC-35245	CPL	225	4884 +/-37	-29.3	5623.5 +/-40.5	soil
UBA-15751	CPL	300	6038 +/-32	-29.7	6880.5 +/-89.5	soil

APPENDIX 2 Details of pollen preparation.

Pollen preparations were made of 1 cm³ samples at 2 cm intervals for the majority of the core, and 4 cm, 8 cm and 16 cm intervals towards the base. A Meiji microscope, at 400× magnification, was then used to count a minimum of 300 pollen grains per sampling level, excluding indeterminate pollen (i.e. grains that were deformed, obscured or unidentified).

APPENDIX 3

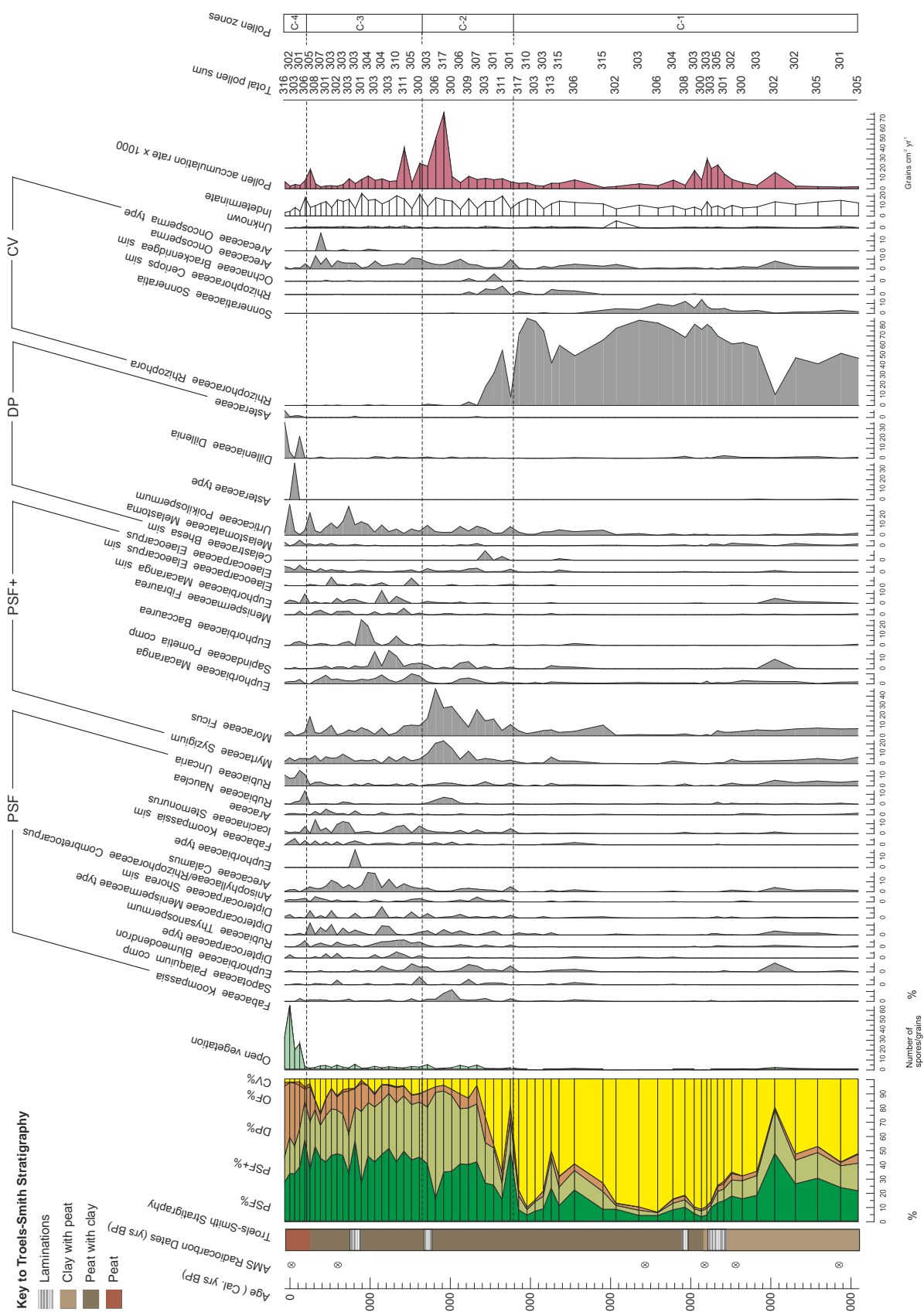


Fig S1 Summary pollen diagram, showing Troels-Smith stratigraphy, five ecological groups and the main pollen taxa (>0.05% contribution to pollen sum).



Paper 4: FLAMING PEAT: SYNERGISTIC EFFECTS OF FIRE AND FOREST CLEARANCE ON TROPICAL PEAT SWAMP FORESTS

Cole, L.E.S.¹, S.A. Bhagwat.² and Willis, K.J.³

¹Oxford Long-term Ecology Lab, Department of Zoology, University of Oxford, Oxford, United Kingdom

²School of Geography and the Environment, University of Oxford, Oxford, United Kingdom

³Biodiversity Institute, Oxford Martin School, Department of Zoology, University of Oxford, Oxford, United Kingdom

Corresponding author: Lydia Cole, tel: 01865 281321, fax: 01865 271249,

lydia.cole@zoo.ox.ac.uk

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Abstract

Recent burning in the tropical peat swamp forests of Southeast Asia, linked with anthropogenic land-use change, has resulted in widespread environmental degradation across the region. Yet little is known about the long-term natural fire regime in these landscapes. Using fossil pollen and charcoal data from three peat cores collected from Sarawak, Malaysian Borneo, we looked at the incidence and impact of local and regional fire on coastal peat swamp forests over the last 7000 years. Results show that burning has occurred in these wetland ecosystems throughout their history. However, prior to the Colonial era *c.* 1839, when human presence in the peat swamp forest was comparatively limited, neither local nor regional burning significantly impacted on the forest vegetation. After the mid 19th Century, at the onset of intensified land-use change, fire incidence elevated significantly within these coastal peat swamp forests. Although fire does not correlate with past vegetation changes in these ecosystems, the long-term data reveal that open vegetation, a proxy for human forest clearance, does to a greater extent. However, results suggest that human activity may be strongly influencing and acting synergistically with fire in the recent past, leading to the enhanced degradation of these peatland ecosystems. These findings support present-day concerns about the increase in fire incidence and combined impacts of fire and human disturbance on peat swamp forests, with serious implications for biodiversity and global climate change.

Introduction

The peat swamp forests of Southeast Asia, covering an area of 25 million ha (Page *et al.*, 2011), hold *c.* 12%, some 69 Gt, of the total carbon stored in the world's peatlands (Page *et al.*, 2011). The performance of these peat swamps as a carbon sink relies on a tight interrelationship between the landscape, vegetation and hydrological conditions (Page *et al.*,

1999; Dommain *et al.*, 2010; Posa *et al.*, 2011), making the forest component of this ecosystem vital for its maintenance. Despite this, peat swamp forests are being lost at a rapid pace: in Southeast Asia between 2000 and 2010, 56% were converted into plantations (Miettinen *et al.*, 2012b), in addition to the area lost through logging and other development (Koh *et al.*, 2011). In particular, fire is considered one of the most important drivers of land-use change and vast areas of these tropical peat swamps burn every year (Razali *et al.*, 2010; Phua *et al.*, 2012), especially on the island of Borneo (Langner & Siegert, 2009; Hoscilo *et al.*, 2011).

Burning has increasingly affected the peat swamp forests of Southeast Asia in the last two to three decades (Taylor, 2010) and is claimed to be one of the most insidious threats to peat-swamp habitats (Lee, 2000; Razali *et al.*, 2010), as well as to all rainforest ecosystems (Laurance, 2003). However, natural fires, predominantly caused by lightning strikes, have constituted an important part of the ecosystem dynamics in these tropical peat swamps (Taylor *et al.*, 2001), by creating gaps in which succession can occur. A study of peat swamp forests in Western Kalimantan suggests that fire has been a component of the landscape for at least the last 30,000 years (Anshari *et al.*, 2001), and in Singapore, for the last 23,000 years (Taylor *et al.*, 2001).

Small-scale forest burning by humans, largely as part of shifting cultivation practices (Haberle *et al.*, 2001), has been recorded in forests in Sarawak from the early Holocene (Hunt & Premathilake, 2012). More recently however, fires are reported to have increased in frequency, magnitude and impact in peat swamp forests in eastern Kalimantan (Hope *et al.*, 2005), in Australasia over the last few centuries (Mooney *et al.*, 2011), and across other areas of Southeast Asia in the last two or three decades (Taylor, 2010). How much recent fire

frequency has increased relative to historical levels, and what impact it has had in shaping ecosystem dynamics in the peat swamp forests of Sarawak, is still poorly understood.

This study aimed to investigate the patterns of fire, both local and regional in scale, in Sarawak's coastal peat swamp forests, using a long-term ecological approach. The overall objective was to determine the change in frequency and magnitude of fire through time in these ecosystems, and how/if this has influenced forest composition. Through reconstructing past burning regimes and vegetation change from fossil records contained in three sedimentary sequences extracted from peatlands on the coast of northern Borneo, this study addressed two key research questions: (i) What is the natural fire regime in these swamps, and how has it changed through time?, and (ii) How do the changing fire regimes impact the peat swamp forest vegetation?

Methods

The State of Sarawak, in northern Borneo, contains the greatest proportion of Malaysia's peat swamp forests, covering an area of approximately 3000 km² or 2% of the State (Miettinen *et al.*, 2012a), and its deforested peatlands, which extend over an additional 11% (FAO, 2012). Until recently, the peat swamp forests of Sarawak were denounced as "marginal wastelands" (Sawal, 2003), of little use except in the absence of alternative land. As such, large-scale conversion has occurred (Miettinen *et al.*, 2012b), predominantly for agricultural production (Koh *et al.*, 2011), where fire is commonly used to clear the forest vegetation (Wooster *et al.*, 2012).

Sedimentary cores were extracted using a hand-held coring device, from three peatlands across the Miri and Batu Niah Districts of north-east Sarawak: Deforested Peatland from

Senadin, Kuala Baram (04°30'47"N, 114°2'47"E), an area of degraded peatland covering >50 km²; Peat Swamp Fragment from Sungai Dua Forest Reserve (04°21'24"N, 114°0'21"E), a c. 2 km² fragment of secondary peat swamp forest; and Converted Peatland from Sungai Niah (03°52'4"N, 113°42'43"E), an agriculture-forest matrix of c. 1 km² (Fig. 1). Though these three sampled sites cover a relatively narrow geographical range of 80 km along the coast of northern Borneo, since there is limited variation in climate, geology and land-use across the region, they are sufficiently representative of the coastal peat swamp ecosystems of Sarawak, and to an extent, of Borneo and parts of Southeast Asia.

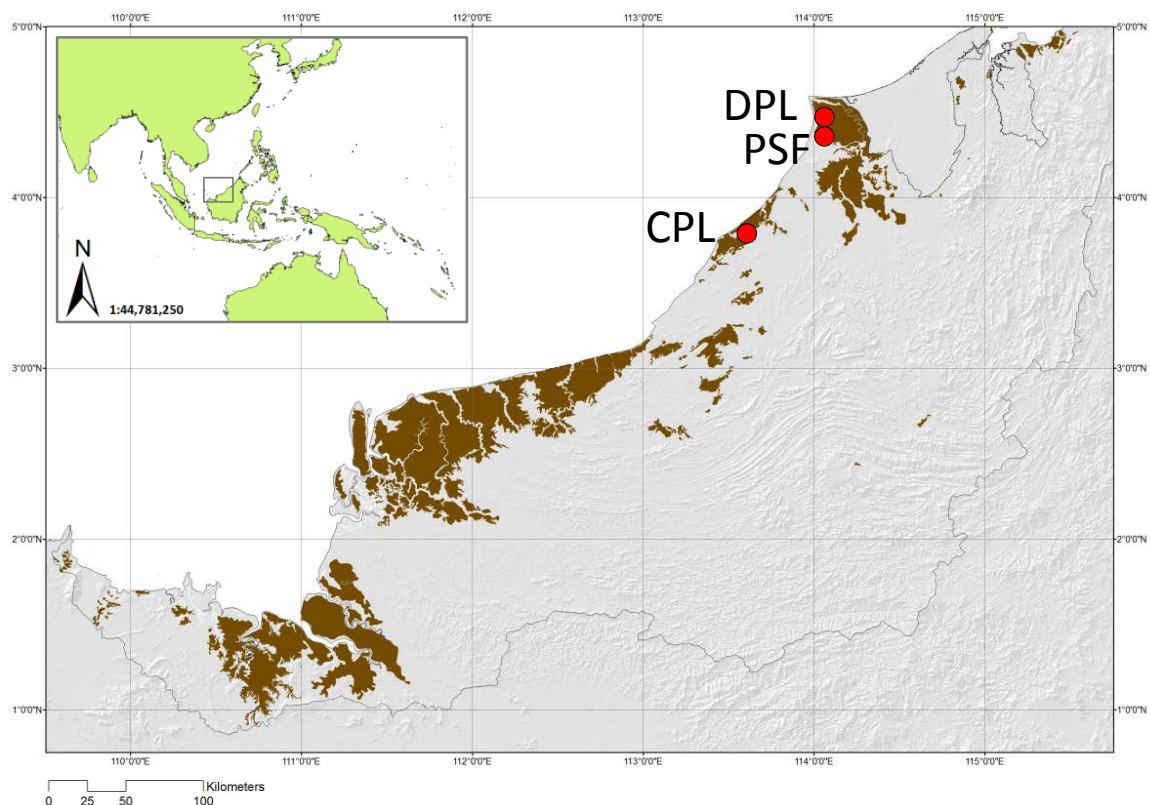


Fig. 1 Map showing the geographical location of Sarawak, Malaysian Borneo (inner box), within Southeast Asia, and the three peat swamp sites from which cores were extracted: Deforested Peatland (DPL), Peat Swamp Fragment (PSF) and Converted Peatland (CPL). (Peatlands are shown in brown. Image courtesy of SarVision, 2011.)

Using standard palaeoecological techniques (Bennett & Willis, 2001), the sedimentary cores were analysed at set intervals through the sequences for fossil pollen, microfossil and macrofossil charcoal and mineral magnetic material (magnetic susceptibility) (see Supporting Material).

Chronology

To determine the age-depth relationship of the sedimentary cores, samples containing organic material suitable for ^{14}C dating were extracted from each and analysed with AMS radiocarbon dating techniques, at the ^{14}C Chrono Centre in the Archaeology and Palaeoecology Department, at Queen's University Belfast, and the SUERC AMS Laboratory, at the NERC Radiocarbon Facility. The coding package *Clam* (Blaauw, 2010) in R (R Core Team, 2012), with a Northern Hemisphere correction, i.e. the IntCal04 curve, was used to calibrate the conventional radiocarbon dates and construct the best-fitting age-depth models (see Supporting Material).

Reconstructing past burning regimes

A size-class analysis of fossil charcoal, i.e. differentiating between macrofossil and microfossil charcoal, was performed to investigate changes in local and regional fire regimes, respectively, in each site through time (Whitlock and Larsen, 2002). Macrofossil charcoal particles, henceforth macrocharcoal, were isolated from each 1 cm^3 sample extracted for pollen analysis, by passing the sample through a $150\text{ }\mu\text{m}$ sieve. This process divides the macro- and microfossil components of the sediment. The resulting macrofossil isolates were then observed under a light microscope and the complete macrocharcoal content counted to give a measure of the number of particles per cm^3 at simultaneous intervals as fossil pollen. Fossil charcoal particles are identifiable as black, opaque, block-shaped and angular (Clark,

1988). The microfossil charcoal concentration, henceforth microcharcoal, was counted at the same intervals. Since microcharcoal particles are both small, i.e. <150 μm causing them to separate out with the pollen component during the sieving of samples, and resistant to the processing performed to isolate fossil pollen grains and spores, they can be counted on the same slides prepared for pollen analysis. Clark's point count method (Clark, 1982), which converts standardised count data into concentration values, measured in cm^2/cm^3 , was used to quantify the microcharcoal concentration in thin section. Macrofossil charcoal is used to broadly reconstruct local fire events, since the larger charcoal particles produced during fires, i.e. those greater than 150 μm , will be heavier and less easily transported by wind or other vectors away from the burning focus, and thus concentrate around it. Whereas microcharcoal, comprising smaller and therefore lighter charred particles, can be transported over large distances from the site of burning, and therefore signal regional fire events (Clark, 1988).

Reconstructing vegetation change over time

Due to the diversity of species in the peat swamp flora and differing levels of pollen production, and to allow for an interpretation of the palaeo-plant communities (for example Muller, 1963), taxa identified in the fossil pollen record were allocated to ecological groups (see Supporting Material) using various publications from the region (Anderson, 1964; 1980; Stuijts, 1993; Coode *et al.*, 1996; Anshari *et al.*, 2001; 2004). A pollen sum was then calculated and used to estimate the relative abundance of each taxa and each ecological group through time, giving a percentage score, e.g. PSF%. Open vegetation types, i.e. those that produce unusually large volumes of pollen per plant which can bias the interpretation of landscape vegetation, were excluded from the pollen sum. The different ecological groups are defined as follows: total PSF (TotPSF), which encompasses all peat swamp forest (PSF)

associated taxa; the mature PSF community (PSF); the pioneer PSF community (PSF+); taxa of degraded peatlands (DP); taxa of other forests (OF); coastal vegetation (CV), and open vegetation, comprising taxa which dominate open-canopied areas of greater spatial and temporal scale than tree-fall gaps, for example Poaceae, Cyperaceae and ferns (both of monolete and trilete morphologies). This latter ecological group is used as an indicator of human impact.

Significant pollen assemblage zones were constructed using an optimal splitting by information content technique on all pollen data, after assessing the number of zones that were significant via a broken stick modelling approach across different data analyses (Bennett, 1996). *Psimpoll* version 4.26 (Bennett, 1994) was used to display all pollen, spore and charcoal records (Fig. 2).

Data-handling techniques

In order to explore the fire regime of each core and specifically when/if peaks in fire activity have occurred through time, the microcharcoal and macrocharcoal data (*C*), recorded as cm^2/cm^3 and $\text{particles}/\text{cm}^3$ respectively, were transformed to isolate such peaks from background noise. Firstly, background burning levels were assessed, and secondly, peaks in fire activity isolated from these. Prior to the transformation, both sets of data were divided by the sediment accumulation rate calculated in *Clam*, to produce a rate of microcharcoal and macrocharcoal accumulation through time, measured in cm^2/yr and $\text{particles}/\text{yr}$ respectively. This reduced the chances of fossil charcoal peaks in the sedimentary records being an artefact of sediment accumulation variability rather than real elevations in fire activity through time (Higuera *et al.*, 2012). Both sets of fossil charcoal data were then resampled in the first step of the transformation, using a natural logarithm to stabilise the variance in the datasets and

isolate the background fire activity, C_{back} , i.e. the baseline fire activity recorded in each sediment profile, using the following equation:

$$C_{back} = \log(C + 1)$$

The second step then involved subtracting this background trend from the microcharcoal and macrocharcoal data, to create a series of residuals, i.e. peaks:

$$C_{peak} = C - C_{back}$$

This transformation thus provides a record of fossil charcoal fluctuation, C_{peak} , through time for all three sites (Fig. 2), in which unusually intense burning incidences are highlighted.

Although an estimate of the true rate of fire events cannot be estimated due to unequal sampling intervals, episodes of increased burning frequency can be inferred where there are a greater number of elevated peaks within a period of time.

To investigate the relationship between fire and peat swamp forest through time, multivariate analysis was carried out. Principal Components Analysis (henceforth PCA) was performed in CANOCO (ter Braak & Šmilauer, 2002), in order to explore and graphically represent the nature of the relationships between all recorded environmental variables and both internal and external peat swamp forest dynamics. Data were square-root transformed and species scores were divided by standard deviations and scaled according to inter-species correlations. Internal dynamics are represented by changes in PSF% and PSF+%, and external dynamics by the four key ecological groups in the landscape, i.e. TotPSF%, DP%, OF% and CV%. To analyse the strength of the correlation between firstly fire, and secondly all environmental variables, Monte Carlo Permutation Tests were performed, using 999 restricted permutations by sample, to account for the time-series nature of the data.

Results

(i) *What is the natural fire regime in these coastal peat swamps? How has it changed towards the present day?*

Fire has been present in all three sites through time (Fig. 2). Fluctuations in macrocharcoal and microcharcoal levels vary within and between cores, though there are several distinct phases of elevated magnitude and frequency of burning as follows.

2800 – 1800 Cal. yr BP

Within the Peat Swamp Fragment and Converted Peatland sites, there is a coincident increase in size, i.e. magnitude, of macrocharcoal peaks, and microcharcoal for the latter site, between approximately 2800 – 1800 Cal. yr BP. These magnitudes do not exceed those seen in the last 200 years however. In the Converted Peatland site the magnitude and frequency of macrocharcoal peaks and frequency of microcharcoal peaks appear to be greater prior to c. 5000 Cal. yr BP, coinciding with the local presence of a mangrove ecosystem (Fig. 3). After this period, levels of macrocharcoal and microcharcoal demonstrate very low magnitudes in all three sites until the next period of elevated burning, from c. 200 Cal. yr BP.

200 Cal. yr BP to present

Over the last 200 years, macrocharcoal and microcharcoal levels indicate an increase in both magnitude and frequency of local and regional burning respectively, in all three sites. These results further suggest that levels of burning exceed those seen throughout the fossil charcoal records of all cores. Microcharcoal levels in the Deforested Peatland and Peat Swamp Fragment sites, especially, greatly exceed those recorded in the past. The exception to these historically-novel elevations of fossil charcoal is in the Converted Peatland site, though not associated with a peat swamp vegetation community.

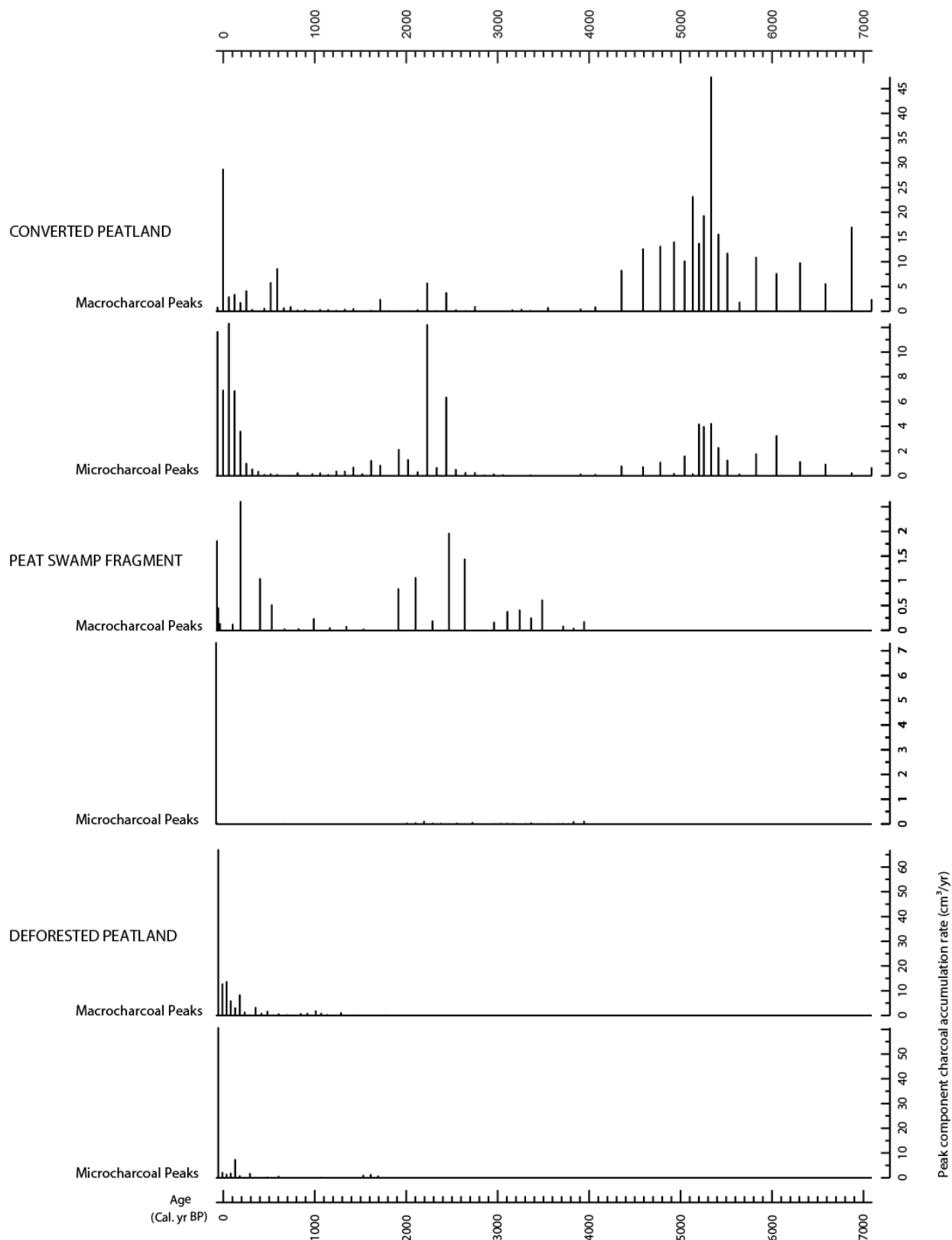


Fig. 2 Macrocharcoal and microcharcoal accumulation data showing the peaks remaining after background charcoal accumulation was removed. The Deforested Peatland record finishes at 1776 Cal. yr BP and Peat Swamp Fragment at 3948 Cal. yr BP, with only the Converted Peatland site yielding a record extending to 7090 Cal. yr BP.

(ii) *How do the changing fire regimes impact the peat swamp forest vegetation?*

Peat swamp forest is the baseline vegetation at all three sites over the late Holocene period that these coastal swamps have been present, dominating the vegetation profile. Each sedimentary core records a different peat development history, with Deforested Peatland having the most recently accumulated peat soils, starting from approximately 1500 Cal. yr BP; in Converted Peatland, organic matter started to accumulate in the substrate of an estuarine mangrove ecosystem several thousand years prior, though the forest associated with peat swamps did not develop until *c.* 2800 Cal. yr BP; and in Peat Swamp Fragment the onset of peat development arose *c.* 3500 Cal. yr BP. (See Supporting Material for full pollen diagrams).

Since the inferred onset of peat swamp development, the percentage of pollen from the total PSF ecological group (aggregate dark and light green components on the pollen sum diagram, Fig. 3) has been relatively constant in each site through time, fluctuating *c.* 80%. However, in the Peat Swamp Fragment and Converted Peatland sites, the total PSF proportion declines in the last *c.* 500 years. The indicator group for disturbance within the peat swamp forest, PSF+, does not appear to follow a pattern within or across sites, thus demonstrating internal dynamism throughout the past. Open vegetation levels in all sites remain low until *c.* 200 Cal. yr BP, with the exception of an anomalous peak in the Peat Swamp Fragment prior to 2000 Cal. yr BP. This recent notable increase in open vegetation taxa suggests that there was a higher incidence of open-canopied areas in the vicinity of these sites in the last several hundred years.

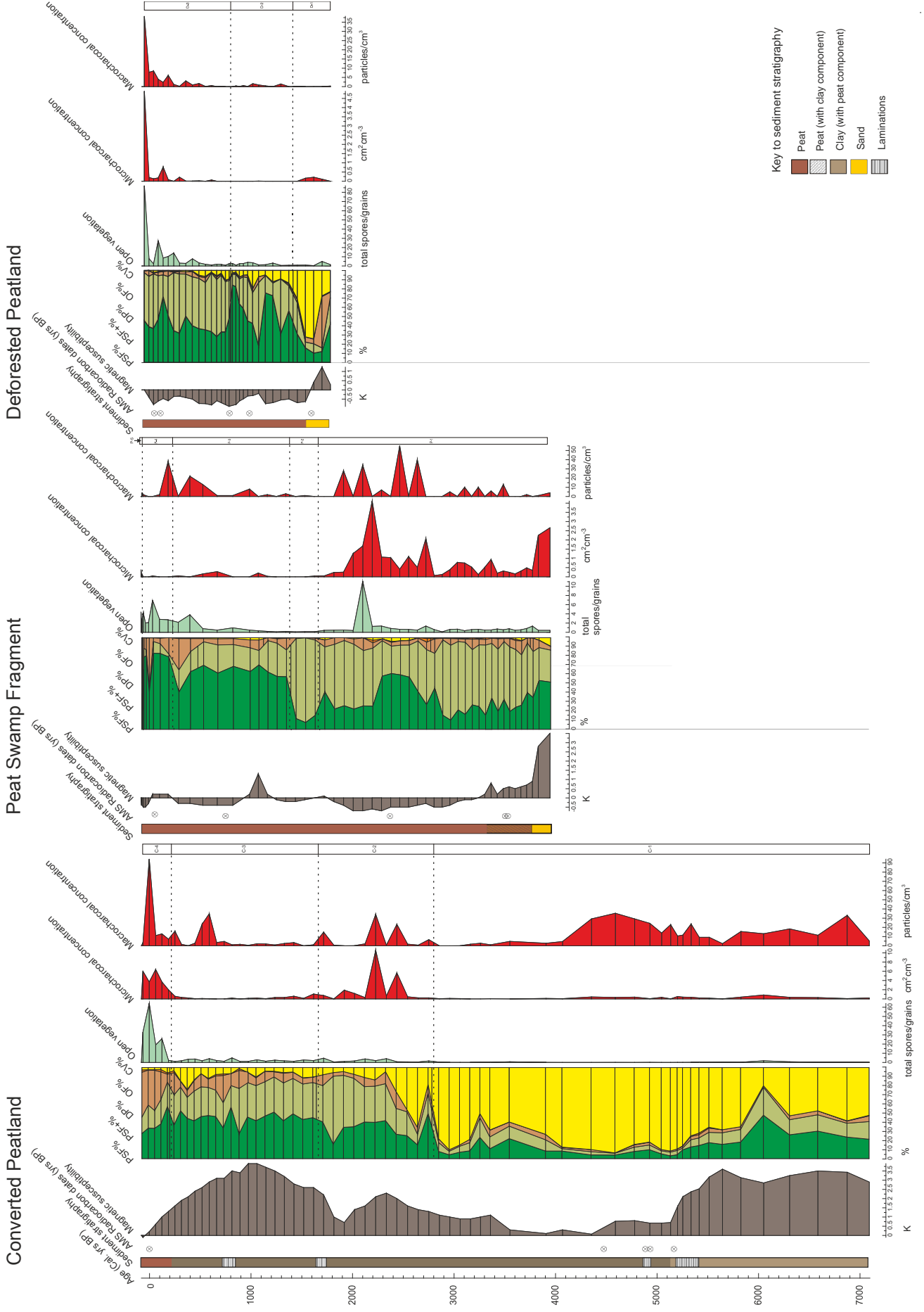


Fig. 3 Pollen summary diagram showing the sediment stratigraphy, magnetic susceptibility, five different ecological groups (represented by the following colours: PSF dark green, PSF+ light green, DP brown, OF orange and CV yellow), open vegetation (light green) and macrocharcoal and microcharcoal (red) for the Deforested Peatland, Peat Swamp Fragment and Converted Peatland sites. Cores have been adjusted to enable their chronological correspondence against one timescale. Significant pollen zones are shown for each. TotPSF% comprises the sum of PSF% and PSF+%, and is represented by the division between PSF+% and DP%.

Both internal peat swamp forest dynamics and external landscape change do not appear to correlate with fire, whether local or regional in scale (Table 1). The exception is the relationship between microcharcoal and external ecological change in the Converted Peatland site. Here, regional burning is correlated with vegetation fluctuations in the wider landscape (F -statistic = 6.08, p value = 0.014): as microcharcoal levels increase, the degraded peat ecological group, and to an extent non-PSF-related forest taxa, increase (Fig. 4c). In terms of other environmental variables, the peat swamp forest and landscape vegetation within the Deforested Peatland site appears to correlate most with magnetic susceptibility changes, and in the Peat Swamp Fragment with changes in open vegetation and regional fire, albeit all non-significantly. In the Converted Peatland site, PSF dynamics had the strongest association with magnetic susceptibility, and landscape dynamics were significantly correlated with changes in open vegetation (F -statistic = 9.55, p value = 0.015).

Despite each core exhibiting different ecological patterns, one key trend is visible from the ordination diagrams: increases in open vegetation are correlated in all three sites with the pollen samples counted within the last 150 years (see circled clusters, Fig. 4). In the Converted Peatland and Peat Swamp Fragment cores, the degraded peat ecological group is also associated with this recent landscape trend, and across all sites, *Trema*, Ulmaceae, increases during this period (see Fig. S3, Appendix vi.).

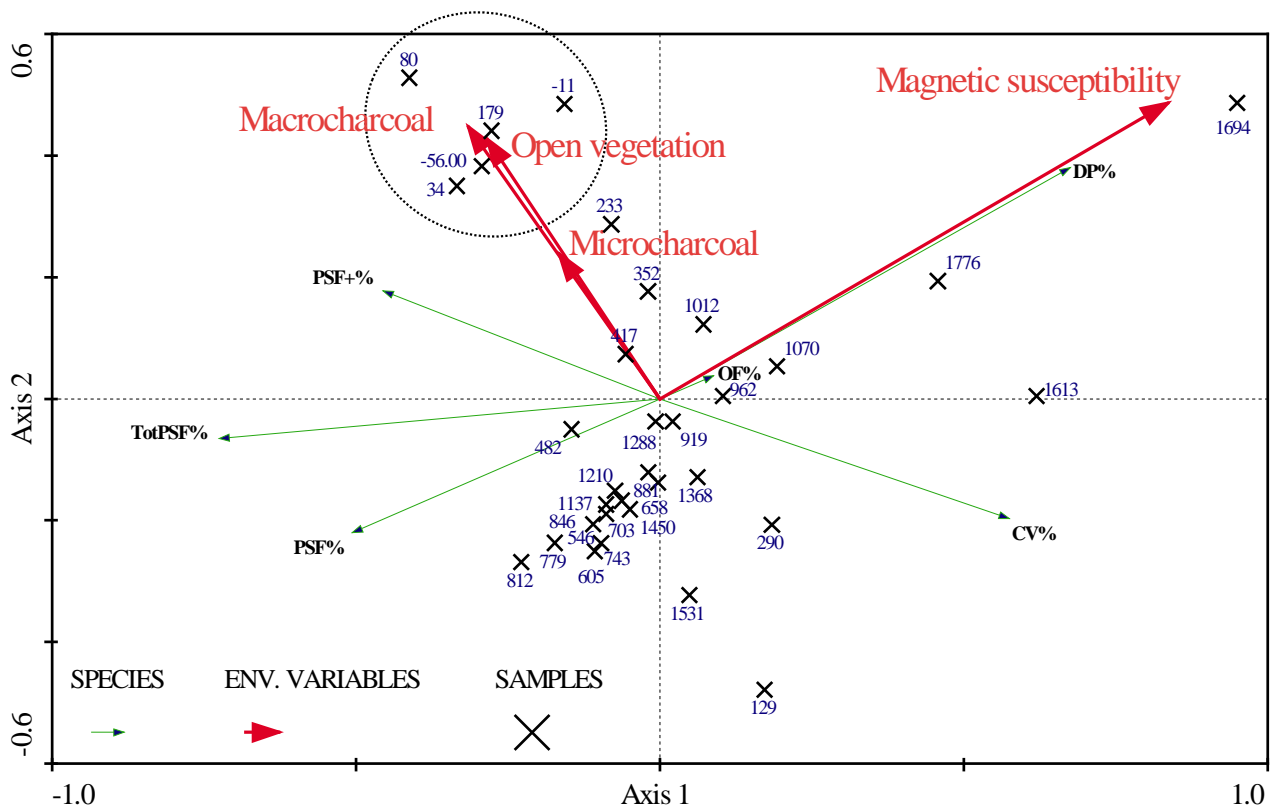
Table 1 Monte Carlo Permutation Test results, performed to analyse the strength of the relationship between the vegetation in each site and (a) microcharcoal and macrocharcoal, and (b) all recorded environmental variables, i.e. macrocharcoal, microcharcoal, magnetic susceptibility and open vegetation (only the strongest relationship is displayed). The vegetation is split into **internal** PSF dynamics, i.e. the most significant recorded factors associated with PSF% and PSF+% dynamics, and **external** landscape dynamics, i.e. factors most strongly linked with changes in all ecological groups in the landscape (TotPSF%, DP%, OF% and CV%). (999 restricted permutations by sample (allowing a time-series analysis) were used to calculate *F*-statistics and *p* values.)

Site	Environmental variable	<i>F</i> -statistic	<i>p</i> value	Degrees of freedom†	
DEFORESTED PEATLAND					
(a)	Internal	Microcharcoal	0.14	0.892	61
		Macrocharcoal	0.82	0.553	61
	External	Microcharcoal	0.57	0.476	125
		Macrocharcoal	1.77	0.180	125
(b)	Internal	Magnetic Susceptibility	6.28	0.078	61
	External	Magnetic Susceptibility	12.75	0.094	125
PEAT SWAMP FRAGMENT					
(a)	Internal	Microcharcoal	1.75	0.482	99
		Macrocharcoal	0.74	0.477	99
	External	Microcharcoal	3.51	0.142	101
		Macrocharcoal	0.55	0.527	101
(b)	Internal	Open vegetation	4.21	0.155	99
	External	Microcharcoal	3.51	0.142	101
CONVERTED PEATLAND					
(a)	Internal	Microcharcoal	2.04	0.097	117
		Macrocharcoal	1.66	0.685	117
	External	Microcharcoal	6.08*	0.014	237
		Macrocharcoal	0.84	0.723	237
(b)	Internal	Magnetic Susceptibility	15.59	0.262	117
	External	Open vegetation	9.55*	0.015	237

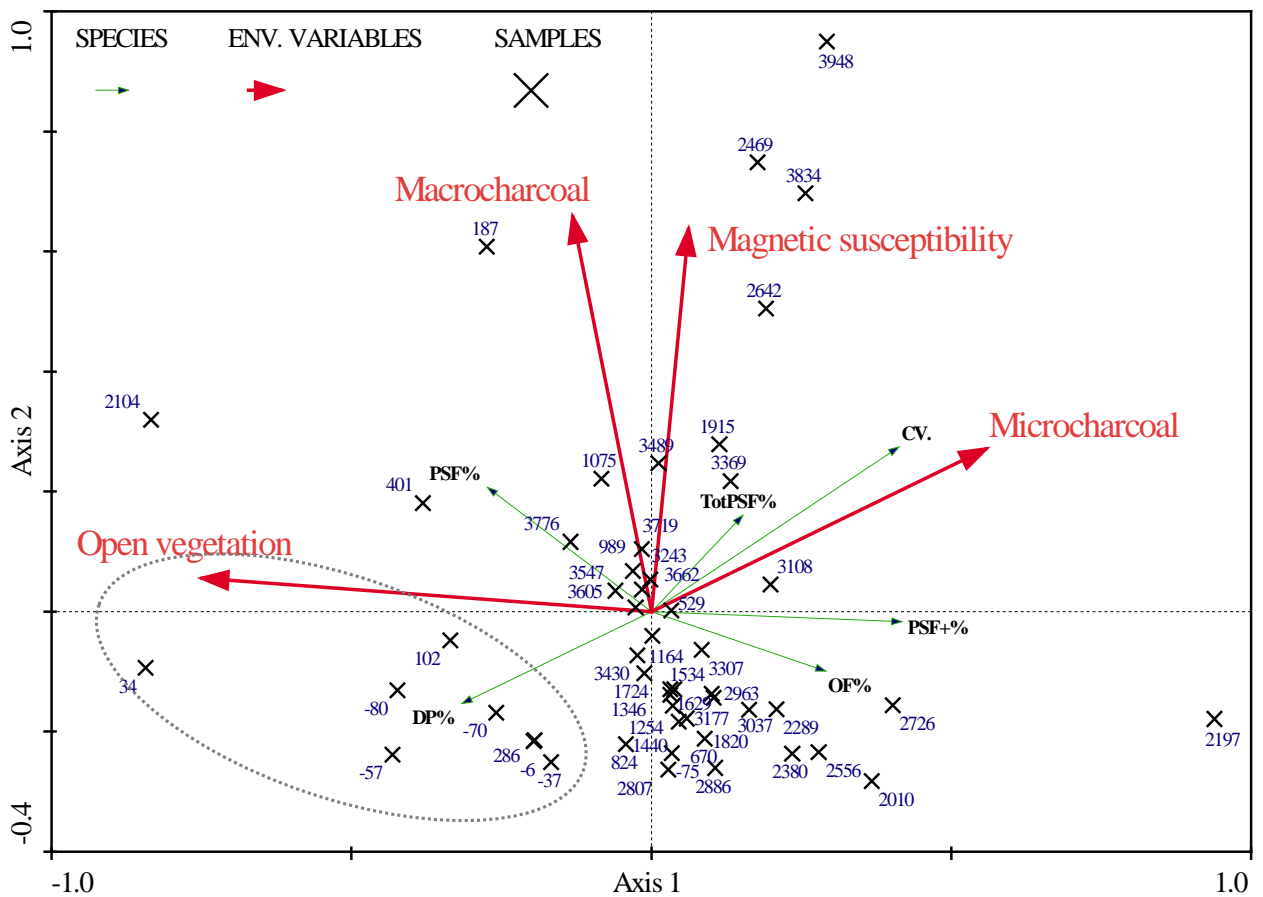
*Significant relationship at $p < 0.05$ level.

†Number of sampled sediment levels per core: Deforested peatland, 33; Peat swamp fragment, 52; Converted Peatland, 61.

(a) Deforested Peat



(b) Peat Swamp Fragment



(c) Converted Peatland

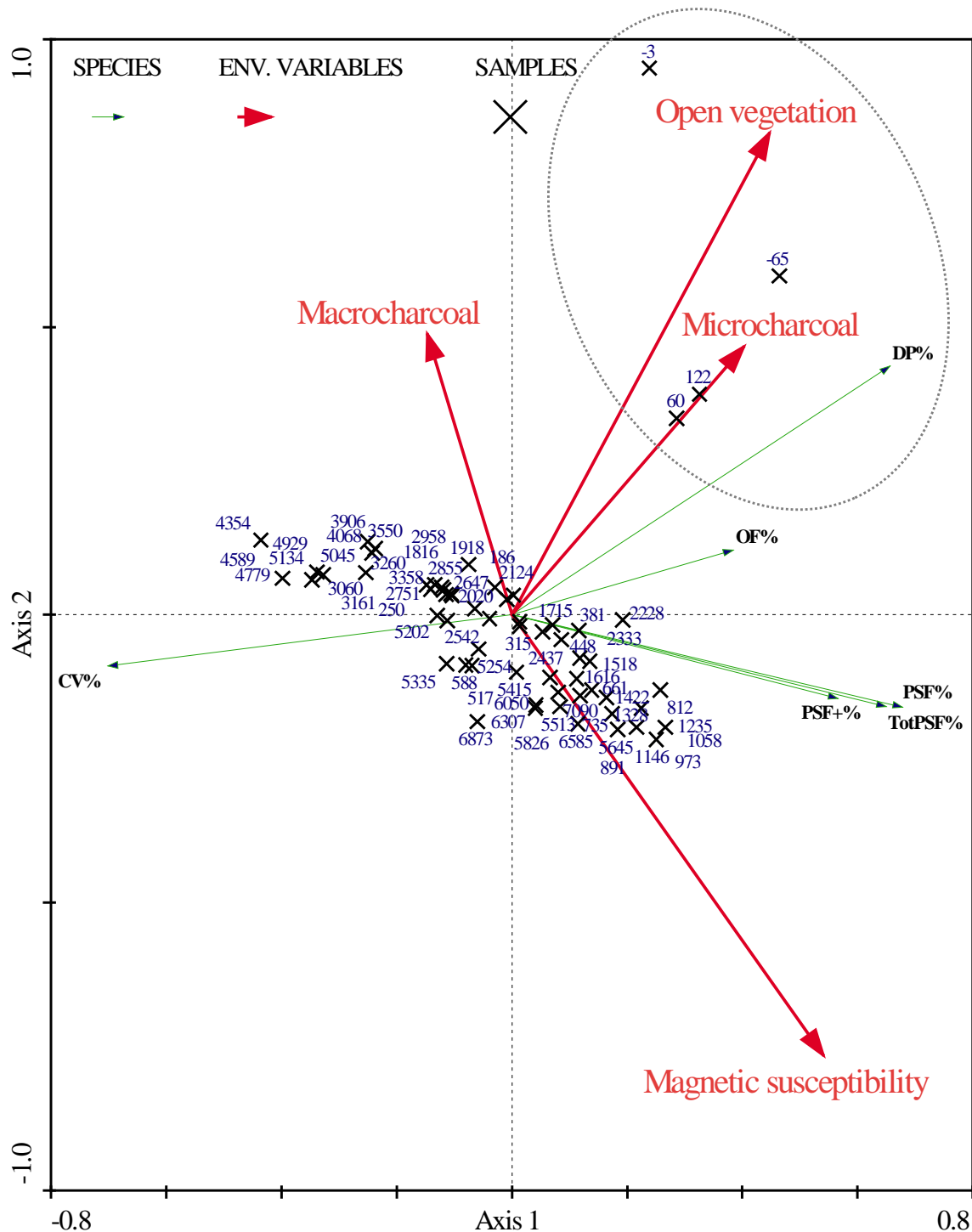


Fig. 4 PCA Ordination diagrams for coring sites (a) Deforested Peatland, (b) Peat Swamp Fragment, and (c) Converted Peatland, showing the relationships between the recorded environmental variables (i.e. macrocharcoal, microcharcoal, magnetic susceptibility and open vegetation), and temporal changes in (i) internal PSF dynamics: mature (PSF%) and pioneer PSF taxa (PSF+%), and (ii) external landscape dynamics: the ecological groups comprising total PSF (TotPSF%), degraded peat (DP%), other forest (OF%) and coastal vegetation (CV%). In (a), the 1st axis of the ordination explains 33.3% of the variance in the distribution of the ecological groups and the 2nd axis, 4.4%; with the inclusion of environmental variables,

this percentage variance accounted for by the 1st and 2nd axes becomes 87.1% and 11.4%, respectively. In (b), 11.3% variance is attributed to the 1st axis and 2.2% to the 2nd axis, with the explained variance increasing to 79.5% and 15.4%, respectively, when environmental variables are accounted for in the assessment of directional distribution of taxa. In (c), 43.9% and 3.1% are due to the 1st and 2nd axes, and 93.1% and 6.6%, respectively, when environmental variables are included. As Table 1 demonstrates, only microcharcoal and open vegetation are significantly correlated with external landscape dynamics in the Converted Peatland site. Groups of samples from the recent past have been circled where there is a notable association with environmental variables, i.e. predominantly open vegetation.

Discussion

This investigation found there to be no consistent fire regime across the three studied peat swamp forest ecosystems on the coast of Sarawak over the last 2000 to 7000 years. It also demonstrates that fire has not had a significant impact on either internal peat swamp forest vegetation communities or ecological change within the wider landscape through time.

Rather, patterns of burning appear to be predominantly idiosyncratic and drivers of vegetation change predominantly anthropogenic.

(i) What is the natural fire regime in these coastal peat swamps? How has it changed towards the present day?

Results from this study demonstrate that fire has been present throughout the past within these coastal peat swamp forests, in accordance with findings from elsewhere in the region (Anshari *et al.*, 2001; Taylor *et al.*, 2001). However, there is no apparent 'natural' or predictable baseline local or regional burning regime. Instead, evidence suggests that there were two notable episodes of increased fire across sites, overlaying a background of heterogeneity. However, there are lengthy periods, for example between *c.* 1800 – 500 Cal. yr BP, where fire frequency and magnitude appear to be low. Other studies have reported similar findings. Hope *et al.* (2005) found that fire was a rare occurrence in peat swamp forest at a distance from rivers before 3000 years ago, and from contemporary work,

Miettinen *et al.* (2012c) report the near absence of burning in pristine peat swamp forests in Sumatra. The large elevation in local and, to an extent, regional burning in the Converted Peatland site prior to 5000 Cal. yr BP can be explained by the existence of an estuarine ecosystem during that period. It is likely that charcoal from extra-local fires was washed in with tidal currents and accumulated in the mangrove muds. Thus, these earlier elevated levels of burning are associated with tidally-influenced mangrove communities, rather than peat swamp forests, which results suggest as having a baseline of low fire incidence.

Two episodes where considerable coherence and elevation in the fossil charcoal records do occur across sites, suggestive of increased regional burning or pervasive landscape change, are as follows: the first occurs between approximately 2800 – 1800 Cal. yr BP, and the second, within the last 200 years. In order to explore the factors that could have influenced these fire patterns over the late Holocene, records of regional climate and information on local anthropogenic land-use change were sourced.

What caused such patterns of fire in this landscape?

In general, climate did not have a significant impact on the burning regime in any of the three sites through time. Other papers support such a finding. For example, Cole *et al.* (*in prep*, see Chapter 4) report that the intensification of El Niño Southern Oscillation (ENSO) events in the late Holocene do not correlate with increasing fire activity in these coastal peat swamp forests. However, the first simultaneous episode of elevated local and regional burning observed between *c.* 2800 – 1800 Cal. yr BP, coincides with a period of climatic drying in the Tropics that is reported to occur in the interval 2000 – 3000 Cal. yr BP (Woodroffe *et al.*, 2003; Selvaraj *et al.*, 2007). Anshari *et al.* (2001) report a similar increase in microfossil charcoal particles during this period, in a peat core extracted from West Kalimantan, and

suggest that increased ENSO-related climatic variability may have been one reason for such an increase, predominantly through causing stress to the previously stable ecosystem. They also refer to human disturbance as a potential driving force for greatly elevated charcoal to pollen ratios recorded from *c.* 1400 yr BP (Anshari *et al.*, 2001).

In order to assess the probable anthropogenic influence on burning regimes in the coastal peat swamp forests studied here, there is a complex history of human-environment interactions (Fig. 3) that warrants consideration. Evidence for the first human presence in northern Borneo comes from a “Deep Skull” found in the Niah Caves in northeast Sarawak, which has been dated to over 35,000 Cal. yr BP (Barker *et al.*, 2007). Other work suggests that people have been living in this area for even longer (Hunt & Premathilake, 2012), and using fire to clear forest vegetation (Hunt and Rushworth, 2005). During the late Pleistocene and much of the Holocene, low-density human communities in Borneo would have had limited impact on their densely-forested environment, and their activities, predominantly as hunter-gatherers and shifting cultivators, are unlikely to have extended far beyond the edges of peat domes, or from river-based transport networks (Hope *et al.*, 2005). Large-scale landscape modification started to happen with the establishment of Colonial rule. Captain James Brooke, the first Viceroy of Sarawak, landed on Borneo’s shores in 1839, and proceeded to organize her politics and landscape to improve levels of peace amongst resident communities and increase the productivity of the land for its residents (Macdonald, 1956). Fire would have played an important role in this strategic landscape conversion. At this time, people would have searched for land on which to farm and secure rights, in some cases turning to the relatively under-exploited peat swamps. Interview data suggests that people began living in these areas from *c.* 1850, but the majority settled in peatlands much later, *i.e.* the early 1970s (Cole *et al.*, *in prep*, see Chapter 7). Approximately 100 years after the first settlement, mechanisation

had drastically increased, along with the wealth and population of the State, and developing this waterlogged “wasteland” on a large scale became both more feasible and more financially rewarding. Selective logging in the coastal peat swamps started in the early 1950s, and constituted a key income for the State for 20 years. It continues today, although with declining extraction rates due to the much depleted tree stocks. Prior to the Environmental Quality Act of 1974 (Dolmat, 2005), open burning to clear peat swamp forest was legal, and thus would have been used extensively by smallholder and plantation farmers. After this time, only small controlled burns were permitted by the Department of the Environment, and clearance fires were replaced by large machinery that also drained, compressed and piled peat in preparation for the establishment of oil palm and pulpwood plantations, amongst other land uses. Such modification of the land, in particular the drying caused by drainage, makes peatlands more vulnerable to fire (Page *et al.*, 2002; Hoscilo *et al.*, 2011), whether ignited by natural or anthropogenic sources.

KEY

- - increased precipitation in the Tropics (reduced ENSO)
- - decreased precipitation in the Tropics (intensified ENSO)
- relatively stable climate
- - increased humidity

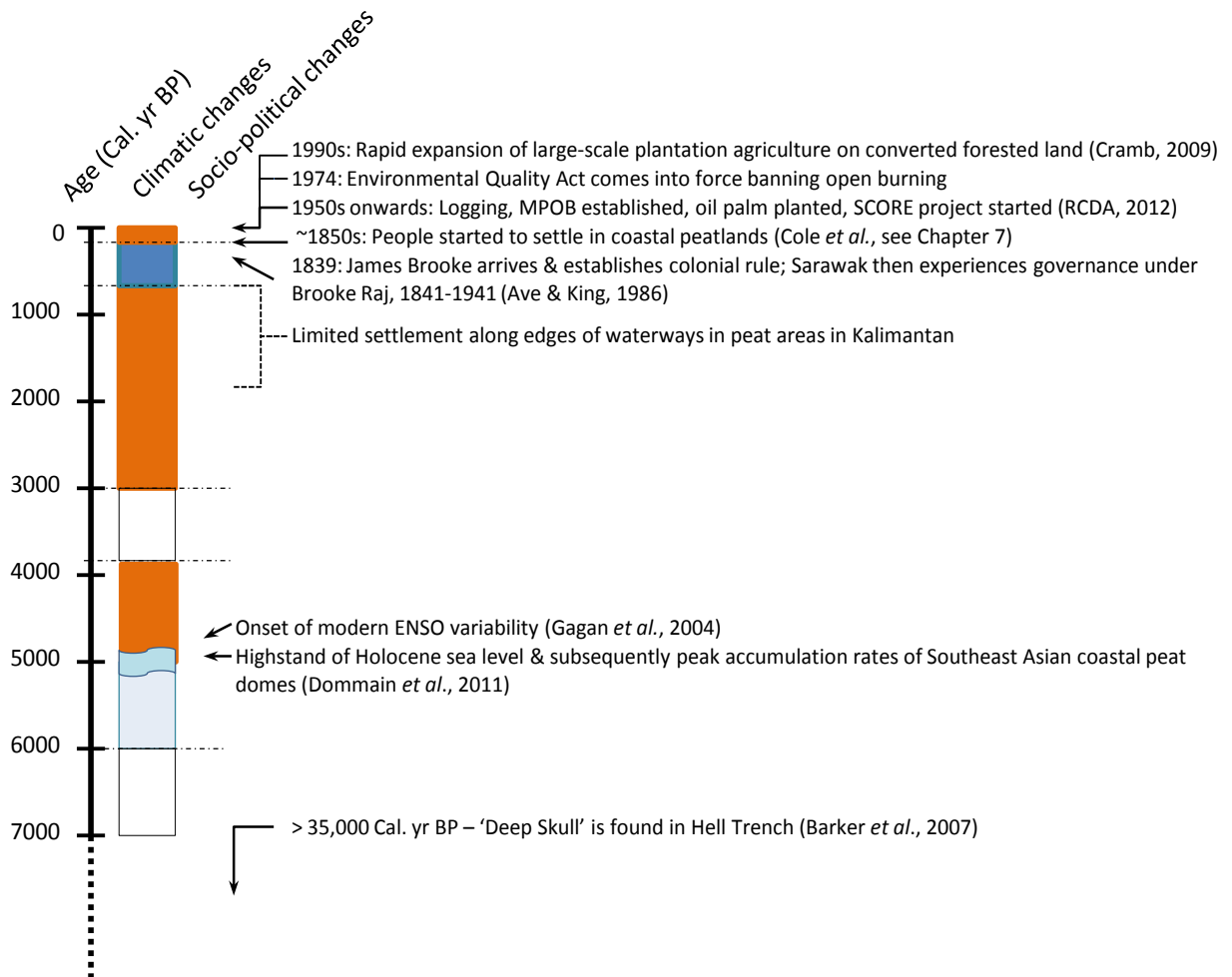


Fig. 5 Independent proxies for significant local and regional climatic and socio-political changes of relevance in Sarawak over the period covered by the sedimentary cores studied. (For a more detailed description of ENSO variability, see Cole *et al.*, *in prep*, Chapter 4. For more information on the history of political development in Sarawak, see Cramb (2009) and references therein.)

Until several hundred years ago, local fires (those within peat swamp forest) would predominantly have been driven by natural disturbances such as lightning strikes, especially during dry climatic periods, i.e. El Niño years (Hope *et al.*, 2005). Human disturbance would have been minimal (Sawal, 2003), restricted to activities such as subsistence sago cultivation: a crop that grows well on marginal lands (Donner, 1987). Within the last 200 years however,

the coincidence of data showing dramatic increases in the magnitude and frequency of local and regional fire (and open areas), with the reporting and documenting of increased human interaction with Sarawak's coastal peat swamp forests, suggests that humans were responsible for these elevations in burning. Significant landscape exploitation by people is likely to have started after Colonial Rule was established in Sarawak approximately 170 years ago. The following quote, attributed to the Second Raj of Sarawak, Charles Brooke, in 1867, illustrates the attitude towards 'idle' forested land that would have driven large-scale landscape conversion: "[We want] to see the jungle falling left and right and people settled over what are now lonely wastes and turning them into cultivated land." The dramatic recent increase in peatland burning has also been recorded in Sumatra (Miettinen *et al.*, 2012c) and across Southeast Asia (Van Eijk *et al.*, 2009).

(ii) *How do the changing fire regimes impact the peat swamp forest vegetation?*

Results from this study suggest that fire has not caused significant disturbance to these three coastal peat swamp forests through time. Even during episodes of elevated burning in the past, for example during the hypothesised dry phase between *c.* 2800 - 1800 Cal. yr BP, there is no decline in the peat swamp forest or apparent impact on the vegetation within these ecosystems. In terms of internal peat swamp forest dynamics through time, the fluctuation between mature and pioneer taxa does not correlate with fire incidence, again suggesting that, in general, burning has not played a significant role in the regeneration of these ecosystems. Since anthropogenic burning is hypothesised to have only started in the last two centuries, it appears that the natural burning regimes in each site, which have been predominantly idiosyncratic, have not had a significant negative impact on these peat swamp forests. An exception to this appears in the results of the Converted Peatland site, where regional fire appears to have a significant impact on peat swamp forest ecosystem abundance within the

wider landscape. Further sampling is required to decipher reasons for this unusual finding in the Converted Peatland site.

In contrast to the long-term burning and peat swamp forest vegetation dynamics, as levels of local and regional fire elevate to historically-novel levels in the most recent past, declines in peat swamp forest within the landscape and an apparent lack of regeneration within the forests, suggests fire is now impacting on these ecosystems. However, the most influential drivers of peat swamp forest change across sites appear to be disturbances associated with anthropogenic activity: open vegetation, signifying forest clearance, and magnetic susceptibility, indicating disturbance and/or drying in the peat substrate. These relationships are strongest in the recent past (Fig. 4), coinciding with and, most probably, driving the large elevations in local and regional fire, as suggested by other studies in this region (Lee, 2000; Langner & Siegert, 2009; Van Eijk *et al.*, 2009). Despite these associations between peat swamp forest and environmental variables, it is important to note that the only significant relationship observed in this study occurs between open vegetation and external landscape change, i.e. a decline in peat swamp forest, in the Converted Peatland site. Further evidence for the predominantly anthropogenic origin of fire within peat swamp forest in the last 200 years, is the coincident increase in ferns, Poaceae and other non-woody taxa of open areas (Hoscilo *et al.*, 2011), such as Ulmaceae's *Trema*. This plant has been associated with the creation of gaps within the peat swamp forest greater than those resulting from local disturbances (Flenley & Butler, 2001), such as wind-throw (Anderson, 1964).

In conjunction, the results from the three studied sedimentary cores strongly suggest that fire has been present in tropical peat swamp forests for thousands of years and that it is not the most prominent driver of long-term or recent changes in coastal peat swamp forest

vegetation, contrary to the common concern expressed in the literature on the sustainable management of tropical peat swamp forests today (for example Razali *et al.*, 2010; Miettinen *et al.*, 2012c). Instead, human impact has had the most influence on internal peat swamp forest dynamics and peat swamp forest decline, and this disturbance has manifested only in the last *c.* 200 years. In reality however, it is likely that forest clearance, drainage and fire occur simultaneously and act synergistically in these landscapes, exacerbating impacts, reducing forest regeneration potential and thus jeopardizing the resilience of these peat swamp forests.

Management implications

The causes of fire are complex, and include underlying cultural, political and socio-economic conditions, not simply environmental factors (Stolle *et al.*, 2003; Langner & Siegert, 2009; Carlson *et al.*, 2012). However, when considering peat swamp forest management, it is important to note that degraded, in comparison to relatively intact peatlands, are more susceptible and fundamentally less resilient to fire (for example Page *et al.*, 2002, Wösten *et al.*, 2008, Hoscilo *et al.*, 2011). The interaction between different drivers of disturbance requires further investigation when considering management interventions.

Draining and/or forest clearing, which accompanies the majority of peat swamp forest land-use change, leads to highly flammable conditions, and inevitably subsidence (Hooijer *et al.*, 2011) and degradation. This often results in peatlands becoming “unmanaged wastelands” or entirely converted to agriculture (Miettinen *et al.*, 2012b). Restoration of such areas is being attempted in peatlands in Central Kalimantan (Page *et al.*, 2009), but unless these areas are protected against fire, notably through re-wetting (Dommain *et al.*, 2010), restoration may prove impossible (Van Eijk *et al.*, 2009).

Contemporary studies have shown that the impacts of local fire within peat swamp forest can be severe: once the substrate is alight, fires can burn both above and, devastatingly, below-ground for many months (Goldammer & Seibert, 1989; Goldammer, 1992; Saharjo & Nurhayati, 2007; Posa *et al.*, 2011), destroying metres of peat. In addition to destroying the current understory vegetation, these fires can hinder regeneration post-fire (Saharjo & Nurhayati, 2007; Cole *et al.*, *in prep*, see Chapter 3) and thus reduce the possibility of future recovery, especially if soil seed banks are disturbed (Posa *et al.*, 2011).

Unusually intense and frequent fires can also disturb natural regeneration cycles, such as those that have burnt in Indonesia's inland peat swamps during the recent extreme drought events of strong El Niño years, exemplified by the 1997-1998 episode (Page *et al.*, 2009). Biomass burning during this period released vast amounts of carbon (between 0.81-2.57 Gt) into the atmosphere (Page *et al.*, 2002). In addition, these fires caused a host of serious health and environmental problems in the region, as well as disrupting economic activity (Aiken, 2004). Although the peatlands of the Southeast Asian coast appear to have been less impacted by these climatic events in the past (Dommain *et al.*, 2011), managing for increased fire risk during dry El Niño years, in conjunction with the effects of more recent land-use change, may help to prevent the disastrous effects that have occurred from repeating in the future (Phua *et al.*, 2007; 2012). Fire hazard mapping, looking at impacts of infrastructure, for example roads and settlement, may also help (Razali *et al.*, 2010), since historical fire incidence in peatlands in Kalimantan has been associated with accessibility (Hope *et al.*, 2005). Furthermore, if the international mechanisms being developed to encourage countries to reduce their carbon emissions through forest conservation, such as the Reducing Emissions from Deforestation and Degradation (REDD+) scheme (see FAO, 2012, for a description of

its relevance to peatlands), are to include tropical peat swamp forests, the huge volumes of carbon gases released from peat fires will need to be abated (Murdiyarso *et al.*, 2010).

If recent elevated trends in burning can be prevented, predominantly through halting forest clearance and drainage, this and other studies (e.g. Hope *et al.*, 2005) provide evidence that peat swamp forests are resilient to less frequent and less intense fire. However, in the face of current conversion rates and future land-use planning in the region (Miettinen *et al.*, 2012b), potential disturbance by fire must be a central consideration in the more sustainable management of these carbon-rich ecosystems.

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SUPPORTING MATERIAL

- i. Sediment & Pollen Preparation & Analysis Techniques
- ii. **Table S1** AMS radiocarbon dates for each core.
- iii. **Fig. S1** Age-depth profiles of (a) DPL, (b) PSF, and (c) CPL.
- iv. **Table S2** Pollen types recorded within each ecological group and descriptions of their key characteristics.
- v. **Fig. S2** Summary pollen diagrams of (a) DPL, (b) PSF, and (c) CPL.
- vi. **Fig. S3** PCA diagrams illustrating relationships between pollen taxa and environmental variables.

i.

Sediment & Pollen Preparation & Analysis Techniques

For each core sequence the sediment stratigraphy was described according to the Troels-Smith classification system (Troels-Smith, 1955). Through measuring the changing mineral magnetic content of a sediment profile, i.e. the relative composition of iron oxides with depth (Gubbins & Bervera, 2008), it is used to determine changes in sedimentary type over time. It can also provide additional evidence for defining chronological units (Yeloff *et al.*, 2006). A Bartington Instruments MS2C Magnetic Susceptibility System with a low-frequency core-scanning loop sensor, in conjunction with MULTISUS 2 software, was used to measure this proxy. Magnetic susceptibility can be used as an indicator of various environmental changes, predominantly those indirectly resulting from climatic change. These include information on: changes in sedimentation regime, erosion events and soil water content, all linked to precipitation (Balsam *et al.*, 2011); burning episodes where soil-charcoal concentrations increase creating a magnetic signal; and information on the organic matter content of the soil. In general, lower and more negative measurements reflect lower density sediments, increased water (Grimley *et al.*, 2008) and increased organic matter content (Hamilton *et al.*, 1986), all indicative of periods of more rapid vegetation growth and thus peat development, potentially coinciding with heightened regional precipitation.

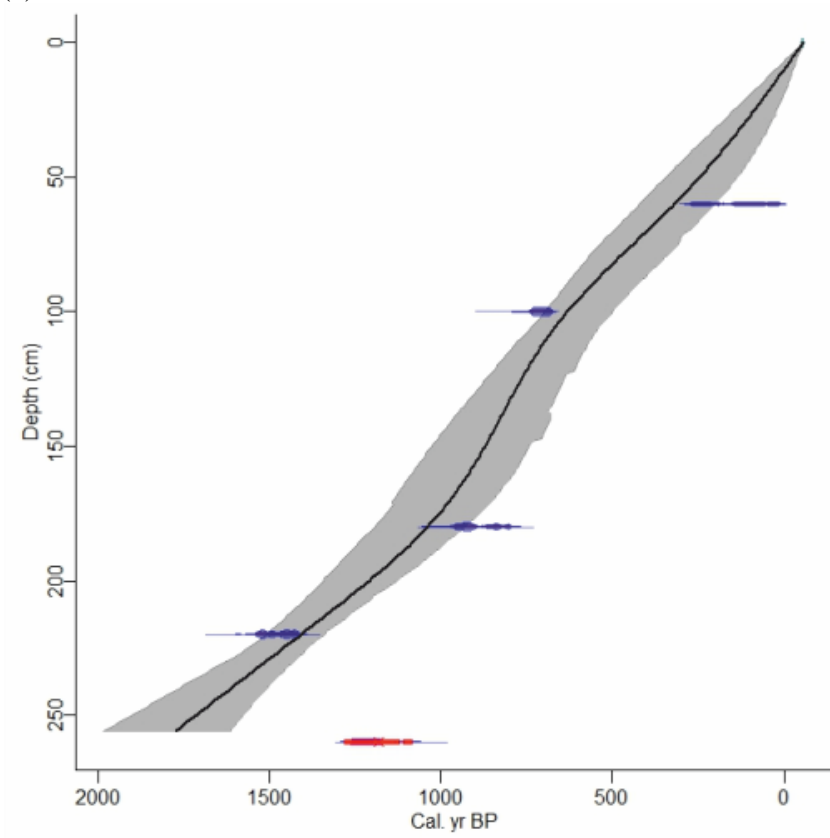
Pollen preparations on the three cores were made from 1 cm³ samples taken at intervals of 8 cm throughout the length of the Deforested Peatland core (with a total length of 285 cm); at 4 cm intervals for the majority of the Peat Swamp Fragment core (total length of 382 cm), and 6 cm and 8 cm intervals towards the top; and at 2 cm intervals for the majority of the Converted Peatland core (total length of 318 cm), and 4 cm, 8 cm and 16 cm intervals towards the base, to minimise the difference of time intervals between samples within and across cores. A Meiji microscope, at 400× magnification, was then used to count a minimum of 300 pollen grains per sampling level, excluding indeterminate pollen (i.e. grains that were deformed, obscured or unidentified). A reference collection was compiled from various sources and published plates used to aid the identification of pollen grains.

ii.

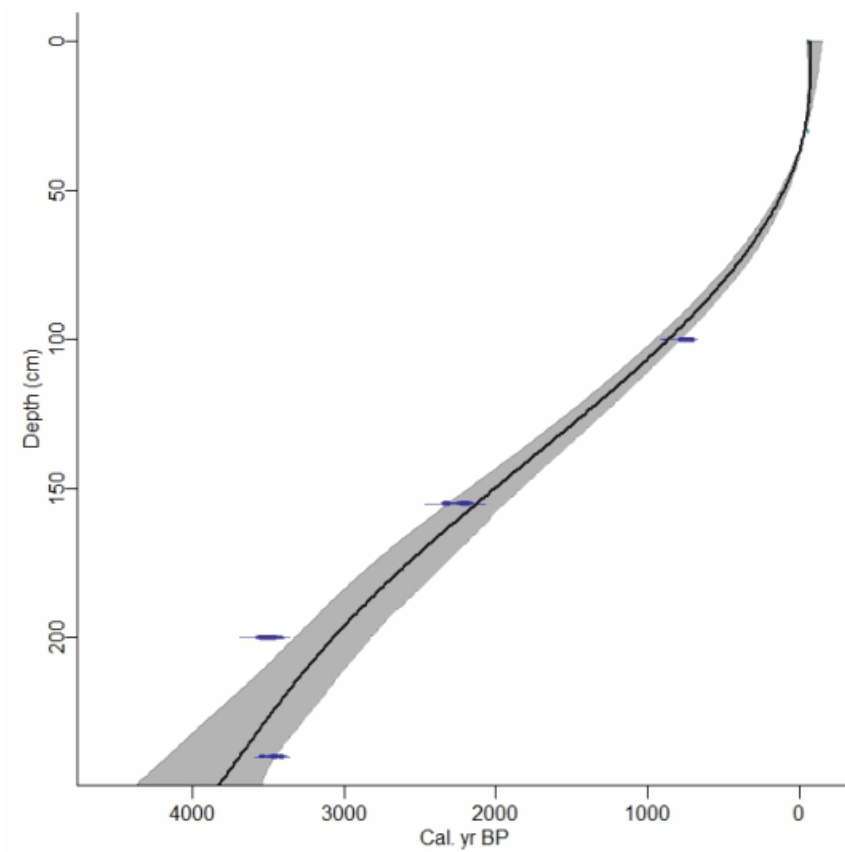
Table S1 Accelerator mass spectrometry (AMS) ^{14}C ages along with calibrated ages for radiocarbon dated samples, calculated using Calib 601, from each core: CPL – Converted Peatland; PSF – Peat Swamp Fragment; DPL – Deforested Peatland. (An age of 50 Cal. yr BP was given to the Peat Swamp Fragment sample taken at 30 cm depth, to approximate a modern date.)

Lab Code	Core	Depth (cm)	^{14}C yr BP	$\delta^{13}\text{C}$ (‰)	Calibrated ages (cal yr BP)	Dated material
SUERC-35243	CPL	30	618 +/-35	-30.2	603 +/-56	soil
UBA-14322	CPL	97	4018 +/-26	-32.8	4475 +/-54	soil
SUERC-35244	CPL	170	4486 +/-35	-29.4	5166 +/-129	soil
SUERC-35245	CPL	225	4884 +/-37	-29.3	5623.5 +/-40.5	soil
UBA-15751	CPL	300	6038 +/-32	-29.7	6880.5 +/-89.5	soil
SUERC-35240	PSF	30	modern	-29.9	50	peat
UBA-15749	PSF	100	841 +/-25	-32.4	741.5 +/-48.5	peat
SUERC-35241	PSF	155	2275 +/-37	-30.2	2209.5 +/-52.5	peat
SUERC-35242	PSF	200	3270 +/-35	-30.7	3506 +/-70	peat
UBA-15129	PSF	240	3242 +/-22	-31.6	3441 +/-46	peat
SUERC-35235	DPL	60	119 +/-37	-29.5	80 +/-70	peat
UBA-15750	DPL	100	797 +/-25	-29.3	708.5 +/-33.5	peat
SUERC-35236	DPL	180	998 +/-37	-29.2	931 +/-40	peat
UBA-15131	DPL	220	1602 +/-25	-26.4	1477 +/-63	peat
SUERC-35239	DPL	260	1260 +/-35	-29.1	1201.5 +/-80.5	sand

iii.
(a)



(b)



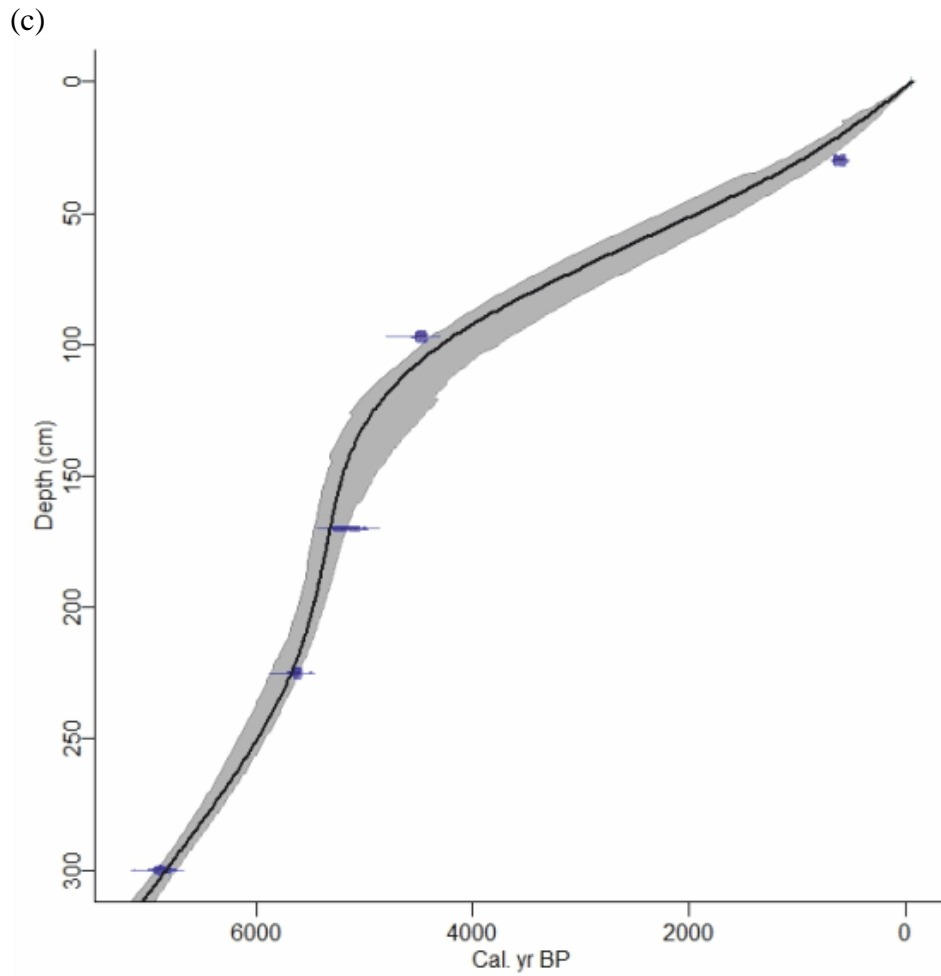


Fig. S1 Age-depth profile of each core: (a) Deforested Peatland, (b) Peat Swamp Fragment, and (c) Converted Peatland. Smoothing spline proved the best-fitting model for each core, with extrapolated basal points in each sequence and surface (0 cm) age set at -55 years. (The final date in the Deforested Peatland site, at 260 cm, has been counted as an outlier, with a radiocarbon date of 1260 ± 35 Cal. yr BP, and discluded in the construction of the age-depth model.)

iv.

Table S2 Ecological groupings of plant taxa identified through fossil pollen analysis, showing the complete list of pollen grains and spores counted and used for past vegetation reconstruction, along with the descriptions of the key characteristics of each group.

Plant family	Pollen taxon	Plant family	Pollen taxon
PEAT SWAMP FOREST (PSF) - if taxa present in peat swamp forest, assumed to be an old-growth forest			
Araceae		Hamelidaceae	<i>Altingia</i>
Arecaceae	<i>Calamus</i>	Icacinaceae	<i>Stemonurus</i>
	<i>Cyrtosperma</i>		Icacinaceae type
	Arecaceae type	Lamiaceae	<i>Salvia</i>
Alangiaceae	<i>Alangium</i>	Lauraceae	<i>Litsea</i>
Anacardiaceae	<i>Camptosperma</i> sim	Loganiaceae	<i>Fagraea</i>
	<i>Melanorrhoea</i> comp		<i>Fagraea</i> sim
Anacardiaceae	Anacardiaceae type	Loranthaceae	Loranthaceae type
Anisophyllaceae/ Rhizophoraceae	<i>Combretocarpus</i>	Meliaceae	<i>Aglaia</i> sim
	<i>Combretocarpus</i> sim		<i>Trichilia</i> sim
	<i>4-colporate</i>	Moraceae	<i>Artocarpus</i>
	Anisophyllaceae type	Myristicaceae	Myristicaceae type
Apocynaceae	Apocynaceae type	Myrsinaceae	<i>Rapanea</i>
Aquifoliaceae	<i>Ilex</i>	Orchidaceae	
Araliaceae	<i>Schefflera</i> sim	Pandanaceae	<i>Pandanus</i>
	Rutaceae type	Podocarpaceae	<i>Dacrydium</i>
	Araliaceae type	Polygalaceae	Polygalaceae type
Burseraceae	Burseraceae type	Rhamnaceae	Rhamnaceae type
Casuarinaceae	<i>Casuarina</i>	Rhizophoraceae	Rhizophoraceae type
Celastraceae	<i>Lophopetalum</i>	Rosaceae	<i>Parastemon</i>
	Celastraceae type		Rosaceae type
Crypteroniaceae	<i>Dactylocladus</i>		Rosaceae/Sterculiaceae type
Cunoniaceae	<i>Weinmannia</i>	Rubiaceae	<i>Gardenia</i>
Dipterocarpaceae	<i>Shorea</i> sim		<i>Ixora</i>
	Dipterocarpaceae type		<i>Ixora</i> type
	Dipterocarpaceae Fagaceae type		<i>Nauclea</i>
	Dipterocarpaceae		<i>Nauclea</i> sim
	Menispermaceae type		<i>Tarenna</i> sim
Ebenaceae	<i>Diospyros</i>		<i>Thyasanospermum</i>
	<i>Diospyros</i> sim		<i>Timonius</i>
	Ebenaceae Fagaceae		<i>Timonius</i> sim
	<i>Diospyros</i> type		<i>Uncaria</i>
Euphorbiaceae	<i>Blumeodendron</i>		<i>Melicope</i>
	<i>Cephalomappa</i> sim	Rutaceae	<i>Tetractomia</i> sim
	<i>Glochidion</i>		<i>Palaquium</i>
	Euphorbiaceae type	Sapotaceae	<i>Palaquium</i> comp
Fabaceae	<i>Albizia</i> comp		<i>Planchonella</i> comp
	<i>Archidendron</i>		Sapotaceae type
	<i>Copaifera</i>		<i>Reevesia</i>
	<i>Copaifera</i> comp	Sterculiaceae	Sterculiaceae type
	<i>Koompassia</i>		
	<i>Koompassia</i> sim		

Plant family	Pollen taxon	Plant family	Pollen taxon
Fagaceae	<i>Castanopsis</i> Fagaceae type	Theaceae	<i>Eurya</i> Theaceae type
Flacourtiaceae	<i>Casearia</i> <i>Casearia</i> sim	Thymeliaceae	<i>Gonystylus</i>
Guttiferae	<i>Callophylum</i> <i>Callophylum</i> sim <i>Cratoxylon</i> sim <i>Garcinia</i> Guttiferae <i>Cratoxylon</i> Theaceae type	Tiliaceae	Tiliaceae type
		Trigoniaceae	<i>Trigoniastrum</i> Trigoniaceae type

PEAT SWAMP FOREST pioneers (PSF+) - if taxa increases in abundance in pollen diagram, indicates early successional plant community of secondary peat swamp forest

Acanthaceae		Menispermaceae	<i>Fibraurea</i>
Annonaceae	Annonaceae type		<i>Fibraurea</i> sim
Elaeocarpaceae	<i>Elaeocarpus</i> <i>Elaeocarpus</i> sim Elaeocarpaceae type	Moraceae	<i>Ficus</i>
		Myrtaceae	<i>Syzygium</i> Myrtaceae type
Euphorbiaceae	<i>Baccaurea</i> <i>Baccaurea</i> comp <i>Macaranga</i> <i>Macaranga</i> sim <i>Mallotus</i> <i>Mallotus</i> type	Piperaceae	<i>Piper</i>
		Sapindaceae	<i>Dodonea</i> <i>Pometia</i> comp Sapindaceae type
		Ulmaceae	<i>Trema</i>
		Verbenaceae	Verbenaceae type
		Vitaceae	<i>Cayratia</i>

DEGRADED PEAT (DP) - taxa not found in older-growth peat swamp forest or found in greater abundance in disturbed areas of peat where the forest canopy is open

Asteraceae	Asteraceae type	Lecythidaceae	<i>Barringtonia</i> type
Celastraceae	<i>Bhesa</i> sim	Melastomataceae	<i>Melastoma</i>
Dilleniaceae	<i>Dillenia</i> <i>Dillenia</i> sim	Rutaceae	<i>Euodia</i> <i>Euodia</i> sim
Escallionaceae	<i>Polyosma</i> sim	Smilacaceae	<i>Smilax</i>
Fabaceae	<i>Uraria</i> <i>Uraria</i> sim	Urticaceae	<i>Poikilospermum</i>

OTHER FOREST (OF) - other forest (non-peat swamp forest taxa), e.g. swamp forest or forest on mineral soils

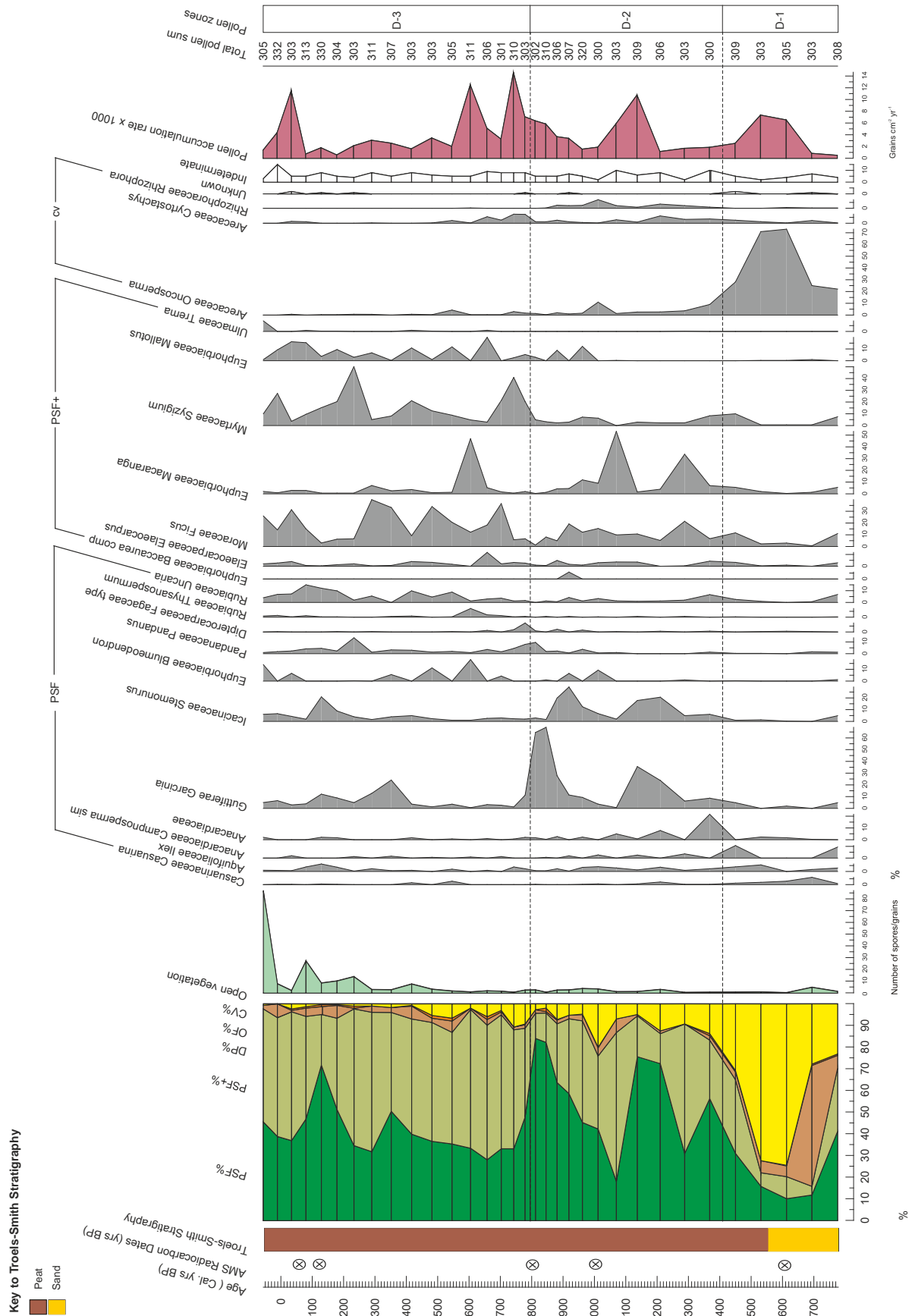
Asclepidiaceae	<i>Dischidia</i>	Myrsinaceae	<i>Ardisia</i> sim
Bombacaceae	<i>Durian</i> comp Bombacaceae type	Rosaceae	<i>Rubus</i> <i>Rubus</i> sim Rosaceae type
Combretaceae		Symplocaceae	<i>Symplocos</i> <i>Symplocos</i> type
Cycadaceae	<i>Cycas</i>		
Ericaceae	<i>Rhododendron</i>	Theaceae	<i>Eurya</i> sim
Icacinaceae	<i>Platea</i> Icacinaceae type	Vitaceae	<i>Ampelocissus</i> sim
	Juglandaceae Myrtaceae type		

Plant family	Pollen taxon	Plant family	Pollen taxon
COASTAL VEGETATION (CV) - coastal vegetation associated with succession to peat from mangrove/littoral habitat type			
Acanthaceae	Acanthaceae type	Pteridaceae	<i>Acrostichum</i>
Arecaceae	<i>Cyrtostachys</i>	Rhizophoraceae	<i>Ceriops</i> sim
	<i>Oncosperma</i>		<i>Rhizophora</i>
	<i>Oncosperma</i> sim		<i>Rhizophora</i> type
Avicenniaceae	<i>Avicennia</i>	Simaroubiaceae	<i>Quassia</i>
Combretaceae	<i>Lumnitzera</i>		<i>Quassia</i> sim
Malvaceae	<i>Hibiscus</i>	Sonneratiaceae	<i>Sonneratia</i>
	Malvaceae type		
Ochnaceae	<i>Brackenridgea</i>		
	<i>Brackenridgea</i> sim		
	Ochnaceae type		
DISTURBANCE TAXA - disturbance tolerant vegetation indicative of open environments (not included in pollen sum)			
Poaceae		Lygodiaceae	
Cyperaceae		Cyathaceae	
Monolete		Trilete	
Lycopodiaceae	<i>Lycopodium cernuum</i>		
	<i>Lycopodium phlegmaria</i>		

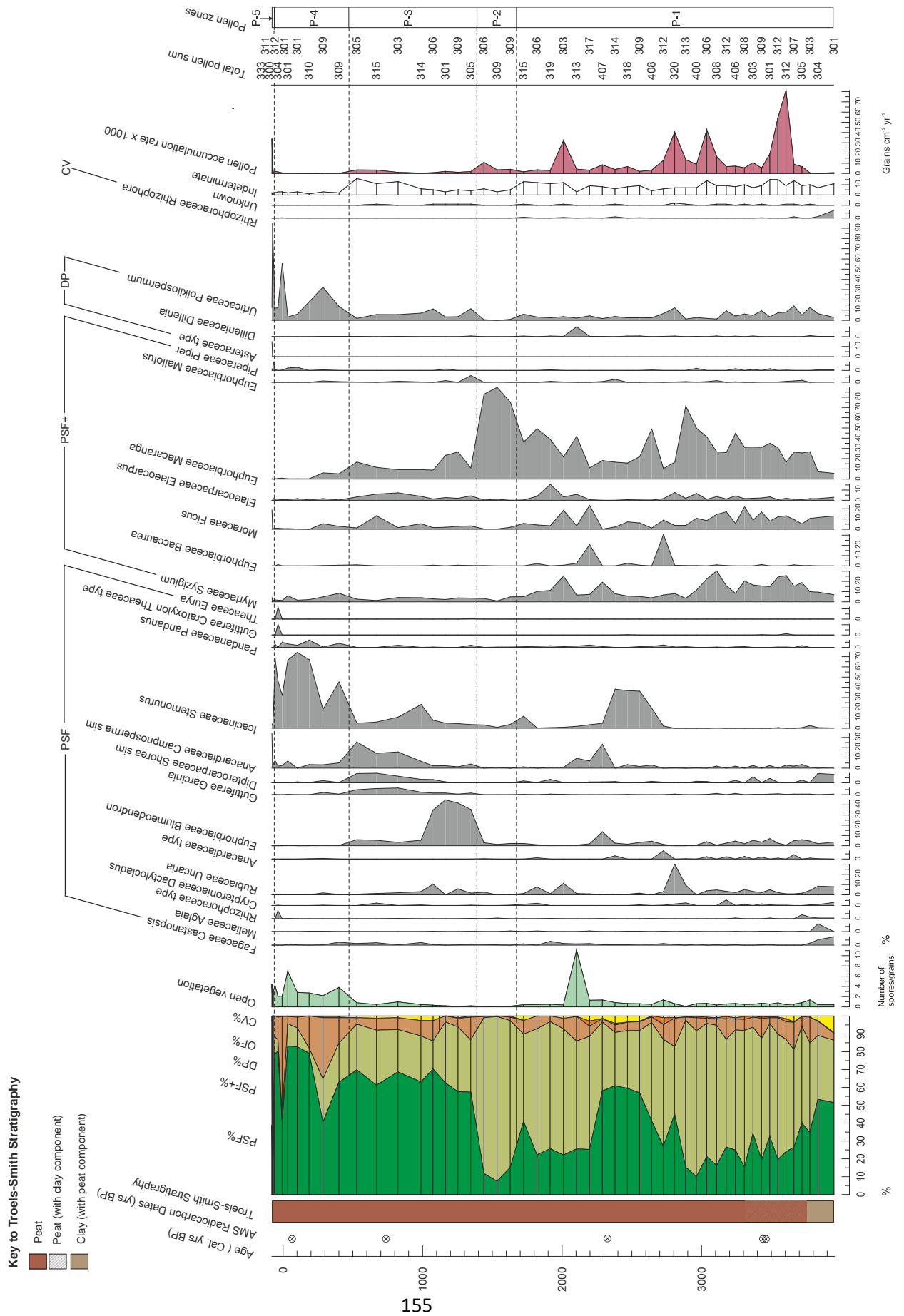
Fig. S2 Summary pollen diagram of each site: (a) Deforested Peatland, (b) Peat Swamp Fragment, and (c) Converted Peatland. Only pollen taxa that contribute >0.05% to the pollen sum, at any one level, are included. (For full list of taxa see Table S2, Appendix (iv)). Terminology for pollen types identified follows that used by Benninghoff and Kapp (1962) to reflect the level of certainty: ‘comp’ indicates a grain that is almost certainly the same as the reference taxon; ‘sim’, one that is more similar to the reference taxon than any other known reference taxa, but there is less certainty in the association; and ‘type’, a grain corresponds with one morphology within a polymorphic taxonomic unit. Major ecological groups are represented by the following colours: PSF dark green, PSF+ light green, DP brown, OF orange and CV yellow. TotPSF% comprises the sum of PSF% and PSF+%.

(v)

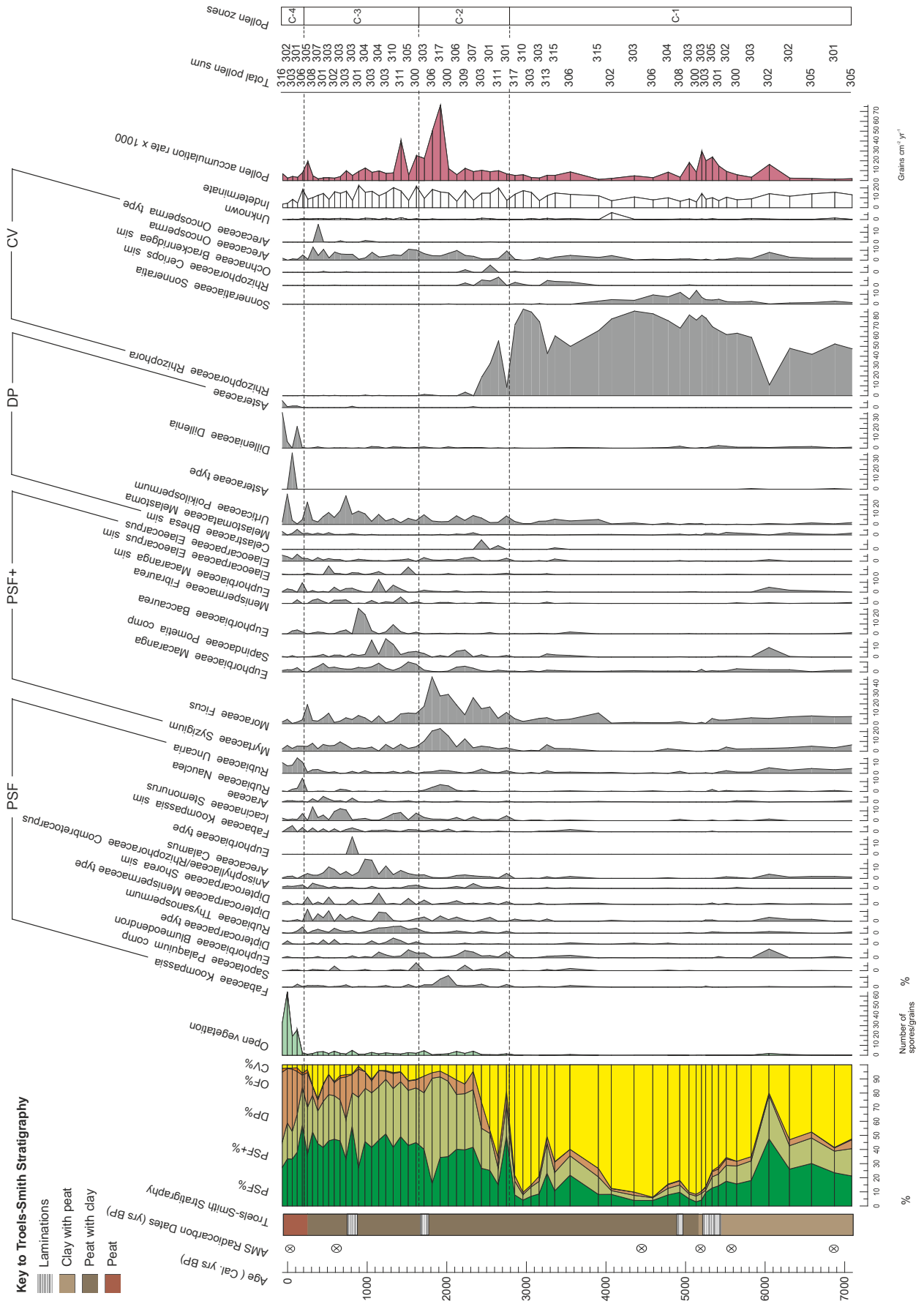
(a) Deforested Peatland



(b) Peat Swamp Fragment



(c) Converted Peatland



(vi)

(a)

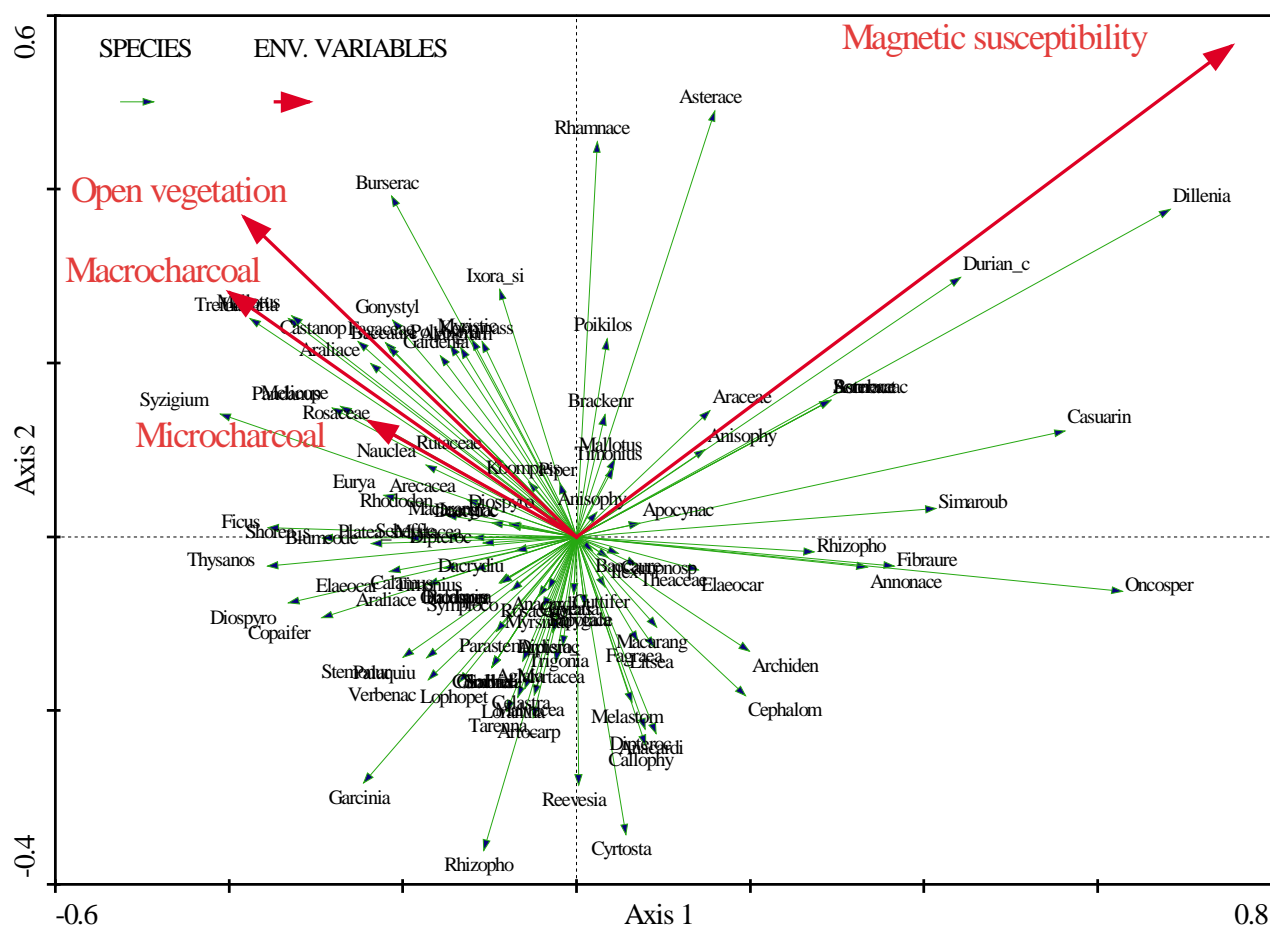
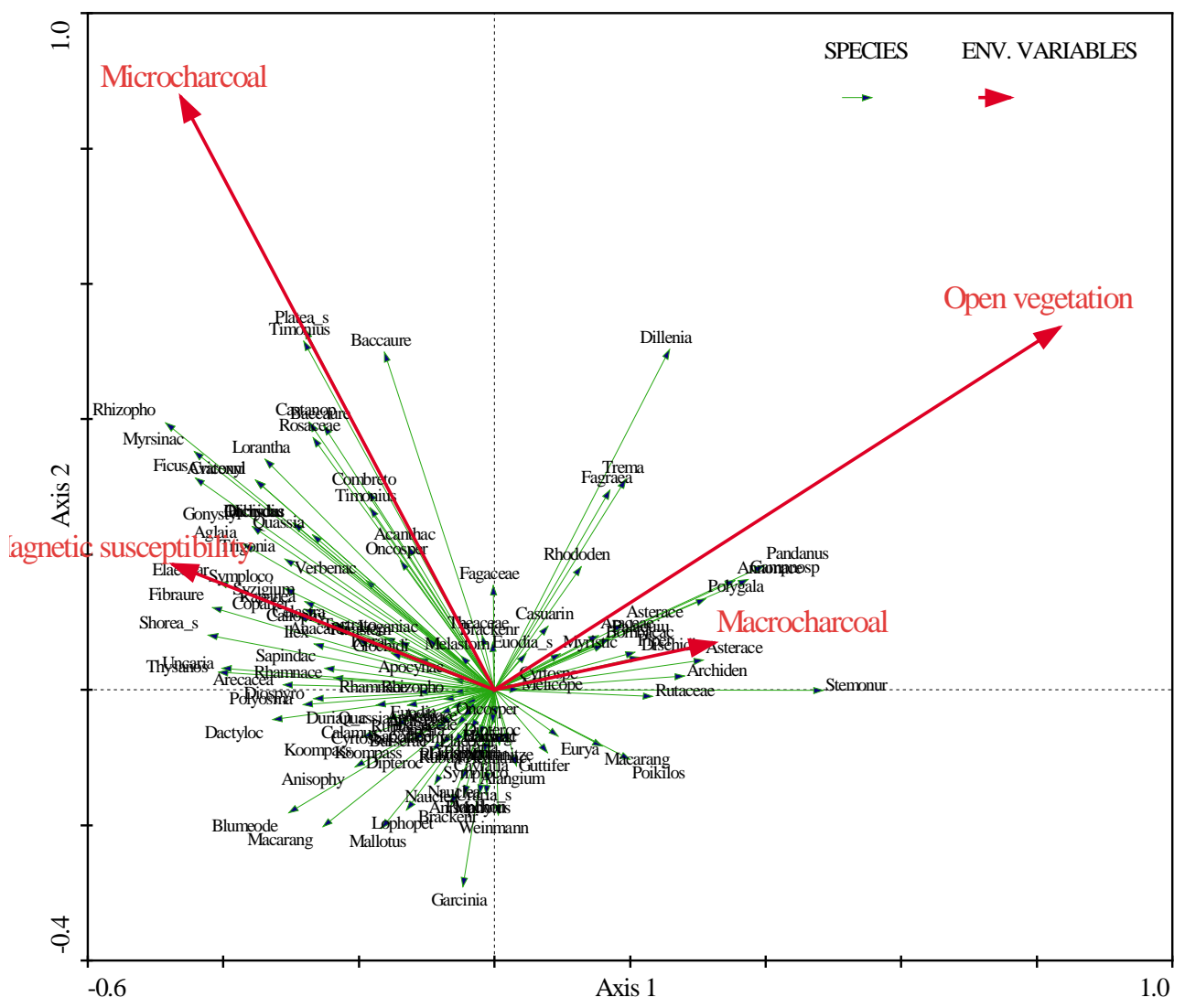
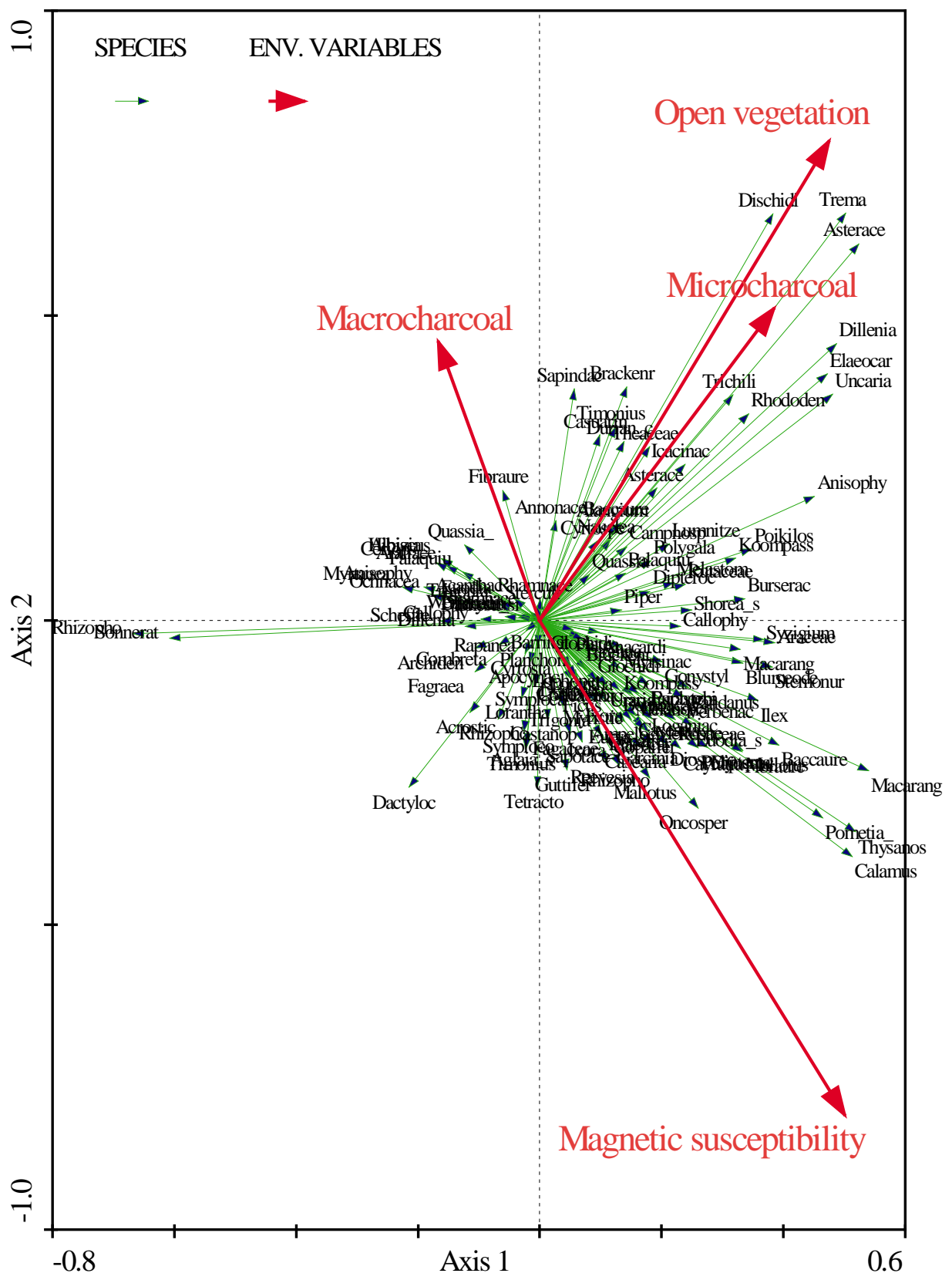


Fig. S3 Ordination diagrams for coring sites (a) Deforested Peatland, (b) Peat Swamp Fragment, and (c) Converted Peatland, showing the relationships between the recorded environmental variables (i.e. macrocharcoal, microcharcoal, magnetic susceptibility and open vegetation), and all counted pollen taxa (excluding fern spores, Poaceae and Cyperaceae). See Table S2, Appendix (iv), for full names of taxa.) In (a), the 1st axis of the ordination explains 11.8% of the variance in the distribution of the ecological groups and the 2nd axis, 3.3%; with the inclusion of environmental variables, this percentage variance accounted for by the 1st and 2nd axes becomes 59.2% and 16.8%, respectively. In (b), 10.1% variance is attributed to the 1st axis and 3.2% to the 2nd axis, with the explained variance increasing to 56.8% and 7.8%, respectively, when environmental variables are accounted for in the assessment of directional distribution of taxa. In (c), 21.5% and 3.3% are due to the 1st and 2nd axes, and 79.1% and 12.2%, respectively, when environmental variables are included.

b)



(c)





CHAPTER 6

PAPER 5: LONG-TERM DISTURBANCE DYNAMICS, RECOVERY AND RESILIENCE OF TROPICAL PEAT SWAMP FORESTS IN MALAYSIAN BORNEO

Cole, L.E.S.¹, S.A. Bhagwat.² and Willis, K.J.³

¹Oxford Long-term Ecology Laboratory, Department of Zoology, University of Oxford, Oxford, United Kingdom

²School of Geography and the Environment, University of Oxford, Oxford, United Kingdom

³Biodiversity Institute, Oxford Martin School, Department of Zoology, University of Oxford, Oxford, United Kingdom

Corresponding author: Lydia Cole, tel: 01865 281321, fax: 01865 271249,

lydia.cole@zoo.ox.ac.uk

Key words peat swamp forest, long-term ecology, disturbance dynamics, Sarawak, resilience, fossil pollen, vegetation change, fire, climate change, sustainable management

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ABSTRACT

The coastal peat swamp forests of Sarawak, Malaysian Borneo, are rapidly undergoing logging and conversion into oil palm plantations. Peat swamp forest ecosystems are assumed to have experienced little significant natural or anthropogenic disturbance in the past, persisting under a single ecologically-stable regime. However, the long-term disturbance regime of peat swamp forests has been poorly assessed, and little is known of their resilience to internal and external stresses. Have peat swamp forests been disturbed in the past? What were the drivers? How did the vegetation respond? In order to answer these questions, three peat sedimentary sequences were extracted from coastal peat swamp habitats in Sarawak, Malaysian Borneo, and their ecology reconstructed using palaeoecological techniques. These long-term ecological datasets were used to examine past disturbance events and vegetation responses, in order to characterise the disturbance dynamics of these peat swamp forests through time. Results from this study indicate that forest has been the dominant vegetation type in these ecosystems throughout the length of the records (post-initiation of peat swamp development), demonstrating resilience to episodes of burning and climatic change in the late Holocene. Only recent increases in fire and human impact appear to be challenging the persistence of these peat swamp forest communities. Evidence that recent, and historically-novel, anthropogenic disturbance is altering this ecosystem is important knowledge for developing more sustainable peatland management strategies.

Introduction

Southeast Asia's peat swamp forests are globally important ecosystems, storing approximately 20% of the World's terrestrial carbon (Gopal, 2012) as well as supporting a wide diversity of floral, faunal and human communities (Silvius & Giesen, 1996; Ewel, 2010; Yule, 2010). Despite this, relatively little is known about how these ecosystems have

changed through time, and how sensitive they are to internal and external disturbances. This is especially so for the peatlands of Sarawak in northern Borneo (Liong & Siong, 1979), where over 80% of Malaysia's peat swamp forests are found (Page *et al.*, 1999). Very few studies exist that document their longevity or dynamics through time (for example Anderson, 1964; Anderson & Muller, 1975; Morley, 1981; Yulianto *et al.*, 2005).

Sarawak's coastal peat swamps accommodate some of the last intact Dipterocarp forests, containing valuable tree species such as *Shorea albida* (Dipterocarpaceae) and ramin, *Gonystylus bancanus* (Thymeliaceae) (IUCN, 1996), and provide a number of ecosystem services. Locally, they act as a buffer against flooding and drought (Andriessse, 1988), prevent saline water intrusion (Liong & Siong, 1979; Phillips, 1998), and provide a source of non-timber forest products, such as latex, resins, fish, fruit, tannins, dyes, and sago palm, *Metroxylon sagu*, as well as other more indirect services for communities (Silvius & Giesen, 1996; Cole *et al.*, *in prep*, see Chapter 7). Globally, they represent a vast CO₂ sink and are becoming increasingly important as potential revenue streams and strategies are being developed to manage carbon emissions (Page *et al.*, 2011). However, it is widely recognised that this is a vulnerable ecosystem (Page *et al.*, 2004) and activities that disrupt the tight interrelationship between peat, water and vegetation (Dommain *et al.*, 2010), could shift the system from a vast sink into a vast source of greenhouse gases. Changes in future climate, especially reduced regional precipitation (Li *et al.*, 2007), and land-use, may also contribute to such a shift (for example see Fargione *et al.* (2008) for an illustration of the carbon debt generated through palm oil production from plantations established in Southeast Asian peatlands).

In the peat swamp forests of Sarawak, deforestation rates are up to 12 times greater than those across Asia (SarVision, 2011), and approximately 25% higher than those in the island's lowland dipterocarp forest (Langner *et al.*, 2007). Peatlands are described as the final frontier for agricultural expansion (Koh *et al.*, 2011). Most recently this has been driven by the pulpwood industry and the rapid growth of the palm oil market (Murdiyarso *et al.*, 2010; Miettinen *et al.*, 2012b), as well as State development initiatives, such as Sarawak Corridor of Renewable Energy (SCORE) (RCDA, 2012). For example, between 2005 and 2010, 65% of peat swamp forest conversion in Sarawak was attributed to oil palm plantation development (SarVision, 2011). Prior to this, evidence suggests that people did not practice shifting cultivation or permanently settle in these ecosystems (Verhagen *et al.*, 2004), mostly due to the waterlogged nature of the landscape (IUCN, 1996), despite the extensive history of human presence and ecological degradation in other parts of Borneo (Flenley, 1988; Anshari *et al.*, 2004; Hunt & Rushworth, 2005; Yulianto *et al.*, 2005; Hunt & Premathilake, 2012).

In the face of today's high rates of tropical peat swamp forest conversion, if these forests are to persist it is important to understand what impact such disturbance is having on the long-term functioning of these ecosystems and what potential there is for their recovery once the perturbation has been removed. Oil palm plantations, for example, usually follow a 25 year cycle of planting, after which they are either replanted with young palms or abandoned, since the plantation is no longer profitable (Henson, 2006). If abandonment does happen at this point, a key question that needs to be addressed is whether the degraded peatlands can recover from this disturbance and the peat swamp forest re-establish. Other important questions include those seeking knowledge on the response of peat swamp forests to different forms of disturbance, and the rate at which they can recover. Such information is not only

critical for managing these areas for agriculture and conservation, but also for the modelling and prediction of the current and future carbon storage potential of these lands.

One driver of disturbance that greatly impacts on the carbon stored in peatlands, yet is a natural form of perturbation central to the dynamics of all forest ecosystems (Pausas & Keeley, 2009), is fire. When this driver, as well as others, elevate to a larger-scale, spatially and temporally, and reach historically-unique levels to which the vegetation has not co-evolved, the issue of resilience, i.e. “the ability of an ecosystem to maintain its structure and function despite disturbance” (Holling, 1973), comes into the fore. A loss of resilience occurs when an ecosystem is disturbed beyond its threshold, causing it to shift into an alternative state (Ficetola & Denöel, 2009; Bhagwat *et al.*, 2012) from which passage back to the original vegetation type may be prevented by extreme physical or ecological change (Scheffer & Carpenter, 2003). Understanding the disturbance dynamics of these oft-described ‘fragile’ peat swamp forests represents a large knowledge gap.

This study takes a palaeoecological approach to examine the disturbance dynamics of the tropical coastal peat swamp forests of Sarawak. Palaeoecology utilises proxies, such as fossil pollen, sedimentary isotopes and micro- and macrofossil charcoal, to extend the scope of ecological studies to past ecosystems (Rull, 2010). Peat swamps are excellent repositories of such multiple proxies, storing information on environmental and climatic changes in an area through time (Barber, 1993; Zhao *et al.*, 2007; Zhu *et al.*, 2010). This is especially useful when trying to establish patterns of human precipitated disturbance, especially in these coastal peatlands where surface archaeology is lacking (Hunt & Rushworth, 2005), and in assessing patterns of biodiversity change in the face of current rapid species loss (Willis *et al.* 2010) and climatic changes (Dawson *et al.* 2011).

The aim of this study is to investigate the disturbance dynamics of the highly threatened coastal peat swamp forests of Sarawak. In particular, we ask: (a) How has the vegetation of these peat swamp forests changed through time?; (b) What indicators of past disturbance are there and when? (with a focus on fire, climatic and human drivers), and (c) How did the peat swamp forest vegetation respond to these disturbances? Understanding the impact that different disturbances have had on the dynamics of these peat swamp forests in the past, and specifically how quickly and to what extent they have recovered after the disturbance has stopped, is vital for managing this carbon, biodiversity and human resources reservoir (Gardner *et al.*, 2007) and for modelling how this ecosystem will respond to future global change (Haberle *et al.*, 2010).

Modern environmental setting

The peat swamp forests of Sarawak, one of the two East Malaysian States in northern Borneo (Fig. 1), are predominantly found along the coast, covering approximately 13% of the State's land area (Wetlands International, 2010). Northern Borneo is described as having a tropical ever-wet climate (Morley & Flenley, 1987) with an average temperature of 25°C, an average annual rainfall exceeding 370 cm and humidity levels ranging from 55% in the daytime to almost 100% at night. Sarawak experiences very little seasonality, with the exception of the monsoon period falling somewhere between October and May (Sawal, 2003). These environmental conditions are important for the development of peat (Staub & Gastaldo, 2003): a soil that comprises $\geq 65\%$ organic matter (USDA, 1975), is ≥ 50 cm in depth and at least one hectare in area (Liong & Siong, 1979). There is a tight interrelationship between peat soil accumulation, vegetation and hydrological conditions (Dommain *et al.*, 2010; Posa *et al.*, 2011), making the forest component of this ecosystem vital for its maintenance, and the whole system more vulnerable to disturbance caused by deforestation than other forest types.

Peat swamp forests house a range of species, capable of tolerating the high acidity, low nutrient availability and waterlogged nature of this habitat (Ewel, 2010; Posa *et al.*, 2011).

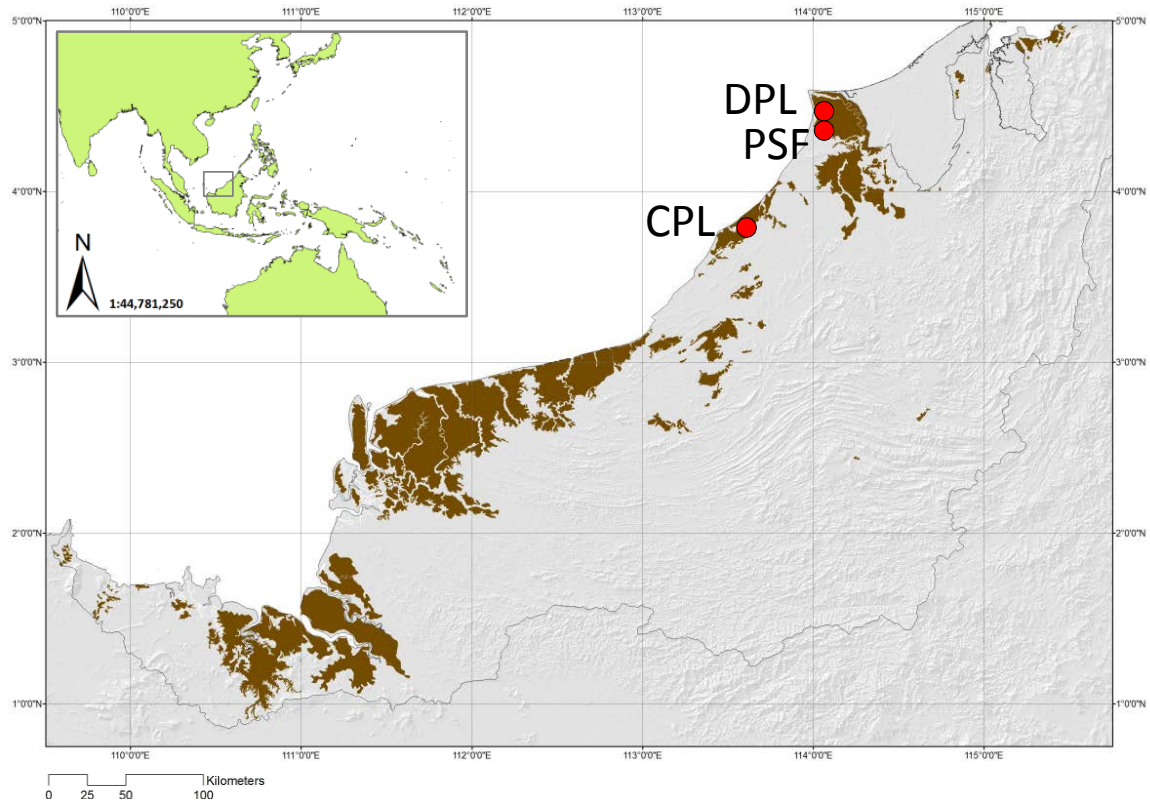


Fig. 1 Map showing the geographical location of Sarawak, Malaysian Borneo (inner box), within Southeast Asia, and the three peat swamp sites from which cores were extracted: DPL, PSF and CPL. (Peatlands shown in brown. Image courtesy of SarVision, 2011.)

Materials and methods

Data Collection

Three sets of sedimentary cores, comprising continuous overlapping sequences, were extracted using a hand-held coring device in October 2009, from the interior of three peat areas across the Miri and Batu Niah Districts of north-east Sarawak: Deforested Peatland from Senadin, Kuala Baram; Peat Swamp Fragment from Sungai Dua Forest Reserve; and Converted Peatland from Sungai Niah (Table 1). Core sediment sections of 50 cm were

recovered until the majority of material extracted was no longer peat. Sections were then wrapped in thin plastic film and tin foil, and kept out of light and below 5°C where possible, to prevent sample contamination, drying or decomposition and to promote pollen preservation. All material was transported back to the Long Term Ecology laboratory at Oxford University, UK, for analysis.

Table 1 Details of the coring sites and basic core attributes. (Deforested Peatland (DPL); Peat Swamp Fragment (PSF), and Converted Peatland (CPL).)

Site I.D.	Site Name	Lat. Long.	Elevation (m)	Land-use type	Vegetation type	Length of core (cm)	No. sub-samples
DPL	Deforested Peatland	04°30'47"N, 114°2'47"E (4.513056, 114.046389)	11	Large area of fire-prone semi-drained peatland	Open, Cyperaceae & fern dominated	285	33
PSF	Peat Swamp Fragment	04°21'24"N, 114°0'21"E (4.356667, 114.005833)	17	Small patch of peat swamp forest on outskirts of Miri town	Closed, peat swamp tree dominated	382	52
CPL	Converted Peatland	03°52'4"N, 113°42'43"E (3.867778, 113.711944)	6	Fallow land adjacent to small paddy plot & oil palm plantation	Open with small forest patches, herb & grass dominated	318	61

Palaeoecological analysis

For each core sequence the sediment stratigraphy was described according to the Troels-Smith classification system (Troels-Smith, 1955). This is used to determine changes in sedimentation form over time and can be used to provide additional evidence for defining chronological units (Yeloff *et al.*, 2006). Magnetic susceptibility, the relative composition of iron oxides with depth (Gubbins & Bervera, 2008), was then recorded using a Bartington Instruments MS2C Magnetic Susceptibility System with a low-frequency core-scanning loop sensor, in conjunction with MULTISUS 2 software. Magnetic susceptibility can be used as a proxy for several environmental phenomena and disturbances, mostly all indirectly resulting

from climatic change. These include information on: changes in sedimentation regime, erosion events and soil water content, all linked to precipitation (Balsam *et al.*, 2011); burning episodes where soil-charcoal concentrations increase creating a magnetic signal; and information on the organic matter content of the soil. In general, lower and more negative measurements reflect lower density, increased water (Grimley *et al.*, 2008) and organic matter content (Hamilton *et al.*, 1986), indicating a period of more rapid vegetation growth and thus peat development, potentially coinciding with heightened regional precipitation. Using standard techniques (Bennett & Willis, 2001), fossil pollen was extracted from each sedimentary core at regular intervals (see Supplementary Material). A known concentration of spores of the exotic species, *Lycopodium*, was added to all samples in order to determine pollen concentration. Using a Meiji microscope, at 400× magnification, a minimum of 300 pollen grains was counted per sampling level, excluding indeterminate pollen (i.e. grains that were deformed, obscured or unidentified). Microcharcoal was counted simultaneously on the pollen slides, according to Clark's point count method (Clark, 1982), and macrocharcoal content was determined using a light microscope, at the same intervals as fossil pollen, in order to broadly reconstruct regional and local fire events respectively (Clark, 1988).

Reference collections for pollen identification were gathered from Queen's University Belfast, The Royal Botanical Gardens in Kew, the Plant Sciences Department in Oxford, and from within Oxford University's Long-Term Ecology Laboratory. The Pollen Flora of Taiwan (Huang, 1972), and plates found in Stuijts (1993) and Anderson and Muller (1975) were also used for identification of grains. Due to the diversity of species in the peat swamp flora and differing levels of pollen production, taxa identified through pollen counting were allocated to ecological groups (Table 2) to aid interpretation of the palaeo-plant communities (for example Muller, 1963), using the Checklist of Coode *et al.* (1996), as well as various

other publications from the region (Anderson, 1964; 1980; Stuijts, 1993; Anshari *et al.*, 2001; 2004). The identification of the majority of plant taxa was not resolved beyond generic level, as is common amongst palaeoecological studies in tropical regions (for example Muller, 1963; Anshari *et al.*, 2004). Thus the system of notation developed by Benninghoff and Kapp (1962) has been used to reflect the level of certainty in the identifications made: ‘comp’ indicates a grain that is almost certainly the same as the reference taxon; ‘sim’, one that is more similar to the reference taxon than any other known reference taxa, but there is less certainty in the association; and ‘type’, a grain corresponds with one morphology within a polymorphic taxonomic unit (Fig. 3).

Table 2 Definition of ecological groups, acronyms used, and key indicator taxa, identified through fossil pollen analysis, used to reconstruct past vegetation dynamics. (For a complete list of fossil pollen grains and spores counted, see Table S1, Appendix 1.)

Ecological			
Group	Name	Explanation	Major plant taxa
PSF	peat swamp forest	mature taxa of peat swamp forest, assumed to grow in old-growth forest	<i>Combretocarpus</i> (Anisophyllaceae), <i>Shorea</i> (Dipterocarpaceae), <i>Stemonurus</i> (Icacinaeae)
PSF+	peat swamp forest – pioneers	pioneer taxa of peat swamp forest, indicating an early successional plant community	<i>Elaeocarpus</i> (Elaeocarpaceae), <i>Macaranga</i> (Euphorbiaceae), <i>Ficus</i> (Moraceae)
TotPSF	peat swamp forest	mature and pioneer taxa of peat swamp forest	(see above)
DP	degraded peat	taxa not found in older-growth peat swamp forest or in greater abundance in disturbed areas of peat where the vegetation is open	<i>Dillenia</i> (Dilleniaceae), <i>Poikilospermum</i> (Urticaceae)
CV	coastal vegetation	coastal vegetation associated with succession to peat from mangrove/littoral habitat types	<i>Oncosperma</i> (Arecaceae), <i>Sonneratia</i> (Sonneratiaceae)
OF	other forest	other forest (non-peat swamp forest taxa), e.g. swamp forest or forest on mineral soils	<i>Terminalia</i> (Combretaceae), <i>Rubus</i> (Rosaceae)
OP	open vegetation	disturbance tolerant vegetation indicative of open environments greater than tree-fall gaps, not included in pollen sum	Monoletes, Triletes, Poaceae, Cyperaceae

Bulk sediment samples were sent for AMS radiocarbon dating, to either the ¹⁴Chrono Centre in the Archaeology and Palaeoecology Department, at Queen’s University Belfast, or the SUERC AMS Laboratory, after preparation to graphite at the NERC Radiocarbon Facility. The coding package *Clam* (Blaauw, 2010), in R (R Project, 2012), with a Northern Hemisphere correction, i.e. the IntCal04 curve, was used to calibrate the conventional radiocarbon dates (Table 3) and construct the best-fitting age-depth models (Fig. 2).

Table 3 Accelerator mass spectrometry (AMS) ¹⁴C ages along with calibrated ages for radiocarbon dated samples from each core, calculated using Calib 601. (An age of 50 Cal. yr BP was given to the PSF sample taken at 30 cm depth, to approximate a *modern* date.)

Lab Code	Core	Depth (cm)	¹⁴ C yr BP	δ ¹³ C (‰)	Calibrated ages (cal yr BP)	Dated material
SUERC-35243	CPL	30	618 +/-35	-30.2	603 +/-56	soil
UBA-14322	CPL	97	4018 +/-26	-32.8	4475 +/-54	soil
SUERC-35244	CPL	170	4486 +/-35	-29.4	5166 +/-129	soil
SUERC-35245	CPL	225	4884 +/-37	-29.3	5623.5 +/-40.5	soil
UBA-15751	CPL	300	6038 +/-32	-29.7	6880.5 +/-89.5	soil
SUERC-35240	PSF	30	modern	-29.9	50	peat
UBA-15749	PSF	100	841 +/-25	-32.4	741.5 +/-48.5	peat
SUERC-35241	PSF	155	2275 +/-37	-30.2	2209.5 +/-52.5	peat
SUERC-35242	PSF	200	3270 +/-35	-30.7	3506 +/-70	peat
UBA-15129	PSF	240	3242 +/-22	-31.6	3441 +/-46	peat
SUERC-35235	DPL	60	119 +/-37	-29.5	80 +/-70	peat
UBA-15750	DPL	100	797 +/-25	-29.3	708.5 +/-33.5	peat
SUERC-35236	DPL	180	998 +/-37	-29.2	931 +/-40	peat
UBA-15131	DPL	220	1602 +/-25	-26.4	1477 +/-63	peat
SUERC-35239	DPL	260	1260 +/-35	-29.1	1201.5 +/-80.5	sand

Significant pollen assemblage zones were constructed using an optimal splitting by information content technique on all pollen data, after assessing the number of zones that were significant via a broken stick modelling approach across different data analyses (Bennett, 1996). *Psimpoll* version 4.26 (Bennett, 1994) was used to display all pollen, spore and charcoal counts, magnetic susceptibility results and resilience analyses (Fig. 3). Relative

abundance was calculated using a total pollen sum, which excluded Poaceae, Cyperaceae and fern spores.

Three key variables have been used in this study to indicate disturbance in these forests through time: charcoal counts (both macro- and microcharcoal) for fire disturbance, open vegetation counts for human disturbance, and independent climate records for climatic change. Magnetic susceptibility is used as a further proxy to investigate such impacts on the peat swamp forest vegetation. Independently-sourced climate data that can be used to investigate climate-vegetation relationships in the sampled region are limited, and those which are available are fragmented (Partin *et al.*, 2007) or from other regions (e.g. Griebinger *et al.*, 2011; Selvaraj *et al.*, 2012). Thus several different sources were used here to investigate the impact of precipitation (Griebinger *et al.*, 2011) and temperature changes (for example Mayewski *et al.* 2004; Partin *et al.*, 2007; Selvaraj *et al.* 2011; Selvaraj *et al.* 2012) on peat swamp vegetation, specifically focusing on ENSO-related climatic change (Fig. 4). (See Table S2, Appendix 2, and Cole *et al.*, *in prep* (Chapter 4), for a more complete description of climatic change, and the list of relevant references.) In addition, magnetic susceptibility results are used to infer past soil moisture content.

Disturbance Analysis

There are numerous definitions of and methods for measuring disturbance dynamics and associated resilience (Ludwig *et al.*, 1997; Carpenter *et al.*, 2001). In this study, a resilient ecosystem is described as one with the ability to recover from different drivers of disturbance, and maintain its ecological structure and function, in line with Holling (1973). Two metrics were calculated to measure the change in PSF taxa in response to disturbances, as indicators of peat swamp forest resilience: (1) palynological richness, and (2) rate of

change of the vegetation. Palynological richness represents the change in diversity of fossil pollen taxa between each sample through time (Birks and Line, 1992) and is used here as a crude proxy for ecological structure: a richer palynological diversity equates to a more stable ecological structure (Hooper *et al.*, 2005; Mougi and Kondoh, 2012), and thus, by inference, a greater ability to recover from disturbance. *Psimpoll* was used to compute the change in rarefied PSF taxonomic richness through time, measured in $E(T_n)$ units (estimated taxonomic richness in a sample of n individuals (Birks and Line, 1992)), using the minimum counts for PSF individuals recorded at one sampling point (in the period after peat swamp forest development), i.e. all those pollen grains that are associated with the TotPSF ecological group, in each core to standardize the data and account for differing sample sizes. Minimum count sizes were 201, 15 and 83 for Deforested Peatland, Peat Swamp Fragment and Converted Peatland, respectively. The rate of change (RoC) was measured in various ways depending on the vegetation data used and provides a crude metric for the rate of turnover of taxa in these sites through time. Chord Distance (Bennett & Humphry, 1995), calculated in *Psimpoll*, was the dissimilarity coefficient used to look at the rate of change between assemblages of adjacent samples of (i) all fossil pollen recorded, RoC(All), and (ii) those taxa within the total PSF ecological group (comprising PSF and PSF+ taxa), RoC(PSF). In order to investigate the rate at which the total PSF ecological group, i.e. TotPSF%, changed through time as a relative proportion of all taxa recorded, a basic measure of rate of change was computed in Excel:

$$\text{RoC(TotPSF\%)} = \frac{\text{TotPSF\%}_{T_2} - \text{TotPSF\%}_{T_1}}{|T_2 - T_1|}$$

where T_2 represents the younger date. A negative result for RoC(TotPSF%) indicates a period of peat swamp forest decline and a positive result, growth; a greater value in either direction represents a more rapid speed of change in the relative extent of the PSF group

within the landscape, and increasing fluctuation suggests instability of this ecological component (Carpenter & Brock, 2006; Dakos *et al.*, 2012).

RESULTS

Radiocarbon dates & stratigraphy

Radiocarbon dates were obtained for each sedimentary core (Table 3), providing an age-depth profile and allowing for comparison of disturbance events across these sites (Fig. 4). Basal dates for Deforested Peatland and Peat Swamp Fragment show age inversions and therefore interpretation of pollen data recorded from these cores beyond 200 cm depth, equating to approximately 1200 Cal. yr BP and 3000 Cal. yr BP respectively, is tentative. Deforested Peatland covers the shortest time period, with the peat swamp starting to develop less than 1500 Cal. yr BP (Zone D-2, Fig. 3) on a silty-sandy substrate, suggestive of a riverine environment in proximity to the coast. A shift to negative magnetic susceptibility readings at this point provide further support for this change from a more mineral-rich to waterlogged environment (Fig. 4). In Peat Swamp Fragment, the peat swamp was present from approximately 3500 Cal. yr BP, developing on a clay substrate, probably also associated with a riverine environment; with ecosystem development again reflected by magnetic susceptibility readings. Converted Peatland shows a different pattern of development, with organic-rich deposits originating on what was predominantly a clay substrate *c.* 5000 Cal. yr BP. After this point, a clay-peat soil started to accumulate, interspersed with laminations, which, coupled with the presence of coastal vegetation, indicates the existence of a tidally-influenced estuarine mangrove habitat. A greater clay and lower water and organic matter content are indicated by the more positive magnetic susceptibility results. Peat swamp forest did not start to develop in this site until *c.* 2800 Cal. yr BP (Zone c-2, Fig. 3). Accumulation rates broadly reflect this transition in depositional environment and associated vegetation

through time. In terms of magnetic susceptibility, there are no consistent relationships between the results and recorded climatic changes across all sites (Fig. 4).

(a)

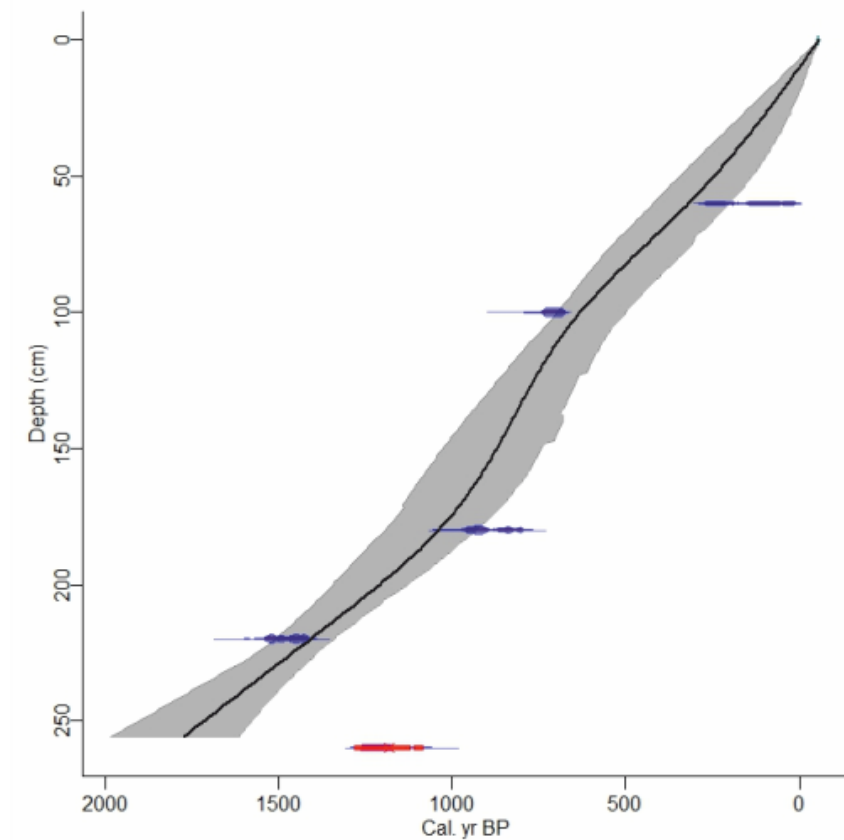
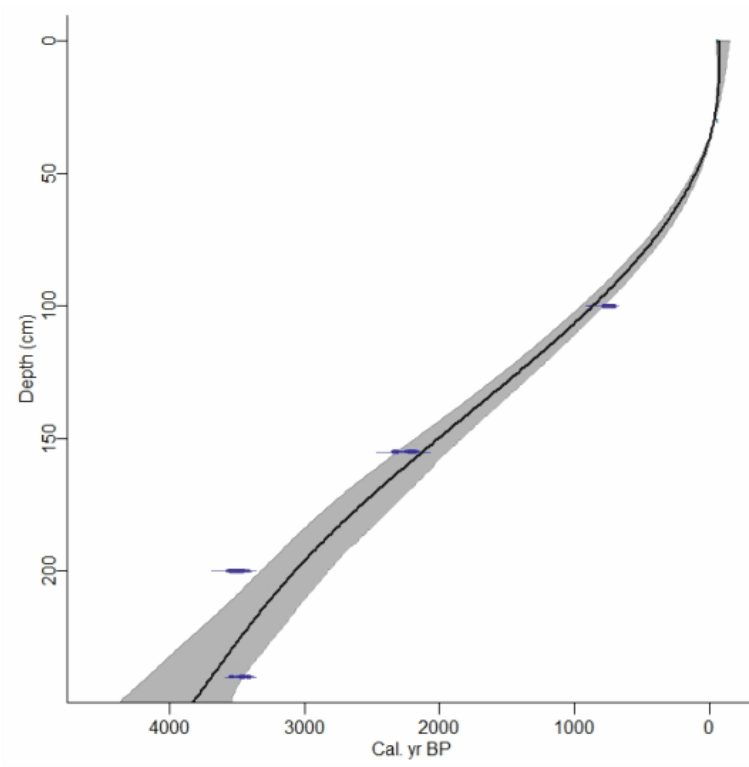
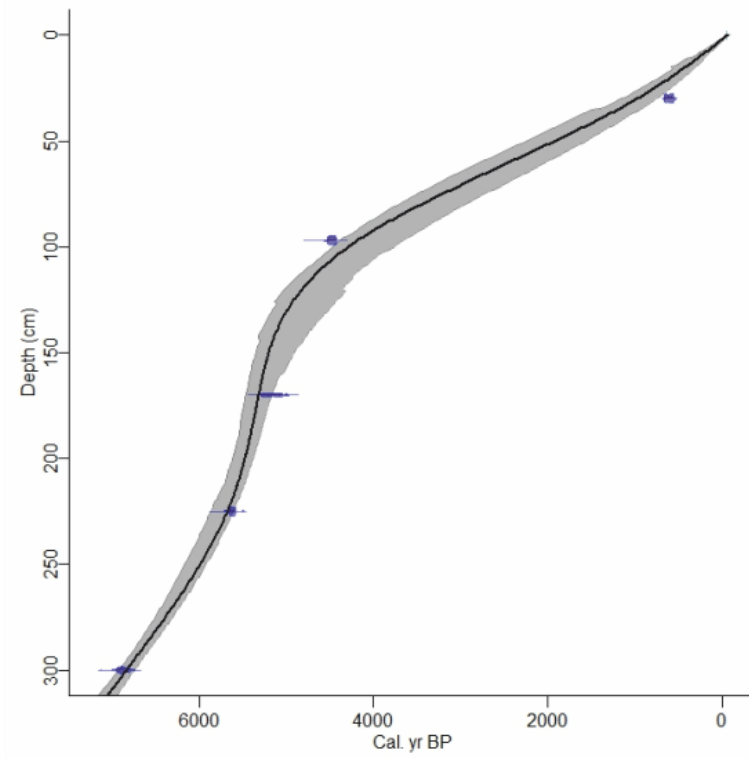


Fig. 2 Age-depth profile of each sedimentary core: (a) Deforested Peatland, (b) Peat Swamp Fragment, and (c) Converted Peatland. Smoothing spline proved the best-fitting model for each core, with extrapolated basal points in each sequence and surface (0 cm) age set at -55 years.

(b)



(c)



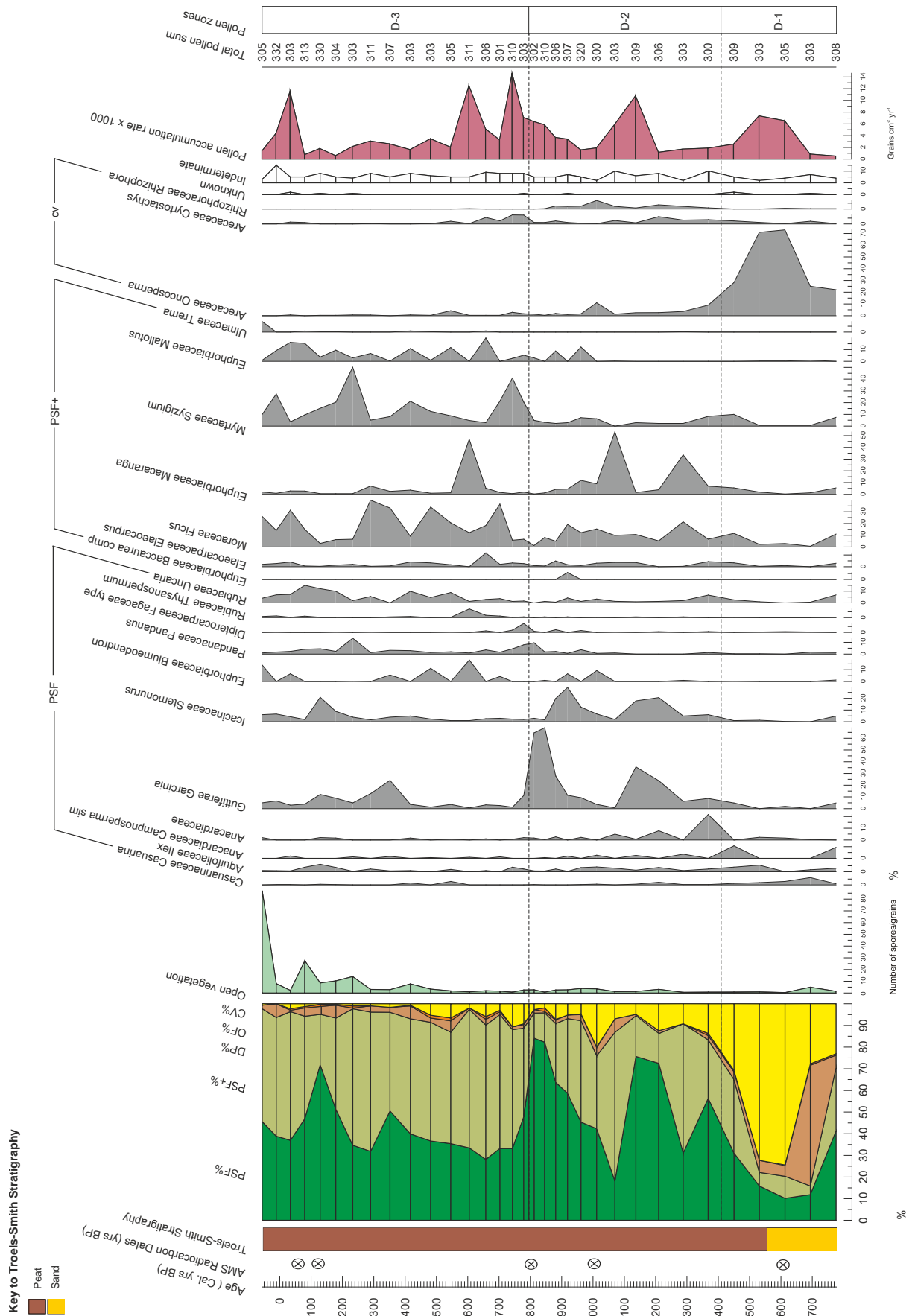
How has the vegetation of the peat swamp forests changed through time?

Description of pollen diagrams

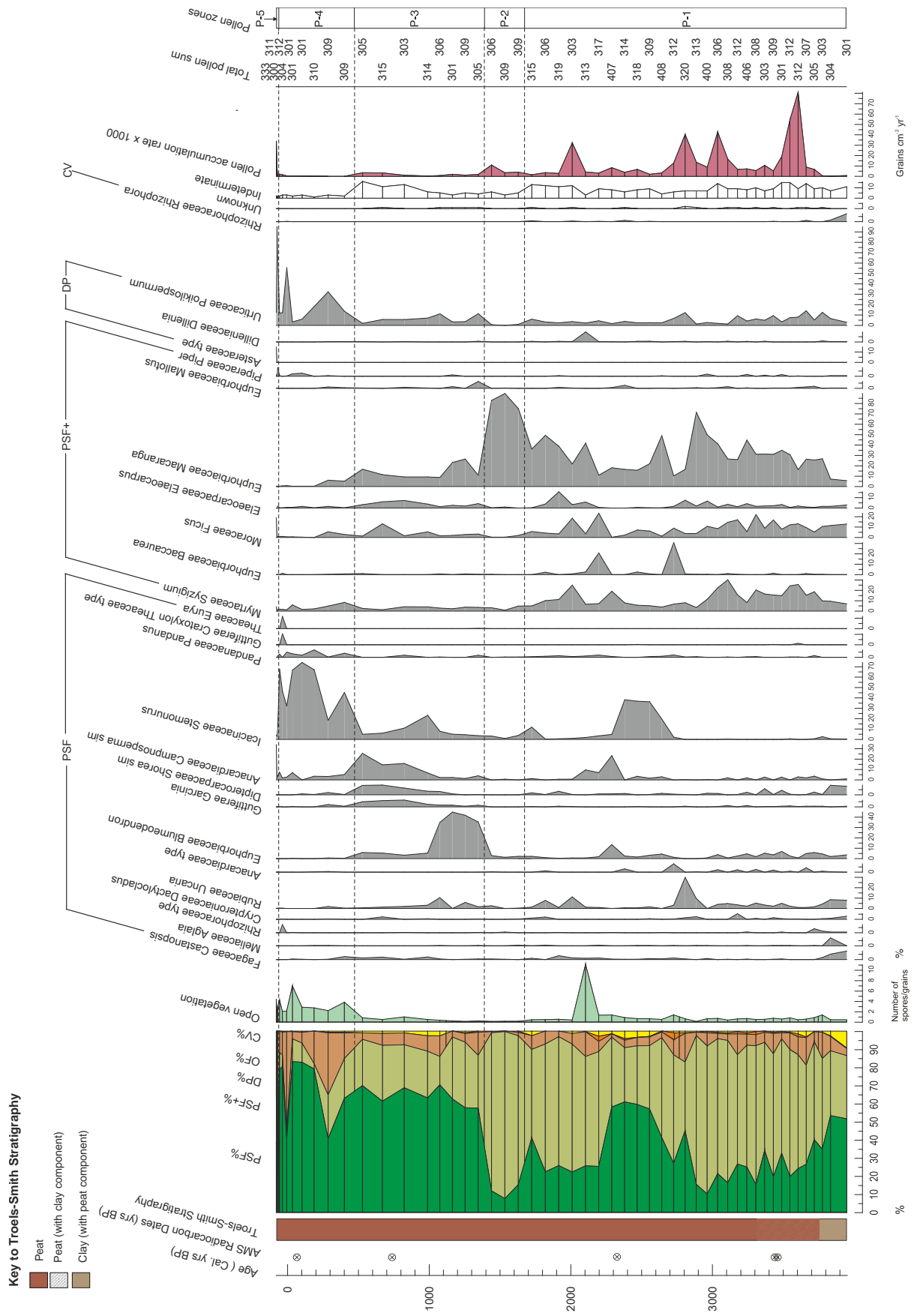
The majority of the 179 pollen types identified were from the PSF and PSF+ ecological groups, demonstrating that peat swamp forest has dominated all three sites over the period of peat swamp presence in each (Fig 3), and providing a proxy for the baseline vegetation for all sites from which to compare subsequent vegetation changes and disturbance impacts. The other two groups of vegetation that appear most frequently in the results of pollen counting are degraded peat and coastal vegetation. Several pollen taxa were common across sites, for example *Dillenia* and *Poikilospermum*, common disturbance indicators associated with degraded peat, and *Oncosperma*, found in saline-freshwater transition zones. Approximately 10 pollen types were not identified; levels of damaged or obscured grains and spores were greater and varied across samples and sites. Thus the apparently random occurrence of unknown and indeterminate grains across the three sites through time does not have implications for the interpretation of this study's results. There was little concurrence of pollen concentration peaks across sites, except where concentrations broadly increase at peat swamp forest development.

Fig. 3 Summary pollen diagram of each site: (a) Deforested Peatland, (b) Peat Swamp Fragment, and (c) Converted Peatland. Only pollen taxa that contribute > 0.05% to the pollen sum, at any one level, are included.

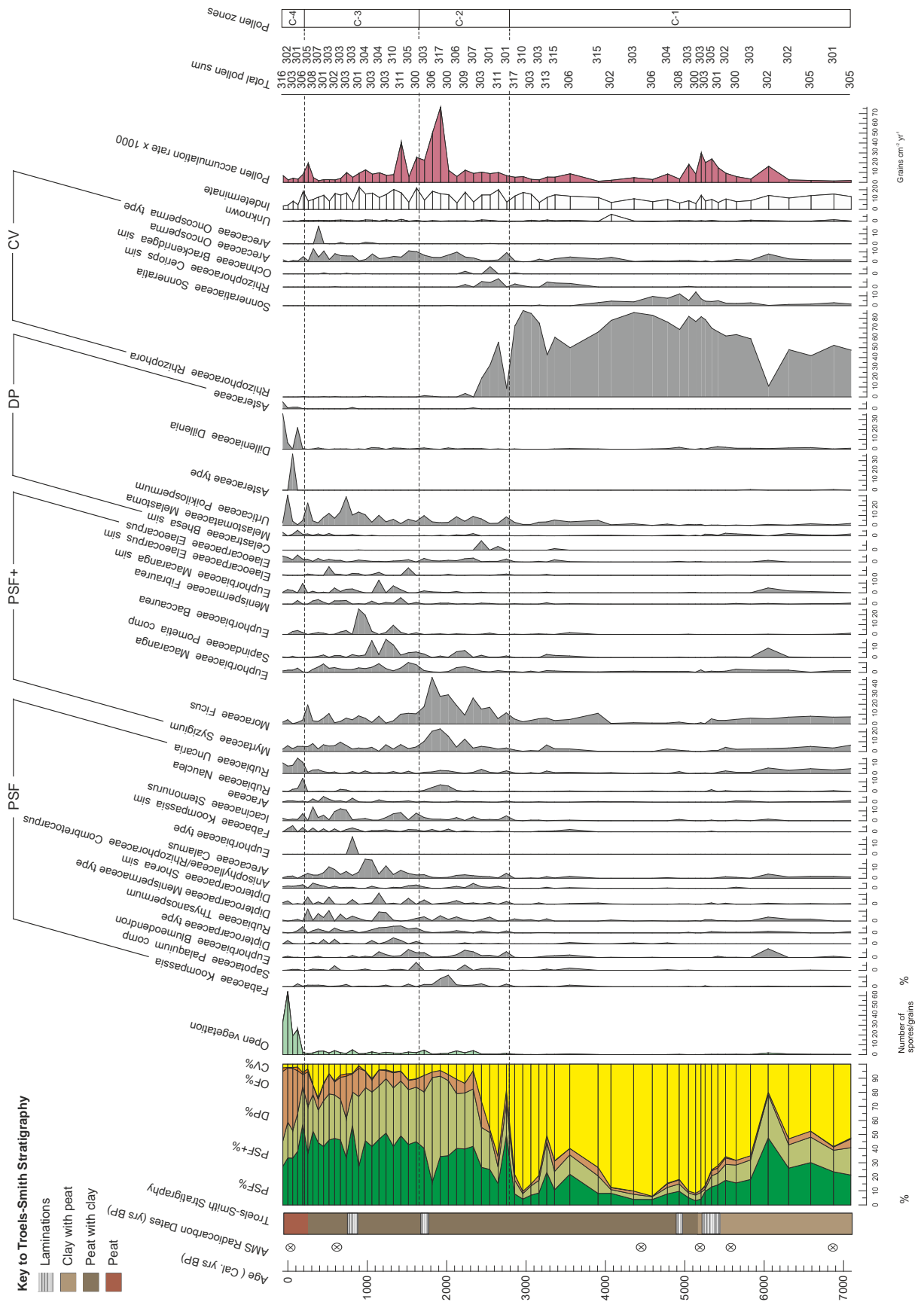
(a) Deforested Peatland



(b) Peat Swamp Fragment



(c) Converted Peatland



Peat swamp forest assemblages within and across sites are unique, with varying taxa and abundances through time and space, as exemplified by the different location of vegetation zones in most cases. However, there does appear to be a shared pool of species that feature to some extent in all sites. No successional patterns, such as those documented in sedimentary cores taken by Anderson (1964) from peat swamps in Sarawak, are visible, but the majority of the PSF taxa recorded in all sites could be attributed to his Phasic Community I, i.e. pioneer species and those found on shallow peat at the edge of a dome (Anderson, 1964), as might be expected given the short depths of peat recovered in this study (Fig. 2).

Despite the reported differences between sites, there are three notable similarities observed across them. One is the dominance of PSF vegetation through time, post-initiation of peat swamp development. The next is the strong presence of PSF+ taxa within the peat swamp forest, and frequent fluctuations between pioneer and more old-growth taxa coinciding broadly in each site with changes in fossil charcoal levels. The final similarity is the sharp increase in open vegetation taxa across all sites within the last 1000 years, which, although at varying times, coincides with a change in vegetation zone in all sites. From 300 Cal. yr BP, there is a particularly sharp increase, corresponding with the largest counts of degraded peat taxa in Converted Peatland and Peat Swamp Fragment sites.

What indicators of past disturbance are there and when?

Fire, human impact (inferred from large increases in open vegetation counts) and climatic change are the three disturbance types examined in this study (Fig. 3).

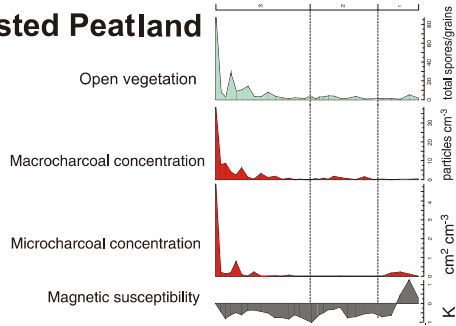
Although to varying degrees, fire appears to have been present in all sites through time, and there is a general coherence between micro- and macrocharcoal levels, signifying a

synchrony between local and regional fire events. One obvious exception to this is the large abundance of macrocharcoal coinciding with low levels of microcharcoal from 7000 - 4000 Cal. yr BP in the Converted Peatland site, indicating intense local burning albeit in a different ecological context (Fig. 3). Such macrocharcoal levels are only exceeded in the last 100 years in this site. The Peat Swamp Forest locality experienced greatest levels of local and regional fire between 2000 to 3000 Cal. yr BP, after which microcharcoal declined significantly until the present day. Charcoal counts from the Converted Peatland site share this trend of heightened burning during this approximately 1000 year period, coincident with an arid episode in the Tropics (Selvaraj *et al.*, 2011; Selvaraj *et al.*, 2012). The record for the Deforested Peatland site does not cover this period in time. Here, the highest levels of burning occur within the last 200 years. This pattern of increasing fire in the recent past is also seen in Converted Peatland and Peat Swamp Fragment sites, starting from *c.* 300 and *c.* 500 Cal. yr BP, respectively.

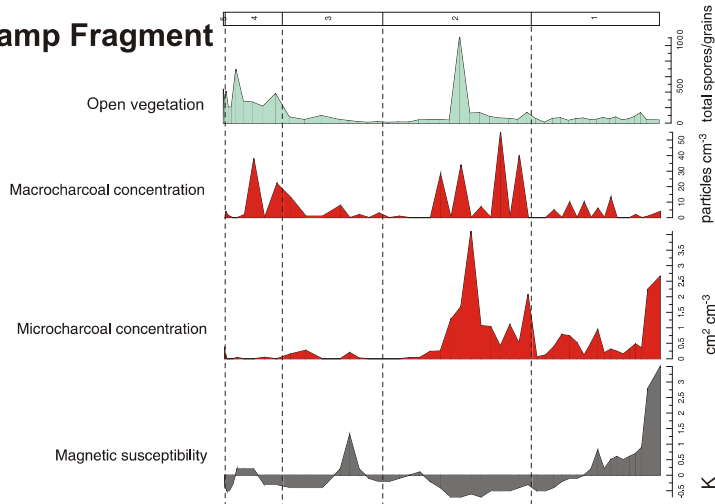
Open vegetation, after maintaining near-zero levels through the majority of the past in all sites, rises significantly from approximately 500 Cal. yr BP. This trend across sites broadly follows that of charcoal in the latter half of the last millennium, but with a dramatic increase within the last 200 years. Only in the Peat Swamp Fragment site was there a somewhat anomalous peak *c.* 2200 Cal. yr BP.

Despite the regional climate fluctuating significantly throughout the Holocene, there is both little apparent impact on or coherence of such with the vegetation, or the magnetic susceptibility results across the sites.

Deforested Peatland



Peat Swamp Fragment



Converted Peatland

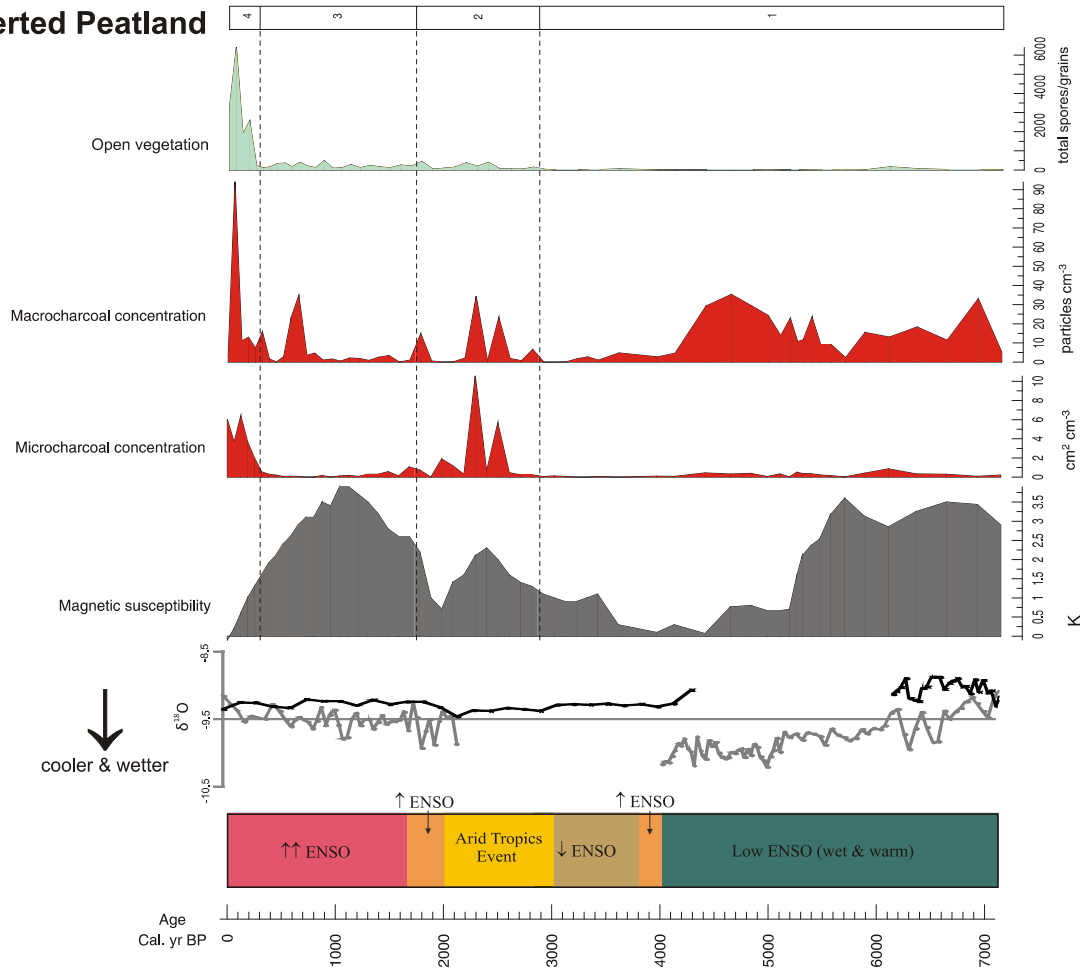


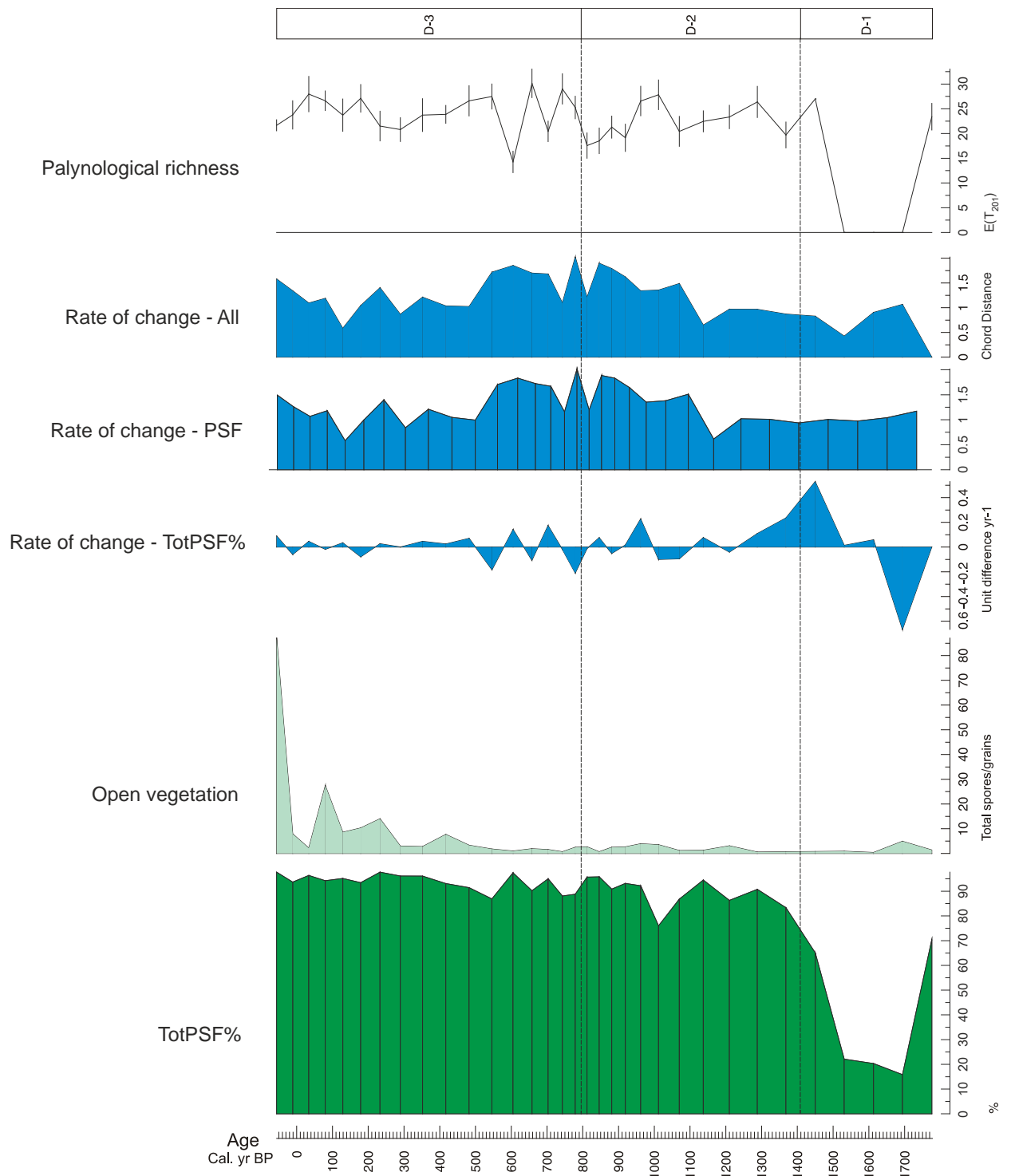
Fig. 4 Main disturbance types across sites, plotted against time. The $\delta^{18}\text{O}$ profile reflects climatic change as indicated by the directional arrow (Partin *et al.*, 2007). The approximate timing of major periods of climatic change, linked to the ENSO phenomenon, are marked (the direction and number of arrows attached to the ENSO label describe the relative intensity of ENSO in comparison to its activity pre-5000 Cal. yr BP) (for details of periods, see Table S2 in Supplementary Material, and Cole *et al.*, *in prep*, Chapter 4). Macro- and microcharcoal data (red) represent past fire episodes; magnetic susceptibility (grey) past soil-water and charcoal content, and open vegetation taxa (light grey), a proxy for degraded forest and open areas linked to anthropogenic disturbance. The datasets of each core were adjusted to enable their chronological correspondence against one timescale. Significant pollen zones are shown for each.

How did the peat swamp forest vegetation respond to these disturbances?

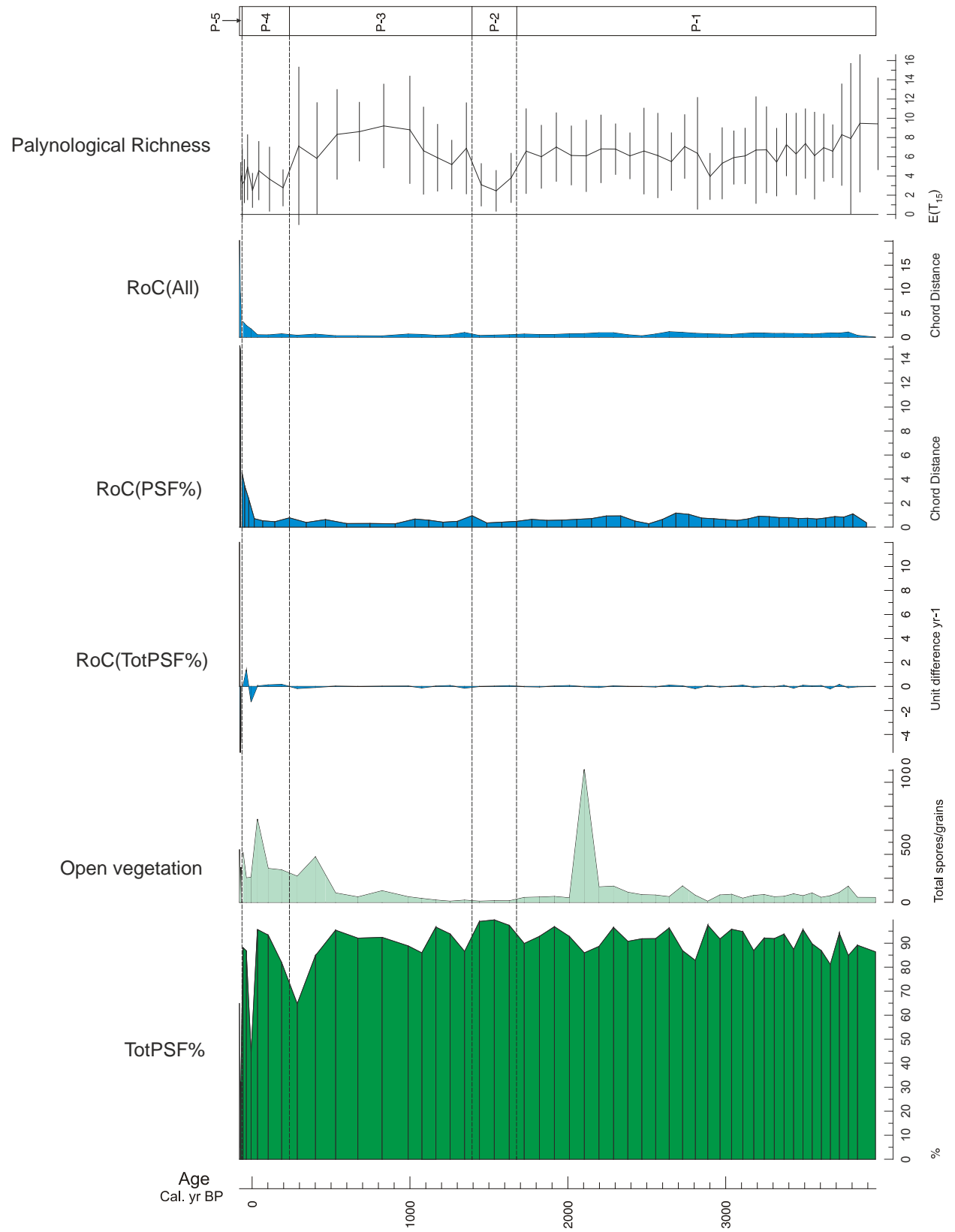
Each site behaves differently when disturbance metrics are considered. However, one notable similarity across Converted Peatland and Peat Swamp Fragment sites occurs in the last several hundred years, when there is an increase in the rate of change of the PSF and rate of change of all taxa, and greater fluctuations in the rate of change of the total PSF% group. In the Peat Swamp Fragment site, these changes are coincident with a decrease in palynological richness to levels only reached previously between *c.* 1400-1700 Cal. yr BP, in Zone P-2 (Fig. 5). This site also shows no change in PSF palynological richness or rate of change of any measure during one of the major inferred episodes of disturbance, *c.* 2000 – 3000 Cal. yr BP, where increased burning and a peak in open vegetation coincide with the period of reduced precipitation.

Fig. 5 Results of the disturbance analysis for: (a) Deforested Peatland, (b) Peat Swamp Fragment, and (c) Converted Peatland sites. The following variables are displayed: rates of change (blue) of the total PSF% (RoC(TotPSF%)), PSF taxa and all vegetation recorded in sedimentary cores (the latter two measured using the Chord Distance metric), and palynological richness of all PSF taxa recorded in pollen counts. Total PSF% (TotPSF%) (green) and open vegetation (light grey) are included to illustrate general changes in these key ecological groups. Significant pollen zones are shown for each.

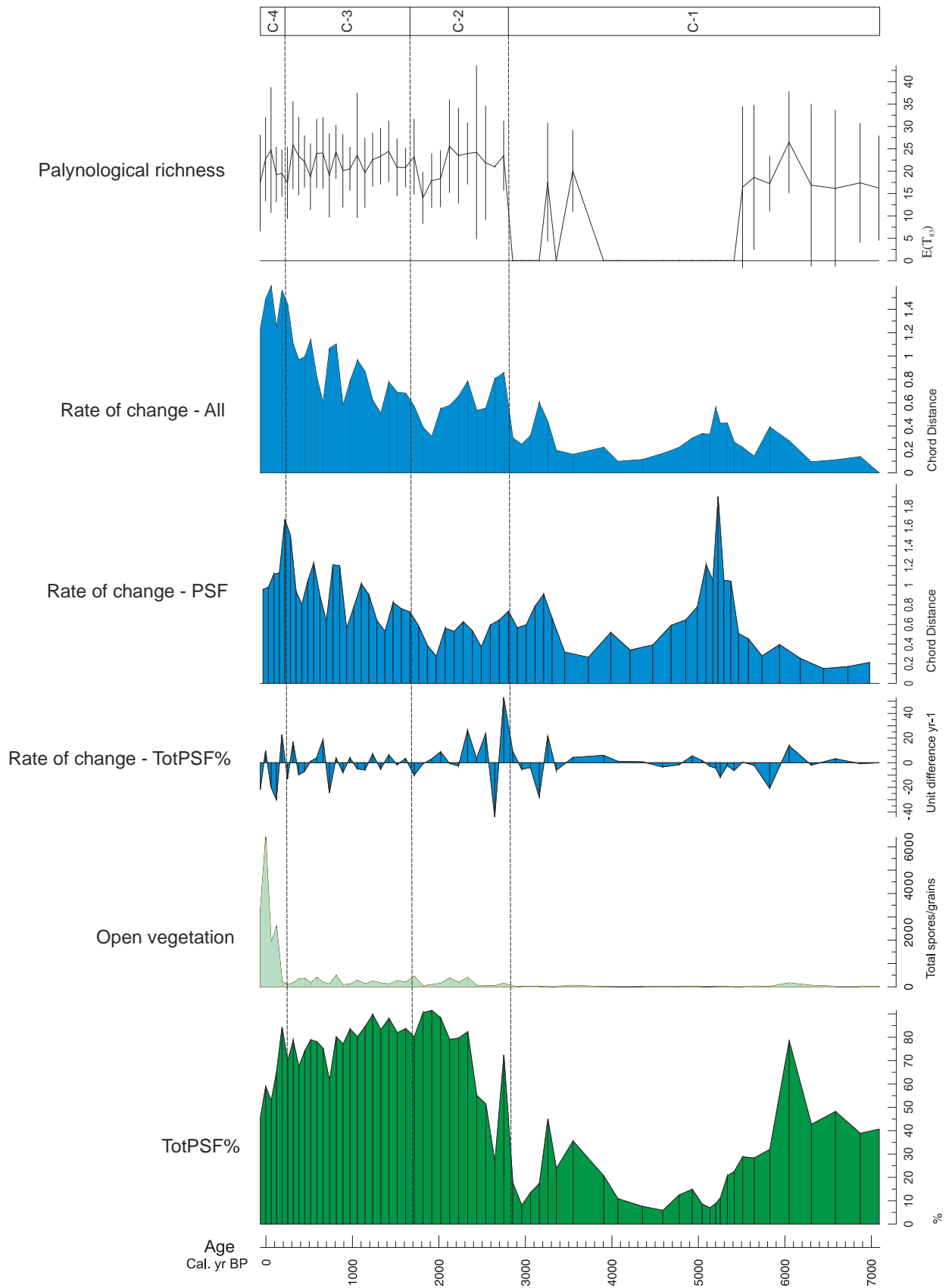
(a) Deforested Peatland



(b) Peat Swamp Fragment



(c) Converted Peatland



Results of the disturbance analysis for the other two sites are more varied throughout. Post-peat swamp development in the Deforested Peatland site, reflected by an increase in palynological richness and rate of change of the total PSF%, the metrics show only minor fluctuations. Between 500 – 800 Cal. yr BP, at the D-2 to D-3 zone boundary, there is an increased flux in all rate of change metrics, and significant variation in palynological richness.

The Converted Peatland site again demonstrates idiosyncratic trends. Corresponding with a sharp increase in palynological richness at the transition between zones C-1 and C-2, coinciding with peat swamp forest development at approximately 2800 Cal. yr BP, the rate of change of the total PSF% starts to fluctuate and continues until the present day, with a slight elevation in the past 500 years. This is reflected in the pollen data of this period: the PSF% declines slightly, disturbance and degraded taxa, and open vegetation and charcoal increase, all indicative of increased disturbance. Results suggest that natural climatic variability initiated the ecosystem transition *c.* 3000 years ago, whereas there is more conclusive evidence for anthropogenic drivers of vegetation change within the last 200 years, corresponding with zone C-4.

The different rate of change computations have been performed to look at the relative changes experienced by the different vegetation groups through time. As a result of the PSF taxa dominating the pollen sum through time, the rate of change of all taxa approximates that of the rate of change of the PSF taxa. However, the rate of change of the total PSF% does not consistently reflect the rate of change of the PSF, i.e. external and internal PSF fluctuations do not correspond, suggesting a certain dynamism within the PSF ecological system, with vegetation changes occurring irrespective of overall ecosystem coverage (illustrated by Fig.

3). The rate of change of the total PSF% appears to be closely associated with the relative abundance of the peat swamp forest vegetation community in Peat Swamp Fragment and Converted Peatland sites (Table 4). As the proportion of total PSF increases within the landscape, the fluctuations of the rate of change of the total PSF decrease, or alternatively, at lower levels of total PSF%, the rate of change of the total PSF% fluctuates more, both positively and negatively (Fig. 6).

Table 4 Spearman's rho correlation coefficients for the relationship between the total PSF% and the rate of change of the total PSF% shown in Fig. 5.

Site	Spearman's rho	Correlation Coefficient	<i>p</i> value
Deforested Peatland	0.322	0.309	0.072
Peat Swamp Fragment	0.493	0.293	0.000**
Converted Peatland	0.262	0.250	0.043*

*Correlation is significant at the 0.05 level (2-tailed).

** Correlation is significant at the 0.01 level (2-tailed).

(a) Deforested Peatland

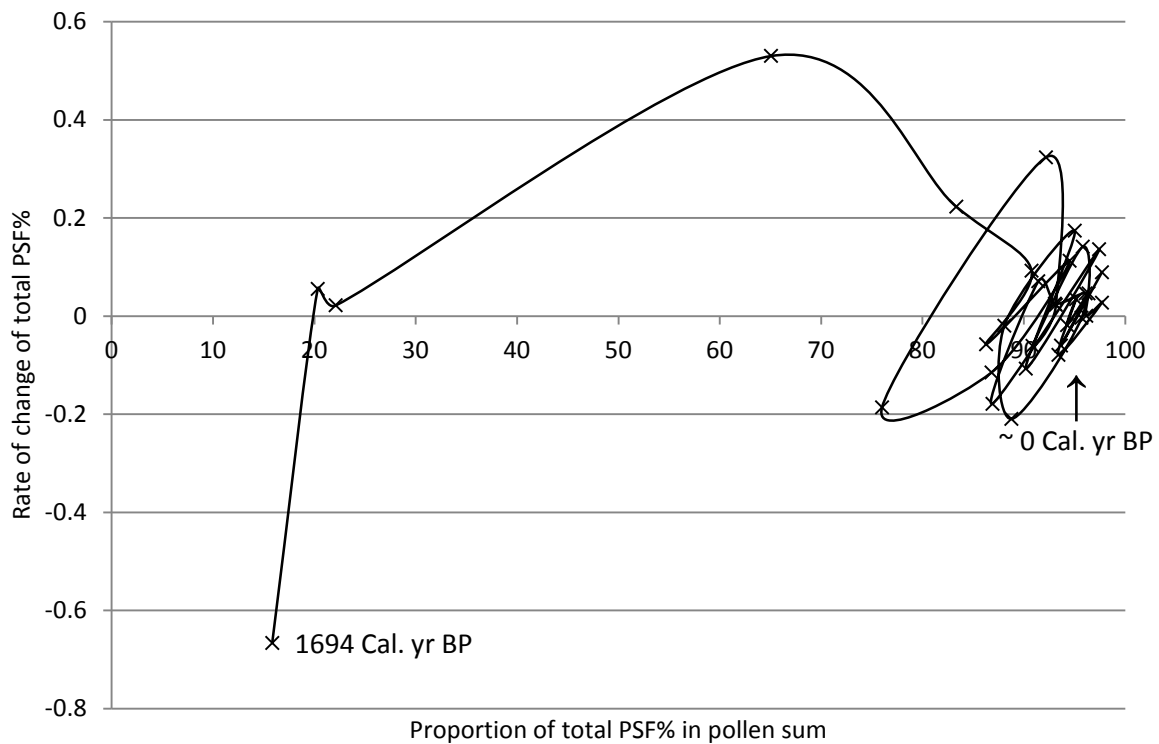
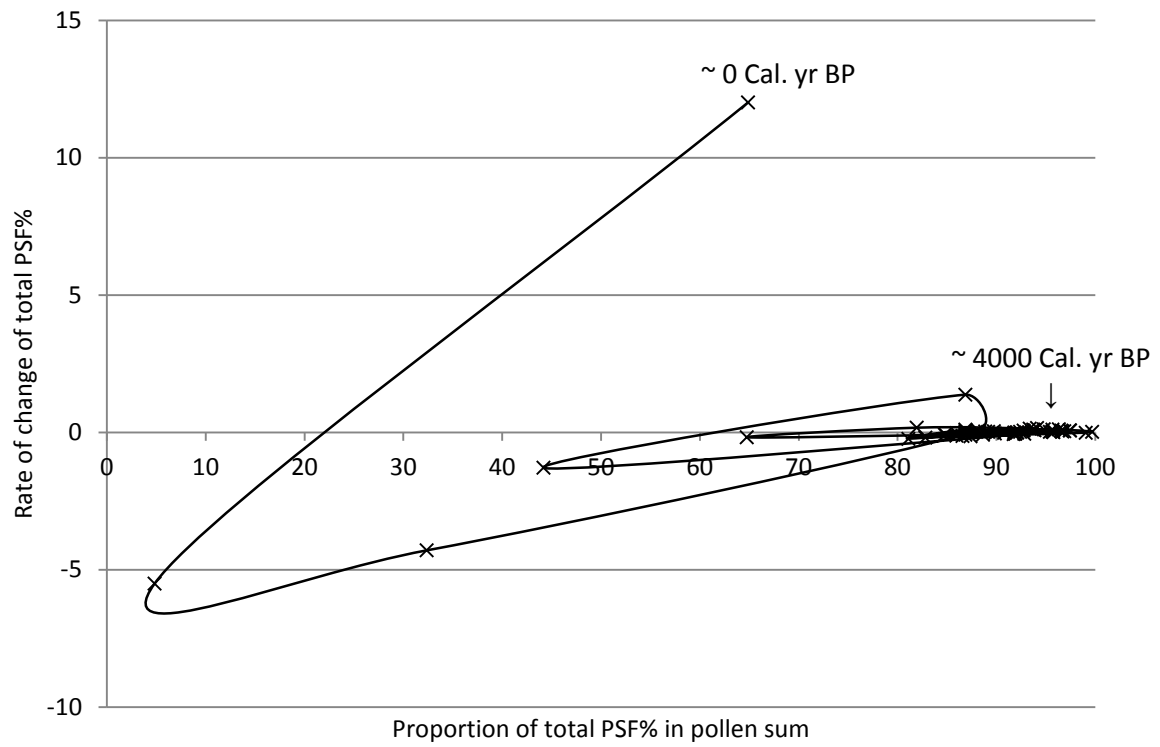
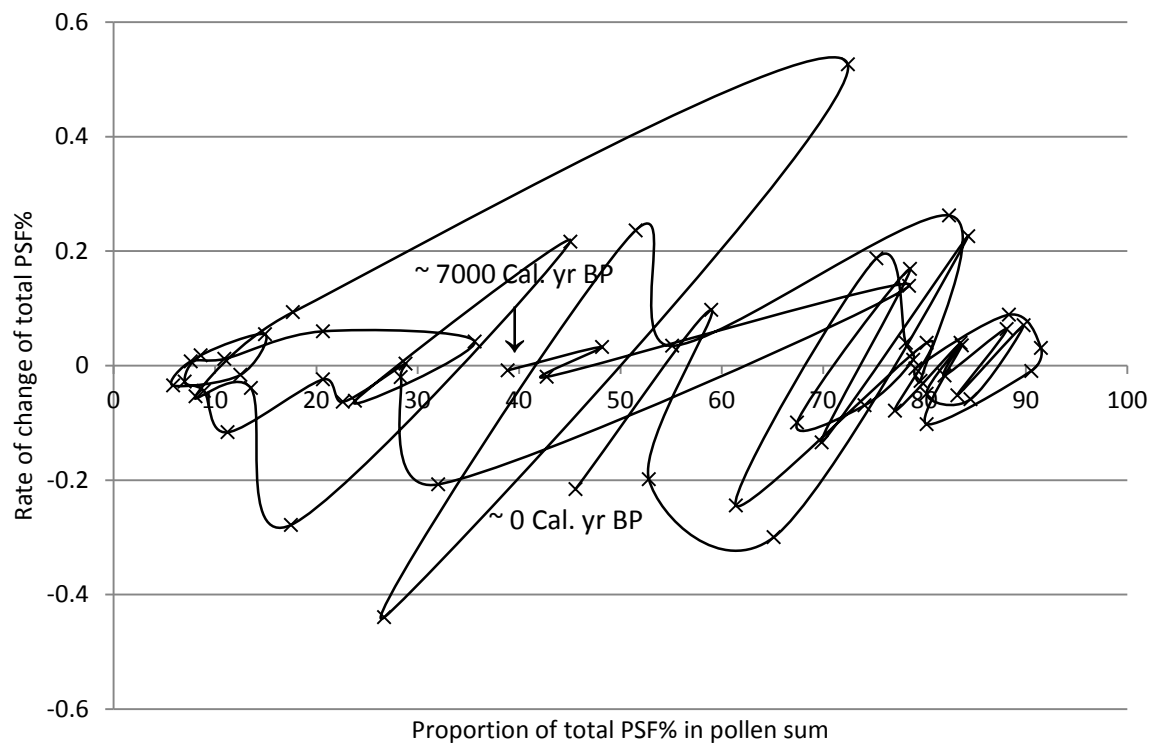


Fig. 6 Scatter diagrams demonstrating the relationship through time between the rate of change of total PSF% and the proportional contribution of all PSF taxa, i.e. TotPSF%, to the pollen sum in (a) Deforested Peatland, (b) Peat Swamp Fragment, and (c) Converted Peatland sites, illustrating the results of Table 4. (Data points have been joined with a line and approximate youngest and oldest ages included to further illustrate the pattern of change through time.) The rate of change of the total PSF% increases, both positively and negatively, at lower relative abundances of PSF taxa.

(b) Peat Swamp Fragment



(c) Converted Peatland



Discussion

This study characterises the vegetation change in three coastal peat swamp forests in Sarawak over the late Holocene, and the associated disturbance dynamics. It specifically identifies the past disturbance regimes in these ecosystems, focusing on evidence for fire, climatic or human perturbation, and how the peat swamp forest vegetation responded to these drivers. The impact of disturbance over time on the resilience of these ecosystems is also considered. In order to investigate this and, fundamentally, the responses of the forest vegetation to disturbances in the past, details of the baseline peat swamp forest dynamics and long-term ecological change were first determined.

How has the vegetation of these peat swamp forests changed through time?

In each site, the baseline vegetation has comprised PSF, fluctuating at approximately 80% of the total pollen sum through the majority of the late Holocene, post-peat swamp development. Studies have reported such peat formation in Singapore (Taylor *et al.*, 2001), and West Kalimantan (Anshari *et al.*, 2004) coinciding with the onset of sea-level fall and coastal progradation, i.e. the 'Anderson model' (Anderson, 1964), recorded *c.* 4000 Cal. yr BP in the South China sea (Maloney, 1992; Hesp *et al.* 1998; Proske *et al.*, 2011). Dommain *et al.* (2011) document this process of peat swamp development with sea-level regression across Southeast Asia during the Late Holocene. In the Peat Swamp Fragment site evidence suggests that the peat swamp started to develop at this time, and in the Deforested Peatland at approximately 1500 Cal. yr BP and Converted Peatland at 2800 Cal. yr BP, reflecting differing proximities to the coast and inland rivers. (For a more detailed description of landscape development in Converted Peatland, refer to Cole *et al.*, *in prep*, see Chapter 4.) The large reduction in magnetic susceptibility readings *c.* 5000 years ago in Converted Peatland may result from the coincident decrease in temperature (Partin *et al.*, 2007) and

increased regional precipitation, resulting from the re-establishment of the Asian Summer Monsoon (Selvaraj *et al.*, 2011). A subsequent increase at approximately *c.* 2300 Cal. yr BP may be caused by heightened charcoal levels in the Converted Peatland site, as shown by the peak in micro- and macrocharcoal during this period.

In contrast to the relative dominance and stability of the PSF ecological group through time, within the forest there has been constant fluctuation between the pioneer and mature PSF communities. This internal dynamism, also reflected in differing rate of change results for internal and external PSF change, represents local regeneration dynamics within the peat swamp forest, for example gap-phase replacement dynamics (Flenley & Butler, 2001) associated with natural phenomena such as wind-throw disturbance. Such processes are important for maintaining species diversity and ecosystem functioning (Hector & Bagchi, 2007). The only notable changes in the external levels of PSF within the landscape occur in the last 500 years and predominantly in Peat Swamp Fragment and Converted Peatland sites. During this time, degraded peat taxa increase, indicating a conversion of peat swamp forest, most likely related to human land-use change for the purposes of agricultural production.

What indicators of past disturbance are there and when?

The lack of coincident evidence for soil moisture or vegetation change with differing ENSO intensity across sites suggests that climatic changes have not acted as a significant form of disturbance in these coastal peat swamp forests. Results of a study synthesising peat accumulation data from across coastal peat domes in South-east Asia (Dommain *et al.*, 2011) demonstrate that these ecosystems have shown resilience to falling sea levels and dry El Niño episodes over the late Holocene, supporting the finding that the climatic changes of the past have not caused significant disturbance. There also appears to have been limited impact on

the peat swamp forest ecosystem or peat substrate during periods of elevated burning or open vegetation (albeit rare) prior to 500 Cal. yr BP, suggesting that external perturbations of a natural origin have not significantly disturbed these peat swamp forests in the past.

In the last several hundred years however, the latter two proxies do appear to act as drivers of disturbance. Although fire has been present throughout the past in all sites and in some cases to levels exceeding recent ones (i.e. 2000-3000 Cal. yr BP linked with ENSO-induced drying), it only appears to coincide with inferred disturbance in these peat swamp forest ecosystems in the last 500 years. Open vegetation follows a similar trend: there is a dramatic increase across all sites within the last 200 years. Prior to this, open vegetation was at minimal levels. Despite other studies suggesting that humans have been present in and exerting significant impacts on the wet tropical forest in this region since the early Holocene (Flenley, 1988; Hunt & Premathilake, 2012), or indeed prior to this (Barker *et al.*, 2007; Hunt *et al.*, 2007; Higham *et al.*, 2009), results here indicate that their presence in these coastal peat swamps has been a relatively recent phenomenon. There are several lines of evidence in support of this. Firstly, the significant increase in monoete spores in all sites over the last 300 years (a major component of the open vegetation ecological group) may result from large increases in the edible fern *Stenochlaena palustris* (Blechnaceae), locally known as *paku miding*, which grows highly successfully on peat soils where forest has been cleared. Secondly, people reported to have lived in these areas only in the recent past (Cole *et al.*, *in prep*, see Chapter 7). Thirdly, an extensive study of Sarawak's peatlands performed in the late 1970s ascribed the development of this ecosystem to the last 30 years (Liong & Siong, 1979); similarly, other studies report of human activities having increased rapidly in these peatland ecosystems over approximately the last twenty years (Miettinen & Liew, 2010). In addition, studies from across Southeast Asian swamps show increased biomass burning only

within the last two to three centuries (Hope *et al.*, 2005) or decades (Taylor *et al.*, 2010). Thus, this evidence, in combination with the recent and simultaneous elevation of both fire and open vegetation levels, suggests a strong association with local anthropogenic activity and further, that anthropogenic forest degradation is likely to have involved biomass burning.

It is important to note that deciphering the timing, magnitude and relative impact of different disturbances is often challenging. Anshari *et al.* (2004) suggest that peat development and its attributes have had a complex relationship with climatic changes and human activity during the Holocene, making the allocation of regional environmental drivers, especially climatic impacts, challenging. Climatic changes predominantly manifest in other environmental changes, i.e. indirect drivers of ecosystem change via fire or drying, further complicating the characterisation of individual disturbance events.

How did the peat swamp forest vegetation respond to these disturbances?

Peat swamp forest vegetation has dominated throughout periods of increased burning and climatic changes prior to 500 years ago, suggesting that none of these apparently *natural* disturbances have had a significant impact on the vegetation of these coastal peat swamp forests. Although the disturbance indicators cannot be separated such that their individual effects can be assessed, results do suggest that higher intensities of the different drivers may impact more significantly on the peat swamp forest. For example, incidences of elevated local burning do not appear to coincide with the process of peat swamp forest regeneration: a key process in a functioning forest. This implies that a threshold may have been crossed beyond which peat swamp forest recovery is limited and thus resilience compromised. For further discussion of disturbance thresholds for these wetland ecosystems, refer to Cole *et al.* (*in prep*, see Chapter 3).

Pollen data from the last 500 years, and notably from 200 Cal. yr BP, indicates a deviation from peat swamp forest stability associated with an approach to such disturbance thresholds. In both the Peat Swamp Fragment and Converted Peatland sites, fluctuations in the rate and direction of the total PSF% change increase, as well as the rate of species turnover within the peat swamp forest and wider landscape, coincident with the period when people are thought to have started clearing these ecosystems. In the Peat Swamp Fragment site, the palynological richness also reaches the lowest recorded levels, despite prior incidence of elevated burning and climatic change. The other sites do not share this trend however. Similarly, the Deforested Peatland site does not show increasing rate of change values in the recent past, and changes prior to this are likely to reflect site-specific disturbances and/or potential perturbation associated with climatic phenomenon such as the Little Ice Age, falling approximately 100 – 600 years ago (Park, 2011). Changes in climate, sea-level and consequently the depositional environment, are likely to have been the drivers of peat swamp forest development in the Converted Peatland site from approximately 3000 Cal. yr BP, but once established, there is limited impact on the PSF vegetation until *c.* 200 Cal. yr BP. Therefore, for both this site and the Peat Swamp Fragment, results of the disturbance analysis suggest that there has been a reduction in the resilience of the peat swamp forest to disturbance in the *recent* past, coincident with increasing fire and open vegetation which are indicative of human land-use change. Further support for this finding in the Peat Swamp Fragment site comes from a concomitant decrease in palynological richness during this period.

Another indicator that the resilience of the peat swamp forest is compromised under greater disturbance and degradation is the higher rate and magnitude of fluctuations of total PSF% when the PSF community is at a lower relative abundance in the landscape, i.e. at lower

levels of total PSF the forest is less stable. In support of this finding, Wösten *et al.* (2008) report that intact peat swamp forests demonstrate resilience to disturbances to their hydrological integrity, whilst in a degraded state they were more susceptible to further disturbance, especially fire. Similarly, Nishimura *et al.* (2007) suggest that peat swamp forests have the potential to recover from a single drought event, but not a succession of them. Again, there may be a threshold ecosystem state, in this case a level of peat-water-vegetation integrity (Dommain *et al.*, 2011), below which peat swamp forest recovery is highly limited. Whether there is a measurable critical threshold of hydrological integrity for these coastal peat swamp forests, whether other factors also contribute to determining ecosystem resilience, or whether such a potential threshold has been surpassed requires further investigation.

If the recent loss of resilience, inferred most strongly from the results of the Peat Swamp Fragment site, is pervasive across all study sites, there are several reasons why the Deforested Peatland and, to an extent, the Converted Peatland sites may not provide similarly clear evidence for such ecosystem change. Firstly, pollen grains and spores produced by plants characteristic of open areas are generally anemophilous, i.e. wind-transported, and as such, these plants have evolved to produce large volumes of highly mobile pollen grains/spores. This mobility enables transport over longer distances by wind and thus these pollen grains/spores can provide a signal for regional vegetation. However, the zoophilous, i.e. insect-transported pollen produced by most tropical forest trees (Colinvaux & Oliveira, 2001) gives a more local signal, and large quantities can accumulate in one site distorting pollen-based vegetation reconstructions. In general, tropical peat swamp forests comprise a dense closed-canopy environment, which can restrict long-distance pollen and charcoal transportation to the coring sites (Muller, 1963). Therefore, in combination with the form of

pollen grain transport occurring, high concentrations of a certain pollen grain may not reflect the regional dominance of that taxa, simply a high local deposition obscuring wider landscape change (Haseldonckx, 1977). Studies performed in other dense tropical forests claim that pollen grains found in sedimentary cores are likely to have been generated by parent plants within a distance of only 20-50m from the site (Jolly *et al.*, 1996; Elenga *et al.*, 2000).

Increasingly, studies are measuring and statistically comparing modern pollen rain with fossil pollen data from the same area to improve the objectivity and thus accuracy of interpretations of past plant communities. These have mostly focused on Latin American ecosystems (for example Bush, 1991; Bush and Rivera, 1998; Bush, 2002; Burn *et al.*, 2010), but several have been conducted in similar environments to those studied here, for example Taylor *et al.* (2001) investigate the relative export ability of modern pollen from local trees in a peat swamp forest in Singapore and Kershaw and Strickland (1990) study the rainforests of Queensland, Australia. In terms of PSF species richness, changes that suggest a loss of resilience may not be apparent as a result of the long lifespan of rainforest trees, being typically two centuries (Chambers *et al.*, 1998), which means that standing trees can continue to produce pollen despite a broad loss of surrounding forest and failure of forest regeneration.

The further analysis of disturbance dynamics and resilience in these coastal peat swamp forests would benefit from an assessment of the effect of magnitude of disturbance on recovery dynamics and, specifically, how the rate of recovery changes with cumulative disturbance over time (for example Cole *et al.*, *in prep*, see Chapter 3). Both of these may prove to be more significant and sensitive variables for detecting change in peat swamp forest resilience.

Management considerations

Conversely, the inferred loss of resilience in the Peat Swamp Fragment site may be idiosyncratic, and the peat swamp forest in the other two sites may prove resilient to these contemporary disturbances. However, several factors warrant attention when making such assumptions that have the potential to influence peat swamp forest management on the ground. Firstly, any conclusions made at this point are lacking sufficient evidence. Nonetheless, the elevations in disturbance indicators observed in the recent past provide a warning signal for resilience changes alluded to in the Peat Swamp Fragment site. Secondly, the disturbances these forests are experiencing today are of a higher magnitude and novel type to those experienced in the past, for example the contemporary logging, subsequent drainage and establishment of oil palm plantations over vast areas. These disturbances all result in disruption of the peat soil structure, and thus the disruption of the tight interrelationship between soil, hydrology and vegetation, critical to peat swamp forest self-regulation and, consequently, hydraulic integrity (Dommain *et al.*, 2010). To date, there is no evidence to suggest that these forests can recover from such disturbance, potentially driving the ecosystems into a landscape trap (Lindenmayer *et al.*, 2011). Thirdly, the peat swamp forest itself may maintain its ability to regenerate, but current environmental conditions and land-use practices, with a constant disruption of the soil and local seed sources, and increased prevalence and intensity of fires (Hope *et al.*, 2005), are warranting it a non-renewable resource (Gomez-Pompa *et al.*, 1972). A recent study predicted that if the current rate of peatland deforestation in Southeast Asia is maintained, its peat swamp forests will have disappeared by 2030 (Miettinen *et al.*, 2012b). If this continued disturbance is halted however, and the hydraulic integrity preserved, forests can recover with little or no assistance, as exemplified by the rapid regeneration observed in a deforested and partially drained peat swamp in Kuching, Sarawak, where mowing is required to prevent forest

regrowth (personal observation, L.E.S.C.). Finally, there is limited evidence of successful restoration in heavily degraded peatlands (Van Eijk *et al.*, 2009; Jaenicke *et al.*, 2011; Graham & Page, 2012). For example, a restoration project underway in the vast area of deforested and drained peatland in Central Kalimantan, known as the Ex-Mega Rice Project area, is proving challenging due to high fluctuations in ground water levels, peat subsidence and fire (Cheyne, personal communication; Page *et al.*, 2009).

From contemporary work, the largest disturbance experienced by peat swamp forests during conversion is drainage (Hoekman & Vissers, 2007; Jauhiainen *et al.*, 2008; Dommain *et al.*, 2011), and improving the nutrient and water balance of converted areas may be the key to their sustainable use (Murdiyarso *et al.* 2010). However, Hooijer *et al.* (2011) warn that any land-use change in forested peat swamps requires drainage, and whatever level of drainage is implemented, substantial carbon losses through oxidation and consequential subsidence is inevitable. Vitally, peat swamp forests need to be considered as an ecosystem, both in terms of their central interdependent components, i.e. the pivotal interrelationship between vegetation, hydrology and peat soil, and the interconnections they have with the wider landscape (Dommain *et al.*, 2010; Ewel, 2012). Sustainable Forest Management (SFM) (Imai *et al.*, 2009) and paludiculture, the practice of wetland agriculture (FAO, 2012), may provide a means of delivering a direct service from these areas without jeopardizing their future persistence, so long as management carefully considers the requirements for maintaining the hydrological integrity of the peat swamp (Dommain *et al.*, 2010). However, much more research and trialling are required to understand the parameters and potential impacts of these two management strategies before they are ready for widespread implementation.

Evidence from this study suggests that peat swamp forests are able to recover from natural disturbance, but that this recovery is questionable when human perturbation is introduced. Therefore, designing land-use strategies in these peatlands that limit disturbances to natural levels, may be key to managing them more sustainably. Given the factors discussed above and the, as yet, limited knowledge of peat swamp forest disturbance dynamics and recovery potential, the adoption of a management approach that balances potential benefits with potential risks, analogous to the precautionary principle, seems pertinent for these tropical peat swamp forests. However, whether such an approach can be upheld amongst the contemporary pressures of economic development are questionable given recent trends in agricultural markets (Carter *et al.*, 2007; Koh, 2007), Sarawak's development plans (for example see RCDA, 2012) and experience elsewhere (Koh *et al.*, 2011; Miettinen *et al.* 2011; Miettinen *et al.*, 2012a). This study provides key insights into the long-term disturbance regimes and recovery dynamics of these tropical coastal peat swamp forests, providing important information for informing the debate on sustainable peat swamp forest management in the face of contemporary and future disturbance.

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SUPPLEMENTARY MATERIAL

- Appendix 1 **Table S1** Ecological groupings
- Appendix 2 **Table S2** ENSO-related Late Holocene climatic changes in the region surrounding northern Borneo, along with the references from which information was compiled.
- Appendix 3 Details of fossil pollen sampling frequency in each sedimentary core.

APPENDIX 1

Table S1 Ecological groupings of plant taxa identified through fossil pollen analysis, showing the complete list of pollen grains and spores counted and used for past vegetation reconstruction, along with the descriptions of the key characteristics of each group.

Plant family	Pollen taxon	Plant family	Pollen taxon
PEAT SWAMP FOREST (PSF) - if taxa present in peat swamp forest, assumed to be an old-growth forest			
Araceae		Hamelidaceae	<i>Altingia</i>
Arecaceae	<i>Calamus</i>	Icacinaceae	<i>Stemonurus</i>
	<i>Cyrtosperma</i>		Icacinaceae type
	Arecaceae type	Lamiaceae	<i>Salvia</i>
Alangiaceae	<i>Alangium</i>	Lauraceae	<i>Litsea</i>
Anacardiaceae	<i>Camptosperma</i> sim	Loganiaceae	<i>Fagraea</i>
	<i>Melanorrhoea</i> comp		<i>Fagraea</i> sim
Anacardiaceae	Anacardiaceae type	Loranthaceae	Loranthaceae type
Anisophyllaceae/ Rhizophoraceae	<i>Combretocarpus</i>	Meliaceae	<i>Aglaia</i> sim
	<i>Combretocarpus</i> sim		<i>Trichilia</i> sim
	<i>4-colporate</i>	Moraceae	<i>Artocarpus</i>
	Anisophyllaceae type	Myristicaceae	Myristicaceae type
Apocynaceae	Apocynaceae type	Myrsinaceae	<i>Rapanea</i>
Aquifoliaceae	<i>Ilex</i>	Orchidaceae	
Araliaceae	<i>Schefflera</i> sim	Pandanaceae	<i>Pandanus</i>
	Rutaceae type	Podocarpaceae	<i>Dacrydium</i>
	Araliaceae type	Polygalaceae	Polygalaceae type
Bursaceae	Bursaceae type	Rhamnaceae	Rhamnaceae type
Casuarinaceae	<i>Casuarina</i>	Rhizophoraceae	Rhizophoraceae type
Celastraceae	<i>Lophopetalum</i>	Rosaceae	<i>Parastemon</i>
	Celastraceae type		Rosaceae type
Crypteroniaceae	<i>Dactylocladus</i>		Rosaceae/Sterculiaceae type
Cunoniaceae	<i>Weinmannia</i>	Rubiaceae	<i>Gardenia</i>
Dipterocarpaceae	<i>Shorea</i> sim		<i>Ixora</i>
	Dipterocarpaceae type		<i>Ixora</i> type
	Dipterocarpaceae Fagaceae type		<i>Nauclea</i>
	Dipterocarpaceae		<i>Nauclea</i> sim
	Menispermaceae type		<i>Tarenna</i> sim
Ebenaceae	<i>Diospyros</i>		<i>Thyranospermum</i>
	<i>Diospyros</i> sim		<i>Timonius</i>
	Ebenaceae Fagaceae		<i>Timonius</i> sim
	<i>Diospyros</i> type		<i>Uncaria</i>
Euphorbiaceae	<i>Blumeodendron</i>	Rutaceae	<i>Melicope</i>
	<i>Cephalomappa</i> sim		<i>Tetractomia</i> sim
	<i>Glochidion</i>		<i>Palaquium</i>
	Euphorbiaceae type		<i>Palaquium</i> comp
Fabaceae	<i>Albizia</i> comp	Sapotaceae	<i>Planchonella</i> comp
	<i>Archidendron</i>		Sapotaceae type
	<i>Copaifera</i>		<i>Reevesia</i>
	<i>Copaifera</i> comp	Sterculiaceae	Sterculiaceae type
	<i>Koompassia</i>		
	<i>Koompassia</i> sim		

Plant family	Pollen taxon	Plant family	Pollen taxon
Fagaceae	<i>Castanopsis</i> Fagaceae type	Theaceae	<i>Eurya</i> Theaceae type
Flacourtiaceae	<i>Casearia</i> <i>Casearia</i> sim	Thymeliaceae	<i>Gonystylus</i>
Guttiferae	<i>Callophylum</i> <i>Callophylum</i> sim <i>Cratoxylon</i> sim <i>Garcinia</i> Guttiferae <i>Cratoxylon</i> Theaceae type	Tiliaceae Trigoniaceae	Tiliaceae type <i>Trigoniastrum</i> Trigoniaceae type

PEAT SWAMP FOREST pioneers (PSF+) - if taxa increases in abundance in pollen diagram, indicates early successional plant community of secondary peat swamp forest

Acanthaceae		Menispermaceae	<i>Fibraurea</i>
Annonaceae	Annonaceae type		<i>Fibraurea</i> sim
Elaeocarpaceae	<i>Elaeocarpus</i> <i>Elaeocarpus</i> sim Elaeocarpaceae type	Moraceae Myrtaceae	<i>Ficus</i> <i>Syzygium</i> Myrtaceae type
Euphorbiaceae	<i>Baccaurea</i> <i>Baccaurea</i> comp <i>Macaranga</i> <i>Macaranga</i> sim <i>Mallotus</i> <i>Mallotus</i> type	Piperaceae Sapindaceae Ulmaceae Verbenaceae Vitaceae	<i>Piper</i> <i>Dodonea</i> <i>Pometia</i> comp Sapindaceae type <i>Trema</i> Verbenaceae type <i>Cayratia</i>

DEGRADED PEAT (DP) - taxa not found in older-growth peat swamp forest or found in greater abundance in disturbed areas of peat where the forest canopy is open

Asteraceae	Asteraceae type	Lecythidaceae	<i>Barringtonia</i> type
Celastraceae	<i>Bhesa</i> sim	Melastomataceae	<i>Melastoma</i>
Dilleniaceae	<i>Dillenia</i> <i>Dillenia</i> sim	Rutaceae	<i>Euodia</i> <i>Euodia</i> sim
Escallionaceae	<i>Polyosma</i> sim	Smilacaceae	<i>Smilax</i>
Fabaceae	<i>Uraria</i> <i>Uraria</i> sim	Urticaceae	<i>Poikilospermum</i>

OTHER FOREST (OF) - other forest (non-peat swamp forest taxa), e.g. swamp forest or forest on mineral soils

Asclepiadiaceae	<i>Dischidia</i>	Myrsinaceae	<i>Ardisia</i> sim
Bombacaceae	<i>Durian</i> comp Bombacaceae type	Rosaceae	<i>Rubus</i> <i>Rubus</i> sim Rosaceae type
Combretaceae		Symplocaceae	<i>Symplocos</i> <i>Symplocos</i> type
Cycadaceae	<i>Cycas</i>		
Ericaceae	<i>Rhododendron</i>	Theaceae	<i>Eurya</i> sim
Icacinaceae	<i>Platea</i> Icacinaceae type Juglandaceae Myrtaceae type	Vitaceae	<i>Ampelocissus</i> sim

Plant family	Pollen taxon	Plant family	Pollen taxon
COASTAL VEGETATION (CV) - coastal vegetation associated with succession to peat from mangrove/littoral habitat type			
Acanthaceae	Acanthaceae type	Pteridaceae	<i>Acrostichum</i>
Arecaceae	<i>Cyrtostachys</i>	Rhizophoraceae	<i>Ceriops</i> sim
	<i>Oncosperma</i>		<i>Rhizophora</i>
	<i>Oncosperma</i> sim		<i>Rhizophora</i> type
Avicenniaceae	<i>Avicennia</i>	Simaroubiaceae	<i>Quassia</i>
Combretaceae	<i>Lumnitzera</i>		<i>Quassia</i> sim
Malvaceae	<i>Hibiscus</i>	Sonneratiaceae	<i>Sonneratia</i>
	Malvaceae type		
Ochnaceae	<i>Brackenridgea</i>		
	<i>Brackenridgea</i> sim		
	Ochnaceae type		
DISTURBANCE TAXA - disturbance tolerant vegetation indicative of open environments (not included in pollen sum)			
Poaceae		Lygodiaceae	
Cyperaceae		Cyathaceae	
Monolete		Trilete	
Lycopodiaceae	<i>Lycopodium cernuum</i>		
	<i>Lycopodium phlegmaria</i>		

APPENDIX 2

Table S2 Major periods of ENSO-related climatic change, the score for relative intensity awarded to each and references used to construct them.

ENSO Time Period (Cal. yr BP)	ENSO-related characteristics of period	Score	References (in order of characteristics)
0 – 100	Intensified ENSO	2	Gagan <i>et al.</i> (2004)
100 – 600	Little Ice Age; declining ENSO frequency	1	Grießinger <i>et al.</i> (2011); Moy <i>et al.</i> (2002)
600 – 1700	Amplification of ENSO	3	Woodroffe <i>et al.</i> (2003)
1700 – 3000	Abrupt increase in ENSO magnitude & Holocene maximum	2	Gagan <i>et al.</i> (2004); Woodroffe <i>et al.</i> (2003)
3000 - 3800	Reduced ENSO intensity	1	Woodroffe <i>et al.</i> (2003)
3800 - 5000	Onset of modern ENSO variability; reductions in Summer East Asia Monsoon; series of periods of tropical aridity; drought in New Guinea	2	Gagan <i>et al.</i> (2004); Selvaraj <i>et al.</i> (2011); Mayewski <i>et al.</i> (2004); Haberle <i>et al.</i> (2001)
5000 - 7000+	Relatively high precipitation in northern Borneo, & a relatively stable climate regionally; Summer Monsoon dominant & ENSO weak	0	Partin <i>et al.</i> (2007); Haberle <i>et al.</i> (2001); Abram <i>et al.</i> (2007); Moy <i>et al.</i> (2002)

APPENDIX 3

Details of fossil pollen sampling frequency in each sedimentary core.

Pollen preparations were made from 1 cm³ samples taken at intervals of 8 cm throughout the length of the Deforested Peatland core; at 4 cm intervals for the majority of the Peat Swamp Fragment core, and 6 cm and 8 cm intervals towards the top; and at 2 cm intervals for the majority of the Converted Peatland core, and 4 cm, 8 cm and 16 cm intervals towards the base, to minimise the difference of time intervals between samples within and across cores.



Paper 6: CHALLENGES AND OPPORTUNITIES FOR THE *SUSTAINABLE* MANAGEMENT OF TROPICAL PEAT SWAMP FORESTS

Cole, L.E.S.^a, S.A. Bhagwat.^b and Willis, K.J.^c

^a*Oxford Long-term Ecology Laboratory, Department of Zoology, University of Oxford, Oxford, United Kingdom, lydia.cole@zoo.ox.ac.uk, Corresponding Author

^cBiodiversity Institute, Oxford Martin School, Department of Zoology, University of Oxford, Oxford, United Kingdom, kathy.willis@zoo.ox.ac.uk

^bSchool of Geography and the Environment, University of Oxford, Oxford, United Kingdom, shonil.bhagwat@ouce.ox.ac.uk

*Corresponding author: tel: +44(0)1865 281321, fax: +44(0)1865 271249

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ABSTRACT

There is concern among the international conservation community that tropical peat swamp forests are being managed unsustainably, principally through the drainage and deforestation that occurs in the process of land conversion for agriculture. Such modification to this unique ecosystem is reported to generate large emissions of CO₂, principally through peat decomposition and burning, as well as threaten biodiversity and impoverish local communities. Despite such concerns over peat swamp forest destruction, land-use conversion continues in the peat-rich nations of Southeast Asia, where local stakeholders' priorities appear to lie more with livelihood needs than those of conservation. This study aims to investigate whether the concerns raised by the international conservation community align with those held by the stakeholders of these ecosystems. Semi-structured interviews were conducted with smallholder farmers, oil palm plantation managers and key informants involved in peatland management in the coastal peat swamp forest zone in Sarawak, Malaysian Borneo. The questions focused on historical and contemporary use, management challenges and future visions of the coastal peatlands. Through a stakeholder analysis, areas of conflict and potential opportunities for improving the sustainable management of tropical peat swamp forests are identified. Results suggest that local stakeholders see the benefits arising from using the peatlands as far outweighing the challenges of management advertised by the international community, and that on-going development and livelihood security are more important factors than biodiversity conservation and carbon storage in determining peatland management. This study has highlighted that through extending the scope of current research, education and awareness raising, and policy development and funding, there lie opportunities for developing a more sustainable approach to the management of peatlands in this rapidly developing region.

Key words drainage, fire, land conversion, oil palm plantations, peat swamp forest, Sarawak

1. Introduction

Over the last few years, the international community, driven by scientists and conservation organisations, has been expressing increasing concern about the management and use of tropical peat swamp forests, especially those undergoing rapid conversion in Southeast Asia (for example Miettinen & Liew, 2010; Koh *et al.*, 2011). These unique wetland forests have developed over thousands of years along the coast of this region (Dommain *et al.*, 2011), and provide multiple ecosystem services to people both locally and across the world (Silvius & Giesen, 1996; Phillips, 1998). At present, over 45% of the peat swamp forests of Southeast Asia have been logged or drained (Hooijer *et al.*, 2006), and converted into agricultural land and infrastructure, or left as degraded ecosystems (Koh *et al.*, 2011). Peat swamp forests are described as the “main wetland ecosystem type....and one of the most critical ecosystems in South East Asia” (APFP, 2010), since the value of converted peat swamps to local stakeholders greatly outweighs that of the intact ecosystem. Thus development, to the most part, is unchecked by the concerns voiced by the international conservation community, namely the carbon emissions (for example Fargione *et al.*, 2008; Couwenberg *et al.*, 2010; Hooijer *et al.*, 2010; Page *et al.*, 2011) and biodiversity loss (Yule, 2010; Posa *et al.*, 2011) associated with conversion. The peat swamp forests of Sarawak, one of the two East Malaysian States in northern Borneo, are experiencing deforestation rates 12 times greater than those across Asia (SarVision, 2011), and approximately 25% higher than those of the island’s lowland dipterocarp forest (Langner *et al.*, 2007), with an average annual rate of 7.7% reduction per year over the last decade (Miettinen, *et al.*, 2011).

1.1 *Peat swamp forests in Sarawak*

Approximately 70% of Malaysia's peatlands lie in Sarawak, covering an area of 1.6 million hectares (UNDP, 2009). Peat soils are defined as those that comprise $\geq 65\%$ organic matter (USDA, 1975), are ≥ 50 cm in depth and at least one hectare in area (Liong & Siong, 1979). They form when the rate of accumulation of dead plant matter from over-standing forest vegetation exceeds that of decomposition, due to the anaerobic conditions of the naturally waterlogged forest floor (DOA, 2003). Forest cover and these unique hydrological conditions are vital components of this ecosystem, forming a tight interrelationship with peat soil accumulation (Wösten *et al.*, 2006; Posa *et al.*, 2011). The resulting build-up of carbon-rich matter over thousands of years creates a repository of historical information on the area (CC-GAP, 2005), especially where there is deep peat, i.e. some 89% of Sarawak's peatland. The peat swamp forest comprises a rich flora, uniquely adapted to the low nutrient, acidic ($< \text{pH } 4.5$), water-logged environment (UNDP, 2009; Yule, 2010; Posa *et al.*, 2011). In comparison, *peatland* includes areas where peat accumulation may be compromised by disturbances, such as land-use change. Traditionally the peat swamp forests of Sarawak were largely considered as "marginal wasteland" (Sawal, 2003) as a result of their limited accessibility and inhospitable physical characteristics. However, for those that do gain access, and indeed for people across the world, they are the providers of numerous ecosystem services.

1.2 *Ecosystem services provided by peat swamp forests*

The international body of research documenting the services provided by tropical peat swamp forests is increasing in response to the threat faced by this ecosystem (for example Silvius & Giesen, 1996; Phillips, 1998; Yule, 2010; Posa, 2011; Prentice, 2011). The following ecosystem functions constitute those most documented by, and of benefit indirectly to the

international community. Firstly and perhaps the most researched is the function of tropical peat swamps as the “most important carbon stores in the world” (CC-GAP, 2005; APFP, 2010), storing 5800 tonnes of carbon per hectare in a 10 m deep peat swamp (depths that are found in more developed peat domes in Sarawak), compared to 300-500 tonnes per hectare in other types of tropical forest (UNDP, 2009); they provide a reservoir of fossil carbon (Jaenicke *et al.*, 2008) and contribute to global climate regulation. Of similar importance is the role these ecosystems play in biodiversity conservation (Yule, 2010). Tropical peat swamp forests are highly important for the conservation of freshwater diversity, including many fish adapted to the blackwaters (Posa *et al.*, 2011), as well as being the home to many threatened species, ranging from freshwater turtles to an array of primates (Phillips, 1998; Posa *et al.*, 2011), including the Bornean orang-utan, *Pongo pygmaeus* (Morrogh-Bernard *et al.*, 2003; CC-GAP, 2005; APFP, 2010). In terms of plant diversity, they are a natural gene bank of species of known edible and medicinal value, and potentially harbour much more yet to be discovered (UNDP, 2009). The third major function, highlighted by the international conservation community, but also acknowledged by local stakeholders, is the role of peat swamp forests in water regulation. They provide flood mitigation, prevent saline water intrusion and act as reservoirs, providing a water supply, albeit of poor quality, throughout the year (Phillips, 1998; CC-GAP, 2005; UNDP, 2009; APFP, 2010).

There are a number of major uses of tropical peatland, most of which provide direct value to local stakeholders (Ramakrishna, 2005). Agriculture is the predominant one (Koh *et al.*, 2011) and generates large revenues from this ecosystem (Morel & Morel, 2012). The main smallholder crops are oil palm, coconut, pineapple, sago palm and rubber (Mittinen *et al.*, 2012b), with vegetables, tapioca and rice also grown (DOA, 2003). Industrial crops are predominantly oil palm, *Elaeis guineensis*, and *Acacia crassicarpa*, for pulp wood

(Jauhainen *et al.*, 2012). Despite the income provided by farming in these ecosystems, there are divergent claims about the suitability of peatland for such uses. Forestry is another large industry (UNDP, 2009), with the selective logging of the coastal peat swamps forming a key income for Sarawak from the 1950s to 1970s. It continues today, although with declining extraction rates due to the much depleted tree stocks (Sawal, 2003). Peat swamp forests are also used for fishing, hunting and energy (UNDP, 2009), and for livelihood acquisition (APFP, 2010). Local people are reported to collect timber and non-timber forest products, traditional medicines and herbs, the fern *Stenochlaena palustris*, gain water and hunt for cat fish, Clariidae, and other species adapted to the “black waters”. However, evidence suggests that people in Sarawak have only used these forests for the last 200 years (Sawal, 2003). Such evidence can be gathered from the peat soils themselves (for example, Cole *et al.*, *in prep*, see Chapters 3, 4, 5 & 6; Hunt & Premathilake, 2012); they play an important role as archives, providing information useful for research and education (CC-GAP, 2005). In addition, peat swamp forests have attributes, such as cultural/spiritual, aesthetic and wilderness values, which have the potential to generate benefits beyond economics or direct use. Such benefits and consequential management strategies to preserve them, are however reliant on stakeholders perceiving such values (for example see Menzel & Teng, 2009; Lamarque *et al.*, 2011).

1.3 *History of Sarawak’s peatlands & contemporary threats*

Recent trends in peat swamp forest degradation illustrate that the indirect values mentioned above are inferior to the more tangible values offered by conversion. The rainforests of Southeast Asia in themselves are challenging places to live for humans, with little light penetrating the canopy, poor soil fertility and low faunal populations, making cultivation and hunting difficult (Reid, 1995); in addition to this, Sarawak’s coastal peat swamps are water-

logged and mosquito-ridden. However, since only 28% of the State's land is classified as suitable for any kind of agriculture and the rest is either "forest land" and settlement (67.6%) or waterlogged (Siong, 1994), land on which development can happen is limited, increasing the pressure to develop peat swamp forests.

With little past experience of using these ecosystems for commercial purposes, especially for the cultivation of an exotic plant such as oil palm (native to West Africa (Corley & Tinker, 2003)), they were initially seen as risky ventures. They were simply traversed where possible to connect Sarawak's coastal and inland areas. Gradually, experience was gathered from West Malaysia, where peatland plantings started some 40 yrs earlier than in Sarawak (Estate Manager, personal communication). Large-scale development in the peat swamp forests of the State started with logging in the early 1950s (Sawal, 2003), removing all valuable timber species prior to plantation establishment.

Subsequently, as agricultural practice grew, and valuable timber for extraction, along with land on alternative soils, became short in supply, Sarawak's State Planning Unit looked to peat. They initiated feasibility studies from 1989 to identify potential areas in which to establish estate plantations, including for oil palm (Siong, 1994). Following this, the coastal peatlands became "an important land resource for agriculture in the State" (Sarawak Agriculture Perspective Plan Study, 1992), despite the need to clear, drain, and apply fertilizer and lime to increase the pH and boost microbial activity prior to agricultural use (Posa *et al.*, 2011). Less than half a decade later, large oil palm plantations became common along the coastal strip. Development has continued since, with estates now occupying over a quarter of the State's peatland, 0.48 million ha (Scientist, personal communication). Even by 1999, oil palm had the largest coverage across the peatlands, with an area of 326,500 ha, or

63% of the total peatland alienated for agriculture (518,254 ha) (Siong, 2004). Currently, the State's peatlands are seen as the "last frontier of an important arable land" still capable of accommodating oil palm agriculture (Dolmat, 2005).

However, this development has resulted in extensive losses of peat swamp forest in the State. A recent study measuring forest cover change in Southeast Asia between 2000 and 2010, identified the peat swamp forests of Sarawak as having one of the most rapid rates of deforestation in the region, with half of the peat forests in 2000 having been lost by 2010 (Miettinen *et al.* 2011). This ongoing development therefore appears to be neglecting the call, predominantly of the international community, for the conservation and sustainable management of these often-quoted "fragile" ecosystems; "peat is a precious commodity that should be handled with care to prolong its life" (DID, 2001). International conventions, such as the Convention on Biological Diversity (CBD) and Ramsar Convention on Wetlands of International Importance, ratified by the Malaysian Government in 1992 and 1994 respectively, encourage protection of these peat swamp forests. Yet such protection is not being given. It appears that the key challenge is to define what constitutes sustainable management: "use....while allowing exploitation that does not irreversibly destroy the wetland's functions or its potential to support people and wildlife" (UNDP, 2009).

1.4 *Multi-stakeholder analysis for sustainable natural resource management*

For any effective resource management policy, the many people with a stake in that resource need to be involved. Each group of people is likely to differ in their method, drivers, requirements and visions of resource use, and thus, in order to understand the dynamics of exploitation and potentially unsustainable resource use, the dynamics of each stakeholder must be understood (Meijaard & Sheil, 2011; Persha *et al.*, 2011; Pfund *et al.*, 2011; Wicke *et*

al., 2011). The peatlands of Sarawak are no exception: “planning a lowland peat swamp development project is an interdisciplinary undertaking” (DID, 2001), both in the initial stages of information gathering and in the latter stages of strategy development. Currently, there are complaints amongst local users of “misconceptions” and “pious reporting” on aspects of peatland use by the international conservation community, but each group has access to a different set of incomplete information. Due to a lack of knowledge and understanding in both Federal and State Governments, and a lack of engagement of local stakeholders, damaging policies and initiatives are in place, promoting mismanagement of this unique ecosystem (APMI, 2005). Such a scenario has been demonstrated in Central Kalimantan (Galudra *et al.*, 2011).

For peatlands in particular, given the unique interconnected nature of peat domes (Dommain *et al.*, 2011; Posa *et al.*, 2011), there is a greater need for integrated management and a systematic ecosystem approach (UNDP, 2009). Knowledge on ecosystem processes and the full range of services, biological thresholds and social and economic information must be integrated to enable sustainable use, within the biological capacity of the system (UNDP, 2009). In addition, an analysis of the similarities and differences in discourses across stakeholder communities, which may impact on conservation policy (Feintrenie & Levang, 2011), is required. This study will investigate the different discourses, and information gaps, amongst these peatland stakeholder groups.

Through emphasizing the international importance of this unique and under-researched ecosystem, the international conservation community is campaigning for peat swamp forest protection rather than conversion. Yet, conversion continues unabated in Southeast Asia, with little apparent consideration by local stakeholders of the values ascribed to peat swamp

forests internationally, notably for carbon storage. This paper aims to investigate this conflict between local and international stakeholders and assess the potential for overcoming it. Specifically, the objectives of this study are to: (i) identify peatland stakeholder groups; (ii) investigate, through interviews, what each group perceives as (a) the main challenges involved in using peatlands sustainably, (b) the functions provided by peat swamp forests, and (c) the future of the peat swamp forests of Sarawak; and (iii) analyse similarities and differences between stakeholder issues in order to identify both sources of conflict and where opportunities lie for promoting the *wise* management of these unique ecosystems.

2. Materials and methods

2.1 Study area

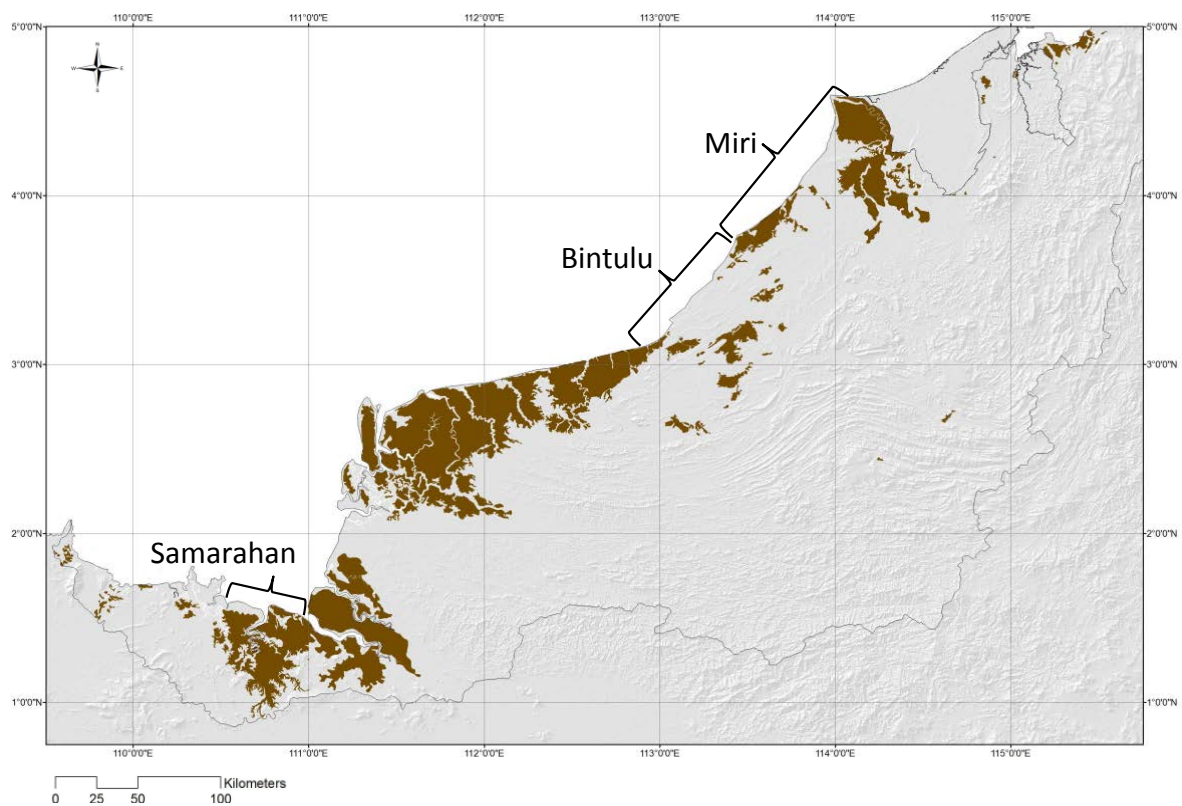


Fig. 1 Map of Sarawak, showing the main peatland areas and approximate coastal extent of the three Divisions where interviews were performed: Samarahan, Bintulu and Miri. (Image courtesy of SarVision (2011).)

Sarawak covers an area of 12.2 million hectares (Siong, 1994) and, as part of the island of Borneo (Fig. 1), lies within Conservation International's Sundaland Biodiversity Hotspot (CI, 2007). This illustrates the rich biodiversity it houses (MacKinnon *et al.*, 1996) and the rapid rates of deforestation and habitat loss it is experiencing (Langner *et al.*, 2007; SarVision, 2011; Sodhi *et al.*, 2010; Miettinen *et al.*, 2012a, the latter two recording deforestation across Southeast Asia), even within protected areas (DeFries *et al.*, 2005; Miettinen *et al.*, 2011). Sarawak's peatlands, extending over 13% of the State (Wetlands International, 2010), mostly along the developing coastline, form an integral part of this Hotspot. Northern Borneo is described as having a tropical ever-wet climate (Morley & Flenley, 1987) with an average temperature of 25°C, an average rainfall exceeding 370 cm yr⁻¹ and humidity levels ranging from 55% in the daytime to almost 100% at night. These climatic conditions are important for the development of tropical peat swamps (Staub & Gastaldo, 2003).

2.2 *Data Collection & Analysis*

This study employed a mixed methods approach to assess the differences between the common issues of international institutions concerning the sustainable management of Southeast Asian peat swamp forests and those of the stakeholders involved in the management of these ecosystems in Sarawak. It comprised two parts: a literature review to identify the broad issues and concerns amongst the international community, and a series of interviews with the stakeholders of Sarawak's peatlands to assess where sources of dichotomy lie between the discourses of the different interest groups. Each method is described in turn.

The literature review comprised both published and grey literature, such as reports from international non-governmental organisations (NGOs) and international scientists working on

the promotion of the sustainable management of Southeast Asian peatlands, to identify which issues arise most frequently in the discourse surrounding these tropical ecosystems. A full search on Scopus (www.scopus.com), using search terms *tropical peat swamp* and *tropical peatland* in the Title-Abstract-Key Words-Author, and of literature of key NGOs, such as the Global Environment Centre, was performed, yielding over 100 records between the period of 1983 to 2012. (See Appendix A, Table A.1, for literature reviewed.) Once the most frequently cited common issues had been identified, they were grouped into three categories: (i) challenges to using tropical peatlands sustainably (Table 2); (ii) functions of tropical peat swamp forests (Table 3); and (iii) future prospects and actions for sustainable peat swamp forest management (Table 4). They were subsequently used to form the main themes employed in the coding of the open-ended questions asked during stakeholder interviews.

A total of 30 semi-structured interviews were conducted with ‘user’ stakeholder groups, i.e. Smallholders (SH) and Estate Managers (EM), based broadly in the following key peatland areas: Samarahan, Bintulu and Miri divisions (Fig. 1). Ten interviews were also conducted with a variety of key informants (Table 1). The aim of the interviews was to identify the key issues, history, challenges and future visions of these people living, working, or in some way participating in the management of Sarawak’s coastal peatlands, and to allow comparison with the key issues expressed by the more remote international community. Stakeholders were identified through observation and enquiry in the region of interest and through discussions with other stakeholders, in order to gather information from the broad range of people involved in peatland management. All interviews used an interview guide, compiled after performing a literature review and an initial excursion to the field, which included questions on interviewee’s knowledge of the history of Sarawak’s peat swamp forests, current

use of the peatlands and challenges faced by such, and thoughts on the future management of these areas (see Appendix B for Interview Guides for each stakeholder group).

The majority of data collected is qualitative, obtained through open-ended questions in the semi-structured interviews. Qualitative research methods are important in conservation studies where knowledge of human behaviour is required; they provide an opportunity to investigate a potentially complex array of perceptions, attitudes and beliefs of different stakeholders, and identify new and emerging themes, in addition to those identified from the literature (Drury *et al.*, 2011). In this study, where we seek to compare an international perspective with that of the communities on the ‘ground’, enquiring through non-prescriptive techniques is an important approach. Quantitative interview methods can be restrictive where prior knowledge of the situation is limited and where such an exploration of different views is required, especially with people for which the culture of such defined questioning for information retrieval is novel (Drury *et al.*, 2011). In this study, numerical data are employed to provide context and support for other questions, for example to identify when Sarawak’s coastal peat lands were first inhabited by people.

Smallholders, i.e. people with some agricultural plantings in peat areas, were selected for interview opportunistically, but with the aim of including as broad a range of Sarawak’s different ethnic groups as possible. Suitable areas for finding such stakeholders were geographically located using land-cover type and infrastructure maps. Estate Managers were selected according to location, using a Malaysian Palm Oil Board (MPOB) list of oil palm plantation companies as a sampling frame. Key informants were identified through the literature search and by using a snowball sampling technique during discussions with other stakeholders. Interviews typically lasted 40-60 minutes, but ranged from 30 minutes to three

hours. They were carried out throughout the day, predominantly in the interviewee's home or office. SH interviews were conducted in Malay or a local dialect shared with the translator. The majority of the other interviews were conducted in English. All answers were noted at point of interview and later transcribed into electronic format. Where interviews were performed over email, data was also stored electronically for consistency.

Table 1 Number of interviewees in and characteristics of each stakeholder group involved in Sarawak's peatland management. (The responses of one interviewee, chairman of an oil palm company with experience also in estate management, have been used in both Estate Managers and Capitalists categories since the respondent was asked both sets of questions.)

Stakeholder group	Acronym	Description and key characteristics	No. interviewees
USERS			
Smallholders	SH	Users of peatland, generally ≤ 100 ha, for agriculture	22
Estate Managers	EM	Managers of oil palm estates (commonly > 500 ha)	8
KEY INFORMANTS			
Government	GO	Members of State Departments	3
Capitalists	CA	Senior employees of large oil palm companies	2
NGOs	NGO	Employees of international NGOs	2
Scientists	ST	Scientists researching Sarawakian or Southeast Asia peatland ecosystems	3
TOTAL			40

All interviews were coded according to the common issues identified through the literature review, and arising themes extracted for each stakeholder group. Answers to closed questions asked to Smallholders and Estate Managers, such as "Is fire a problem?", were summed and turned into percentages in order to observe the most common view held by these 'user' stakeholders. Where quotes are displayed in tables they reflect the common view held by the number of respondents displayed in brackets. Where a quotation is reported in the text, it is accompanied by the respondent's acronym.

Due to a lack of databases of Smallholders & Estate Managers with plantings on peat, and time constraints, interviews with ‘users’ were limited to the three aforementioned Divisions. Since results appear to be broadly similar between these geographical areas, and the nature of the interview technique allowed for an extensive exploration of interviewees’ perceptions, it is assumed that interviews with stakeholders of other coastal peat swamp areas in Sarawak, for example Sibul, will yield comparable results. Limited time, institutional barriers and the current sensitive nature of peatland exploitation in Malaysia (see http://news.mongabay.com/2011/0201-sarawak_palm_oil_vs_peat.html amongst other news stories) also meant that key informant interviews were confined to ten. However, a diverse range of people were interviewed and exploratory techniques employed, such that the data collected is sufficient for the nature of this study, i.e. a broad overview of stakeholder opinions on the various aforementioned aspects of peat swamp forest management in Sarawak.

3. Results

3.1 Challenges involved in using peatlands sustainably

Fire appears to be the first source of conflict between the international conservation community and Sarawak’s stakeholders: the former perceive it as a large problem, occurring often and in an uncontrollable manner, whereas the majority of Smallholders and Estate Managers (83%) see it as a manageable component of peatland use (Table 2). Similarly, water management is not an issue of concern amongst stakeholders, with 70% of respondents claiming to manage the water level on their plantations such that neither flooding nor drought is a problem (the latter of which was not mentioned, illustrating this). Subsidence, described as an inevitability by the international community, was common but not reported by all respondents. The fact that people *are* using peatlands for agricultural purposes refutes the

claim that they are “unsuitable for agriculture”, but there was no consensus on the reported direction of change in peat soil fertility with time.

3.2 *Functions provided by peat swamp forest*

The performance of peat swamp forests as a “refuge for biodiversity” was not alluded to by any respondents (Table 3); in contrast, several reported that the forests were depleted of species now, and of unsuitable quality, i.e. waterlogged, for most fauna. There was no mention of the flora that has evolved with unique adaptations for this “harsh waterlogged environment” (UNDP, 2009). The only reason offered for why peat swamp forest should be conserved for its biodiversity value was that peatlands would be unusable in the absence of biodiversity (Scientists, personal communication).

Very little was mentioned about the carbon storage function of peat swamp forest, and respondents did not seem to be aware of the value that the international community place on these ecosystems as globally important carbon stores. The issue was raised in relation to the negative press from the international community surrounding forest conversion to agriculture, and that there are many assumptions made without the support of scientific data. Several Scientists reported to be attempting to fill the research gaps.

Table 2 Reported incidence amongst interviewed Estate Managers & Smallholders (n = 30), of the main challenges associated with using tropical peatlands, as described by the international conservation community. (*SUBSIDENCE reflects the *impact* of drainage on the peatlands. ↓ represents a decrease in soil fertility, ↑ an increase, and ↔ no change.)

Challenges	International discourse	Question asked	Results	Non-response
FIRE	<i>large international concern, increasing in likelihood with peat swamp forest conversion</i>	Is fire a problem?	No - 83% Yes - 4%	13%
DRAINAGE	<i>must be carefully managed otherwise irreversibly degrades peat</i>	Is flooding a problem? i.e. is water management unachievable?	No - 70% Yes - 17%	13%
SUBSIDENCE*	<i>inevitable, occurs rapidly and generates emissions</i>	Have you experienced subsidence on your plantation?	No - 13% Yes - 60%	27%
SOIL FERTILITY	<i>peatlands are low nutrient environments, unsuitable for most agriculture</i>	Have you noticed a change in soil fertility since establishing your plantation?	↓ - 30% ↑ - 3% ↔ - 30%	37%

The importance of peat swamp forests for their water regulating value was mentioned by 18% of respondents, and came across as the most uncontroversial and clear function provided for local stakeholders (Table 3). However, the importance of these ecosystems for livelihoods was in great contrast to international opinion: the majority of Smallholders claim not to gain any resources from peat swamp forests (with subsistence extraction being legal) and do not think people generally want access to them, seeing the opportunity for poverty alleviation through agricultural development as a priority. Although some respondents reported that the peat swamp forest was used more in the past, prior to increased pollution and reduced access due to land conversion, it is no longer considered a livelihood option. Responses to the question of how long interviewees have lived in the coastal peatlands suggest that people have only been a component of this landscape for less than 200 years.

Table 3 Thoughts and concerns of the different stakeholder groups, categorised according to the main functions of peat swamp forest as described by the international conservation community: **(a)** categorised thoughts and concerns; **(b)** summarised direction of comments in relation to the international discourse, with “+” signifying alignment, “-” contention, or “0” neutral comments. (The *Percentage responses* column details the percentage of the total interviewees that commented on the topics listed in the table, during the open-ended section of each interview. Numbers in brackets illustrate the number of interviewees in each group, or the number of those that voiced the reported thought. Phrases in bold align with the International Discourse.) (EM, Estate Managers; SH, Smallholders; GO, Government; CA, Capitalists; NGO, Non-governmental organisation; ST, Scientists.)

(a) (Displayed on following page)

(b)

Functions of peat swamp forest		Percentage responses	Stakeholder groups & discourses					
	International discourse	(those aligned)	EM (8)	SH (22)	GO (3)	CA (2)	NGO (2)	ST (3)
BIODIVERSITY CONSERVATION	<i>important refuge for biodiversity</i>	15% (5%)		0	+	0	+	0
CARBON STORAGE	<i>vast store & potential sink of carbon</i>	15% (8%)	0			0/ -	+	+
WATER REGULATION	<i>water supply, flood control & prevention of saline water intrusion</i>	18% (18%)	+	+	+		+/ 0	+
LIVELIHOODS	<i>provides resources and income for local communities</i>	70% (18%)	0	+/-	-	-	+/-	-

(a)

Stakeholder groups & discourses								
Functions of peat swamp forest	International discourse	Percentage responses (those aligned)	EM (8)	SH (22)	GO (3)	CA (2)	NGO (2)	ST (3)
BIODIVERSITY CONSERVATION	<i>important refuge for biodiversity</i>	15% (5%)	(0)	forest conservation is a sensitive issue (1)	important (1)	"we do take note of that" (2)	identify critical peatland areas for conservation and take steps to protect & manage them (1)	positive inter-relationship between biodiversity and ecosystem function, e.g. fertility (1)
CARBON STORAGE	<i>vast store & potential sink of carbon</i>	15% (8%)	no system for monitoring areas of high carbon (1)	(0)	(0)	emissions are the biggest problem but result from any crop (1); plantings add carbon, not remove it (1)	needed for carbon sequestration in future (1)	doing research on emissions (2)
WATER REGULATION	<i>water supply, flood control & prevention of saline water intrusion</i>	18% (18%)	water catchment (1)	water treatment and reduced flooding (2)	reason why forest important, i.e. for drinking water (1)	(0)	needed for water supply & will be needed for flood control (1); flooding will become a big problem (1)	factor making peat swamp forest important (1)
LIVELIHOODS	<i>provides resources and income for local communities</i>	70% (18%)	poverty alleviation will cause a reduction in peat swamp forest (1)	use for fishing, hunting, timber (6); do not use (15)	peat swamp forest not used by people anymore (1); poverty-reduction achieved through agricultural development (1)	peat not suitable for smallholders (1)	local communities acquire non-timber products, timber, & water but will not be needed for such in the future (1); peatlands have little agricultural value if un-developed for OP (1)	people do not want access (1)

3.3 *Future vision and considerations for the sustainable management of peat swamp forest*

In response to questioning, the vast majority of Estate Managers and Smallholder respondents see the peat swamp forest continuing to decline in the future, mostly as a result of oil palm plantation development (Fig. 2). Despite this, 67% think that maintaining access to peat swamp forest for the next generation is important (Fig. 2). However, when dissecting the reasons for this opinion, 47% thought it was important in providing a resource of land that would be available for conversion in the future, to provide an income for people in need or wanting to develop further. The remaining 41% who commented did appreciate various values of the intact peat swamp forest, but only two claimed that people still had a direct reliance on the forest for resource provision.

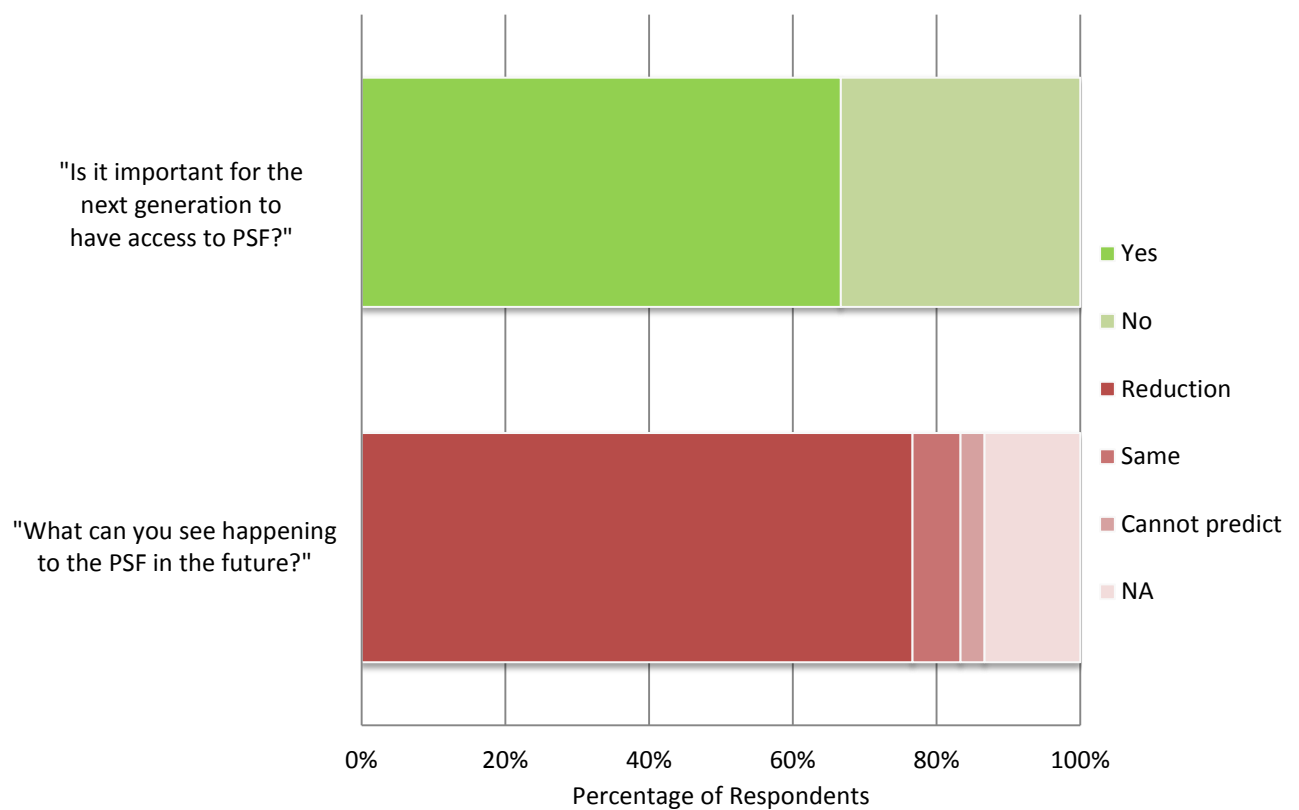


Fig. 2 Summed Estate Managers & Smallholders responses to the questions: “Is it important for the next generation to have access to peat swamp forest?” and “What can you see happening to the peat swamp forest in the future?” (NA = no answer given.)

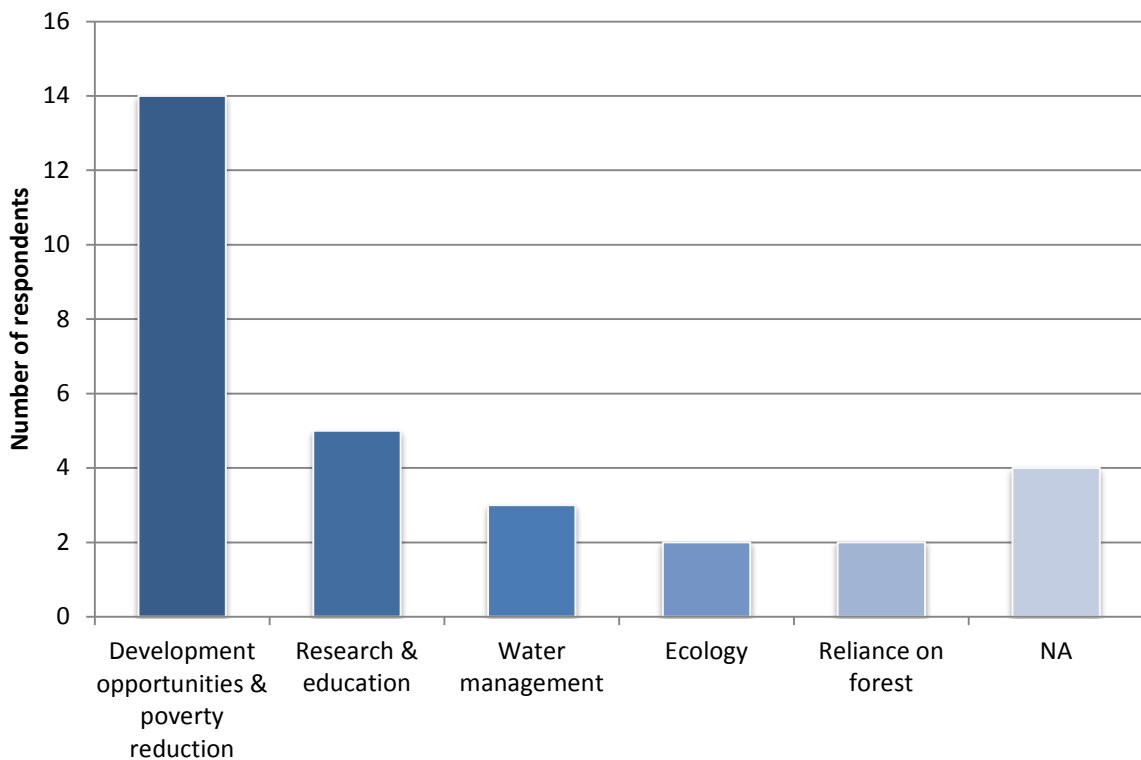


Fig. 3 Summed responses for Estate Managers & Smallholders, showing reasons quoted by interviewees for why it is important for the next generation to have access to peat swamp forest. “Development opportunities & poverty reduction”, contrary to the other reasons shown for conserving peat swamp forest, was cited by respondents who felt it important to have access to the peatland under the forest as a resource on which development could occur.

When looking at general themes that arose in open conversation about the future of Sarawak’s peat lands, the need for development dominated (Table 4): agriculture is seen as an unavoidable and necessary reality for this developing nation, and one that generates more value from peatlands than standing forest. Although the need for “balanced development” and “wise use” was mentioned, the emphasis was placed on the importance of the development component, and any peat swamp forest areas that were unsuitable for conversion, for reasons of peat depth, access, etc., were then designated protected by the State. This runs counter to the opinion/desire of the international community, which calls for areas of peat swamp forest to be conserved for their intrinsic values foremost and only developed if they lack such as a result of previous degradation. International conservationists

see the Government (with land management responsibilities falling predominantly at State Government level (NGO, personal communication)) as the key player in increasing areas of peat swamp forest under protection, but one that needs encouragement in appreciating the importance of such policy changes. Respondents shared this view: the State Government has the ultimate control over which and how much peat swamp forest is gazetted as protected, and there needs to be increased political will to develop policies that do not contradict conservation or sustainable development objectives, as they currently do, and take into account the increasing volume of relevant research. At the same time, one respondent was of the opinion that the Government is improving environmental standards on oil palm plantations, with more stringent regulations and frequent checks, but in terms of conservation, more can be done. Respondents and the international community are in agreement that more research on sustainable peatland management and peat swamp forest restoration is required, as most guidance is currently based on insights from temperate peat, a very different ecological system. The fact that several Smallholders thought fruit trees provided sufficient 'forest' emphasizes that there is a lack of awareness of the importance of peat swamp forest, illustrated by the responses of other stakeholders towards the issue of capacity building: Sarawakian society does not share the same awareness as the international conservation community of this ecosystem's uniqueness, with poverty reduction being a more pressing issue. Finally, the Round Table on Sustainable Palm Oil (RSPO) was mentioned by only four respondents, who commented that the institution had not yet defined its Principles and Criteria for managing peatland-based oil palm plantings and that currently certification was an expensive endeavour, in terms of time and money, with little reward.

Table 4 Themes arising in interviews through discussion of the future of Sarawak’s peat swamp forest, grouped according to the main themes identified in the international conservation literature and ordered according to frequency of occurrence amongst respondents: **(a)** categorised issues; **(b)** summarised direction of comments in relation to the international discourse, with “+” signifying alignment, “-“ contention, or “0” neutral comments. (The *Percentage responses* column details the percentage of the total interviewees that commented on the topics listed in the table, during the open-ended section of each interview. Numbers in brackets illustrate the number of interviewees in each group, or the number reporting each statement. Phrases in bold align with the International Discourse.) (EM, Estate Managers; SH, Smallholders; GO, Government; CA, Capitalists; NGO, Non-governmental organisation; ST, Scientists.)

(a) (Displayed on following page)

(b)

Considerations for the future	International discourse	Percentage responses	EM (8)	SH (22)	GO (3)	CA (2)	NGO (2)	ST (3)
DEVELOPMENT	<i>needs to be managed in a sustainable manner</i>	28%	0/+	0	+	-	0/+	0
GOVERNMENT	<i>strengthened Government support needed</i>	23%	0		0/+	/+	0/+	+/0
RESEARCH	<i>more needed</i>	23%		+	0	+	+/-	+
RESTORATION	<i>important option for peatland conservation</i>	18%	+	-				+
BUILDING CAPACITY	<i>increased awareness and support needed in peat swamp forest nations</i>	15%			+	+	+	-
RSPO & CERTIFICATION	<i>options for improving management of peatland plantations</i>	10%				0	0	+

(a)

Considerations for the future	International discourse	Percentage responses	EM (8)	SH (22)	GO (3)	CA (2)	NGO (2)	ST (3)
DEVELOPMENT	<i>needs to be managed in a sustainable manner</i>	28%	aspirations to achieve developed country status (2); "protection of the environment and economic development are equally important" (3)	aspirations to achieve developed country status (1)	"need balanced development" (1)	development makes peat more valuable and under control, i.e. water and fire management (1)	need "wise use", considering environment and development simultaneously (1); currently no integrated management, just more areas being opened up for OP development with little benefit to & displacement of local communities (1)	agricultural development is a reality (1)
GOVERNMENT	<i>strengthened Government support needed</i>	23%	government to decide on conservation (1)	(0)	Government dictates conservation (1); needs to gazette more peatland protected areas (1)	"Government taking bold proactive steps" (1), but creates pressure for opening up new areas & needs to develop a protection policy (1)	acts as a consultant to Government (1); State Government and its relevant agencies should be shown research results, since currently relying on "political will" for suitable peatland management strategies and existing policy favours conversion (1)	need "political will" (1); Government has control (1)
RESEARCH	<i>more needed</i>	23%	(0)	research needed (1)	specialist research stations for developing technical info (1)	much research being done & more needed, since most currently based on temperate peat (2)	much research needed (1); sufficient research has been done on which to base policy decisions (1)	doing research but little done before (2); most understanding based on temperate peat (1)
RESTORATION	<i>important option for peatland conservation</i>	18%	reforestation needed (2)	fruit trees suffice as forest (3)	(0)	(0)	(0)	restoration problematic & must be implemented quickly (2)
BUILDING CAPACITY	<i>increased awareness and support needed in peat swamp forest nations</i>	15%	(0)	(0)	society does not know what is important about peat swamp forest (1); aspirations are to reduce poverty (1)	people unaware about the forest (2)	people not appreciating the value of peat swamp forest and have aspirations to reduce poverty (1)	important to conserve forest to show grandchildren (1)
RSPO & CERTIFICATION	<i>options for improving management of peatland plantations</i>	10%	(0)	(0)	needs a "more thorough perception towards peat plantings" (1)	(0)	involvement in Peatland Working Group (1)	certification important (1), but challenging (1)

4. Discussion

The interview data have highlighted a number of challenges and opportunities in the sustainable management of peatlands in Sarawak, and indeed across other parts of Southeast Asia. The key insights are discussed in relation to the three areas explored.

4.1 *Challenges involved in using peatlands sustainably*

Increasingly, fire is becoming a topic of international concern. This is reflected by the volume of literature researching this theme, coincident with burning incidences and the resultant pollution becoming more severe and far-reaching (Aiken, 2004). However, stakeholders interviewed here claim that fire control is not an issue. Therefore the nature of burning in peatland areas, notably ignition sources and land-use policies (Carlson *et al.*, 2012), must be characterised accurately, and problem-areas of both natural and human-induced fire identified and managed accordingly. Often linked to fire, but cited as being the greater contributor to regional long-term CO₂ emissions (Jauhiainen *et al.*, 2008; Couwenberg *et al.*, 2010) and certainly of great international interest (for example Wösten *et al.*, 2008, Dommain *et al.*, 2010), is the practice of drainage. Universal strategies for minimizing impacts have been proposed (Dolmat, 2005), but since drainage is the crucial first step in the development of peatlands, some level of oxidation, compaction and subsequent subsidence is “the price one has to pay” (Ritzema *et al.*, 1998; DID, 2001; Dolmat, 2005; Dommain *et al.*, 2010; Hooijer *et al.*, 2011). The resulting damage or speed of such peat subsidence, will depend primarily on water level management (Couwenberg *et al.*, 2010), but also on the nature of the underlying substrate, in some cases acid sulphate soils (Okubo *et al.*, 2003) which can be toxic for plants (Maloney, 1992; Posa *et al.*, 2011), and on the depth of the peat. If Sarawak loses its entire peatland resource through subsidence, loss of drainability and exposure of underlying acidic sulphate soils, it will in fact lose >10% of its land area

(Joosten, personal communication). Results from this study suggest that peatland managers do not appreciate these potential long-term impacts, proposing oil palm plantations as an effective means of managing water tables in peat swamp areas. Similarly, land managers are unaware of how soil fertility may change in the future, and what impact this could have on land-use potential. For dealing with all of these physical challenges, Best Management Practices are urgently required (Dolmat, 2005) that take into account hydrological integrity across entire coastal peat domes (Dommain *et al.*, 2010). Nonetheless, the practice of drainage is arguably the greatest (and most expensive – Dolmat, 2005) challenge facing the sustainable management of peatlands into the future, especially for agriculture (Andriesse, 1988; Dommain *et al.*, 2010) and in the face of global climate change (Jauhiainen *et al.*, 2008; Couwenberg *et al.*, 2010).

4.2 *Functions provided by peat swamp forest*

The ecosystem values local stakeholders deem worth conserving appear to be somewhat different to those emphasised in the discourse of international conservationists. In particular is the immense carbon storage service provided by peat: a major theme in the published literature (for example Couwenberg *et al.*, 2010; Hooijer *et al.*, 2010; Dommain *et al.*, 2011; Page *et al.*, 2011, and see Appendix A, Table A.1). Only NGOs and Scientists touched on this theme, and, in comparison to, for example, the water provision service provided by peatlands, no-one ‘on-the-ground’ mentioned peatland carbon. This is not surprising given the visibility of the water provisioning service in Sarawak: 38 water treatment plants associated with peat swamps function across the State to provide water for domestic supplies (DID, 2001). If the carbon storage, and indeed sequestration function of these ecosystems is to be as strong a driver of peat swamp forest conservation, it also has to become more visible and lucrative, for example through payments for the provision of such a service. The current failure to

incorporate greenhouse gas emissions from tropical peat swamp forest conversion into IPCC Guidelines for National Greenhouse Gas Inventories and terrestrial carbon stock assessments (Page *et al.*, 2011), and REDD portfolios (Murdiyarto *et al.*, 2010), is only slowing the development of payment mechanisms that make sustainable management more profitable than the agricultural alternatives (Butler *et al.*, 2009). Similarly, the “non-integrated and conflicting policies related to agriculture, fisheries, forestry and water resources” (APMS, 2007), that often result in peatlands’ many services being neglected, must be addressed.

Conservation programmes and policies also need to consider the historical relationship local stakeholders have had with this ecosystem. There appears to be little opportunity here for building on long-standing relationships of environmental dependency that can foster stewardship of natural resources (Hayashida, 2005), since results suggest that few people still rely on the coastal peat swamp forests for their livelihoods, and instead view them as “just a wasteland – (they serve) no purpose” (Estate Manager, personal communication). Looking elsewhere within the region’s peat swamp ecosystems may thus provide some useful information on past human-environment interactions of a sustainable nature, such as examples of wetland sago cultivation (Donner, 1987). There was indeed a general consensus that awareness raising and capacity building was needed for all stakeholders concerned; “ignorance underlies the blasé destruction of these habitats” (Dennis & Aldhous, 2004). As shown in this study and others (for example Feintrenie *et al.*, 2010), exposure to economic market opportunities encourages farmers to convert peat swamps into plantations with any, albeit distant, cultural connection to the forest proving insufficient to prevent this from happening.

4.3 *Future vision and considerations for the sustainable management of peat swamp forest*

The vision, and indeed reality (Koh *et al.*, 2011), of peat swamp forest conversion to industrial plantations cannot be ignored. Yet, it may also provide opportunities for peatland management. For example, all oil palm plantations in Malaysia are centrally monitored by the Federal Government-funded MPOB, which is an important resource for the dissemination of information and education. A booklet produced by them describes the current Best Management Practices for planting oil palm on peat, detailing strategies from suitable designs for drain and road construction to optimal planting densities, sanitation and nutrition (Dolmat, 2005), and is carefully adhered to by plantation managers eager to maximise yields. The Federal Land Consolidation and Rehabilitation Authority (FELCRA) plays a similar role for smallholder agriculture, which experiences different challenges and thus requires different management strategies (Lee *et al.*, 2011).

On a more international level, the RSPO scheme for certifying Sustainable Palm Oil (CSPO) has the potential to promote the adoption of more sustainable practices in peat soil plantings, once such practices have been defined. At present, however, few companies in Sarawak have sought RSPO membership because they feel the current moratorium on plantings on peat does not take into account the challenges and options for plantation management in this landscape, and certification is too expensive for the benefits it would bring. Forthcoming reform of the RSPO Principles and Criteria (RSPO, 2005) may broaden the certification potential for companies with plantings on peat.

For areas where the peat is deemed too deep for development, i.e. greater than 3 m, there are opportunities to grant them protection. Currently, the UNDP is in discussion with the

Sarawak Government on a new protected areas system initiative, in which peatlands may feature more strongly (NGO, personal communication). Other initiatives, such as the Ramsar Convention on Wetlands of International Importance, may provide more opportunity for garnering support for protection of Sarawak's peat swamp forest areas. Sarawak may also benefit from a systematic assessment and subsequent protection of key peat swamp forest values across the State, for example water catchment areas (the only value currently protected), biodiversity conservation and livelihood security, approximating a Strategic Conservation Planning approach (Margules & Pressey, 2000). Ecotourism was not mentioned by a single respondent in this study, but may hold potential for incentivising peat swamp forest conservation, as is occurring in the Klias Peninsula Peat Swamp Forest in the neighbouring Malaysian State of Sabah. Government will is still central for all of these initiatives however (Ansari, 2011).

The same is true for the restoration of already degraded areas, extensive in parts of Indonesia (Miettinen & Liew, 2010), but such rehabilitation and reclamation of disturbed peatlands is proving challenging (Funakawa *et al.*, 1996; Van Eijk *et al.*, 2009; Graham & Page, 2012). At present, Government development policies, often inappropriate and conflicting, and complicated by differences in priorities between Federal and State Governments (NGO, personal communication), along with physical limitations (Firdaus *et al.*, 2010) and poor law enforcement, are discouraging such management (APMS, 2007).

Another factor discouraging sustainable peatland management is the lack of resources, from the perspectives of knowledge, funding and support. In terms of the former resource, research is required that investigates the characteristics of *tropical* peat soils, as most current data come from temperate peatlands (Farmer *et al.*, 2011). Whilst several respondents

criticised the application of such research on solving issues in tropical ones, there is an opportunity for information and skills sharing, and research collaborations between temperate and tropical peatland and forest scientists that may provide some useful insights into both systems (Dommain *et al.*, 2010; Lindenmayer, 2010). Research requirements range from what constitutes an optimal drainage strategy for plantations (DID, 2001), bearing in mind that no one part of a peat dome can be drained and converted without impacting on the whole interconnected peat area (Ewel, 2010), under both industrial and smallholder models, to how much peatland development has benefitted/negatively impacted on people and ecosystem services (NGO, personal communication). Research into Best Management Practices for the variety of peatland agricultures and for the extraction of resources from peat swamp forests is an important component of a more sustainable peatland management strategy, since specialised methods, especially for water management, are required for this unique ecosystem (UNDP, 2009). Currently, choices on plantation management are based on maximising crop yield, but the longer-term sustainability and profit implications must be incorporated into management models (Henson, 2006). Sustainable Forest Management, involving reduced-impact logging (Sasaki *et al.*, 2012), should also be investigated as a potential land-use option, especially given research findings that logging impacts on other ecosystems are less than previously thought (Didham, 2011) and there is potential for carbon and biodiversity conservation (Putz *et al.*, 2012). However, even selective logging techniques are not without impacts in tropical peat swamp forests: removal of buttress roots and establishment of drainage canals disrupt the ecosystem's tight hydrological balance (Dommain *et al.*, 2010). Paludiculture, the cultivation of plants under wet or flooded conditions (FAO, 2012), may provide a mechanism for using peatlands without excessive drainage, with crops such as sago (Miyamoto *et al.*, 2009) which is adapted to and has been historically grown in this marginal ecosystem. However, this land-use option is still in the early stages of piloting and its

potential ramifications are unknown. Ecosystem service evaluation is an area where knowledge and technical advancement are sorely needed, for example developing methods for measuring carbon dynamics in peatlands (Couwenberg *et al.*, 2010). Further to this, research on the implications of peat swamp forest development for biodiversity conservation, must be a priority (Posa *et al.*, 2011).

As the challenges and risks associated with peatland use in Southeast Asia mount, opportunities for financial support appear to be increasing too. For example, the ASEAN Peatland Management Initiative (APMI) was established in 2003, along with the Agreement on Transboundary Haze Pollution, to coordinate “more sustainable peatland management” in the Association of Southeast Asia Nation (ASEAN) countries (APMI, 2005) and specifically to reduce the risk of and damage caused by peatland fires. The ASEAN Peatland Management Strategy is the programme of action for the APMI, and has support from ASEAN Member Countries, ASEAN pooled resources and external institutes. Soon there may also be funds available from Reducing Emissions from Deforestation and Degradation (REDD) schemes and other financial initiatives (FAO, 2012), although accessing and disseminating this money effectively is another challenge, especially in Sarawak where there is limited knowledge of such an opportunity. At present, much work is still needed on the development of a truly implementable carbon credit system for peatlands that could compete with the opportunity of, for example, oil palm agriculture (Gaveau *et al.*, 2009; Morel and Morel, 2012), which constitutes a major driver of peatland conversion in Southeast Asia (Koh *et al.*, 2011). When it comes to funding rehabilitation, one Malaysian scientist suggested that oil palm companies be encouraged to plant on degraded peatlands since they can accommodate the high cost of rehabilitation, and potentially be incentivised to do so. A spatially explicit development strategy for Sarawak, where oil palm is a key land-use on

otherwise unproductive peat soils (Koh & Ghazoul, 2010), could reduce peat swamp forest conversion whilst allowing continued economic growth, one of the State's central goals.

One of the key concerns voiced by respondents was the lack of political will. Arguably, it is not just *political* will lacking. Respondents from other sectors reported contradictory concerns about conservation and development issues, not unusual in this situation (for example Therville *et al.*, 2011). Their collective future vision of a dwindling peatland area, along with the general importance awarded to development, suggested, however, that the priorities of the latter dominate over conservation ideals, tipping the balance between conservation and development (Campbell *et al.*, 2010).

In this study, development emerges as both a blessing and a curse. Respondents see it as being the main driver of peatland conversion, as a way of making the ecosystem more profitable and of keeping it 'under control', preventing destructive fires and flooding. The people and Government are aspiring to achieve developed-country status, with the development of all available land for agriculture being a key factor in enabling this. At most, the environment and development are awarded equal importance. The Government appreciates that development must be "balanced" but respondents from the NGO sector temper this sentiment with the reality that there is currently no "wise use" or integrated management. With capacity-building within the Government to strengthen support through improved, science-based policies, there is hope that the challenges of a lack of political will can be countered and that policies favouring conservation, rather than conversion, of peat swamp forests can be developed.

Though this investigation employed exploratory techniques to gather information from a wide range of stakeholders, further interviews accessing the views of a greater number of respondents from all categories (Table 1) would enhance findings made, and allow for a nuanced analysis of the key challenges and opportunities discussed here.

5. Conclusion

The aim of this research has been to identify where challenges and, fundamentally, opportunities lie in promoting and implementing the sustainable management of peatlands in Southeast Asia, using Sarawak as a case study. The main challenge arising is the lack of knowledge amongst peatland users (APMI, 2005) of the values, often far-reaching and intangible, of these ecosystems, such as carbon storage, and the physical aspects of management that need to be controlled, for example subsidence, in order to prevent the loss of such functioning and the option of long-term use. Coupled with this is a dearth of research on what sustainable management practices constitute, and indeed incentives to adopt them, both at a political and management level.

But many of these challenges present themselves as a double-edged sword. For dealing with the practical challenges, more targeted, long-term research and monitoring programmes are required under different development scenarios, and their findings disseminated. Agricultural advisory bodies, such as MPOB, hold potential for contributing to these research gaps (if vested interests are controlled), and directing the current main drivers of peat swamp forest conversion into adopting better management practices. However, it is important to note that “we already know enough to conclude that the conversion of deep peats into marginally profitable plantation agriculture makes no environmental, economic or political sense” (Posa

et al., 2011). In this case, the potential for incorporating the precautionary principle approach into management policy and, if required, international agreements, should be investigated (Gasparatos *et al.*, 2011). The engagement of the international community brings with it new sources of international funding, which may also have reverberations on market-based incentives for the adoption of better management practices amongst Sarawak's peatland stakeholders. One challenge is to minimize the knowledge deficit amongst all stakeholders, principally through awareness raising: campaigns are needed that educate the global community about the situation faced by peatland users on the ground, and the local stakeholders about the wider and less tangible values of peatlands. This would provide an opportunity for dealing with some of the ideological challenges discussed, and increase cooperation amongst all parties.

We are facing a period of transition in peatland management, with the plight of tropical peat swamp forests rising in prominence in international discourse, and bringing with it research and funding opportunities. This study has identified a number of opportunities available for the more sustainable future management of the tropical peatlands of Southeast Asia (Box 1). A new strategic approach, involving all stakeholders, is required; one that considers the realities of managing the peatlands on the ground, the past, current and future forces driving land-use change, and fundamentally the physical and ecological requirements for the continued functioning of this unique ecosystem for biodiversity conservation and sustainable resource management (UNDP, 2009). Such a strategy must be developed with local stakeholders in mind, and with the goal of balancing forest resource exploitation with environmental stewardship (Taylor *et al.*, 1994), seeking opportunities where they arise without jeopardizing the central aim of sustainability.

Box 1 Opportunities for the sustainable management of tropical peat swamp forests

RESEARCH:

- develop Best Management Practices for the range of peatland agricultures, notably oil palm; alternative land-use strategies, e.g. paludiculture, ecotourism; ecosystem service evaluation
- establish long-term research and monitoring programmes
- explore the potential of the RSPO for promoting sustainable management of oil palm on peat

EDUCATION & AWARENESS RAISING:

- among local and international stakeholders on the values of tropical peatlands, e.g. for carbon storage, and the local realities of managing them, e.g. for fire control
- disseminate Best Management Practices, e.g. via MPOB
- address the lack of political will

POLICY DEVELOPMENT & FUNDING:

- address conflicting policies nationally
- perform strategic landscape planning & expand protected area network, e.g. increase RAMSAR-accredited wetlands
- incorporate carbon emissions from tropical peatland use into international carbon monitoring and financing schemes
- explore the potential for the adoption of the precautionary principle
- engage with international initiatives, e.g. the ASEAN APMI and carbon financing programmes

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7. Appendices

A **Table A.1** List of references used to identify the international discourse on peat swamp forest conservation, grouped according to key themes.

Each reference is allocated to the issue they most align with, despite some studies discussing/involving work that spans several of the themes. Under *Carbon Storage Function*, studies that are measuring and developing tools for carbon and other greenhouse gases accounting, are also included to give an indication of the volume of research in this area.

Theme	International discourse	Supporting references
MANAGEMENT CHALLENGES		
FIRE	<i>large international concern, increasing in likelihood with peat swamp forest conversion</i>	Miettinen <i>et al.</i> (2012), Miettinen & Kiew (2010), Hendrik <i>et al.</i> (2010), Carlson <i>et al.</i> (2012), Phua <i>et al.</i> (2012), Hoscilo <i>et al.</i> (2011), Razali <i>et al.</i> (2010), Lee (2000), Anshari <i>et al.</i> (2001), Page <i>et al.</i> (2002), Siegert <i>et al.</i> (2004), Hope <i>et al.</i> (2005), Ballhorn <i>et al.</i> (2009), Aiken (2004), Phua <i>et al.</i> (2007), Groot <i>et al.</i> (2007), Langner & Siegert (2009), Tansey <i>et al.</i> (2008), Tosca <i>et al.</i> (2011), Wooster <i>et al.</i> (2011), Van Der Werf <i>et al.</i> (2010), Ainuddin <i>et al.</i> (2006)
DRAINAGE	<i>must be carefully managed otherwise irreversibly degrades peat</i>	Okubo <i>et al.</i> (2003), Wösten <i>et al.</i> (2008), Ritzema <i>et al.</i> (1998), Dommain <i>et al.</i> (2010)
SUBSIDENCE	<i>inevitable, occurs rapidly and generates emissions</i>	Hooijer <i>et al.</i> (2011)
SOIL FERTILITY	<i>peatlands are low nutrient environments, unsuitable for most agriculture</i>	Romshoo (2004), Funakawa <i>et al.</i> (1996), Yule & Gomez (2009)

Theme	International discourse	Supporting references
FUNCTIONS OF PEAT SWAMP FOREST		
BIODIVERSITY CONSERVATION	<i>important refuge for biodiversity</i>	Yule (2010), Quinten <i>et al.</i> (2010), Vaessen <i>et al.</i> (2011), Posa <i>et al.</i> (2011), Cannon <i>et al.</i> (2007), Gaveau <i>et al.</i> (2009), Van der Meer <i>et al.</i> (2008), Hamard <i>et al.</i> (2010), Prentice (2011)
CARBON STORAGE	<i>vast store & potential sink of carbon</i>	Hadi <i>et al.</i> (2000), Shimada <i>et al.</i> (2001), Satrio <i>et al.</i> (2009b), Ballhorn <i>et al.</i> (2011), Englhart <i>et al.</i> (2012), Nuri <i>et al.</i> (2011), Jauhianen <i>et al.</i> (2011), Hergoualc'H & Verchot (2011), Furukawa <i>et al.</i> (2005), Jauhiainen <i>et al.</i> (2005), Melling <i>et al.</i> (2005a), Hirano <i>et al.</i> (2009), Jaenicke <i>et al.</i> (2008), Jauhiainen <i>et al.</i> (2008), Van Der Werf <i>et al.</i> (2008), Danielsen <i>et al.</i> (2009), Inubushi <i>et al.</i> (2003), Mitsch <i>et al.</i> (2012), Murayama & Bakar (1996), Melling <i>et al.</i> (2007), Hirano <i>et al.</i> (2007), Ali <i>et al.</i> (2006), Takakai <i>et al.</i> (2006), Hashidoko <i>et al.</i> (2008), Hoekman & Vissers (2007), Satrio <i>et al.</i> (2009c), Inubushi <i>et al.</i> (2005), Hadi <i>et al.</i> (2005), Melling <i>et al.</i> (2005c), Melling <i>et al.</i> (2005b), Achten & Verchot (2011), Wright <i>et al.</i> (2011), Lahteenoja <i>et al.</i> (2012), Toma <i>et al.</i> (2011), Jauhiainen <i>et al.</i> (2011), Yu (2011), Dommain <i>et al.</i> (2011), Page <i>et al.</i> (2011), Hooijer <i>et al.</i> (2010), Couwenberg <i>et al.</i> (2010), Cameron <i>et al.</i> (1990), Lahteenoja <i>et al.</i> (2009), Chimner (2004), Li <i>et al.</i> (2007), Satrio <i>et al.</i> (2009d), Page <i>et al.</i> (2004), Koh <i>et al.</i> (2011)
WATER REGULATION	<i>water supply, flood control & prevention of saline water intrusion</i>	Langmann & Graf (2003)
LIVELIHOODS	<i>provides resources and income for local communities</i>	Ramakrishna (2005)

Theme	International discourse	Supporting references
CONSIDERATIONS FOR THE FUTURE		
DEVELOPMENT	<i>needs to be managed in a sustainable manner</i>	Kyuma (1983), Page <i>et al.</i> (1999), Phillips (1998), APFP (2010), APMI (2005), APMS (2007), ASEAN (2011), CC-GAP (2005), UNDP (2006)
GOVERNMENT	<i>strengthened Government support needed</i>	Fuller <i>et al.</i> (2011)
RESEARCH	<i>more needed</i>	Lahteenoja & Page (2011), Miettinen <i>et al.</i> (2011), Satrio <i>et al.</i> (2009a), Farmer <i>et al.</i> (2011), Pemberton (2005), Dennis & Aldhous (2004), Murdiyarso <i>et al.</i> (2012)
RESTORATION	<i>important option for peatland conservation</i>	Graham & Page (2012), Tawaraya <i>et al.</i> (2003), Shimamura <i>et al.</i> (2006), Wösten <i>et al.</i> (2006), Chittapun <i>et al.</i> (2005), Van Eijk <i>et al.</i> (2009), Page <i>et al.</i> (2009), Jaenicke <i>et al.</i> (2011), Hoekman (2007)
BUILDING CAPACITY	<i>increased awareness and support needed in peat swamp forest nations</i>	Gopal (2012), Murdiyarso <i>et al.</i> (2010), Morel & Morel (2012),
*RSPO & CERTIFICATION	<i>options for improving management of peatland plantations</i>	

*Literature referring to this theme is limited at present, but the theme was included in order to explore Stakeholders' knowledge and thoughts on this emerging topic.

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(formatting does not follow the style of the article & references below are not all included in Bibliography, page 281)

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B Interview Guides for each Stakeholder group

B.1 SMALLHOLDERS

1 BASELINE (LANDCOVER & USE) - History of human occupation of coastal peatlands:

- i. How long have you lived in this peatland?
- ii. Why did you move here? (if applicable)
- iii. When did your ancestors settle here? (if applicable)
- iv. What was the land used for before you/your ancestors settled here?
- v. When was the area last covered in forest?
- vi. How much forest is there left now?

2 DRIVERS of land use change & realities on the ground - Current land use & management:

- i. How much land do you use?
- ii. Do you own it? (Land tenure details)
- iii. How are you using the land?
- iv. What crops are being grown?
- v. What challenges do you face in using the land as you do today?
 - a. Flooding
 - b. Drainage
 - c. Fire – human OR natural?
 - d. Animals
 - e. Fertility – change in harvest?
 - f. Why? (change in fertility)
- vi. How do you deal with these challenges?
- vii. Do you sell produce? What percentage of harvest?
- viii. How long does it take to get to the market (by motor vehicle)?
- ix. Do you use the land for anything else (other land uses)?
- x. Why? (for each)
- xi. Do you get any outside assistance in land management?
- xii. Do you follow any guidelines on how to use the peatland?

3 FUTURE VISION & land use for peatland:

- i. Ideally, how do you **hope** to use the land in the future?
- ii. Why?
- iii. Are there factors that might make it difficult to use the land in this way?
 - iii.a. What are they?
- iv. Therefore, what **will** you use it for?
- v. Do you use the peat swamp forest?
 - v.a. For what purposes?
- vi. What can you see happening to peat swamp forests in the future? (c. PSF % change in XX yrs?)
 - vi. What will cause a change in area?
 - vii. What will be the consequences of that change? (Will it cause a problem?)
 - ix. What do you think is important for the next generation?
 - x. Is it important for the next generation to have access to PSF?
 - xi. Why/why not?

B.2 ESTATE MANAGERS

1 BASELINE (LANDCOVER & USE) - History of human occupation of coastal peatlands:

- i. When was the plantation established?
- ii. Why was it developed in this area?
- iii. What was the previous land use?
- iv. When was the area last covered in forest?
- v. Is there any forest left in the area?

2 DRIVERS of land use change & realities on the ground - Current land use & management:

- i. How much land do you use?
- ii. Do you own it? (Land tenure details)
- iii. How are you using the land?
- iv. What crops are being grown?
- v. What challenges do you face in using the land as you do today?
 - a. Flooding
 - b. Drainage
 - c. Fire – human OR natural?
 - d. Animals
 - e. Fertility – change in harvest?
 - f. Why? (change in fertility)
- vi. Is there any forest left within your concession?
- vi.a. Why did you keep some forest?
- vii. Do use the land for anything else (other land uses)?
- viii. Why? (for each)
- ix. Are you given any assistance in managing the estate land?
- x. Are there guidelines/laws to follow?
- xi. What guidelines are there for peatland management? State vs. Federal?
- xii. Do you adhere to them?
- xiii. Why (not)?

3 FUTURE VISION & land use for peatland:

- iv. Ideally, how do you **hope** to use the land in the future?
- v. Why?
- vi. Are there factors that might make it difficult to use the land in this way?
- iii.a. What are they?
- iv. Therefore, what **will** you use it for?
- v. Do you use the peat swamp forest?
- v.a. For what purposes?
- vi. What can you see happening to peat swamp forests in the future? (c. PSF % change in XX yrs?)
- viii. What will cause a change in area?
- ix. What will be the consequences of that change? (Will it cause a problem?)
- ix. What do you think is important for the next generation?
- x. Is it important for the next generation to have access to PSF?
- xi. Why/why not?

B.3 CAPITALISTS

1 BASELINE (LANDCOVER & USE) - History of human occupation of coastal peatlands:

- vi. When did you start establishing plantations in peatland areas?
- vii. Why did you start developing in peatlands?
- viii. What were the previous land uses?
- ix. When were the areas last covered in forest?
- x. Is there any forest left in the areas now?

2 DRIVERS of land use change & realities on the ground - Current land use & management:

- vi. How much land do you have in your plantations?
- vii. Do you own it? (Land tenure details)
- viii. How are you using the land?
- ix. What crops are being grown?
- x. What challenges do you face in using the land as you do today?
 - a. Flooding
 - b. Drainage
 - c. Fire – human OR natural?
 - d. Animals
 - e. Fertility – change in harvest?
 - f. Why? (change in fertility)
- vi. Is there any forest left within your concession?
- vi.a. Why did you keep some forest?
- xiv. Do use the land for anything else (other land uses)?
- xv. Why? (for each)
- xvi. Are you given any assistance in managing the estate land?
- xvii. Are there guidelines/laws to follow?
- xviii. What guidelines are there for peatland management? State vs. Federal?
- xix. Do you adhere to them?
- xx. Why (not)?

3 FUTURE VISION & land use for peatland:

- vii. Ideally, how do you **hope** to use the land in the future?
- viii. Why?
- ix. Are there factors that might make it difficult to use the land in this way?
- iii.a. What are they?
- iv. Therefore, what **will** you use it for?
- v. Do you, or people you know of, use the peat swamp forest?
- v.a. For what purposes?
- vi. What can you see happening to peat swamp forests in the future? (c. PSF % change in XX yrs?)
- x. What will cause a change in area?
- xi. What will be the consequences of that change? (Will it cause a problem?)
- ix. What do you think is important for the next generation?
- x. Is it important for the next generation to have access to PSF?
- xi. Why/why not?

B.4 GOVERNMENT

1 BASELINE (LANDCOVER & USE) - History of human occupation of coastal peatlands:

- i. How long have people been living in coastal peatlands?
- ii. Why did they move there?
- iii. What was the land used for before?/When was the area last covered in forest?
- iv. How much forest is there left now?

2 DRIVERS of land use change & realities on the ground - Current land use & management:

- i. What development is the Government currently managing in peat areas?
- ii. How much land under different land uses?
- iii. Who owns/manages the land?
- iv. What challenges do you face in using the land as you do today?
 - a. Flooding
 - b. Drainage
 - c. Fire – human OR natural?
 - d. Animals
 - e. Fertility – change in harvest?
 - f. Why? (change in fertility)
- v. How do you deal with these challenges?
- vi. Does the Government/State produce guidelines/laws for peatland use & management?
- vii. Are these the sustainable project management schemes for peatland palm oil?
- viii. How were these guidelines developed? (who input data)
- ix. Who carries out the Environmental Impact Assessment prior to peat development?
- x. What are the criteria assessed?
- xi. Are the guidelines for coastal peatlands adhered to, by smallholders/estates?

3 FUTURE VISION & land use for peatland:

- i. Where are the biodiversity conservation areas and water catchment areas?
- ii. Who manages them and how are they managed?
- iii. What (future) develop plans are there for these coastal peatlands?
e.g. State development plans such as Integrated Coastal Zone Management (ICZM) initiative; oil palm - planned areal coverage; smallholder schemes
- iv. Are there factors that might make it difficult to use the land in this way? What are they?
- v. Therefore, what will it be used for?
- vi. Do people still use the peat swamp forest? For what purposes?
- vii. What can you see happening to peat swamp forests in the future? (c. PSF % change in XX yrs?)
- viii. What will cause a change in area?
- ix. What will be the consequences of that change? (Will it cause a problem?)
- x. What do you think is important for the next generation?
- xi. Is it important for the next generation to have access to the PSF?
- xii. Why/why not?

B.5 NON-GOVERNMENTAL ORGANISATIONS

1 BASELINE (LANDCOVER & USE) - History of human occupation of coastal peatlands:

- i. How long have people been living in coastal peatlands?
- ii. Why did they move there?
- iii. What was the land used for before?/When was the area last covered in forest?
- iv. How much forest is there left now?

2 SUSTAINABLE MANAGEMENT PRACTICES:

- i. What projects do you have working with peatland use/management?
- ii. What are you promoting through these projects?
- iii. Are they proving successful?
- iv. Why/why not?
- v. Have you recommendations for peatland management based on your work?
- vi. Who are/would you direct these recommendations to?
- vii. In your opinion, are the peatlands of Sarawak being managed in a sustainable way?
(sustainable referring to the ability of these peatlands to continue being used for their current function by future generations of people)
- viii. If not, why not?
- ix. What improvements could be made, especially those based on scientific or 'field' findings?
- x. What more work/research is needed in order to develop better guidelines?

3 FUTURE VISION & land use for peatland:

- i. What can you see happening to peat swamp forests in the future? (c. PSF % change in XX yrs?)
- ii. What will cause a change in area?
- iii. What will be the consequences of that change? (Will it cause a problem?)
- iv. What do you think is important for the next generation?
- v. Is it important for the next generation to have access to the PSF?
- vi. Why/why not?
- vii. Do you have recommendations as to how the conservation of peat swamp forests can be promoted?

B.6 SCIENTISTS

1 Sustainable management practices:

- i. What research into peatland ecology, functioning and management are you participating in?
- ii. What are your findings relevant for current and future peatland management? (e.g. on drainage, fire use, etc.)
- iii. Have you made recommendations based on your work? To whom?
- iv. Have your recommendations been incorporated into any policy?
- v. Are State guidelines or laws for peatland use?
- vi. What are they?
- vii. Are there different guidelines for different stakeholders, e.g. for smallholders versus large estate owners?
- viii. Are they based on the research findings?
- ix. Are such regulations adhered to by the different stakeholders?
- x. In your opinion, are the peatlands of Sarawak being managed in a sustainable way?
(sustainable referring to the ability of these peatlands to continue being used for their current function by future generations of people)
- xi. If not, why not?
- xii. What improvements could be made, especially those based on scientific findings?
- xiii. What more research is needed in order to develop better guidelines?

2 FUTURE VISION & land use for peatland:

- i. What can you see happening to peat swamp forests in the future? (c. PSF % change in XX yrs?)
- ii. What will cause a change in area?
- iii. What will be the consequences of that change? (Will it cause a problem?)
- iv. What do you think is important for the next generation?
- v. Is it important for the next generation to have access to the PSF?
- vi. Why/why not?
- vii. Do you have recommendations as to how the conservation of peat swamp forests can be promoted?



GENERAL DISCUSSION & CONCLUDING REMARKS

Knowledge of the resilience of tropical forest ecosystems is of key importance for managing them in the face of on-going anthropogenic disturbance. This is especially true for the carbon-rich peat swamp forests of the Tropics, which have the potential to either significantly help, or hinder global climate change mitigation. This dissertation aimed to investigate disturbance, ecosystem response and resilience in tropical forests, with a particular focus on the highly-threatened tropical peat swamp forests of Southeast Asia, in order to provide insights that may better enable the sustainable management of these forest resources into the future.

Palaeoecological records were employed to measure fluctuations in fossil pollen, a proxy for vegetation change, of tropical forest taxa and those of associated tropical landscapes through the Holocene, both from published pollen diagrams and from cores collected from three locations in the peatlands of Sarawak, Malaysian Borneo. In addition, fossil charcoal was counted in these three cores as an indicator of the past fire regime, and information on past climatic change and human land-use was gathered from literature. Results from the various proxies and indicators were compared in order to assess the impact of different disturbances on tropical forest recovery, and hence resilience. Stakeholder interviews provided both background information and data used for investigating the current use, values and future prospects for the coastal peat swamp forests of Sarawak.

The central research questions asked in this thesis were:

- (i) How rapidly do tropical forests recover from disturbance, and are there factors that affect their recovery rates and resilience?
- (ii) What factors caused disturbance in tropical peat swamp forests in Sarawak, Malaysian Borneo, in the past, and how did the vegetation respond?
- (iii) Is ENSO-induced climatic change linked to burning incidence in tropical peat swamp forests and what impact does it have on forest vegetation change?
- (iv) What is the burning regime in these tropical peat swamp forests and what role does fire play in driving vegetation dynamics through time?
- (v) How and why has vegetation changed through time in the coastal peat swamp forests of Sarawak, and are there implications of such changes for ecosystem resilience?
- (vi) What are the key challenges and opportunities for managing these peat swamp forests more sustainably under contemporary human disturbance?

In relation to each of the above, the following findings emerged:

Tropical forest disturbance history & resilience

Tropical forest ecosystems have been far from static over the Holocene, or indeed further back through the Quaternary period. The meta-analysis performed in Chapter 2 (Paper 1) highlighted that there has been variation in the following characteristics of disturbance in tropical forests through time: (i) type, ranging from natural sea-level rise (Yulianto *et al.*, 2005) to anthropogenic forest clearing for agriculture (Marchant & Taylor, 1998); (ii) magnitude, disrupting the forest cover by over 90% in some cases (for example van Zeist *et al.*, 1979; Denham *et al.*, 2003); (iii) timing, from inter-glacial disturbances to clusters *c.*

3000 Cal. yr BP (Urquhart, 2009; Neff *et al.*, 2006); and (iv) frequency, with some forests experiencing 13 different events over approximately 1000 years (Figuroa-Rangel *et al.*, 2012). In response to these disturbances, tropical forests responded at a wide variety of rates, with the slowest recovery taking 6846 years (Haberle, 1998), and the fastest taking just one year (Berrio *et al.*, 2006) for the equivalent of 95.5% re-growth. Recovery rates did appear to follow certain trends, according to attributes of the forest or characteristics of the disturbance. Firstly, forests that achieved more complete recovery post-decline re-grew more quickly. The tropical forests of Central America and Africa generally re-established more rapidly after disturbance than those of South America and Southeast Asia. The former two forests have evolved in a more disturbance-prone environment, where hurricanes and coastal storms (Vandermeer *et al.*, 2004), expansive ancient civilisations (Mueller *et al.*, 2010), and drought events (van Gernerden *et al.*, 2003), respectively, have been frequent components of the environment, to which these ecosystems appear to have adapted. On the other hand, South American and Southeast Asian forests are thought to have developed in an environment of relatively greater climatic stability and lesser large-scale anthropogenic landscape modification, and thus evolved without adaptations for more rapid responses to disturbance (Cole *et al.*, *in prep*, see Chapter 2). Magnitude of disturbance, inferred through the degree of forest decline, also affected recovery rates: the greater the decline, the slower the recovery. This is also reflected in the finding that perturbations caused by climatic changes or human activity, i.e. disturbances that in general occur over larger spatial, and often temporal scales, or are of a novel form and magnitude, cause a greater impact on forests. Consequently, re-growth occurs more slowly than after events such as large-infrequent disturbances, to which the majority of forests have adapted over a long evolutionary period (Connell, 1978).

Contrary to expectation, results suggested that the resilience of these forests was not affected by the total number of disturbance events occurring in a site through time, but, in conjunction with the other findings, the magnitude and frequency, i.e. events per unit time, of disturbance are the more important factors in determining response rates of tropical forest vegetation. In addition, the underlying characteristics of the ecosystem, i.e. its evolutionary history and, fundamentally, past exposure to disturbance, have proven significant. Disturbance intensity, comprising both frequency (measured as the average number of disturbance events in a site per 1000 years) and magnitude (the percentage of forest decline relative to the pre-disturbance baseline) components, appears to be the key factor affecting recovery rates, and thus resilience.

Tropical peat swamp forest disturbance history & resilience

One of the most startling similarities across the three peat swamp forest sites surveyed was the dominance of peat swamp forest vegetation throughout the majority of the past, after the onset of peat development in the mid-Holocene (Dommain *et al.*, 2011). During this period, climatic changes, some rapid (Lozano-Garcia *et al.*, 2010), have occurred, including a general intensification of ENSO events after 5000 Cal. yr BP (Gagan *et al.*, 2004). There have also been episodes of greatly elevated fire. Nonetheless, peat swamp forest vegetation has remained the most abundant ecological group within the fossil pollen record. Inside the peat swamp forest itself, fluctuations have occurred between plant taxa associated with more mature forest and those of secondary forest/pioneer affiliation; mostly with the pioneer taxa rising in relative abundance during periods of disturbance, primarily that of climatic drying. For example, results suggest that coincident with episodes of intensified ENSO, for example from c. 2500 Cal. yr BP, the ratio of pioneer to mature peat swamp forest trees increases greatly. This relative elevation of pioneer taxa is

indicative of internal regeneration within the peat swamp forest: a natural feedback mechanism to ensure forest recovery post-disturbance. Unusual drying events, for example those resulting from the late onset of summer monsoons in the region during ENSO years, are likely to cause peat substrate drying, reducing the groundwater level (lying very close to or above the surface in intact peat swamp forest) and atmospheric moisture, such that the upper layer of peat dries. In order for regeneration to have persisted, this past drought-induced substrate drying must have been localised and relatively low-impact, with consequent mortality of canopy trees on hummocks generating gaps in which the ecological process of succession could be initiated, but not the degradation process of peat oxidation and subsidence. Biomass burning also appears to have been associated with internal peat swamp forest dynamics to an extent, though not linked to intensified ENSO events (see Chapter 4), as would be expected given recent trends (Phua *et al.*, 2007; 2012; Van Der Werf *et al.*, 2008).

Contrary to expectation, fire incidents, most likely of natural origin, have been present throughout the past within the peat swamp forests and the wider landscapes reconstructed through these cores, albeit at extremely low levels during certain periods, for example *c.* 1500 – 500 Cal. yr BP. Evidence suggests that fire impacted on the peat swamp forest in a different way to climatic drying: increases in mature, relative to pioneer peat swamp forest taxa, implies that regeneration is hindered, rather than directly initiated by the disturbance. This hindrance is likely to be a consequence of the burning of the upper carbon-rich peat layer. One incidence of elevated burning, illustrated in the Peat Swamp Fragment and Converted Peatland sites between approximately 2800 – 1800 Cal. yr BP, may be linked to an extended period of aridity in the Tropics (Selvaraj *et al.*, 2007). This association implies that the accumulated drying of ecosystems, more extreme than experienced during

ENSO years, may increase the vulnerability of peat swamp forests to fire ignition and damage. After this incident, similar to the other disturbances of the past, the peat swamp forest recovered. This suggests that there was no significant loss of resilience, predominantly because the self-regulatory component of the peat swamp forest, where hydrological integrity is key (see Chapter 3), and consequently regeneration, were not disrupted.

More recent disturbances do appear to have impacted on the hydrological integrity of these ecosystems, however. Prior to *c.* 200 Cal. yr BP, a lack of pollen from the open vegetation ecological group (i.e. taxa found in large non-forested areas), in addition to interview responses, indicate that human disturbance was minimal. Whereas after this period, notably post-colonial settlement in 1839 and the consequent adoption of coordinated landscape management, open vegetation and fire increased dramatically. Across Sarawak in the last 200 years, the draining of peatlands has occurred, combined with logging, peat compaction and conversion of peat swamp forest into new landscapes (Sawal, 2003). These disturbances constitute novel and more intense forms, to which the peat swamp forest is not adapted. Any activity that involves drainage, of which most anthropogenic peatland uses do, especially agriculture (Hooijer *et al.*, 2011), causes drying of the upper peat layer, and thus the disruption of the hydraulic conductivity of the peat swamp. This is also true for oil palm agriculture, despite the water table in plantations being carefully managed to maintain a prescribed subterranean depth (Dolmat, 2005). In turn, such drainage compromises the potential for regeneration. Today, the large degree of physical impact, coupled with increasing frequency and synergism between drivers (as observed in the context of conservation of tropical forest species, see Laurance & Useche, 2009), has meant that there is minimal opportunity for the peat swamp forest to recover between

disturbance events. One such synergy, of which recognition is especially important for effective fire mitigation planning, is the recent and novel link observed between intensified ENSO events and elevated burning (Phua *et al.*, 2007; 2012; Van Der Werf *et al.*, 2008). The resultant fires have had devastating impacts across SEA, beyond the boundaries of the peat swamp forest ecosystem itself (Aiken, 2004).

The various indicators used to infer changes in resilience through time in this study, i.e. rates of recovery (Chapter 3), palynological richness and rates of change of vegetation (Chapter 6), have not demonstrated clear change in hypothesised directions or correspondence across the three surveyed sites, where each indicator has been measured. However, results from the Peat Swamp Fragment site suggest that increasing numbers of disturbance events do cause a slowing of the rate of peat swamp forest recovery post-disturbance and that over the last several hundred years, the palynological richness of this peat swamp forest has decreased. Additionally, as seen in the Converted Peatland site also, the rate of change has increased towards the present day, which can indicate the approach to a loss of resilience in an ecosystem (Dakos *et al.*, 2012). Despite this, there are universal trends in other indicators of peat swamp forest ecological change: all three cores demonstrate a significant increase in open vegetation and local fire within the last *c.* 200 years, both indicators of human forest clearance and the establishment of large open landscapes, coincident with a reduction, and/or increased fluctuation in peat swamp forest vegetation in the Peat Swamp Fragment and Converted Peatland sites. Time lags inherent in forest landscape change (Lindenmayer & Laurance, 2012) may delay the appearance of clearer indicators to signal a loss of resilience in all three ecosystems, especially in the Deforested Peatland site, which does not appear to show signs of shifting yet. For these unique ecosystems, if such clear indicators do appear, they are likely to reflect the crossing

of a truly critical threshold, notably one where peat swamp forest integrity has been lost and beyond which recovery is no longer possible.

Prospects for the sustainable management of:

(a) Tropical peatlands

Stakeholders of Sarawak's peatlands were not of the belief that peat swamp forest resilience would manifest into the future (Chapter 7). Interviews with smallholders and oil palm plantation estate managers demonstrated that there is limited knowledge amongst local users of the global significance of peat swamp forest for biodiversity conservation and carbon storage. Indeed, the economic return from using these "wastelands", especially with the rising market demand for palm oil and Government incentives for its production, far exceeds the value attained from peat swamp forests in their intact form and the challenges associated with using them. Amongst the international conservation community, there has been limited research on the local significance of peatlands for livelihood security and development. There is also limited appreciation of the use of this ecosystem for activities beyond carbon and biodiversity security, with the vast majority of published literature being concerned with peatland fires and emissions dynamics associated with peat swamp forest conversion and use. Research and knowledge exchange on the multiple values of tropical peat swamp forest amongst the multiple stakeholders; increased political will for their conservation; ecologically sustainable land-use strategies; as well as the potential for alternative livelihoods, are key aspects currently lacking in the effective practice of more sustainable peat swamp forest management.

(b) *Tropical forests*

For the sustainable management of forests across the Tropics, results from this study suggest that focus must be placed on the form of disturbance employed in management, minimising it where possible. Management strategies must also ensure that forests are allowed to regenerate to as complete a degree as possible between each impact (i.e. 100% of pre-disturbance abundance), in line with the recovery rates reported in this study for the different geographical zones of the world.

Concluding Remarks

This thesis has shown that:

- (i) Tropical forests have responded dynamically to a variety of natural and human-induced disturbances through the Holocene, with rates of recovery slowest in response to human and climatic perturbation, and in regions with a less extensive history of disturbance.
- (ii) The resilience of tropical forest ecosystems, measured using rate of recovery, does not decline with successive disturbance events in a site, with increased frequency of disturbance events, or with time towards present. However, the driver of the disturbance and the geographical location do affect the recovery rate, with the highly threatened tropical forests of Asia responding the slowest to disturbance.
- (iii) In the tropical peat swamp forests of Southeast Asia, however, resilience does appear to decline with successive disturbance, due to the unique peat-water-vegetation relationship integral to ecosystem functioning.

- (iv) In the last 200 years, sources of disturbance have shifted from natural to predominantly anthropogenic drivers, with the historically-novel forms and elevated magnitudes of human-induced perturbation causing significant declines in peat swamp forest vegetation, with purported consequences for the current and future resilience of these ecosystems.

This study provides evidence to support the paradigm that disturbance is a natural component of all tropical forest ecosystems. Further to this, it shows that the more common disturbance has been in the past, the more effective the forest is in responding to such, challenging current thought on resilience patterns in ecosystems (Paine *et al.*, 1998; Turner, 2010). Importantly, it also illustrates that tropical forests can recover, given time, from many different disturbances.

Through long-term ecological analysis, this study has shown that today, anthropogenic perturbation is replacing what were predominantly natural drivers of disturbance in many tropical forest ecosystems in the past, with events of novel forms, greater magnitude and increased frequency than those experienced previously. We are yet to observe whether tropical forests can demonstrate the same kind of resilience in the face of these contemporary patterns of perturbation.

Such a potential loss of resilience is of particular importance for the carbon-rich coastal peat swamp forests of Sarawak. Results in this thesis expand current knowledge on the ecological functioning and resilience of tropical coastal peat swamp forests. Herein is some of the first evidence that these ecosystems have demonstrated resilience to disturbances in the past. In contrast to this, results highlight the uncertainty surrounding

whether they can recover as quickly and completely today. Recent anthropogenic disturbance, predominantly forest conversion for oil palm plantation development, has been associated with drainage and, consequently, significant hydrological change in peat swamps. As well as considering the unrelenting character of human perturbation as being a key factor preventing peat swamp forest recovery in these exploited landscapes, drainage may prove to be central in triggering an irreversible shift in ecosystem state, and thus loss of resilience, even in landscapes where disturbance is halted.

The UN FAO has recently joined the cohort of organisations that are concerned with the current management of tropical peatlands, and especially the carbon emissions associated with peatland degradation, resulting in their publishing a guide for sustainable use (FAO, 2012). They provide a general strategy for dealing with the three forms of tropical peatland at present, making divisions according to their degree of hydrological integrity. For peatlands that have not been drained, which is increasingly few in Sarawak, they must be protected from this management eventuality to prevent subsidence and associated emissions; for those that have, they must be rewet, i.e. waterlogged conditions re-established, to reduce emissions; and for the peatlands that have already been drained and cannot be rewet, management must be adapted to maximise benefits from the area (FAO, 2012). Although the precautionary principle has been proposed in this study in response to findings, as a method of conserving these peatlands, the reality of Sarawakian stakeholders adopting it is limited. This is partly because of the strength of the drivers promoting habitat conversion. Primarily though, it is because much of the State's peat swamp forests have already been drained. Across Malaysia and much of Indonesia, estimates suggest that a quarter of the peatland area, some 4 Mha, now lies as unmanaged secondary peat swamp forest, whilst over 5 Mha has been deforested, drained and burned, more than 2 Mha

converted into industrial plantations, and the rest intensively logged (Langner & Siegert, 2009; Miettinen & Liew, 2010). Thus, ironically, it appears to be human land-use change that has generated vast areas of degraded “wasteland”; and we now have to decide how to manage it. Rewetting and establishing a water-level and indeed disturbance strategy that mimics natural regimes as far as possible (for example Kuuluvvenan & Grenfell’s natural disturbance emulation in boreal forests (2012)), should be a priority for land managers. Research on the parameters of effective restoration must also be a future priority (Graham & Page, 2012). Where rewetting and peat swamp forest restoration are not possible, in ecosystems where the shift to an alternative state has already occurred, management must be adapted to maximise ecosystem potential and reduce pressure on more intact peat swamp forests. This will require more political will than appears to be available at present in this Bornean State.

If such pragmatic management is not adopted, the future prospects for this ecosystem are bleak, and the resultant forecast for global carbon emissions even more severe: large-scale peat degradation will create the possibility of snowballing climate change, since the 80% of peatlands across the world that are still in a relatively intact state (such that carbon sequestration continues), store less carbon than what is being emitted from the 20% of degraded peatlands (Joosten, personal communication).

Peat swamp forests *can* recover in areas not too severely drained; but that recovery must be allowed and, further to this, encouraged by humans. Beyond knowledge of effective restoration techniques, the main barriers to the ultimate goal of peat swamp forest regeneration are no longer ecological; they are political and fundamentally economic, with lack of research and education, expanding markets driven by expanding human

populations, and human desire working counter to the sustainable management of these ecosystems. Essentially, for the persistence of tropical forest ecosystems, a long-term view on forest management is required, involving both palaeoecological studies and future-scenario planning. This would form a key part of a new “global forest science” (Grainger, 2009) that works at a national level to develop information on long-term trends in forest cover and models future responses, empowering nations to consider forest management options beyond immediate conversion for short-term gain.

Conservation is about the management of human behaviour (Chan, 2008; Balmford & Cowling, 2006). This project, through palaeoecological insights, has shed light on the resilience of tropical forests and, in particular, the highly-threatened tropical peat swamp forests. These insights may be used to better inform the stakeholders of these ecosystems and promote more sustainable human behaviour. Ultimately, for the long-term conservation of these precious swamp forests, we would be wise to stay out of the peat.

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APPENDIX 0: INCLUSION OF CO-AUTHOR'S STATEMENTS

BIODIVERSITY INSTITUTE

DEPARTMENT OF ZOOLOGY

Tinbergen Building, South Parks Road, Oxford, OX1 3PS
Tel: +44(0)1865 281321 (direct); +44(0)1865 271259 (assistant)
Fax: +44(0)1865 271249; kathy.willis@zoo.ox.ac.uk



13 September 2012

To whom it may concern,

I declare that the manuscripts presented as Chapters 2 to 7 inclusive, within this thesis, for which I am co-author, are substantially the work of the co-author, Lydia Cole, and that my role has been limited to supervisory input and comments on drafts.

A handwritten signature in blue ink, appearing to read 'Kathy Willis'.

Professor Kathy J. Willis
Tasso Leventis Chair in Biodiversity

SCHOOL OF GEOGRAPHY AND THE ENVIRONMENT

Dr Shonil A Bhagwat
Course Director, MSc in Biodiversity, Conservation and Management and Senior Research Fellow
OUCE, South Parks Road, Oxford OX1 3QY
Tel: +44(0)1865 285184 Fax: +44(0)1865 275885
shonil.bhagwat@ouce.ox.ac.uk
<http://www.geog.ox.ac.uk/staff/sbhagwat.html>



14 August 2012

To Whom It May Concern:

I declare that the manuscripts presented as Chapters 2 to 7 inclusive within this thesis, for which I am co-author, are substantially the work of Ms Lydia Cole, the author of this thesis, and that my role has been limited to supervisory input and comments on drafts.

Yours sincerely,

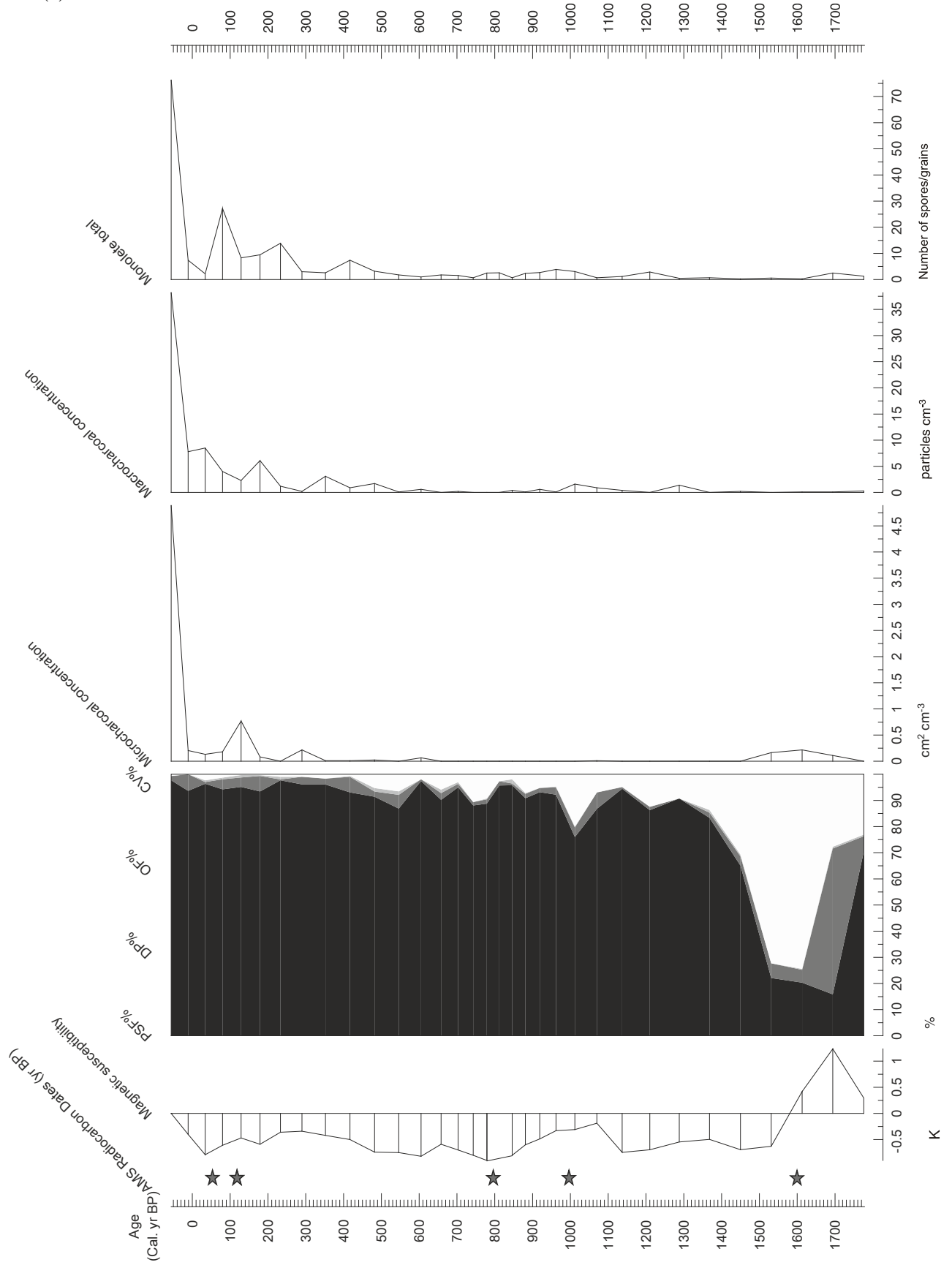
A handwritten signature in blue ink, appearing to read 'Shonil A Bhagwat', with a stylized flourish above the name.

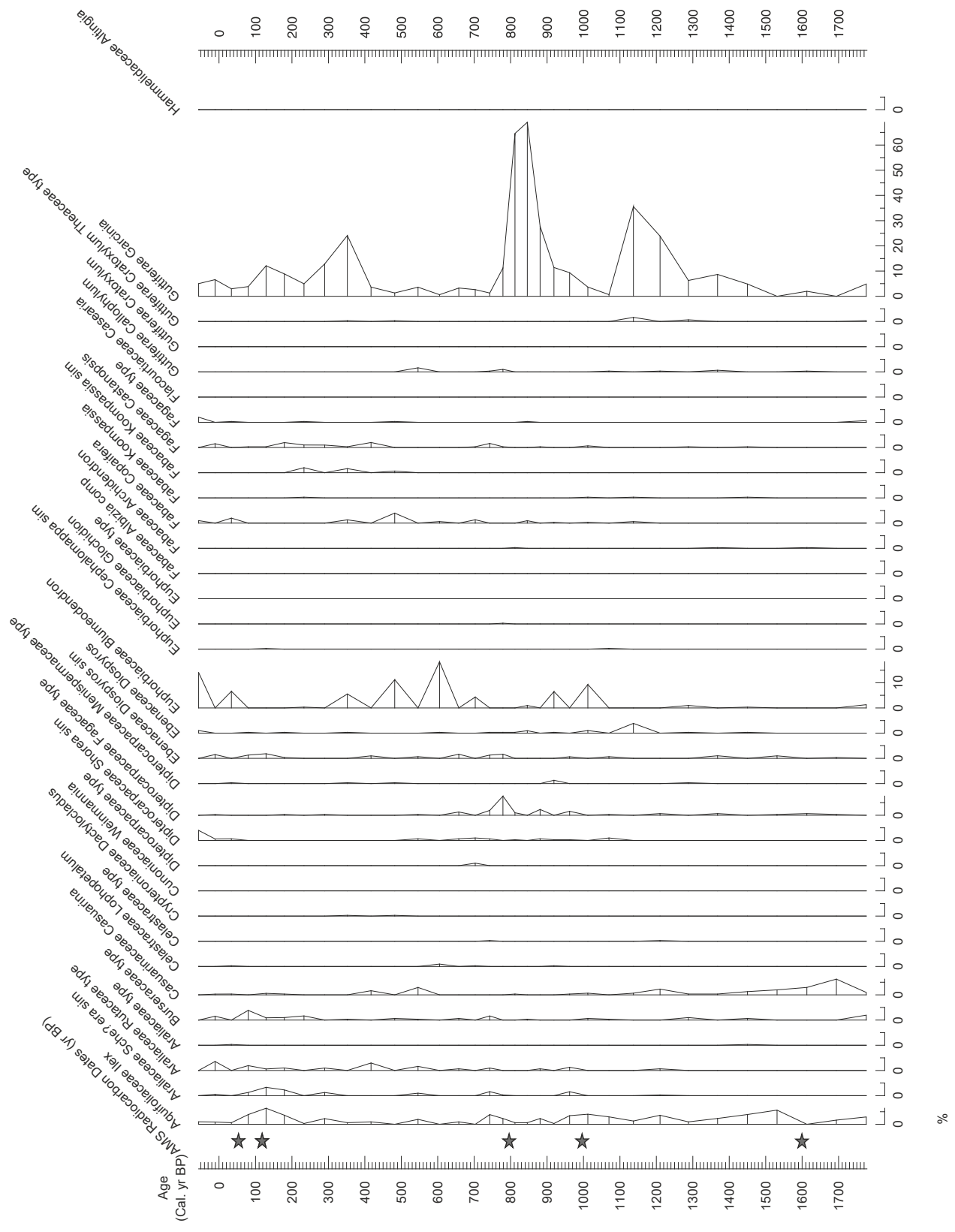
Shonil A Bhagwat

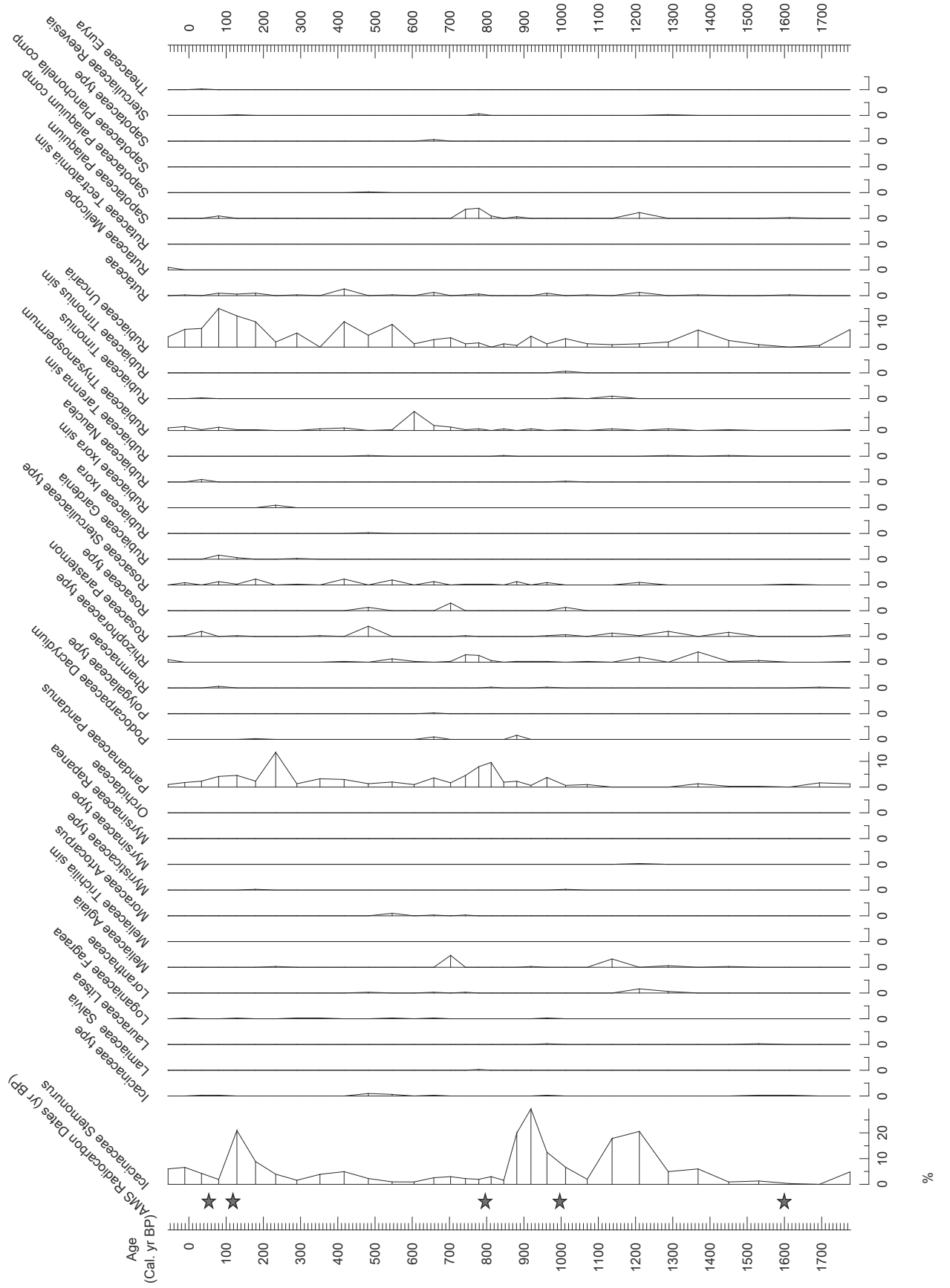
APPENDIX I: COMPLETE POLLEN RECORDS FOR 3 CORES

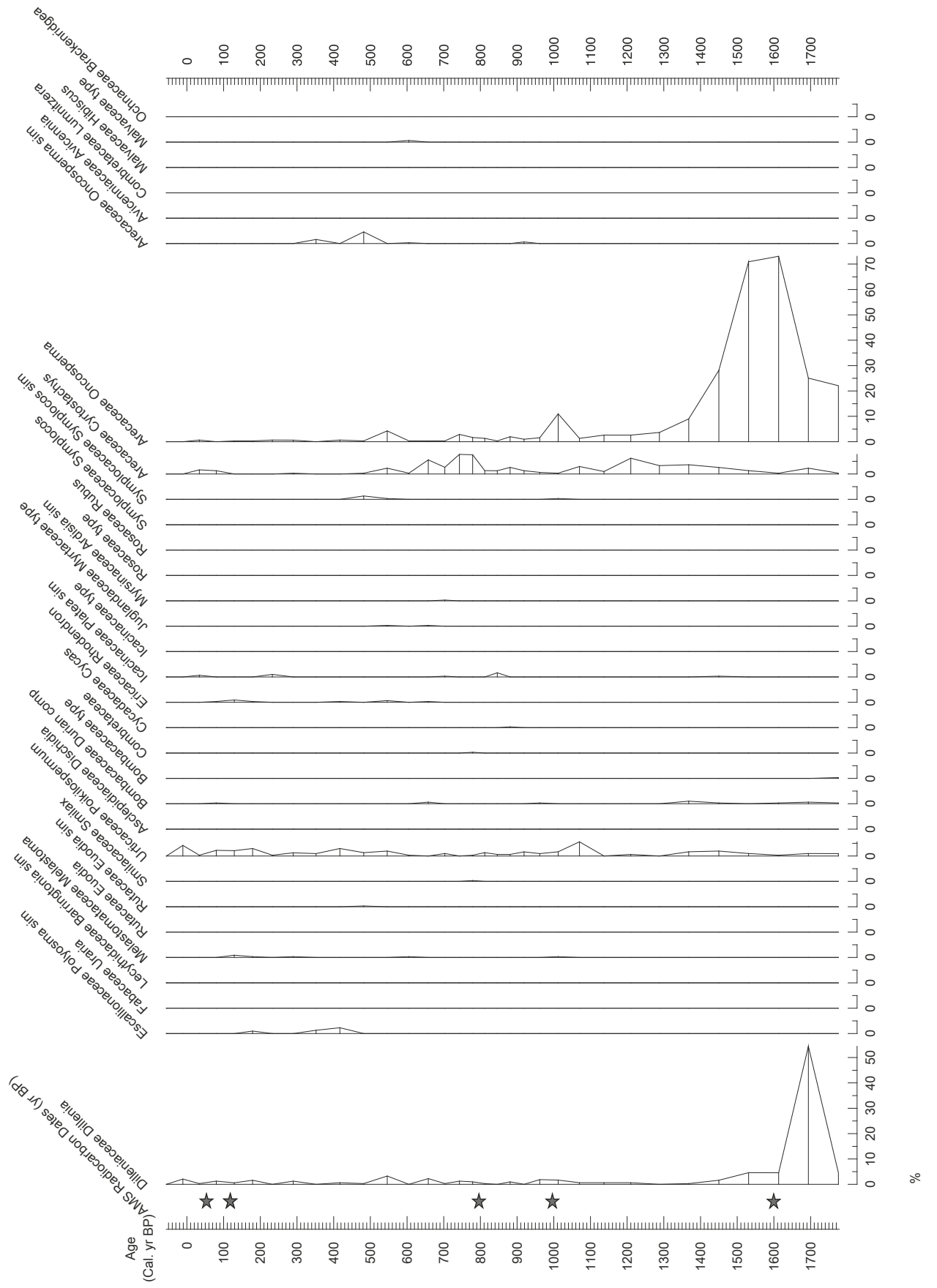
Fig. A1 Full pollen diagram of each site: (a) Deforested Peatland, (b) Peat Swamp Fragment, and (c) Converted Peatland. Terminology for pollen types identified follows that used by (Benninghoff and Kapp, 1962): ‘comp’ - compares well with reference taxa, ‘sim’ - similar to reference taxa, and ‘type’ - grain matches one morphology within the polymorphic taxonomic unit.

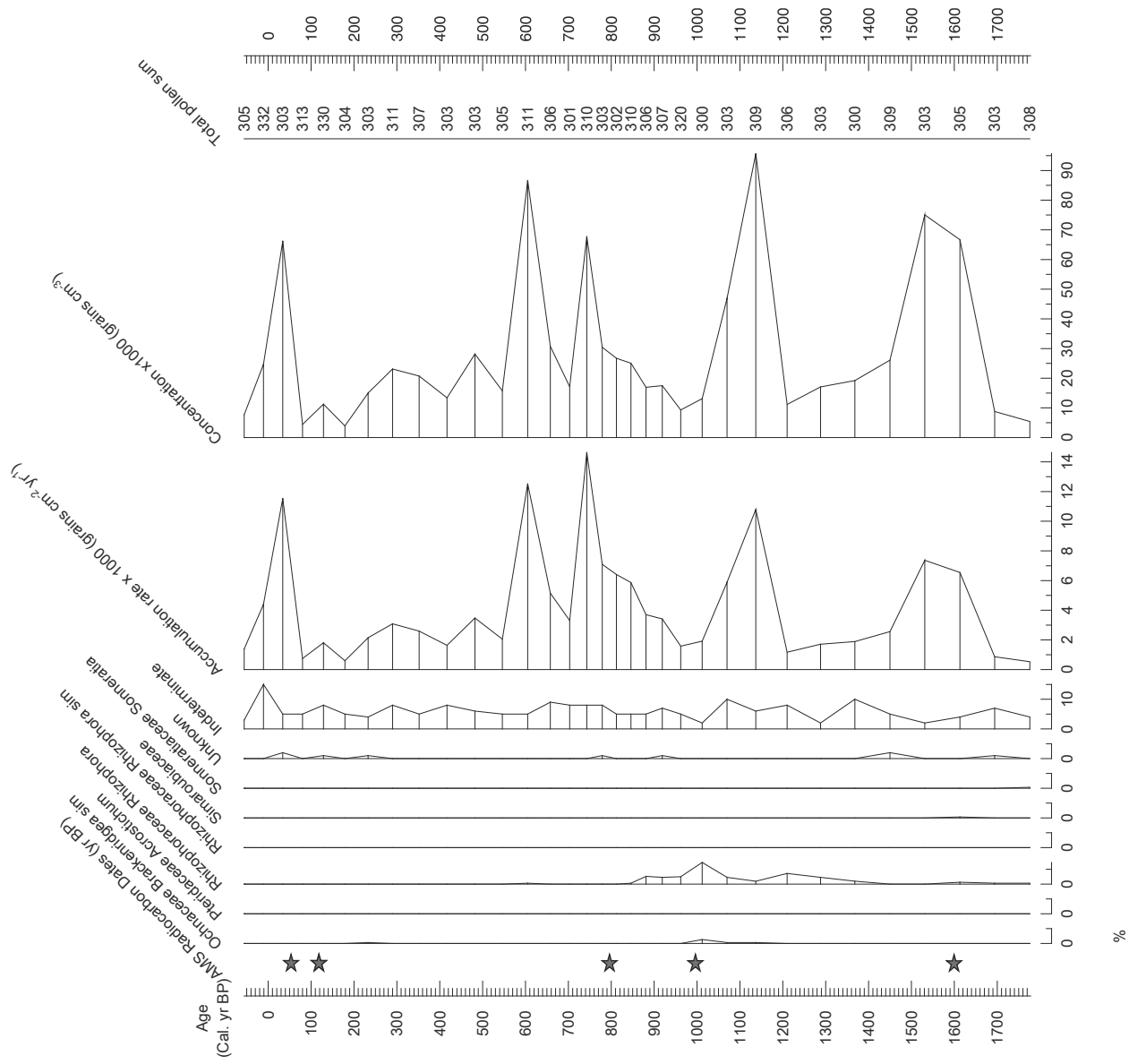
(a) Deforested Peatland



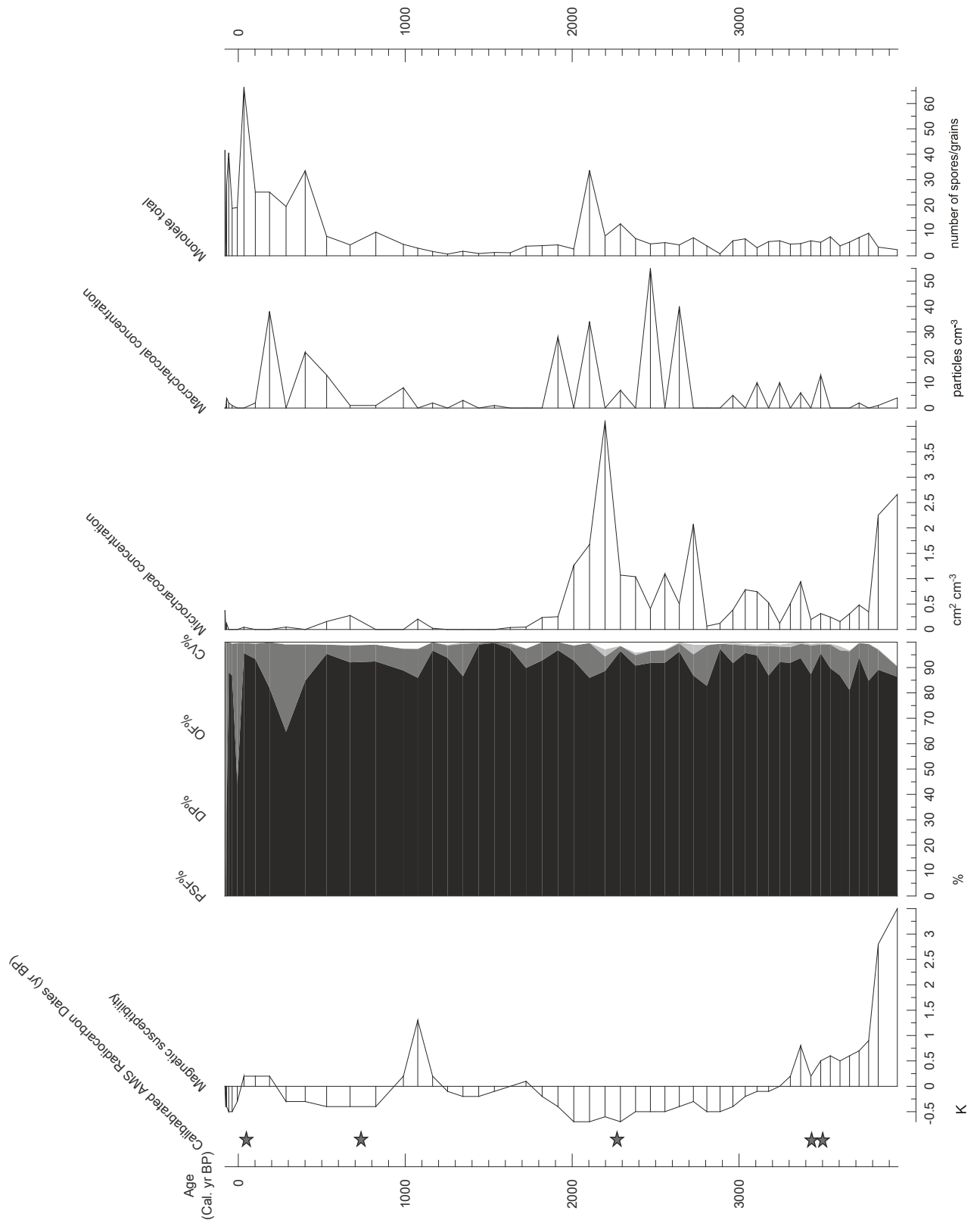


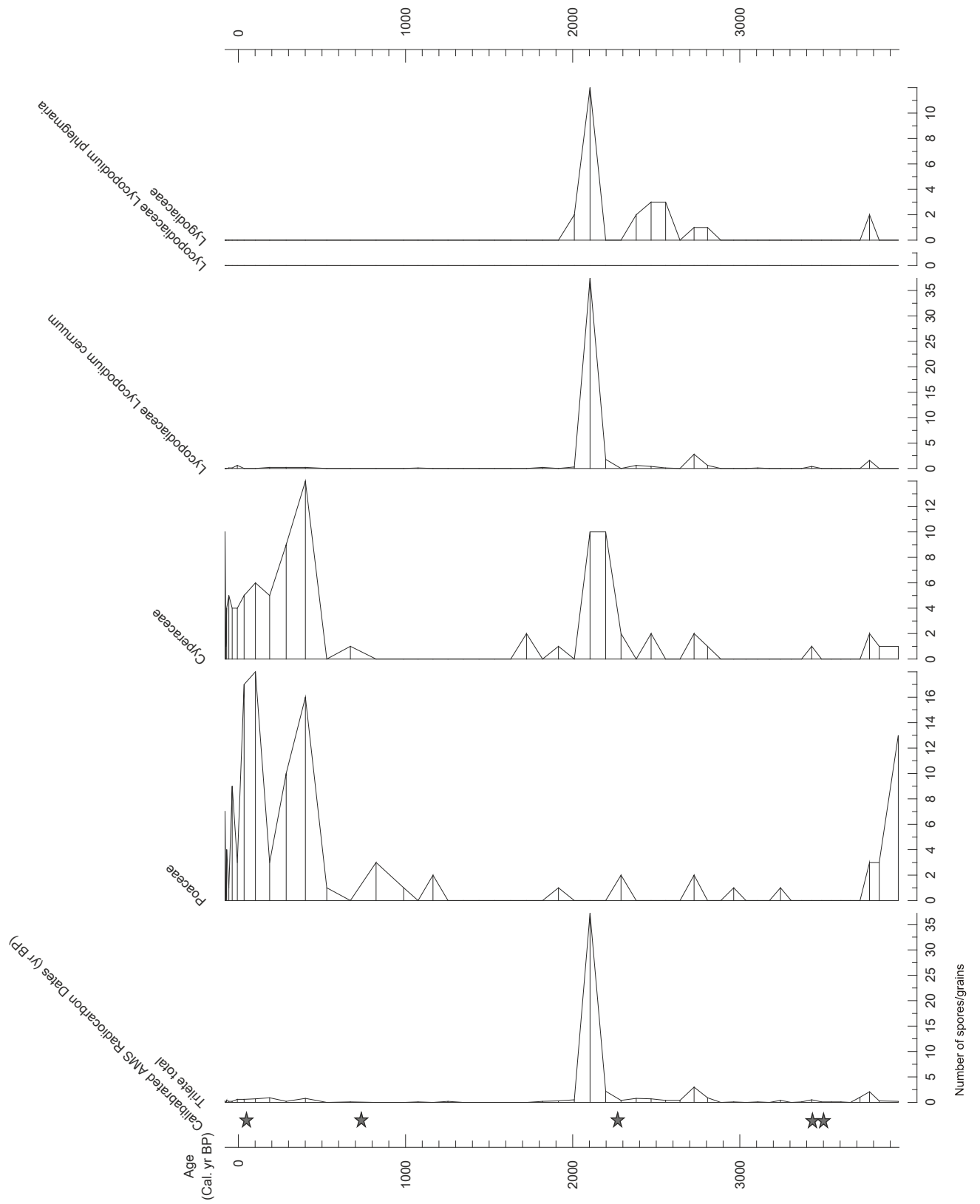


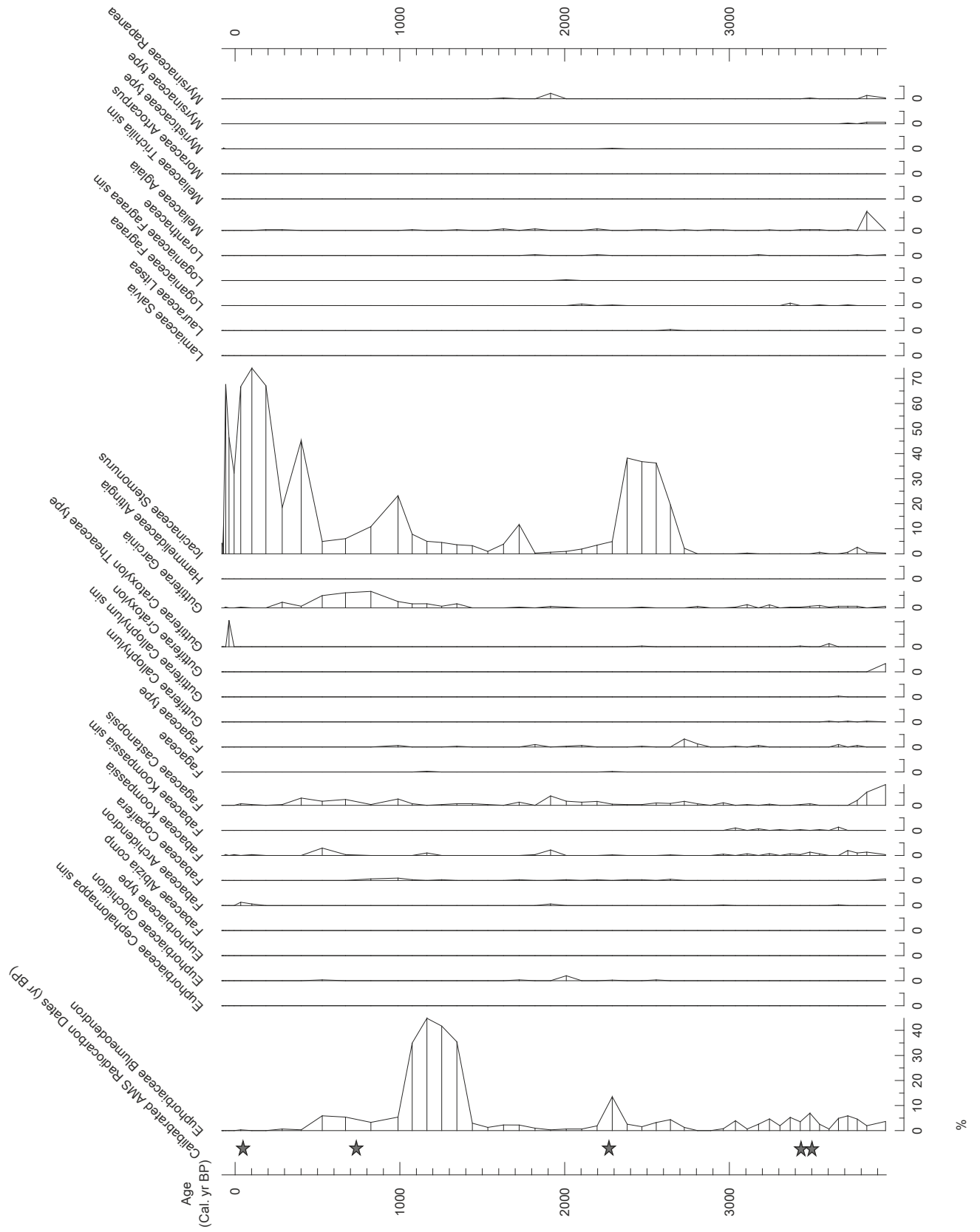


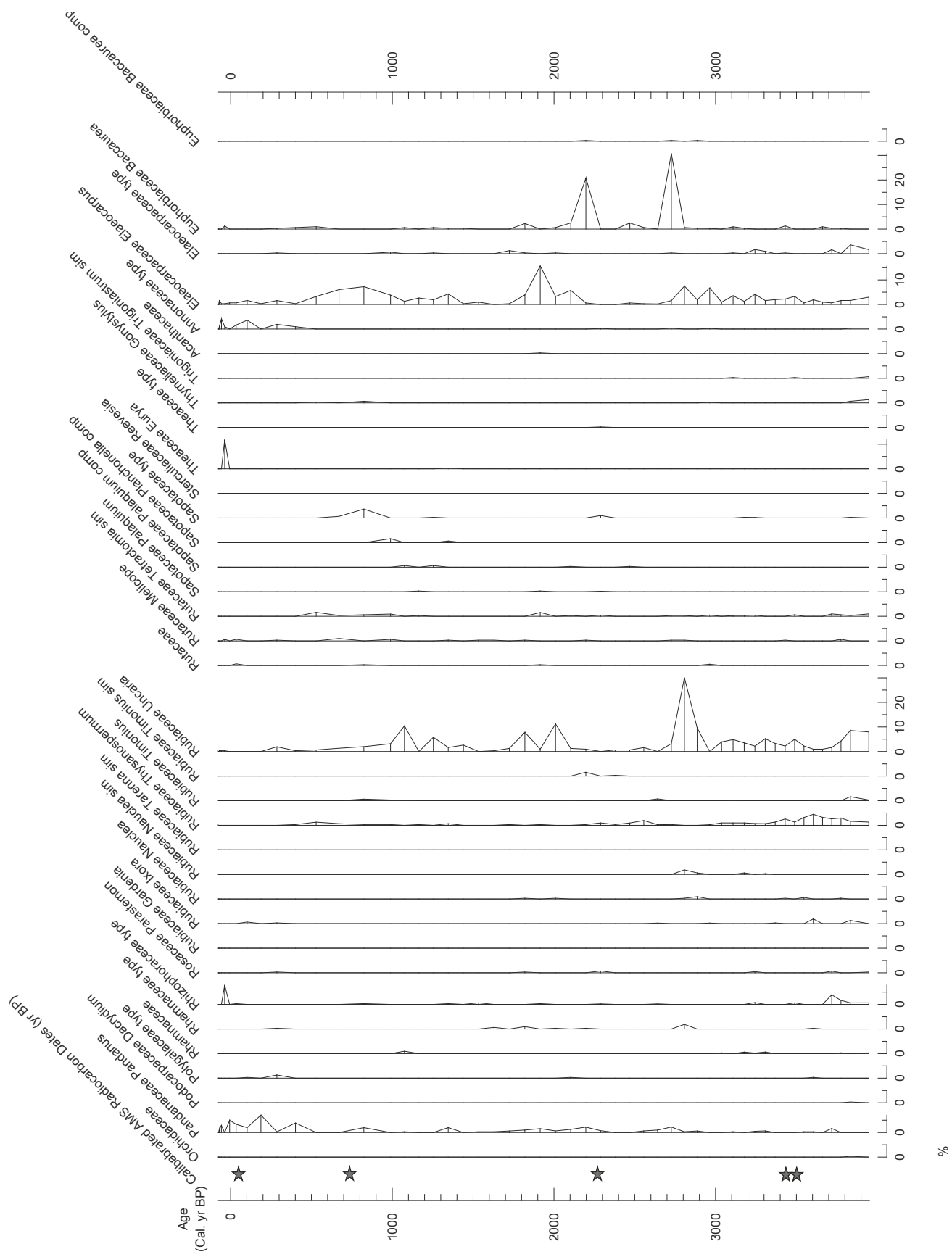


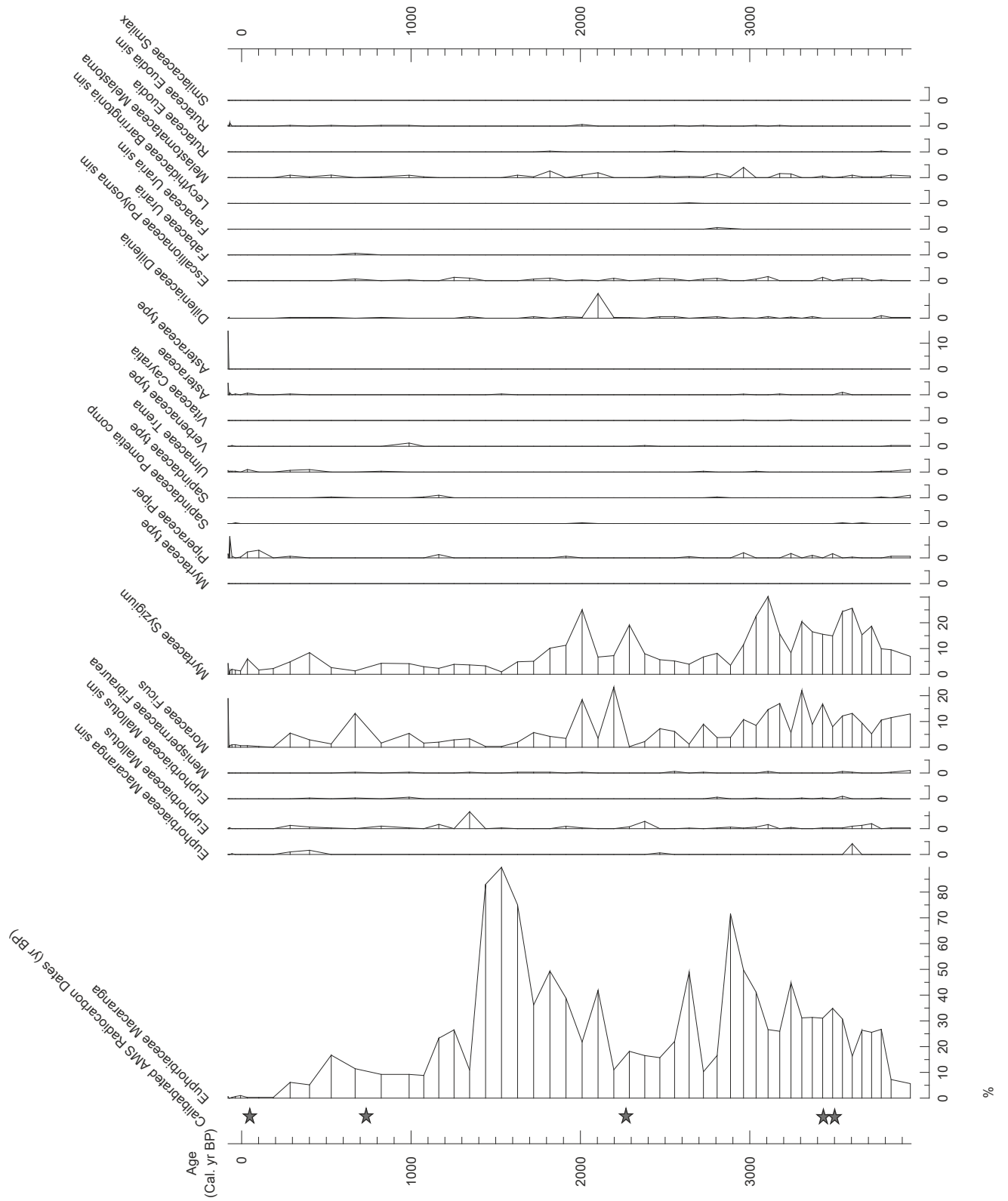
(b) Peat Swamp Fragment

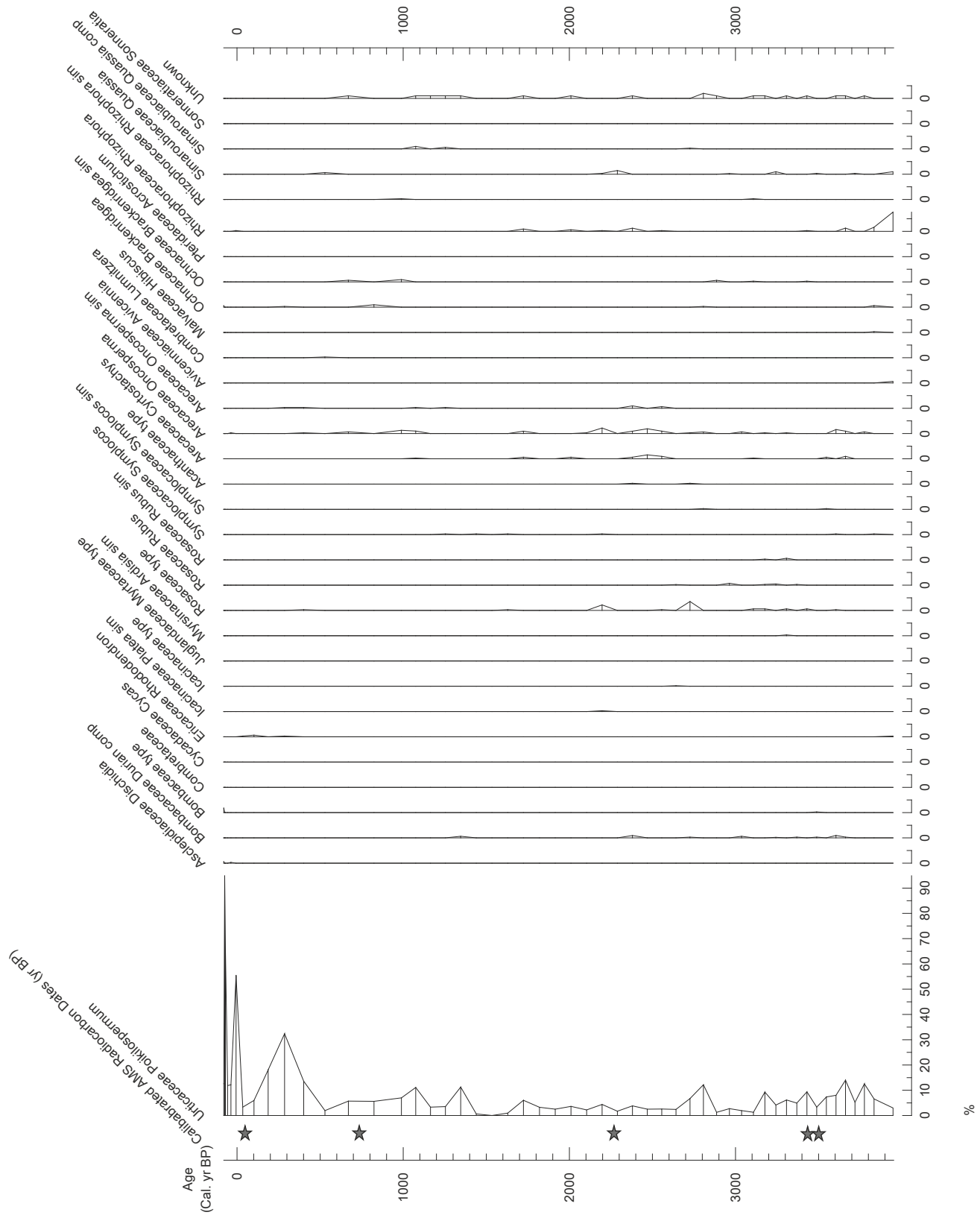


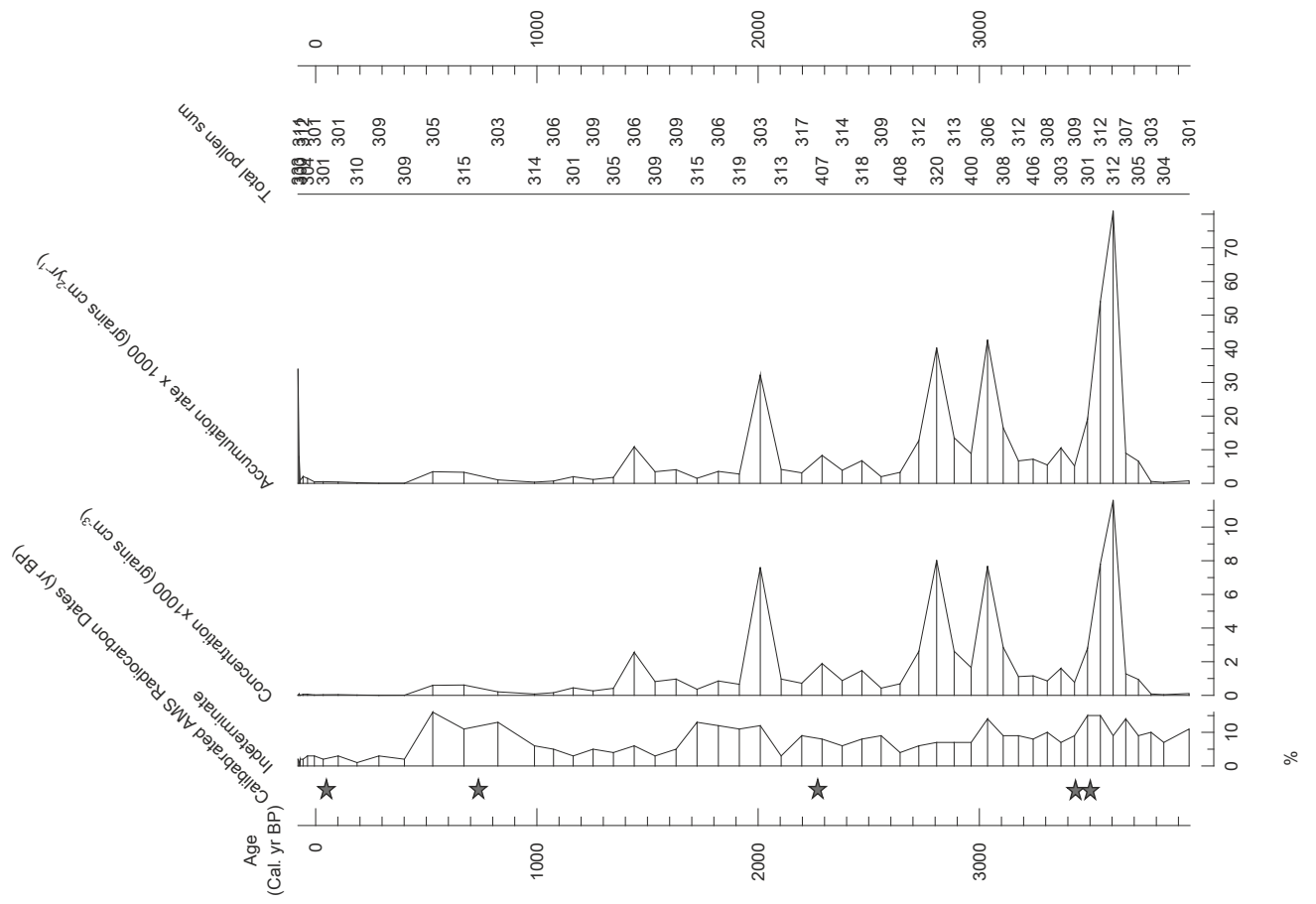




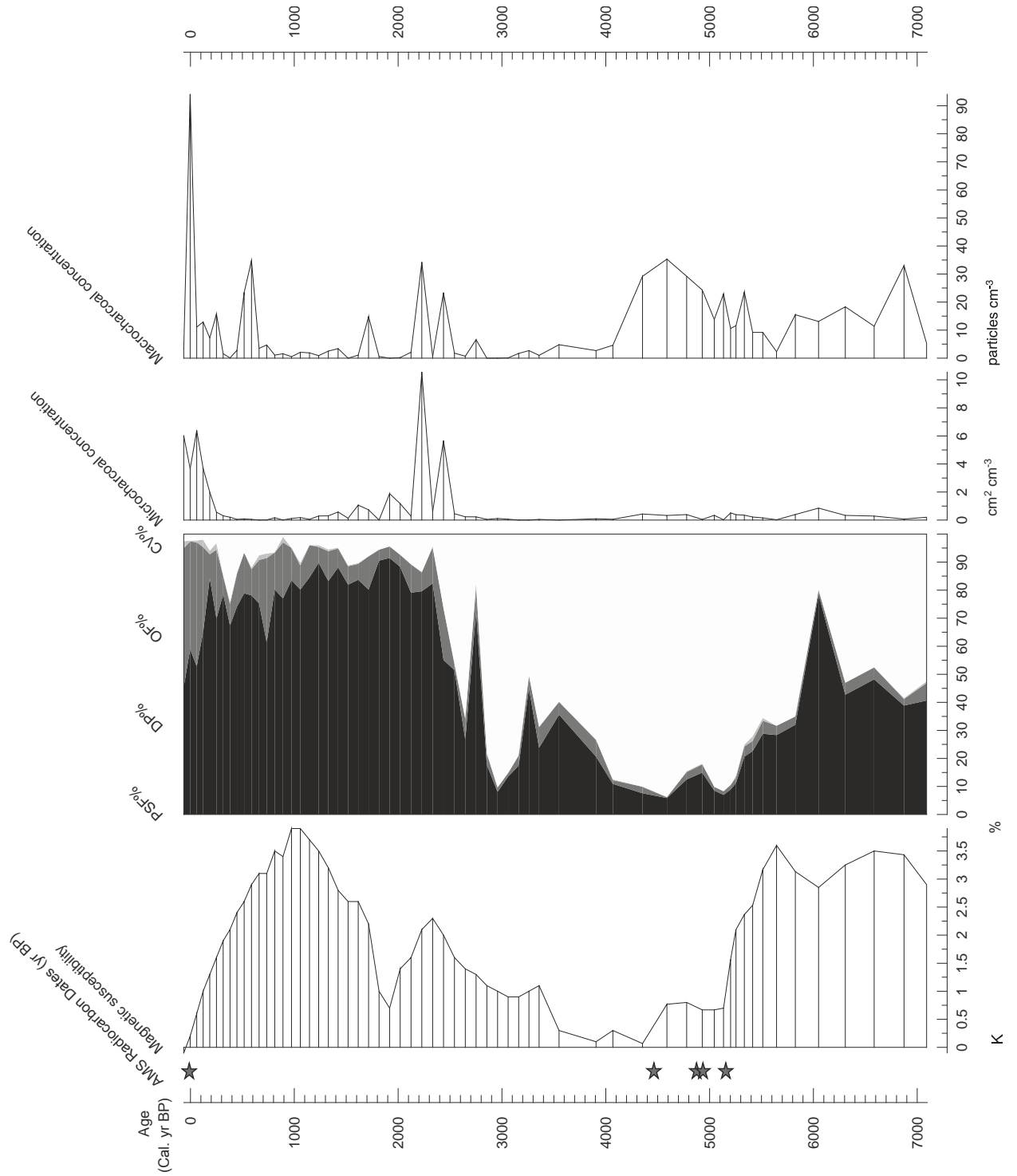


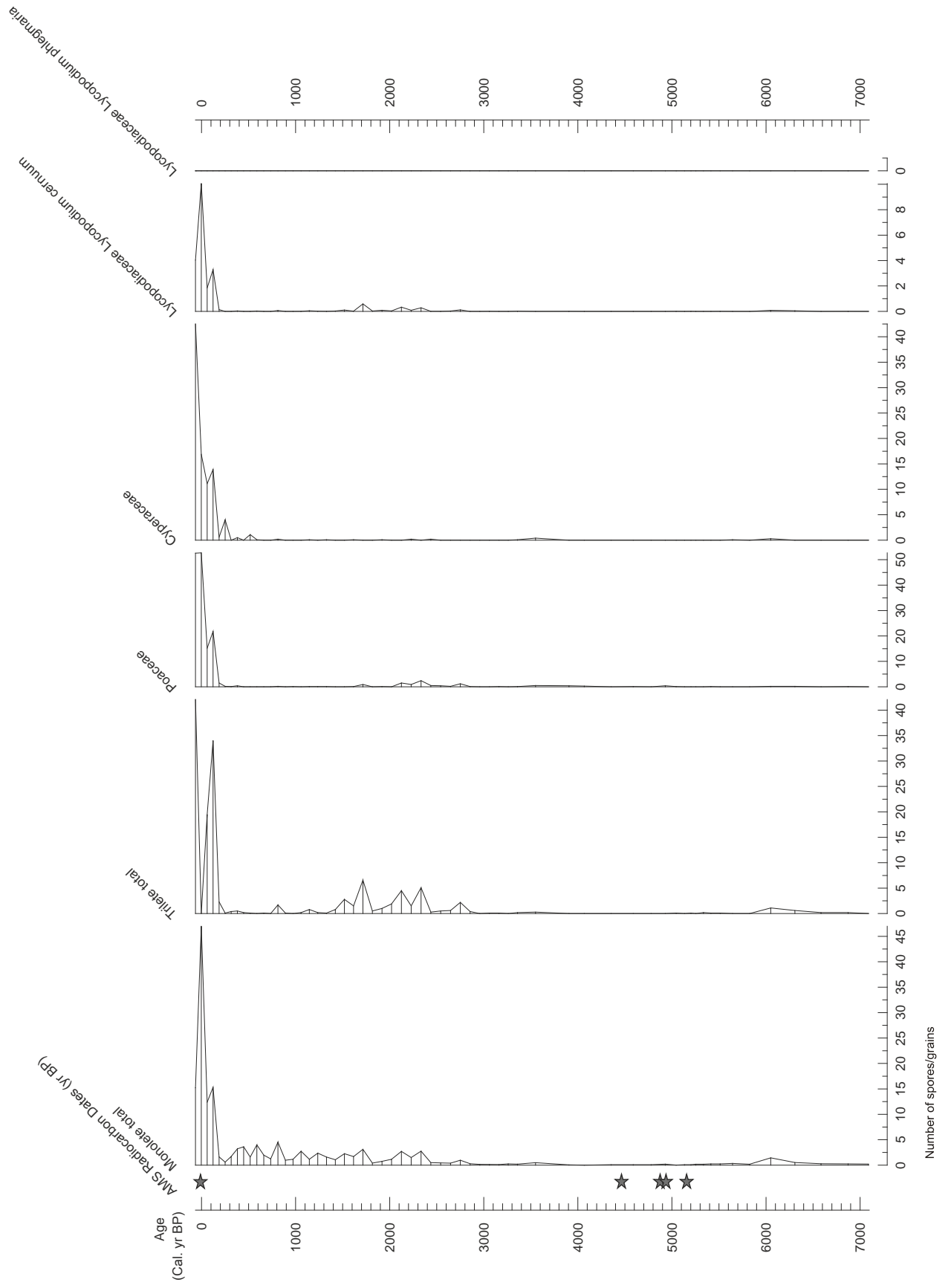


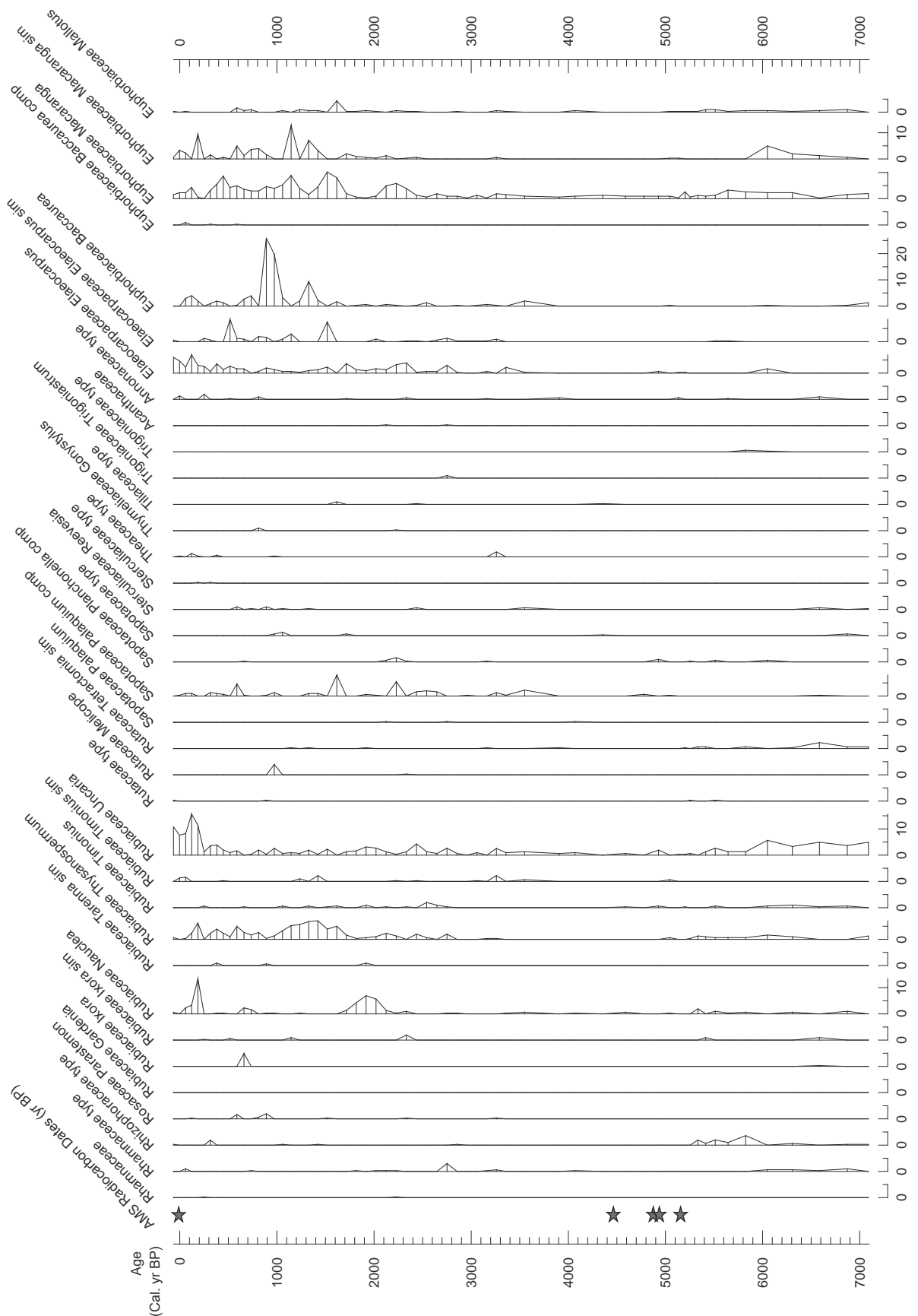




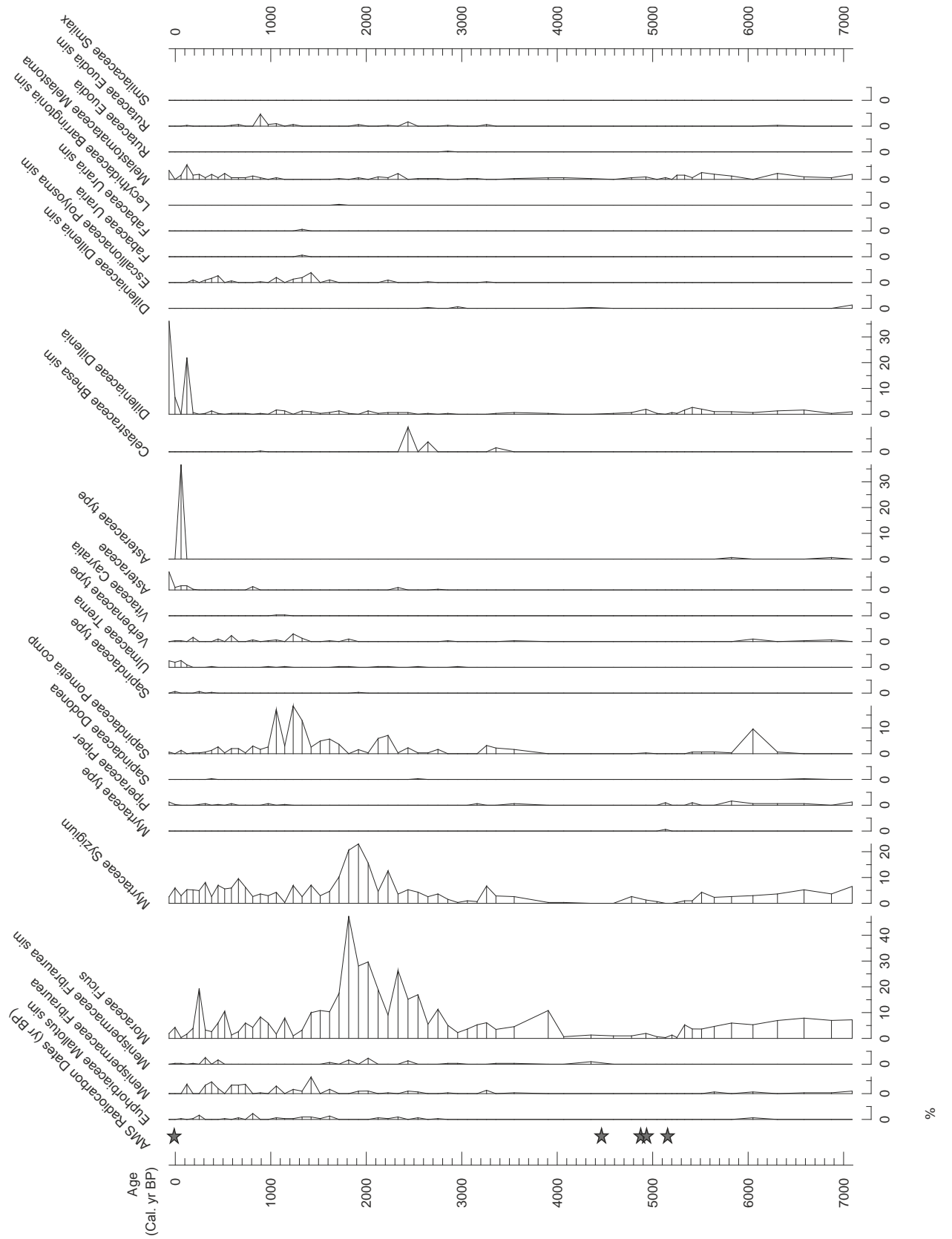
(c) Converted Peatland

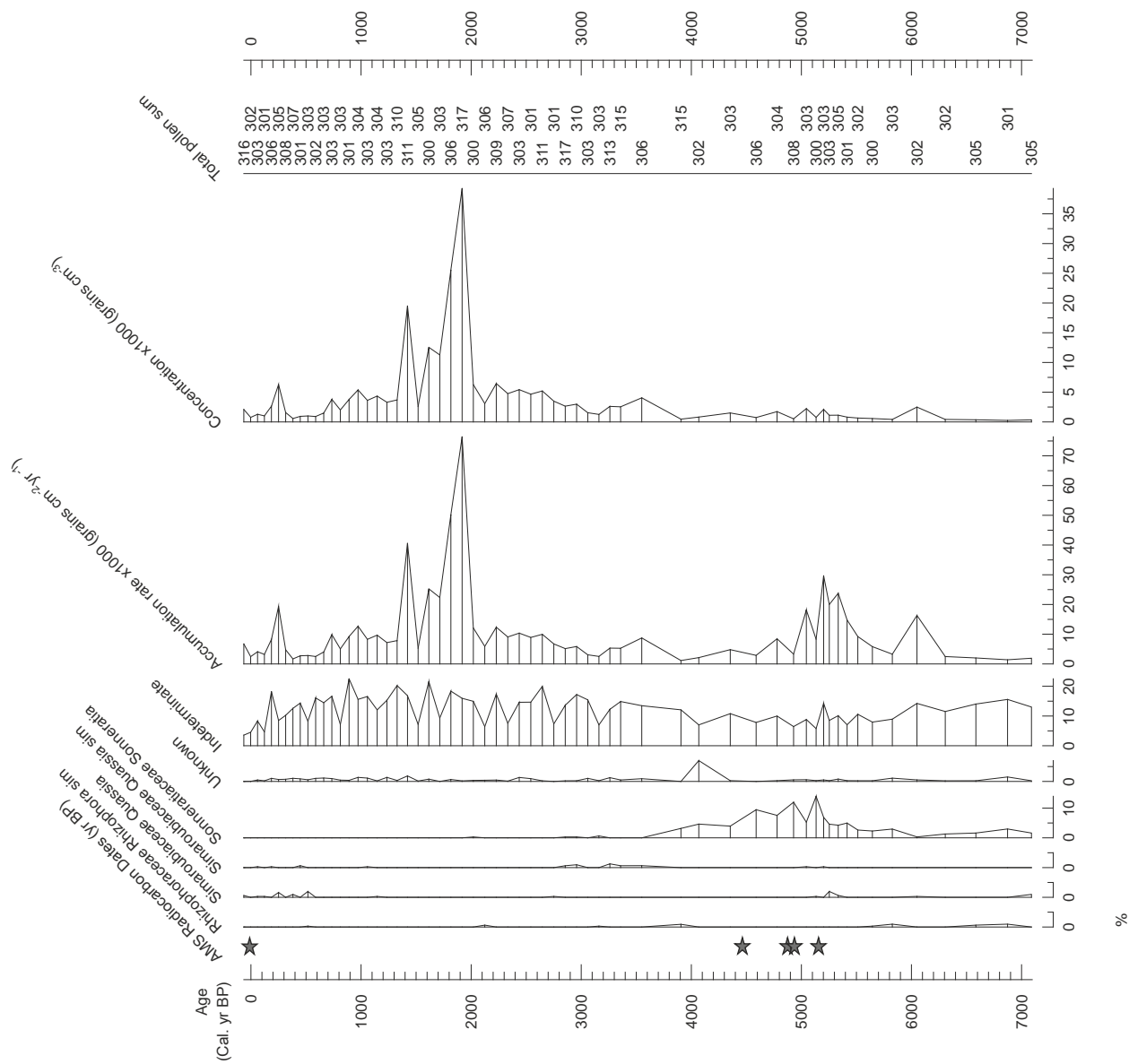






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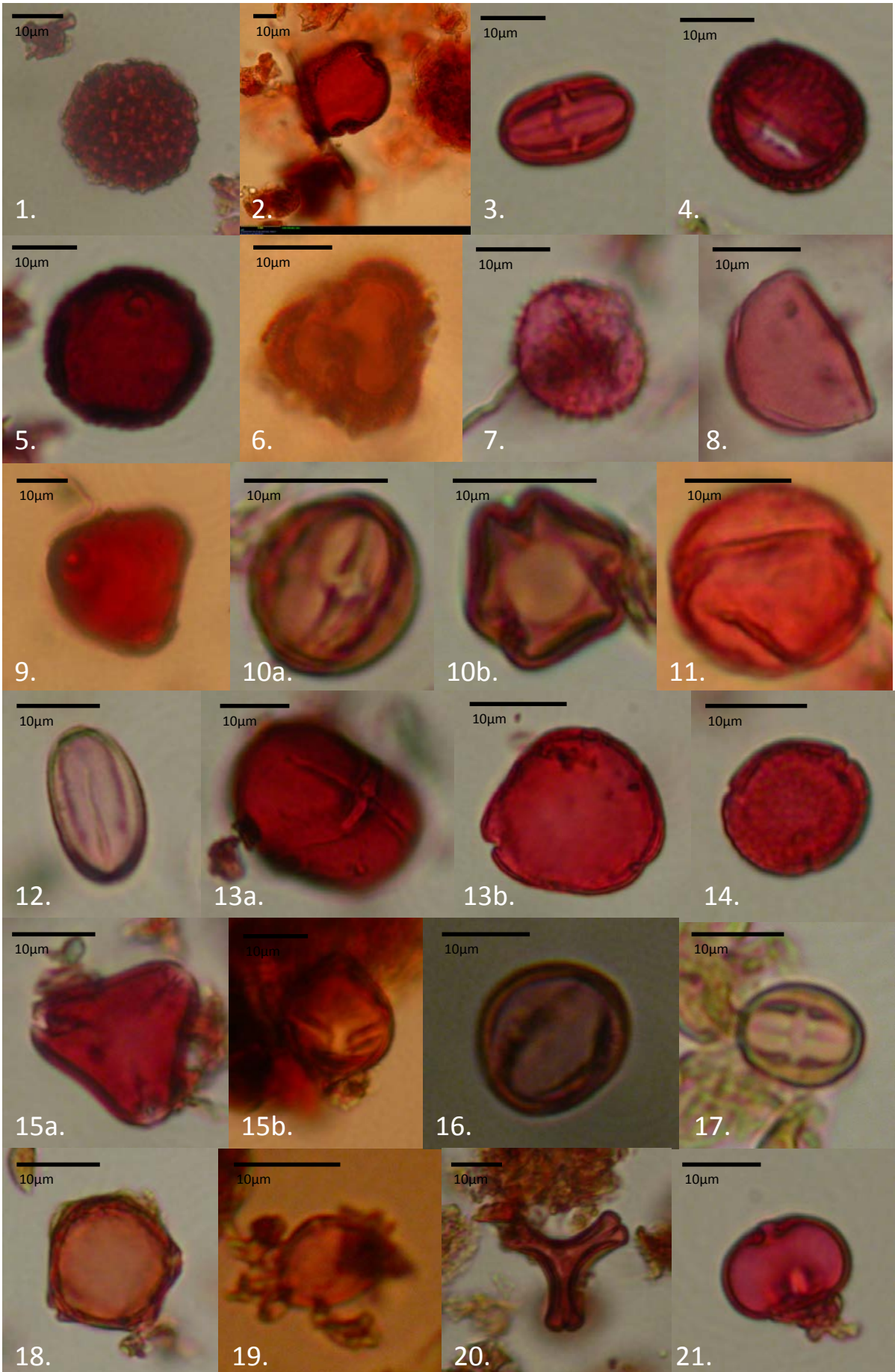
APPENDIX II: PLATES OF COMMON POLLEN & SPORE TYPES

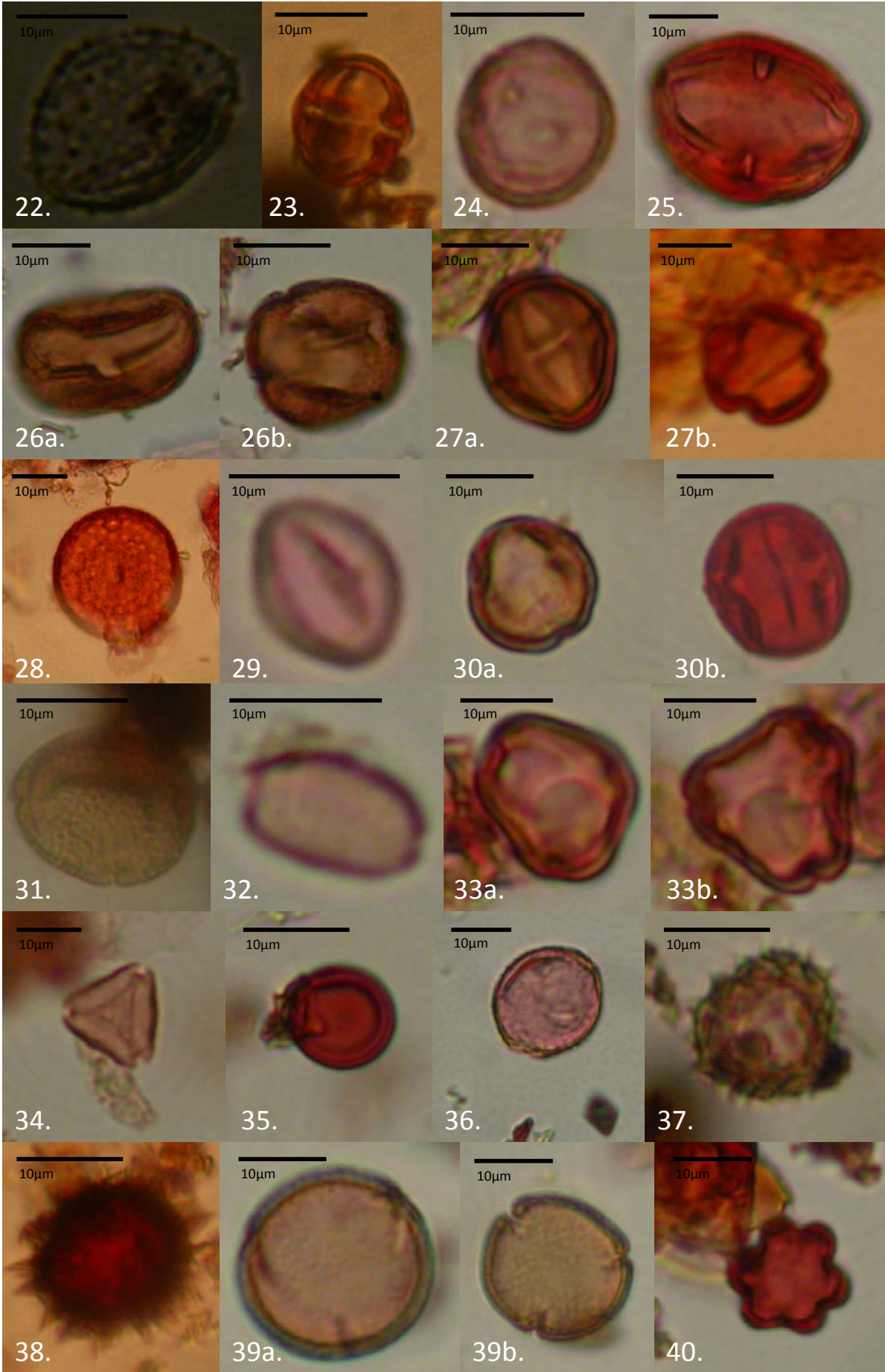
List of taxa represented on pollen plates:

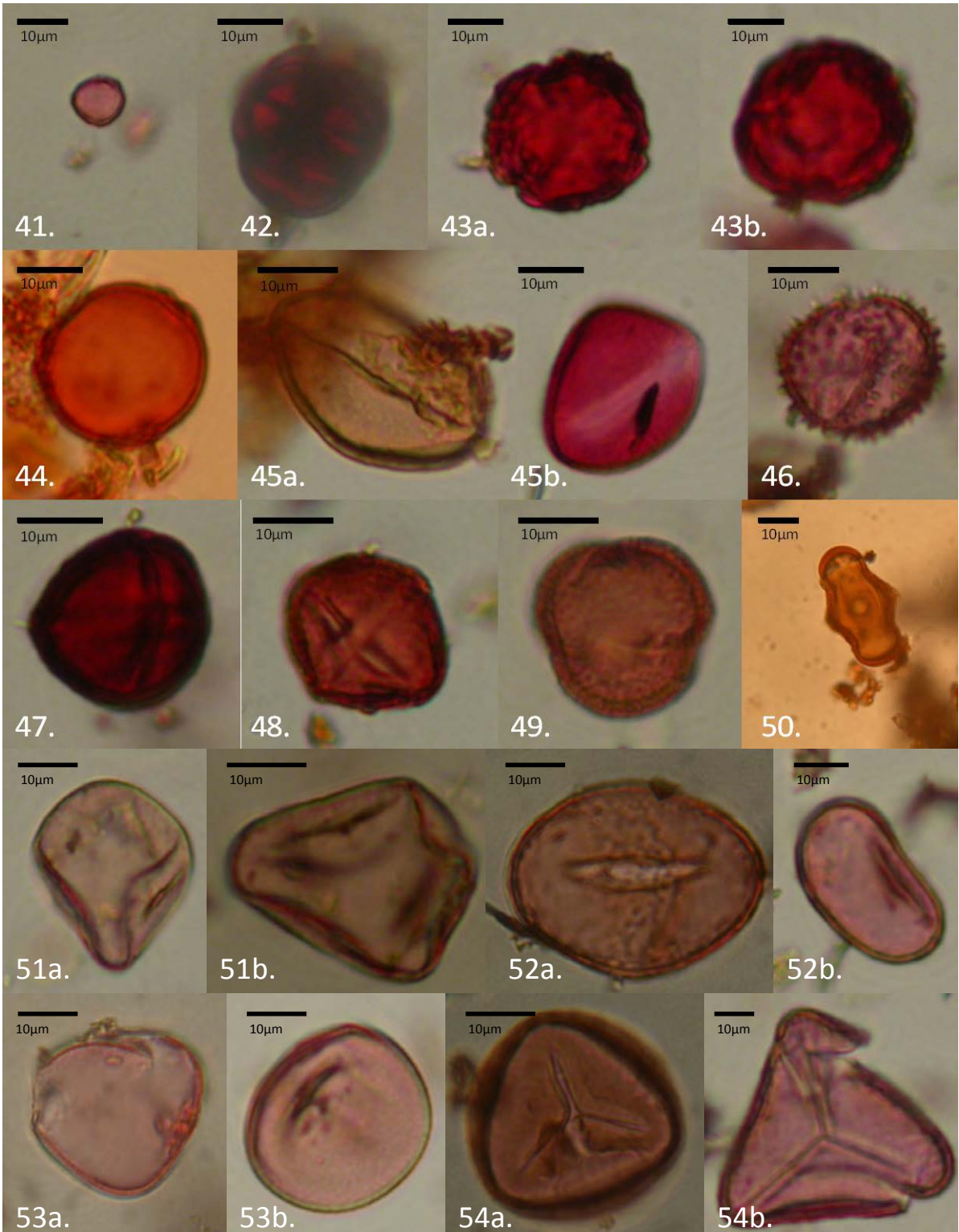
1. Lycopodium
2. Alangiaceae *Alangium*
3. Anacardiaceae type
4. Anisophyllaceae/Rhizophoraceae
Combretocarpus
5. Apocynaceae type
6. Aquifoliaceae *Ilex*
7. Araceae
8. Arecaceae *Calamus*
9. Casuarinaceae *Casuarina*
10. Crypteroniaceae *Dactylocladus* (a & b)
11. Dipterocarpaceae Menispermaceae type
12. Dipterocarpaceae type
13. Ebenaceae *Diospyros* (a & b)
14. Euphorbiaceae *Blumeodendron*
15. Fabaceae *Copaifera* (a & b)
16. Fabaceae *Koompassia* sim
17. Fagaceae *Castanopsis*
18. Guttiferae *Garcinia*
19. Icacinaceae *Stemonurus*
20. Loranthaceae
21. Meliaceae *Aglaia*
22. Pandanaceae *Pandanus*
23. Rhizophoraceae *Rhizophora*
24. Rubiaceae *Uncaria*
25. Sapotaceae *Palaquium*
26. Sapotaceae type (a & b)
27. Theaceae *Eurya* (a & b)
28. Thymeliaceae *Gonystulus*
29. Elaeocarpaceae *Elaeocarpus*
30. Euphorbiaceae *Macaranga* (a & b)
31. Euphorbiaceae *Mallotus*
32. Moraceae *Ficus*
33. Myrsinaceae type (a & b)
34. Myrtaceae *Syzygium*
35. Piperaceae *Piper*
36. Ulmaceae *Trema*
37. Asteraceae
38. Asteraceae type
39. Dilleniaceae *Dillenia* (a & b)
40. Melastomataceae *Melastoma*
41. Urticaceae *Poikilospermum*
42. Ericaceae *Rhododendron*
43. Rosaceae type (a & b)
44. Symplocaceae type
45. Arecaceae *Cyrtostachys* (a & b)
46. Arecaceae *Oncosperma*
47. Ochnaceae *Brackenridgea* sim
48. Rhizophoraceae *Ceriops* sim
49. Simaroubiaceae *Quassia*
50. Sonneratiaceae *Sonneratia*
51. Cyperaceae (a & b)
52. Monolete (a & b)
53. Poaceae (a & b)
54. Trilete (a & b)

The scale bar (—) represents *c.* 10 μ m, giving an indication of the size of each grain and spore.

First developed by Benninghoff and Kapp (1962), the following system of notation has been used to reflect the level of certainty in fossil pollen identifications made: ‘comp’ indicates a grain that is almost certainly the same as the reference taxon; ‘sim’, one that is more similar to the reference taxon than any other known reference taxa, but there is less certainty in the association; and ‘type’, a grain corresponds with one morphology within a polymorphic taxonomic unit.







Description of Images

All photographs taken by LESC during field trips in Sarawak, Malaysia, in 2008-2010, at the following locations:

- Chapter 1, within Peat Swamp Fragment site, Sungai Dua Forest Reserve, Miri District
- Chapter 2, of Sago palm (*Cycas revoluta*) inside Lambir Hills National Park, Miri District
- Chapter 3, of a drain alongside a degraded peatland near to Kuching
- Chapter 4, within Deforested Peatland site, Kuala Baram, Miri District
- Chapter 5, near to Deforested Peatland site, Kuala Baram, Miri District
- Chapter 6, of a remnant of secondary peat swamp forest adjacent to a young oil palm plantation (<1 year) in Kota Samarahan
- Chapter 7, of remnant peat swamp forest trees within a very young (<5 years) oil palm plantation on the Miri-Bintulu road, beyond Sungai Niah
- Chapter 8, of a road-way built into a degraded peatland where an oil palm plantation was being established, on the Miri-Bintulu road, beyond Sungai Niah.