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ORIGINAL PAPER

Biomass burning, humans and climate change in Southeast Asia

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Abstract Biomass burning is an integral part of the Earth system, influencing and being influenced by global climate conditions, vegetation cover and human activity. Fire has long been associated with certain vegetation types and land uses in Southeast Asia, but has increasingly affected forests in Indonesia over the last 50 years or so, and peat swamp forests in particular during the last two to three decades. The role of humans, as igniters of fires and as contributors to the conditions that enable fires once ignited to spread widely, is discussed. Other factors, notably the involvement of anomalous climate conditions linked to variability in the Indian and Pacific oceans, are also considered. Global warming and changes in landuse could result in biomass burning becoming more frequent in the future, threatening biodiversity and human health and leading to positive feedbacks with climate change. Deliberate action is required to break a developing disequilibrium within the Earth system: incentives currently being considered under the UN Framework Convention on Climate Change aimed at curbing climate change-causing emissions from deforestation and forest degradation could help mitigate biomass burning, while the effective management of biochar, a stable form of carbon produced from the incomplete combustion of organic matter, by farmers in Southeast Asia, and in other regions where biomass burning is common, could help in carbon sequestration. The paper concludes by stressing that in order to be effective any action needs to recognise the full range of environmental and human factors underpinning biomass burning.

Keywords Biodiversity · Carbon · Conservation · El Nino · Global warming · Indian Ocean Dipole · Monsoon · Rainforest · REDD

Introduction

Fire, a form of combustion, involves rapid oxidation (Cochrane and Ryan 2009). In the case of biomass burning, the material oxidised is mostly carbohydrates derived from dead

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and living organic matter. Biomass burning facilitates increased diversity and nutrient availability and promotes the germination and growth of taxa (Turner et al. 2003; Moritz and Odion 2004; Bond and Keeley 2005), and can therefore play a useful role in ecosystem functioning and the maintenance of environmental services. Fires are not only a factor in fire-adapted terrestrial ecosystems, however: biomass burning is increasingly and repeatedly encroaching on ecosystems, notably rainforests, which are poorly equipped to deal with a high frequency of fire events (Cochrane 2003). In such cases, the ecological impacts can be hugely detrimental. Moreover, as an integral part of the Earth system, biomass burning plays a major role in global environmental change processes, influencing atmospheric composition, climate systems, human health and economic activities (Schultz et al. 2008). Therefore any major changes in frequency and intensity are likely to have important knock-on effects.

A range of factors determine the occurrence and impact of biomass burning. Vayda (2006) distinguishes between factors that influence when and where ignition takes place, and those that determine fuel loads and therefore the subsequent spread and intensity of a fire. Although there are reports of volcanic activity (e.g., Ainsworth and Kauffman 2009) and lightning (e.g., Larjavaara et al. 2005) leading to burning of forest, rarely are they indisputably the trigger for a major natural conflagration, even in seasonally dry areas. More commonly, humans are the stated source of ignition, either deliberately or accidentally (Stott 2000). This is particularly so for rainforests in the tropics (Cochrane 2003; Lavorel et al. 2007). Undisturbed rainforest, with its generally highly humid microclimate, has a low susceptibility to ignition (Laurance and Williamson 2001). Canopy disturbance, through the addition of dead, combustible organic matter and by altering the micro-climate, thereby providing suitable conditions for the growth and drying-out of herbaceous and shrubby plants, increases the proneness of rainforest to burning, and the extent and destructiveness of a fire once started (Cochrane et al. 1999). This is particularly the case when disturbance coincides with, or precedes, prolonged drought, during which vegetation, litter and surface layers of the substrate are pre-dried (Stott 2000).

The current paper examines the interactions between biomass burning, climate and human activity, and the effects of these interactions. The occurrence of forest fires in Southeast Asia, a focus of this paper, has increased since the 1960s and particularly since the 1980s (Taylor et al. 1999), with major regional and possibly global impacts. For example, fires in 1997–1998 in Indonesia consumed over 11 million ha of forest and are thought to have cost, in economic terms, more than US$9 billion, almost US$150 million of which was in additional health costs, while losses in tourism amounted to over US$100 million (BAPPENAS 1999). Detrimental environmental effects included a major expansion of degraded forest (Fig. 1) and increased threats to biodiversity, water supplies and other ecosystem services, reducing opportunities for current and future human generations. Episodes of greatly reduced air quality in the region are one obvious consequence of major forest fires (Kunii et al. 2002). Less obvious are climate impacts, which are discussed below in some detail and which potentially enhance perturbations linked to global warming. Future climate change and land use scenarios offer little comfort: conditions conducive to tropical biomass burning in general are likely to become even more frequent in their occurrence and profound in their impacts during this century if no mitigating action is taken (Cochrane and Barber 2009). The paper concludes with an examination of the implications of biomass burning in Indonesia within the context of more general debates on climate change and the governance of natural resources.

Fig. 1 Recently burnt peat swamp forest, Jambi Province, Sumatra, Indonesia (photograph taken by the author, February 1998)

Biomass burning and landscape

Biomass burning has exerted strong selection pressures and helped shape landscapes over evolutionary timescales. Since their first appearance in the geological record over 400 million years ago, fires have tracked the spread of vascular plants across the Earth's surface and associated rises in atmospheric oxygen (Lenton 2001; Scott and Glasspool 2006) (Fig. 2). The increased combustion of organic matter during the late Miocene may have contributed to climate changes that facilitated the spread of C_4-characterised, tropical savanna vegetation (Osborne and Beerling 2006). However, distinguishing the precise outcome of selection, in terms of plant morphology, phenology and physiology, is difficult

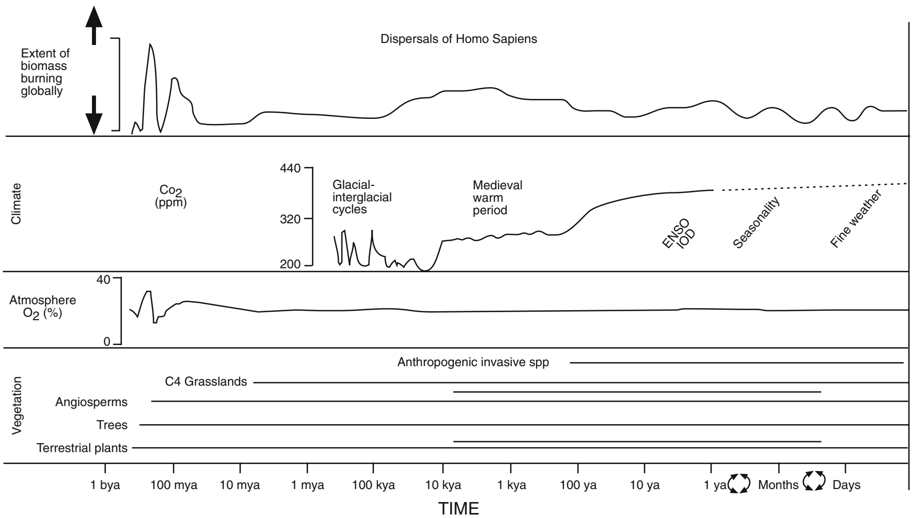

Fig. 2 Schematic of variations in biomass burning activity globally, based on sedimentary charcoal records and satellite data, in relation to changes in atmospheric composition and terrestrial vegetation (based on a figure in Bowman et al. 2009)

because many adaptations to fire, or to fire-influenced habitats, are similar to those arising from other evolutionary drivers (Schwilk and Kerr 2002), notably herbivory (Bond and Keeley 2005).

Biomass burning is generally associated with grasslands and seasonally-dry woodland and forests. These vegetation types can be fire-adapted in that a significant proportion of the component taxa can tolerate frequent, relatively low temperature burns, or are opportunistic and able to benefit from the more open conditions that directly follow a fire. Although not obviously fire-adapted, rainforests have also been subjected to burning over geological timescales. For example, charcoal from the burning of rainforest trees has been recovered from soils on the island of Borneo (Shimokawa 1988; Goldammer and Seibert 1989, 1990) and from mire sediments in southern Sulawesi (Hope 2001) dated to, respectively, 50,000 BP–3,500 year BP and 75,000–50,000 year BP. Thus, rather than precedence, current concerns regarding rainforest fires centre upon the local, regional and global impacts of changes in activity, particularly an increased frequency of fires.

Biomass burning now repeatedly intrudes upon Southeast Asian rainforests where humans have helped to shape and extend highly fire-prone conditions (Stott 1988), as is also the case in tropical Africa and South America. Large areas of formerly intact, closed-canopy and diverse rainforest are reduced by humans to fragmented patches of selectively logged stands of trees and regenerating, burn-scarred, secondary vegetation. These rainforest fragments form part of a landscape mosaic along with commercial plantations and the holdings of smallholder agriculturalists. Fragmented areas of rainforest and derived vegetation are particularly vulnerable to fire (Cochrane 2003) owing to an increased proportion of forest edge habitat that is susceptible to desiccation. Sub-dividing forest into several smaller patches also increases the likelihood of a shared-boundary with agricultural land where fire is used to clear weeds and stubble and to restore soil fertility, as is commonly the case in Southeast Asia (Stott 1988, 1991). The most recently selectively logged areas are also especially fire-prone, owing to the amount of dead and damaged vegetation left behind by loggers and because colonising vegetation is quickly dried and easily ignited (Siegert et al. 2001).

Low-lying peat swamp forests in Indonesia have been a particular focus of biomass burning in Southeast Asia during the last two to three decades. Both swamp forest and the underlying thick deposits of peat are highly prone to fires when drained and selectively logged. Ground-level fires in forests are particularly destructive, not only of vegetation but also the basis for future recovery (root mass, seed banks, soil fertility etc.) (Laurance 2003; Cochrane 2009). Once ignited, the surface layers of peat burn quickly and for longer than fires in the canopy layers, causing profound ecological damage and releasing large amounts of greenhouse gases, particulates and aerosols to the atmosphere (Ali et al. 2006; Page et al. 2009): according to Vayda (2006) much of the smoke haze associated with recent Indonesian fires was from the burning of peat, rather than forest trees. Peat fires are also extremely difficult to extinguish (Brown 1998) as peat at depth can smoulder at high temperatures for long periods, breaking out as surface fires on exposure to air. Exposure of smouldering peat at depth to oxygen can occur, for example, as a result of the excavation of deep drainage ditches and following collapse of the overlying surface peat.

Biomass burning and climate

Seasonal rainfall regimes characterised by oscillating wet and dry seasons can, by promoting accumulations of organic material that are then dried, create conditions that are highly conducive to the ignition and spread of fires. In Southeast Asia, those areas where the year is segmented into distinct seasons that alternate between hot (March–April), rainy (May–October) and cool and dry (November–February) periods are associated with a form of semi-evergreen rain forest commonly known as monsoon forest that is susceptible to burning on an annual basis (Stott 1988, 1990). The central part of the Southeast Asian region is, however, characterised by high, virtually year-round humidity (Fig. 3).

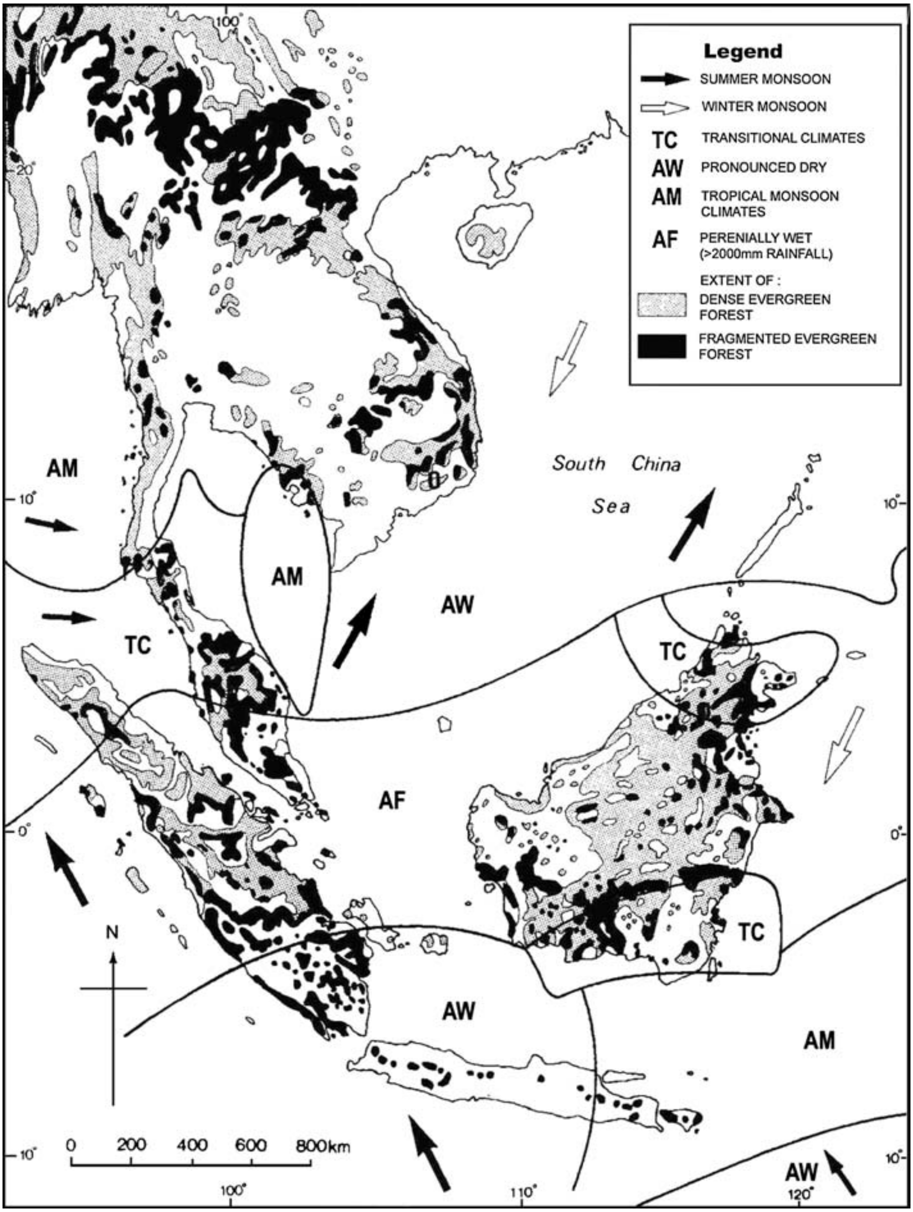

Fig. 3 Climate and forest cover in Southeast Asia (based on a figure originally presented in Taylor et al. 1999)

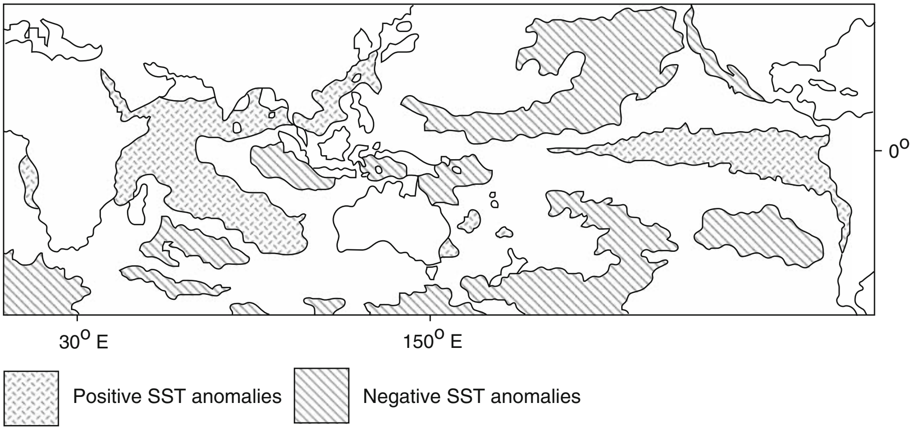

Fig. 4 Sea surface temperature (SST) anomalies arising from the co-occurrence of a positive phase of the IOD and low index phase (El Niño) of ENSO. Note the anomalously cool SSTs off the western Indonesian islands of Borneo, Java and Sumatra. Anomalously cool SSTs limit convection and monsoonal flows and are therefore associated with lower than normal levels of rainfall in Southeast Asia

Prolonged droughts affecting this part of the region generally have a periodicity of longer than 1 year and are driven by variations in the Indian and Pacific oceans [respectively positive phase of the Indian Ocean Dipole (IOD) and low index phase of El Niño Southern Oscillation (ENSO)] (Fuller and Murphy 2006; Le Page et al. 2008; van der Werf et al. 2008; Woodruff this issue). These variations lead to a weakening of monsoonal and convectional flows over the region, and therefore major reductions in levels of rainfall (Ropelewski and Halpert 1987; D'Arrigo et al. 2006). It is during these anomalously climatically dry episodes with a periodicity that varies from about 3–7 years that rainforest fires are most widespread and intense (Taylor et al. 1999). Generally ENSO and IOD are not in lockstep. However, the most severe, supra-annual droughts—and therefore potentially the most extensive and damaging fires—in Southeast Asia (e.g., the droughts of 1972, 1982–1983 and 1997–1998) are associated with a co-occurrence of positive phase IOD and low index ENSO (Saji and Yamagata 2003; Field et al. 2009) (Fig. 4).

In addition to being most commonplace under particular climatic conditions, biomass burning also influences climate through its atmospheric and surface albedo effects. The combustion of biomass releases, *inter alia*, greenhouse gases, aerosols and particulate matter to the atmosphere. Estimated annual total emissions of CO_2 from all biomass burning (comprising the combustion of crop residues, forests and grasslands) on the Asian continent is about 1,100 Tg year^{-1} (Streets et al. 2003), while van der Werf et al. (2008), for the period 2000–2006, calculated emissions from just the burning of forests in Southeast Asia at 128 $\pm$ 51 Tg year^{-1}, and therefore comparable to those from fossil fuels. The burning of vegetation can also expose organic-rich soil horizons to rapid decomposition, thus forming a second major source of greenhouse gases (Ali et al. 2006). Emissions of carbon from biomass burning and related processes, including heightened rates of decomposition of soil organic matter during the post-burning period, in the tropics form a substantial component of effluxes associated with landcover changes, estimated at 1.1 $\pm$ 0.3 GT year^{-1} (Achard et al. 2004). They also account for a considerable part of the global carbon budget (Mouillot and Field 2005). Estimated carbon emissions from the burning of forest and peat in Indonesia during the fires of 1997–1998, at, respectively, 0.4 ± 0.5 Pg C year^{-1} (Page et al. 2002) and 0.2 ± 0.2 Pg C year^{-1} (Houghton et al. 2000), accounted for a sizeable proportion of the global total from forest fires during the same period, calculated at 2.1 ± 0.8 Pg C year^{-1} (van der Werf et al. 2004). Biomass burning also leads to the formation of highly stable black carbon, or biochar, thereby effectively removing some carbon from the environment (Lehmann 2007).

The climate impacts of biomass burning are complex, particularly as they vary spatially, temporally and with the intensity of the fire, and have proven difficult to model (Gustafsson et al. 2009). Increased levels of greenhouse gases could lead to climatic conditions conducive to vegetation fires (Running 2006) and thus to future increased releases of carbon. A positive feedback between biomass burning and climate is complicated, however, by emissions of aerosols and particulate matter. Particulates primarily scatter solar radiation, leading to negative radiative forcing (dimming) and cooling (Ramanathan et al. 2005). Increased aerosol loads, including both organic and black carbon (Menon et al. 2002), are also likely to result in negative radiative forcing overall (Forster et al. 2007). Although not fully understood and difficult to quantify, organic and black carbon are thought to have a tangible influence on rainfall and temperature (Bahner et al. 2007). The effects are generally regarded as being largely regional and restricted to source areas, owing to their short (days to weeks) atmospheric residence times (Chung and Seinfield 2002, 2005; Ramanathan et al. 2005). However, evidence suggests that meteorological conditions in Southeast Asia can accentuate the atmospheric impacts of biomass burning in the region. Strong surface winds, reduced rainfall, and deep convection combined with advection via the subtropical jet stream can disperse emissions widely, impacting conditions over regional and global scales (Folkins et al. 1997; Matsueda et al. 2002; Langmann and Heil 2004; Heil et al. 2007).

The climatic effects of black carbon emissions from biomass burning are currently a focus of scientific attention (e.g., Ramanathan et al. 2005; Ramanathan and Carmichael 2008). Unlike organic carbon, black carbon absorbs in the visible part of the electromagnetic spectrum, has a positive radiative effect and is hydrophobic, oxidising to a hydrophilic state in the presence of oxidants such as O_3 and SO_2 (Menon 2004). The atmospheric lifetime of black carbon varies with climate conditions from region to region but at 3–15 days tends to be longer than other aerosols because, while in a hydrophobic state, wet deposition is delayed (Chung and Seinfield 2002; Croft et al. 2005). The atmospheric lifetime of black carbon has also varied over time, and is currently shorter than during the pre-industrial period because of heightened atmospheric levels of oxidants such as O_3 and SO_2 (Tsigardis et al. 2006). Black carbon influences climate through a complex of mechanisms: directly by scattering solar radiation and scattering, absorbing or emitting thermal radiation; and indirectly by causing increased atmospheric stability, acting as cloud condensation nuclei and through changing the reflective (surface albedo) properties of snow.

The different direct and indirect radiative properties of emissions as a result of biomass burning cannot be simply combined to provide an overall score of climate effect. This is because of nonlinearities and interactions between the different substances emitted, the varying influence of environmental factors, such as altitude, emission factors, including the intensity of burn, and uncertainties over atmospheric residence times (Lohman and Feichter 2005; Yokelson et al. 2007). At a global scale, emissions from biomass burning can alter the hydrological cycle significantly (Ramanathan and Carmichael 2008). The temperature effects are more complex because cooling at the surface by atmospheric dimming (Andreae 2007) may be more than offset by warming of the lower atmosphere (Ramanathan et al. 2001) and changes in surface albedo (Flanner et al. 2007). Climate effects closer to the sources of emissions from biomass burning are a little easier to define and depend, to an extent, on the degree of radiative coupling between surface and atmosphere. A particular effect in Asia is perturbation of monsoonal activity, and emissions from biomass burning in the region could be at least partly responsible for observed declines in rainfall during the Northern Hemisphere summer monsoon period (Ramanathan et al. 2005, 2007; Ramanathan and Carmichael 2008).

Biomass burning and rainforest composition, structure and services

Biomass burning has become one of the most pervasive threats to rainforests and the ecosystem services they provide (Fearnside 2000; Laurance 2003; Berry et al. this issue). The actual effects may, in some cases, be difficult to distinguish from those of other factors, such as droughts, associated with the incidence and spread of the fire (Nepstad et al. 2004; Lingenfelder and Newbery 2009). Small, narrow-stemmed trees are particularly vulnerable to fires (Slik and Eichhorn 2003; Nieuwstadt and Sheil 2005), as are thin-barked taxa (Cochrane 2003). Large trees also suffer increased mortality, and can continue to do so for several years after a fire (Nieuwstadt and Sheil 2005), with topographic and edaphic conditions important in determining survival (Slik and Eichhorn 2003). Increased vulnerability to windthrow, drought and pathogen attack are all mechanisms contributing to increased mortality in the years immediately following a fire (Barlow et al. 2003).

Impacts on rainforest animals are less well understood. Some groups, notably small mammals, and amphibians, increase in abundance or diversity, while others (e.g., birds, insects and some primates) decline (Barlow et al. 2002; Fredericksen and Fredericksen 2002; O'Brien et al. 2003; Cleary and Genner 2004; Slik and van Balen 2006; Sodhi and Smith 2007). Adeney et al. (2006) report that avian impacts on the Indonesian island of Sumatra were highly taxon and guild specific, with insectivorous, understorey birds affected most severely. Effects such as a loss of food sources or shelter from predators (Cochrane 2003) are likely to mean that the full impact of biomass burning is not evident until some time after the fire has burnt out.

Rainforests can recover from fire. Research in Southeast Asia has revealed that rainforest structure, in terms of stem density and canopy cover, recovers first (Slik et al. 2002). However, recovery of species composition and diversity is often delayed because of the destruction of seed stores and sources and the disturbance of animals involved in propagation (Eichhorn 2006; Slik et al. 2008). Mast fruiting, particularly the long period of time that can elapse between fruiting events, may further delay recovery (Cannon et al. 2007). As a result, post-fire conditions strongly favour wind-propagated, fast-growing, light-requiring taxa with low wood densities (Slik et al. 2008). Not all plants are adversely affected by even repeated burning, and climbers, shrubs and herbaceous plants often prosper in recently burned areas of forest (Eichhorn 2006), further inhibiting the germination of seeds from forest trees and increasing the chances of a repeat occurrence of fire through a positive loading of fuel (Laurance and Williamson 2001). With time species that are more characteristic of undisturbed forest become established. The original, pre-fire composition recovers only slowly (Slik et al. 2008), however, and full recovery may never be attained. This is because inter-specific differences in tolerance to burning among forest trees and animals, together with increased opportunities for invasives, mean that the assemblage of taxa surviving a fire can be very different from the pre-burn complement of species and their relative abundances (Barlow et al. 2002; Slik and Eichhorn 2003; Slik and van Balen 2006; Peh this issue).

Rainforest fires and humans

Regional fire histories reflect the peopling of Southeast Asia, currently a source of lively debate (Bird et al. 2004; Woodruff this issue), and subsequent technological developments, including the introduction and spread of agriculture. Initial migrations of *Home erectus* from Africa may have commenced between 1.5 and 1.0 million years ago, and possibly as long ago as 1.9 million years based on a re-dating of simple stone tools attributed to *H. erectus* from a site in southern China, reaching what is now the Indonesian island of Flores by 840,000 years ago (Morwood 2001). *Homo erectus* populations are associated with the early use of fire [e.g., the site at Gesher Benot Ya'aqov in Israel has yielded evidence of the use of fire dating to 790,000 years ago (Goren-Inbar et al. 2004)]. Roland (2000) maintains that *H. erectus* in China had developed the ability to manipulate fire by around 400,000 years ago, and sedimentary charcoal remains from the Loess Plateau, which provide a record of palaeo-biomass burning stretching back more than 400,000 years, provide some support for this, albeit circumstantial (Zhou et al. 2007; 2009). The earliest incontrovertible evidence of anatomically modern humans (*Homo sapiens*) in Southeast Asia dates to the upper Palaeolithic, and to at least 42,000 years ago at Niah cave on the island of Borneo (Barker et al. 2007). Excavations at Niah cave indicate that local populations of *Homo sapiens* could have been using fire to obtain food for more than the last 30,000 years (Barker et al. 2007). Biomass burning in the region greatly increased from about 20,000 to 10,000 years ago, on the basis of records of sedimentary charcoal, when increased climatic aridity facilitated the ignition and combustion of vegetation (Haberle et al. 2001).

Haberle et al. (2001) attribute a second phase of increased burning, again on the basis of sedimentary charcoal and dating to the middle of the current interglacial (Holocene) period (ca. 4,500 year BP), to the spread of agriculture through Southeast Asia. Agriculture has a long history in the region and comprises introduced and indigenous variants (Bellwood 2005). An indigenous form of food production developed in the New Guinea highlands during the early Holocene (Denham et al. 2003) but does not seem to have traveled far beyond its area of origin. More widespread are the remains of food plants that were first cultivated and domesticated outside the region. These make their initial appearance in archaeological records during the mid Holocene. Thus rice farming was present in southern Thailand, the Philippines and on the island of Borneo by 3,500–4,500 year BP (Snow et al. 1986; Beavitt et al. 1996; Higham and Lu 1998). Early farmers are likely to have utilised shifting cultivation, in which areas of vegetation (including forest) were burned and then cultivated, before being abandoned. Shifting cultivation (swidden, or slash and burn) has a long history in the region and is still practiced (Mertz et al. 2009) (Fig. 5), although less now than previously, presumably owing to the spread of more permanent forms of agriculture, notably plantations (Schmidt-Vogt et al. 2009). As fire is central to swidden, the increase in burning from the mid-Holocene identified by Haberle et al. (2001) probably represents an abrupt expansion of the area impacted by shifting cultivation from almost 5,000 years ago.

Swidden agriculturalists were initially identified as responsible for a majority of the area burnt during recent major forest fires in the region associated with anomalously dry years (Jones 2006; Murdiyarso and Adiningsih 2007), with the effects cited as strong reasons for restrictions on shifting cultivation and its replacement by modernised, usually sedentary forms of agriculture (Fox 2000). Swidden agriculturalists were also the primary target of a ban on setting fires in forest areas enacted in Indonesia in 1984, following the devastating forest fires of 1982–1983 and renewed in 1997 during a period of major biomass burning

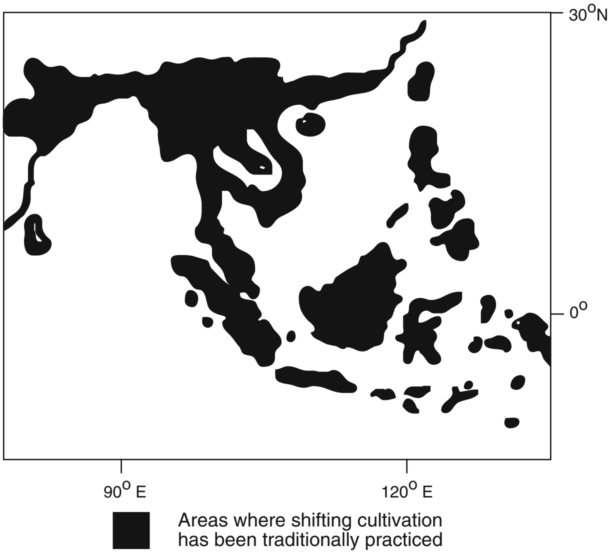

Fig. 5 Extent of area subjected in the past to swidden (shifting cultivation), a form of food production that involves the use of fire to clear land prior to cultivation. A greater awareness of biochar, formed from the incomplete combustion of biomass, in carbon sequestration and as a means of restoring and maintaining soil fertility (Lehmann et al. 2006; Lehmann 2007) could lead to a renewed interest in swidden in the future

(Ketterings et al. 1999). However, research on the causes of the fires during the 1990s identified the development of large-scale plantations as also responsible (Applegate et al. 2001), thus confirming the preliminary conclusions of Stolle and Tomich (1999). Moreover, fire was also being used as a weapon in disputes over natural resources (Suyanto et al. 2004), with such conflicts leading to a let it burn attitude among local farmers when faced with forest fires on land allocated to timber companies, which contrasted with their attempts to extinguish fires that threatened their own fruit orchards and small gardens of rubber trees (Harwell 2000).

Biomass burning has continued to impact forests in Southeast Asia and Indonesia in particular since the beginning of the current century (Murdiyarso et al. 2004). The role of humans is evident in the results of research by Lingenfelder and Newbery (2009), who examined variations in the spatial distribution of forest fires on Borneo over a 10 year period (1997–2006). Their research focused on a study area in which climate and original vegetation were similar throughout. A total of 320,000 fire events were recorded in the ten years of satellite data analysed, with peat swamp forest increasingly impacted during the period of interest. The most dramatic finding, however, is that the proportion of land annually affected by fire in Indonesian Kalimantan was five times greater than parts of the island under the jurisdiction of Brunei and Malaysia. The differences, Lingenfelder and Newbery (2009) suggest, reflect major investments in oil palm plantations, the extent of flammable, degraded forest, difficulties in implementing legislation aimed at outlawing the practice of burning, and a lack of fire management, particularly during the most fire-prone periods. As a result, fires in Kalimantan had a higher likelihood of occurring and, once started, tended to burn over far larger areas than in Brunei, Sabah and Sarawak.

Discussion

Fire has proved to be something of a double-edged sword for humans. The eastern African savanna provided the backdrop for much of hominin evolution (Ségalen et al. 2007). Naturally caused fires, e.g., due to lightning or volcanic activity, would have been experienced from time to time, and were possibly familiar components of the landscape. Subsequently, an ability to harness and utilise fire contributed to ecological dominance (Alexander 1990), allowing hominins to move ahead of their fellow animals by providing a means to manipulate environments and a focus for cultural and social activities, with fire eventually becoming an essential constituent of being human, and part of what Sauer (1956) termed the tripod of culture.

The current extent of modification of the Earth's surface by burning is evident in computer model simulations that include fire as an ecological factor. A switching off of fire in these models (e.g., Bond et al. 2005) generally results in a major increase in the extent of forests and a concomitant decrease in the area covered by fire-adapted biomes. This is particularly the case for tropical parts of the world, with extensive areas of C_4-characterised savanna giving way eventually to closed-canopy forest. Unfortunately models of vegetation response to environmental forcing that include fire cannot, at present, incorporate the full complexity of the Earth system, with all its interactions and feedbacks (Bonan 2008). In any case, rather than being switched off, biomass burning is becoming an increasingly common phenomenon, setting-up positive feedbacks that ultimately lead to a greater proneness to fire (Cochrane et al. 1999; Laurance and Williamson 2001; Page et al. 2009). Climate change-causing emissions from the combustion of organic matter on a massive scale form a critical part of this cycle (Phillips et al. 2009). Reduced activity of the Asian (Northern Hemisphere) summer monsoon is one possible climate outcome, perturbing precipitation throughout the region. Enhanced global warming is another possible effect. Moreover, global warming and increased demands on land and resources in rain-forested parts of the tropics, including land required for the expansion of agro-fuel production and to grow food displaced by, for example, the establishment of oil palm plantations elsewhere (Koh et al. 2009), could energise this feedback still further (Fearnside 2000). Repeated, major fires, concentrated on Indonesian Kalimantan and Sumatra, now undermine important environmental services provided by forests, including maintenance of biodiversity, water cycling and climate regulation.

Despite their magnitude and the trans-boundary nature of their effects, emissions from biomass burning are not included in any major, international emissions-control legislation. Carbon dioxide from forest fires is not currently specifically included in the UN Framework Convention on Climate Change (UNFCCC), despite overall levels of CO_2 released from biomass burning globally being about 50% of those from the burning of fossil fuels (Bowman et al. 2009). Moreover, the Kyoto Protocol, which binds signatory countries to target levels of CO_2 emissions, exempts developing countries such as Indonesia and Brazil, where the majority of biomass burning occurs (Santilli et al. 2005).

The trans-boundary nature of emissions from biomass burning is a particular problem in Southeast Asia. In response, member states of the Associations of South East Asian Nations (ASEAN) signed an agreement (ASEAN Agreement on Transboundary Haze Pollution, AATHP) aimed at combating atmospheric pollution arising from biomass burning in the region. The AATHP came into force on 25 November 2003, 60 days after the sixth signatory country had ratified the agreement. Although providing a collective and prescriptive framework for fire monitoring, mitigation and prevention, and despite being the first environmental agreement within ASEAN that is legally binding on all signatory states, a number of severe shortcomings have emerged (Jones 2006). As with many international agreements, the AATHP is weakened by the amount of discretion allowed to individual nation states (signatories are required to prevent and mitigate fires only ‘to the extent possible’ or ‘within their limits of capabilities’), and by a lack of a mechanism for enforcement and deterrence. These weaknesses seriously erode the ability of the agreement to deliver meaningful reductions in the atmospheric pollution effects of biomass burning in the region (Tan 2005). Perhaps its major shortcoming, however, is that by the present date (November 2009), and almost 6 years after coming into effect, Indonesia has yet to ratify the agreement, and therefore by far the largest source of transboundary pollutants in the region is probably not legally bound by it (Jones 2006).

The AATHP can also be criticised for not dealing with the complexity of underlying causes of major fires. Biomass burning is not just a consequence of environmental conditions; but is also determined by cultural, political and socio-economic factors, some of which at least may have an origin some distance, in space and time, from the area of conflagration. These factors are diverse and often site-specific (Dennis et al. 2005). Recent major burning events in Indonesia, beginning in a major way in Sumatra during the 1960s (Field et al. 2009) before spreading to other parts of the country, notably Kalimantan on the island of Borneo, in the following decades are closely associated with periods of anomalously dry weather. Indeed, as discussed in this paper, major fires in the region may be contributing to the occurrence of environmental conditions, including drought, which increase the likelihood of severe burning events. However, biomass burning is often also a product of factors that are more directly linked to human activity, and this is certainly true for rainforested parts of Southeast Asia over the past five decades or so.

Sunderlin and Resosudarmo (1996) adopt a critical realist perspective in arguing that processes that predispose Indonesian forests to burning include overarching national, regional and international forces that influence decisions on the ground concerning how natural resources are managed and exploited. These forces were encapsulated in the New Order of then President Suharto in 1966, the policies of which preferenced the interests of powerful industrial concerns and politico-business elites over sound environmental management, resulting in a *de jure* state property regime—dating to the colonial period and which itself had effectively stirred conflict by outlawing many customary uses of forest resources (Peluso 1990)—slipping into *de facto* control by private interests (McCarthy 2000). The activities of private industrial concerns and elites were given renewed impetus by Ministerial Decree No. 682/Kpts/Um/8/, issued in 1981 and implemented in 1985. This decree, which did not involve local communities in its drafting, laid out plans to convert up to 30 million ha of forest to other land uses, notably plantations for pulp, timber and oil palm production and transmigration schemes (Murdiyarso and Adiningsih 2007).

The period 1997–1998 coincided with a coupled ENSO-IOD-induced drought in Southeast Asia. In Indonesia, the effects of this drought were added to by those of the Asian financial crisis, which included sharp falls in currency values and economic activity and urban depopulation, the implementation of structural adjustment programmes of the IMF and World Bank, the fall of President Suharto and the launch of a social and political movement (*Reformasi*) aimed at dismantling the New Order structures and ensuring greater autonomy at local (district) level (Silver 2003). The rapid and largely uncoordinated manner in which governance was transferred from central to local governments under *Reformasi*, together with a restricted capacity at district level to administer huge areas of forested, relatively lightly populated land, and the continued influence of powerful local political and business elites, have limited the positive environmental benefits of the movement, and may have contributed to the fires (McCarthy 2001). In Indonesia, ‘forest flammability [has] as much to do with the social as with the ecological landscape' (Harwell 2000, p. 315): given a milieu framed by a long history of economic marginalisation, conflicts over forest resources, environmental degradation, rapacious plundering of natural capital often associated with burning of forests, anomalously dry weather and a weak capacity to respond to environmental catastrophes, major fires can perhaps, in hindsight, be viewed as almost inevitable consequences.

The environmental services provided by rainforests are widely known. In Southeast Asia the value of these services is maximised by high levels of biodiversity and by heavy demands on resources at local, national and international levels. The role of forests, notably rainforests, in regulating climate conditions (Bonan 2008; Candall and Raupach 2008) is also well known. Although not currently part of the Kyoto Agreement, there are plans under the UNFCCC to introduce a financial mechanism aimed at reducing deforestation-linked emissions (Reducing Emissions from Deforestation and forest Degradation, REDD). REDD will most likely credit entire nations for achievements in reducing deforestation (Miles and Kapos 2008) and increase pressure for improved stewardship of forest resources (Agrawal et al. 2008). How governments respond to REDD remains to be seen, although there is already a suggestion that the Indonesian Government could be using the release of new proposals to develop some remaining areas of peat swamp as a means to rachet-up the pressure on the international community to provide compensation (Koh 2009; Simamora 2009). Moreover, how REDD impacts governance at a local level in forested areas, particularly in terms of the human rights of forest dependent people (Seymour 2009), will also be critical to the success of attempts to limit emission-causing activities such as biomass burning and to conserve and maintain the environmental services provided by tropical rainforests. Such limitations should not necessarily include a ban on traditional forms of resource management, seen as inefficient and environmentally damaging. Indeed under careful monitoring and management swidden on mineral soils in particular could, by converting a sizable proportion of living and dead organic material to inert biochar while at the same time promoting new growth, help sequestrate CO_2 and enhance soil fertility (Lehmann et al. 2006).

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