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Biomass burning in Indonesia and Papua New Guinea: natural and human induced fire events in the fossil record

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Abstract

Microscopic charcoal preserved in sediments from ten wetlands in the Indonesian and Papua New Guinea region provide a proxy record of regional fire events during the last 20,000 years. Two periods of high regional charcoal frequency are encountered during the last glacial transition (17,000–9000 years B.P.) and the middle to late Holocene (5000 years B.P. to the present). Despite the presence of humans in the region throughout the last 20,000 years, there is no suggestion that, on a regional spatial scale, fire frequencies were solely related to changing subsistence patterns of the human population. Pollen data from these same sites suggest that during times of high charcoal the rate at which vegetation changes, represented by the fossil pollen spectra, also increases. High climate variability may promote a greater community turnover rate and in turn a more fire susceptible forest community. Rapid climate change and high variability during the last glacial transition and intensification of El Niño-related climate variability during the middle to late Holocene, may have been important mechanisms for promoting fire in rainforest environments and maintaining diversity of tropical rain forests. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

Fire is now recognised as an important agent of vegetation disturbance in tropical rain forest. The extensive destruction of rain forest across the South-east Asia and New Guinea region during the severe 1997–98 El Niño event clearly demonstrated the susceptibility of large areas of rain forest to fire. Large-scale canopy tree death and crown die-back produced many gaps within the forest, providing opportunities for pioneer species to establish. Whether these changes in community structure and composition are permanent or, in the absence of further disturbance, will eventually lead to the re-assembly of pre 1997–98 conditions is not yet known, and can only be answered by examining historic plant responses to similar climatic or other natural disturbance events.

While the role of disturbance events, such as wide-spread fires, in rainforest dynamics is still being evaluated (Connell, 1978; Pimm and Sugden, 1994; Walsh, 1996) there is a need for greater understanding of the long-term frequency and impact of burning in tropical environments. The best long-term, quantitative ecological records of change in rain forest

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communities are no longer than four decades long (Phillips et al., 1994; Condit et al., 1996). Clearly, the study of modern rain forest community dynamics using traditional small-scale ecological approaches encompasses too little time and space to understand how these communities assemble and endure on time scales related to forest tree population dynamics after major disturbance events. Despite the importance of drought and fire to biodiversity, global carbon cycling, agricultural production and forest management, there is little information on the long-term persistence of these events or their consequences for biotic communities.

Microscopic charcoal and fossil pollen preserved in soils, lake and swamp sediments have been used to investigate the record of fire disturbance and ecosystem change in ancient times. Records of ancient charcoal from the Malesian sector (including the eastern Indonesian archipelago and Papua New Guinea) have shown that fires have repeatedly occurred in tropical forests since the Late Pleistocene (Goldammer and Seibert, 1989; Haberle, 1998; Hope, 1998). Analysis of the palaeoecological significance of charcoal records from the Malesian sector have emphasised the strong link between human occupation and the presence of charcoal in the sedimentary records (Kershaw et al., 1997; Haberle, 1998). Nevertheless, it is clear that frequency, intensity and extent of fires in this landscape is likely to be related to complex interactions between climate, vegetation type and human activity (Clark et al., 1997).

Humans have clearly played a major part in altering the nature and distribution of vegetation communities on a global scale, through the use of fire, agricultural activity and the widespread dissemination of plants that accompany human migration and trade (Schüle, 1990). The antiquity of human induced disturbance is generally discerned in the palaeoecological records by the appearance of ecological processes operating at rates that are unprecedented under "natural" conditions and that can be directly related to human activity through archaeological data (Walker and Singh, 1994). However, even when these conditions are met, there is a possibility that "unusual natural" events may have been responsible for recorded vegetation change. For example, in the Cook Islands of the south Pacific, reduced forest cover and increased burning is recorded as early as 2500 years ago (Kirch and Ellison, 1994), which is some 1500 years earlier than archaeological evidence for human colonisation. Without a clear understanding of the natural climate variability the palaeoecological evidence remains open to both anthropogenic and climate based interpretations.

This paper adopts an alternative approach to the problem of distinguishing human induced disturbance from natural events by constructing a long-term cumulative record of abundance of microscopic charcoal at century-scale resolution over the last 20,000 years (the period covered by four or more sites). By assuming that the widespread El Niño-related fires of 1997–98 provide an analogue for natural fire events that would have been synchronous and widespread across the region in the past, then a comparison between charcoal records from geographically separate sites in the region may provide an indication of the past occurrence of similar events. Comparison of the cumulative charcoal record with independently derived palaeoclimate records, archaeological data on human occupation, and pollen data will allow us to investigate fire–environment interactions at both local and regional scales and will provide an indication of the dominant driving force of change in late Pleistocene to Holocene fire regimes.

2. Regional setting

The many islands that make up the Malesian sector are located entirely in the tropics. The region has a tropical–equatorial rain forest climate, with most rain tending to fall during the Southern Hemisphere Summer Monsoon (November to April). A low pressure system prevails over the western Pacific and is fed by southeast trade winds bringing moisture to the region. Circulation patterns over the region are strongly affected by the Southern Oscillation, though the relationship is strongest during the premonsoon from September to November (McBride, 1999). Soil moisture generally remains at or wetter than field capacity for the whole year, except during severe El Niño years, when the low pressure system moves towards the eastern Pacific, limiting the southward penetration of the summer monsoon and significantly reducing rainfall across the Malesian sector.

During the last two major El Niño years (1982–83

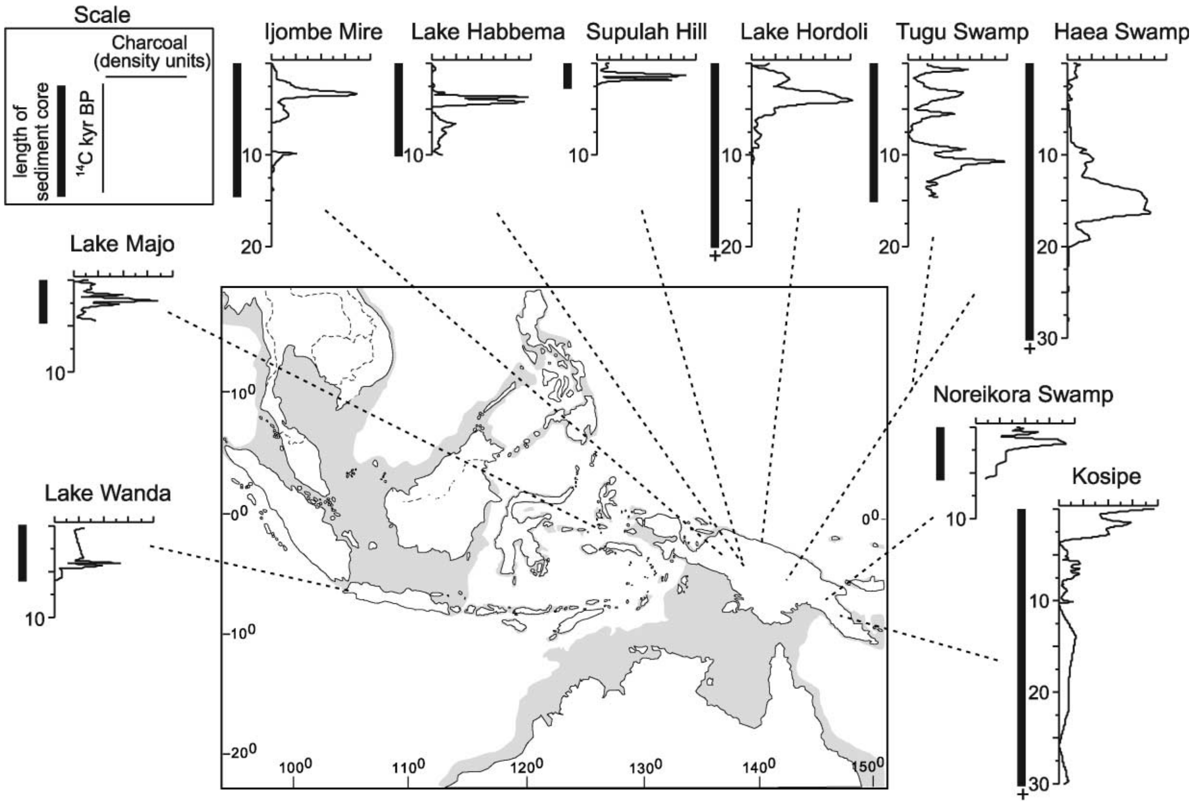

Fig. 1. Charcoal records from sites in Indonesia and Papua New Guinea plotted against age (^{14}C kyr B.P.). See Table 1 for details of site chronology.

and 1997–98) fires were able to penetrate large areas of rain forest causing widespread destruction to these environments. The role of humans versus climate in the ignition of such fires is not clear. Certainly the vulnerability of forests to fire increases as soil moisture is reduced (Uhl et al., 1988), with or without the presence of humans. A very long period of interaction between humans and the environment has been evident from the archaeological data that suggests humans have been present in the island of New Guinea for at least 40,000 years (Groube et al., 1986); perhaps as much as 1.8 million years on the island of Java (Swisher et al., 1994), using fire for hunting and gathering pursuits and, at least during the last 6000 years, for agriculture (Hope and Golson, 1995).

The broad change in vegetation since the arrival of humans in the Malesian sector has been established from more than 80 swamp and lake sites ranging in altitude from close to sea level to over 4000 m above sea level (a.s.l.) (Haberle, 1994; Flenley, 1996; Flenley, 1998; Haberle, 1998). Most records cover the period from before the last glacial maximum (LGM around 18,000 years B.P.) to the present and show that the mountains, and probably the lowlands, were at least 5 °C cooler at the LGM. The Bandung (Java) pollen record (Van der Kaars and Dam, 1995) shows a much more open vegetation at the LGM relative to the Hordorli record from Irian Jaya (Hope and Tulip, 1994), suggesting that the region west of New Guinea would have been relatively drier, possibly due to increased continentality on the exposed Indonesian shelf. On the high mountain peaks the retreat of snowline began around 15,000 years B.P., bringing on a period of some 6000 years of warming and forest invasion. Modern vegetation community patterns were finally established by 9000 years B.P. The evidence of climate change from pollen records

Table 1
Location, description, radiocarbon dates and calibrated dates (Stuiver and Reimer, 1993) for sites used in this analysis.

Site	Site type, altitude, location	Depth (cm)	^{14}C dates (^{14}C years B.P.)	Calib. dates 1σ range (cal years B.P.)	Reference
Kosipe	Sedge Swamp, 1960 m, 8°28′S, 147°12′E, PNG	71–82	2070±70	2120–1950	Hope 1980; Hope, 1982; White et al., 1970
		110–125	3530±80	3900–3700	
		185–198	4190±80	4840–4780	
		360[a]	9330±250	11,060–10,200	
		540[a]	35,900±850	-	
Noreikora Swamp	Grass/Sedge Swamp, 1750 m, 6°20′S, 145°50′E, PNG	340–350	1580±160	1700–1300	Haberle 1996a
		500–510	4470±120	5300–4870	
Haeapugua	Grass/Sedge Swamp, 1650 m, 5°50′S, 142°47′E, PNG	70–78	890±80	920–710	Haberle 1998
		185–190	2860±100	3160–2850	
		290–300	4380±80	5050–4850	
		344–350	8340±150	9520–9090	
		420–430	11,270±100	13,400–13,150	
		480–490	16,640±250	20,250–19,410	
		495–505	16,990±180	20,600–19,850	
		550–560	20,670±150	-	
		642–650	27,760±390	-	
Tugupugua	Grass/Sedge Swamp, 2300 m, 5°40′S, 142°35′E, PNG	60–70	880±70	910–710	Haberle 1998
		195–200	1700±210	1870–1350	
		400–415	5750±80	6660–6410	
		600–615	9290±190	10,690–10,240	
		800–815	12,860±250	16,200–14,250	
Lake Hordorli	Sedge Swamp, 780 m, 2°32S, 140°33′E, Irian Jaya	90–98	7140±120	8100–7800	Hope and Tulip, 1994; Hope 1996
		190–200	10,750±120	12,950–12,650	
		390–400	22,500±240	-	
Supulah Hill	Shallow Lake, 1580 m, 4°7′S, 138°58′E, Irian Jaya	150–170	1770±70	1820–1570	Haberle et al., 1991; Hope 1998
		230–250	32,240±880	-	
		330–350	33,200±1070	-	

Table 1 (*continued*)

Site	Site type, altitude, location	Depth (cm)	^{14}C dates (^{14}C years B.P.)	Calib. dates 1σ range (cal years B.P.)	Reference
Lake Habbema	Lake, 3120 m, 4°7′S, 138°42′E, Irian Jaya	215–225	3050±80	3360–3080	Hope (unpub.)
		382–392	5610±80	6470–6300	
		635–645	9880±130	11,550–11,200	
Ijombe	Sedge Fen, 3630 m, 4°2′S, 137°13′E, Irian Jaya	310	6450±100	7430–7270	Hope and Peterson, 1975, 1976
		480	10,750±260	12,480–12,370	
		1000	13,850±260	17,000–16,250	
Lake Majo	Lake margin, 140 m, 1°28′S, 127°29′E, Maluku	220–240	1300±90	1290–1150	Hope 1993
		414–432	220±190	2350–1950	
		634–648	4270±90	4870–4660	
Rawa Danau	Shallow Lake, 100m, 6°11′S, 105°58′E, Java	270–280	350±80	510–310	Van der Kaars et al., 2001
		380–390	1810±60	1820–1630	
		490–500	3890±160	4450–4090	
		860–870	5450±150	6400–6000	
		1400–1410	11,460±160	13,790–13,170	
		1640–1650	13,200±240	16,220–15,500	

[a] AMS dates.

during the last 9000 years are equivocal due to increased effects of human disturbance, particularly after an apparent intensification of agricultural activity around 5000 years B.P. It has been suggested that drought, possibly related to the intensification of El Niño-Southern Oscillation (ENSO) climate phenomena, were also an increasingly important factor after about 5000 years B.P. in the Malesian sector (Haberle, 1996a).

3. Study sites and methods

Only a relatively small number of the total palaeo-ecological sites have detailed information on changes in abundance of microscopic charcoal preserved in the sediment (Fig. 1). A total of ten sites have been selected for this analysis on the basis of consistent charcoal measurements and chronological control (Table 1). At each site, with the exception of Rawa Danau, detailed counting of microscopic charcoal followed the point counting method outlined by Clark (1982), providing a consistent basis for comparison of data on the abundance of charcoal in the sediment. The charcoal counts from the site of Rawa Danau are expressed as a ratio of charcoal to pollen sum.

Charcoal particle abundance data was standardised (unity) for each site. Using a linear age model (based on ^{14}C age-depth linear relationship) and interpolation, a cumulative charcoal record was constructed by summing the 200-year values for each site. A corrected charcoal curve was then calculated by dividing the cumulative charcoal by the number of sites (Anderson and Smith, 1997). All numerical analyses have been implemented within psimpoll, a C program for plotting pollen data (developed by Bennett, 1994).

4. Results

The stratigraphy and chronology of each site has been described in the relevant publications (Table 1). Individual fires or fire periods are assumed to be reflected in the individual records as major increases in the charcoal abundance curves (Fig. 1). The results presented here cover the last 20,000 years of landscape change, due to sediment discontinuities at some sites and lack of reliable dating control before this period. Four sites have sediment records that extend from the present to before 20,000 years B.P. Charcoal is present in very low amounts in sediments that date to before 50,000 years B.P. in New Guinea (Haeapugua, Haberle, 1998), well before humans are known to have occupied the region and presumably reflecting natural burning of forested environments. However, it is not until after 35,000 years B.P. at three sites in the New Guinea mountains (Haeapugua, Kosipe and Supulah Hill) that a sharp and consistent rise in charcoal density can be tentatively ascribed to human activity (Haberle, 1998; Hope, 1998).

There are clear consistencies in patterns that appear on inspection of individual charcoal records (Fig. 1). This is all the more striking given the geographical spread of these sites. Most sites show consistently high charcoal values during the last glacial period, particularly from around 17,000–12,000 years B.P. High variability in charcoal values is found at the last glacial transition (12,000–9000 years B.P.), though an almost uniformly low occurrence of charcoal characterises the early Holocene period (9000–5000 years B.P.). All records display highly variable charcoal values for the later half of the Holocene, with peaks occurring at a number of sites between 4000 and 2000 years B.P.

The composite charcoal record (Fig. 2a–c) reflects changes in the pattern of burning across the Malesian sector from the last glacial maximum to the present. The corrected charcoal record is compared to a summary of climate change in the region (Fig. 2d) and the number of human occupation sites recorded for the highlands of New Guinea over the same period (Fig. 2e). Low corrected charcoal values are evident between 20,000–18,000 years B.P. at the height of the last glacial maximum. High charcoal values are recorded between 17,000 and 9000 years B.P., with peaks occurring between 17,000–15,000, 13,500–11,000 and 10,000–9000 years B.P. Low charcoal values, similar to those recorded during the last glacial maximum, occur in the interval from 9000–6000 years B.P. The period from 6000–4500 years B.P. shows slightly increased charcoal values. After 4500 years B.P., charcoal increases substantially and remains high through to the present.

5. Discussion

The charcoal records clearly differ in detail at each

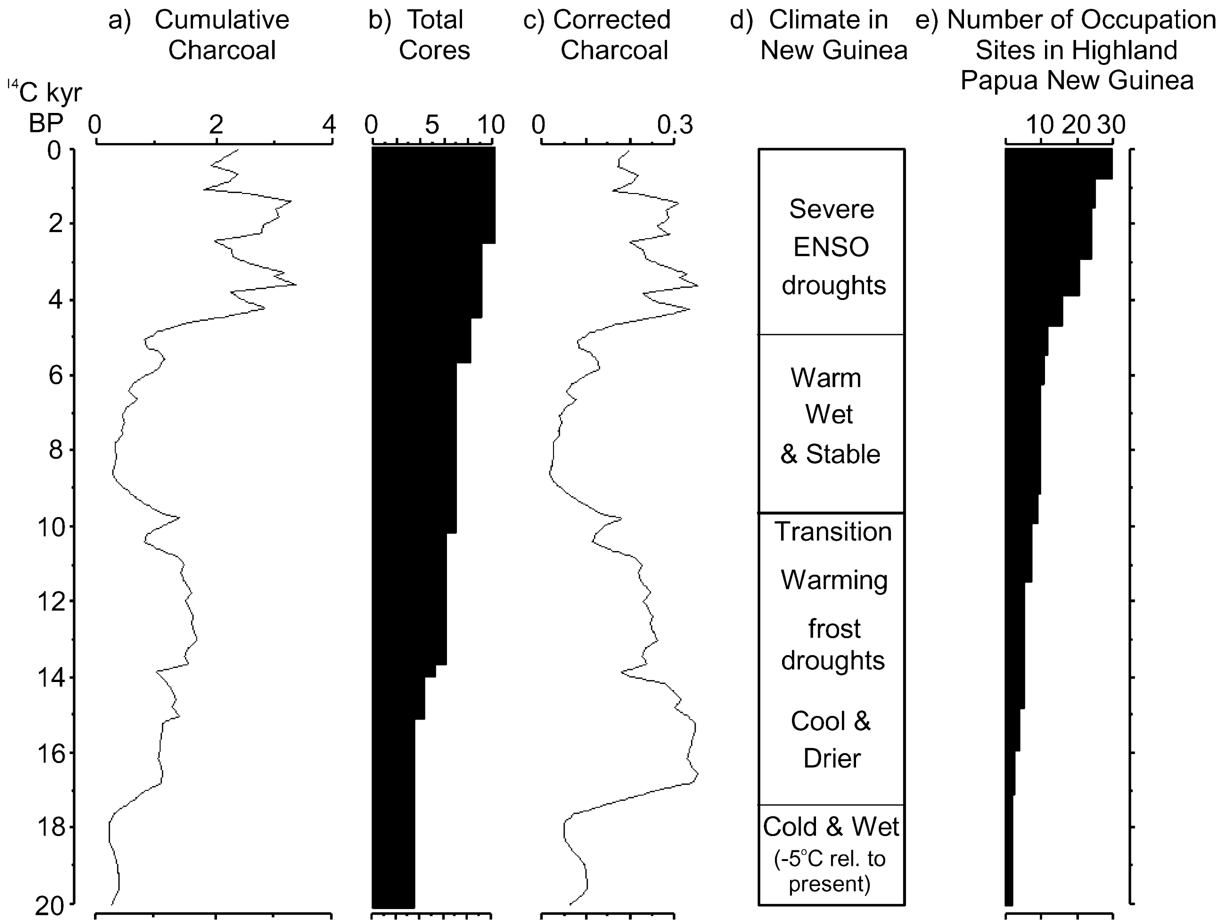

Fig. 2. (a) Cumulative charcoal record constructed by summing the 200 year values for each site in Table 1 plotted against age (^{14}C kyr B.P., see Fig. 1); (b) number of cores with data for each 200 year period; (c) value in 2(a) divided by the corresponding value in 2(b); (d) tentative summary of climate change in the Malesian sector; (e) number of human occupation sites from archaeological data in the highlands of Papua New Guinea as a measure of relative human influence (adapted from Haberle, 1998).

site, as would be expected from such widely separated localities with different vegetation types and variable influence from human activity. Vegetation types vary from alpine grasslands, to montane and lowland forests, all with marked differences in biomass and susceptibility to fire, producing a variable pattern of fire frequency across the landscape. Human influence also appears to be variable across this region as illustrated by the occupation history of highland New Guinea, where initial burning of the landscape is recorded as early as 32,500 years B.P. in the Baliem Valley (Supulah Hill, Hope, 1998), Irian Jaya, and as late as 20,000 years B.P. in the Tari Valley (Haeapugua; Haberle, 1998) some 400 km to the east. Human influences alone are unlikely to have resulted in synchronous fire periods across such a culturally and biologically diverse region, though it is important to note that increased climate variability may exacerbate the environmental impact of human activity (see Fig. 2e).

The general synchroneity demonstrated between climate proxies and the corrected charcoal curve, suggests a broader-scale forcing mechanism such as climate (Fig. 2d). The climate mechanisms that are most likely to have influenced the natural fire regime over this time span in the Malesian sector are; (i) relative position and intensity of the Walker Circulation during the cooler glacial climate shifting zones of convection and subsidence over the region and (ii) relative influence of polar air from the northern and southern hemispheres. Changes in the position or strength of these two factors would in turn have influenced the strength and penetration of the Southern Hemisphere Summer Monsoon (SHSM) altering precipitation (Kutzbach and Guetter, 1986), and development of ENSO conditions increasing climate variability (Diaz and Markgraf, 1992).

The combination of palaeoclimate evidence derived from vegetation histories and ocean sediment records suggests that the SHSM has fluctuated significantly over the last 20,000 year (Huang et al., 1997). Pollen records (Barmawidjaja et al., 1993; Jarvis, 1993; Flenley, 1998; Haberle, 1998) and changes recorded in equatorial glaciers (Hope and Peterson, 1976) indicate that the last glacial maximum was some 5°C cooler and somewhat drier than present. Increased continentality during the low sea level period of the last glacial may also have contributed to the generally drier conditions. This appears to contradict the low charcoal values for the last glacial maximum, though the impact of lower temperatures on limiting soil moisture loss may have been sufficient to have reduced vegetation susceptibility to fire.

Increasing temperatures from around 17,000–9000 years B.P. led to an elevation in forest growth limits and a replacement of open savanna and grasslands with a more closed forest. A very weak and possibly unstable SHSM, possibly increasing the incidence of frost and drought at least in the highlands of New Guinea, are considered the cause of persistent high regional charcoal values throughout this period (Haberle, 1998). A slight reversal of high charcoal levels between 11,000–10,000 years B.P. coincides with the Younger Dryas climate event, during which temperatures may have been reduced by up to 2°C, at least in the northern Hemisphere and possibly globally (Peteet, 1995). Although the Younger Dryas is generally considered not to have had a significant impact in this part of the world (Maloney, 1995), a relatively cool phase here may have tipped the evaporation–precipitation balance towards reduced soil moisture loss and reduced fire vulnerability. This is clearly worthy of further investigation of sediment sequences, particularly in the mountains of New Guinea and Indonesia where small changes in temperature may be recorded in the fossil vegetation or glacial records.

The early Holocene (9000–6000 years B.P.) witnessed increased convection over the Malesian sector with the development of a strong SHSM and the build up of warm waters to the north of the region, producing warmer and somewhat wetter conditions. Seasonality may have been reduced at that time with colder summer and warmer winters due to the state of the earth's tilt relative to the sun (precession data). These stable conditions appear to have produced fire patterns similar to those recorded during the dry last glacial maximum. This re-enforces the argument that it is not simply relative dryness that may determine fire vulnerability, but it is the relative stability of climate. Increased climate instability is likely to increase fire vulnerability, despite different vegetation communities or human influences on a region.

Climate variability associated with the ENSO phenomenon is postulated to have persisted for only the last five millennium in the Pacific on the basis of the distribution of tropical molluscan deposits from the Peruvian coast (Sandweiss et al., 1996) and indications of landscape destabilisation in the tropical Andes (Thompson et al., 1995; Rodbell et al., 1999). The high charcoal values recorded for this period in the Malesian sector support the links made in other studies between increased vegetation disturbance and the initial impact of the ENSO-related climate variability across the Pacific basin (Markgraf et al., 1992; Shulmeister and Lees, 1995; Haberle, 1996a,b).

The role of rapid environmental change and instability in tropical vegetation dynamics is currently receiving considerable palaeoecological attention (Meadows, 1999). The results of this study show that tropical vegetation has been subject to varying levels of fire-related disturbance throughout at least the late Quaternary. While fire is not the only rainforest disturbance mechanism there is a strong suggestion that the disturbance regime per se, so important in the maintenance of diversity in rainforests (Connell, 1978), is closely related to climate change. This implies that areas of high species diversity are neither ecologically nor geographically stable through time.

6. Conclusions

The data presented here for the Malesian sector support the contention that an increase in regional burning patterns is likely to have at least part of its origin in climate change, rather than solely due to human influences. It is suggested that the changing fire pattern is directly influenced by the relative stability of climate, rather than simply to relative dryness. Periods of greatest climate instability are identified as the last glacial transition (17,000–9000 years B.P.) and the mid to late Holocene (5000 years B.P. to present). The biogegraphic implications of these results point to fire as a major driving force behind Quaternary vegetation dynamics and maintenance of tropical forest diversity.

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