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The Holocene vegetation history of Lake Erhai, Yunnan province southwestern China: the role of climate and human forcings

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Abstract: A pollen diagram from a 6.62 m sediment sequence in Lake Erhai in northwest Yunnan, China was obtained to examine the roles of climate change and human impact on the development of the Erhai lake-catchment system since 12950 cal. yr BP. The record extends back into the Younger Dryas, where the dominance of *Betula* and deciduous *Quercus* points to a relatively cold and wet winter climate. After 11 750 cal. yr BP, a warming climate coupled with enhanced summer monsoon precipitation results in the expansion of *Tsuga* and evergreen broadleaved trees (*Cyclobalanopsis*, *Lithocarpus* and *Castanopsis*). An increase in evergreen oaks and dry-tolerant species after 10 320 cal. yr BP suggests a greater seasonality in rainfall, reflecting a southward shift in the winter front across the region. This trend of increasing temperatures and seasonality is seen to continue through into the mid-Holocene and the onset of the Holocene optimum. A marked decline in arboreal taxa coupled with increased levels of grass (Poaceae) and other disturbance taxa provides the first evidence for human impact in the catchment at *c.* 6370 cal. yr BP. This early phase of forest clearance leads to the collapse of the natural altitudinal vegetation gradient that existed in the catchment from the Lateglacial. The subsequent expansion of secondary pine forest suggests that these early clearances were part of a sustained period of shifting agriculture. Archaeological and historical records for the region point to a gradual increase in immigration into the region throughout the late Holocene. The increased pressure on the catchment is reflected in the pollen record by a series of clearance phases, which increase in intensity after 2140 cal. yr BP, linked presumably to intensification of agriculture and early urbanization. This trend continues through the last millennium, before a sharp increase in arboreal pollen at the top of the core reflects a phase of reforestation that took place in the catchment over the last 25 years.

Key words: Lake Erhai, Yunnan, Holocene, pollen, vegetation history, climate change influence, human.

Introduction

Yunnan province is located in southwestern China at the southeast end of the Qinghai-Xizang (Tibetan) Plateau (Figure 1). Uplift of the Qinghai-Xizang plateau has created a sharp altitudinal gradient across the province ranging from *c.* 6000 m a.s.l. in the northwest to 1500 m a.s.l. in the south. Such altitudinal differences result in a marked climatic gradient across the province and consequently a range of geomorphological settings, all of which have contributed to the great species richness and diversity found across the region (Walker, 1986; Li and Walker, 1986; Wu *et al.*, 1987). The subtropical climate of the region is characterized by a cool and relatively dry climate between September and April, with a warmer and wetter season between May and October. This seasonality reflects the influence of the southwest summer monsoon that emanates from the Bay of Bengal. Dry wind tends to dominate the area during the winter, though some precipitation occurs at the disturbance zone of passing polar fronts (Figure 1).

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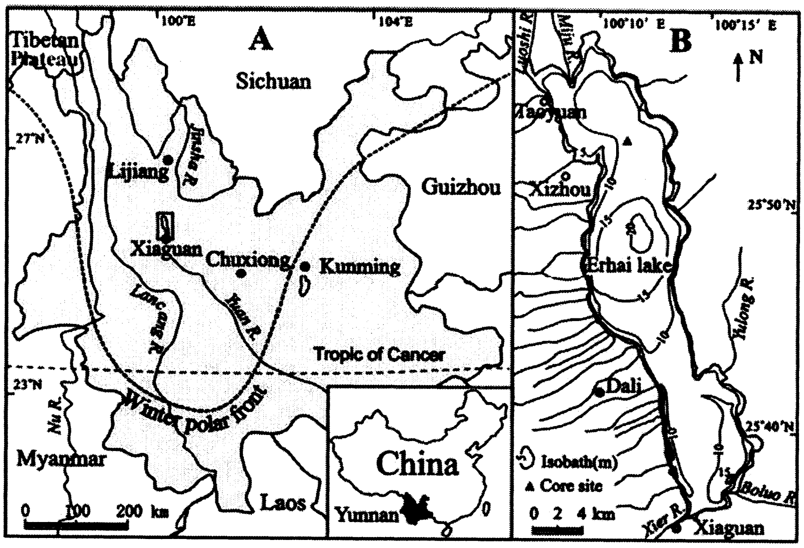

Figure 1 The study area. (A) Location of Lake Erhai in Yunnan (shaded), China, showing the modern position of the winter polar front; (B) Lake Erhai with main streams, underwater contours (m) and coring site

The dominance of the southwest summer monsoon on the regional climate, coupled with its close proximity to the Qinghai-Xizang Plateau, makes Yunnan province a key region for palaeoenvironmental research. The region also boasts a long agricultural tradition, with the Yunnan-Guizhou Plateau thought to be one of the early centres of rice cultivation (Lu, 1999). Of particular interest is the documentary record, which provides a detailed overview of human activity back to the Ch'in dynasty (*c.* 221–206 BCE). Unfortunately, despite the huge potential of the region for palaeoenvironmental study only a handful of high-quality data sets have been published that cover the entire Lateglacial/Holocene (eg, Whitmore *et al.*, 1994b, 1997; Hodell *et al.*, 1999).

The present paper is one of several to arise from a research programme within the PAGES Focus 5 Programme dealing with the long-term perspective to issues of environmental sustainability in subtropical southwestern China, focusing on Lake Erhai and its catchment in Yunnan province. The project seeks to combine sedimentary proxy archives with detailed archaeological, historical and documentary/instrumental records with the aim of disentangling and isolating the separate roles that climate change and anthroprogenic activity have played in the evolution of the Yunnan landscape. A detailed environmental history for the site has already been produced by Elvin *et al.* (2002). Presented here are the first results of the sediment proxy analyses, the first complete Lateglacial/Holocene pollen sequence for Yunnan. The pollen data have been partially calibrated using a modern altitudinal analogue of temperature to infer past changes in monsoonal strength. The results of this study provide an invaluable temporal framework of climate change and human activity in the catchment over the Lateglacial/Holocene.

Study area

Site description

Lake Erhai (25°36′–25°58′N, 100°05′–100°18′E) is a large freshwater body situated approximately 4 km from Dali City in northwestern Yunnan (Figure 1). The lake lies at an altitude of *c.* 1974 m a.s.l. and covers an area of *c.* 250 km^2. The lake is thought to have formed in the Late Pliocene as a result of tectonic movements along a regional NNW–SSE trending fault (Zhu *et al.*, 1989). The lake is comparatively shallow with an average depth of *c.* 10.2 m, reaching a maximum depth of *c.* 21 m in the centre of the basin. The lake has been mesotrophic since 1996 owing to eutrophication brought about by increased fishing production (Whitmore *et al.*, 1997; Pan *et al.*, 1999). The main inflows are to the northern end of the lake through the Miju and Luoshi rivers and to the southeast via the Boluo river (Figure 1), and the lake drains to the southwest via the Xier river and from there into the Yangbi river. The lake sits within an intermountain catchment covering an area of *c.* 5000 km^2, with geology dominated by limestone, gneiss, granite, basalt and other siliceous rocks (Institute of Geography, Chinese Academy of Sciences (CAS), 1990). Elvin *et al.* (2002) subdivided the catchment into four morphogenetic zones: (i) the western shore dominated by the steep-sloped Diancangshan mountains, rising to 4100 m a.s.l., where seasonal snowmelt and springs supply water to an extensive off-take irrigation system on the Dali plain via the 'famous 18 streams'; (ii) the northern catchment drained by the Miju river but dominated hydrogeomorphologically by the rapidly aggrading Miju delta and the Deng Chuan plain reclaimed from drained lakes and wetlands. The heavily embanked and elevated Miju river provides irrigation water for intensive agriculture on the Miju floodplain; (iii) the eastern zone dominated by Chicken Foot mountain, generally dry, barren, treeless and hilly with a sparse population; (iv) the southern zone dominated by terraced spring-fed irrigated farming on the floodplain of the Boluo and the rapidly growing urban area of Xiaguan.

Climate and vegetation

The mean annual temperature at the lakeshore is 15.1°C, with average monthly temperatures in July and January of 20.1°C and 8.8°C, respectively. Annual precipitation varies greatly according to altitude and location, from 800–900 mm on the relatively dry eastern lakeshore to 1800 mm on the Diancang mountains, where about 80–90% falls between May and October. Normally, the precipitation in western and northern parts is greater than that of the southern and southeastern area (Duan, 1995). The annual evaporation in the catchment varies between 900 and

1400 mm, with the higher levels in low-lying basins and river valleys, such as the recorded 1160 mm at Dali.

The catchment vegetation can be subdivided into four main groups, the distribution of which reflects the strong altitudinal gradient of the catchment. Below an altitude of 2500 m the vegetation is primarily a semi-humid evergreen broadleaved forest, a zonal subtype of SEBF (subtropical evergreen broadleaved forest: Li and Walker, 1986). The forest is mainly composed of evergreen oaks and chestnuts (*Castanopsis*, *Cyclobalanopsis* and *Lithocarpus*), accompanied by other trees such as *Pinus yunnanensis* and sclerophyllous *Quercus* (as *Q. pannosa*). Owing to human disturbance, the secondary forest is now composed primarily of *Pinus yunnanensis* and *Quercus* (Wu *et al.*, 1987). On the fluvial plain and lakeshore areas the vegetation is exclusively agricultural, with extensive areas irrigated.

Between 2500 and 2800 m the cooler temperatures and increased precipitation result in a montane, humid evergreen broadleaved forest, a subtype of SEBF. *Lithocarpus* is the dominant forest taxon, with *Castanopsis*, *Cyclobalanopsis*, *Schima* and *Skimmia* also present. Above 2800 m, this assemblage gives way to a mixed conifer woodland, which extends up to *c.* 3200 m and is associated with the higher moisture levels at this altitude. Lying within the cloud belt, this woodland would be dominated by *Tsuga* in the absence of human impact. However, today, only a few stands survive at sites in western, northwestern and central parts of Yunnan (Li and Walker, 1986; Wu *et al.*, 1987). In the Diancangshan mountains and Yulongshan mountains to the north of Erhai, *Tsuga* frequently co-exists with both conifer (eg, *Picea*, *Abies*, *Pinus densata)* and broadleaved trees (eg, *Quercus*, *Acer* and *Betula)*. The understorey is typically composed of *Rhododendron*, *Sinarundinaria*, *Viburnum*, *Rosa* and herbs such as *Viola*, *Arisaema* and *Ainsliaea*. Above 3200 m, *Abies* forest dominates, although its distribution is patchy owing to the steepness of the mountain summits. *Picea*, *Rhododendron*, *Sorbus* and *Sabina* are also present.

Modern montane pollen rain

Modern pollen rain data can be used to understand better the pollen records at Erhai. According to pollen rain studies in the Yulongshan mountains by Tong *et al.* (2003), the zone above 3400 m is dominated by *Abies* and *Pinus* pollen, *Picea* pollen peak between 3200 and 3400 m, *Tsuga* pollen are mainly found between 3050 and 3200 m and pollen of evergreen broadleaved taxa, including *Cyclobalanopsis*, *Castanopsis*, *Lithocarpus* and sclerophyllous *Quercus*, dominate between 2250 and 3050 m (Figure 2). Modern *Pinus* pollen percentages dominate both the highest (> 3400 m) and lowest (< 2250 m) slopes, the former an artefact of anemophilous dispersal and the latter mainly of reforestation. Even though Tong *et al.* (2003) fail to separate some *Pinus* and some evergreen broadleaved taxa, the clear distributions of main pollen types (except for *Pinus*) parallels their associated vertical vegetation spectra, controlled mainly by climate gradients. This suggests that, in the absence of strong human impact, the fossil record could be used

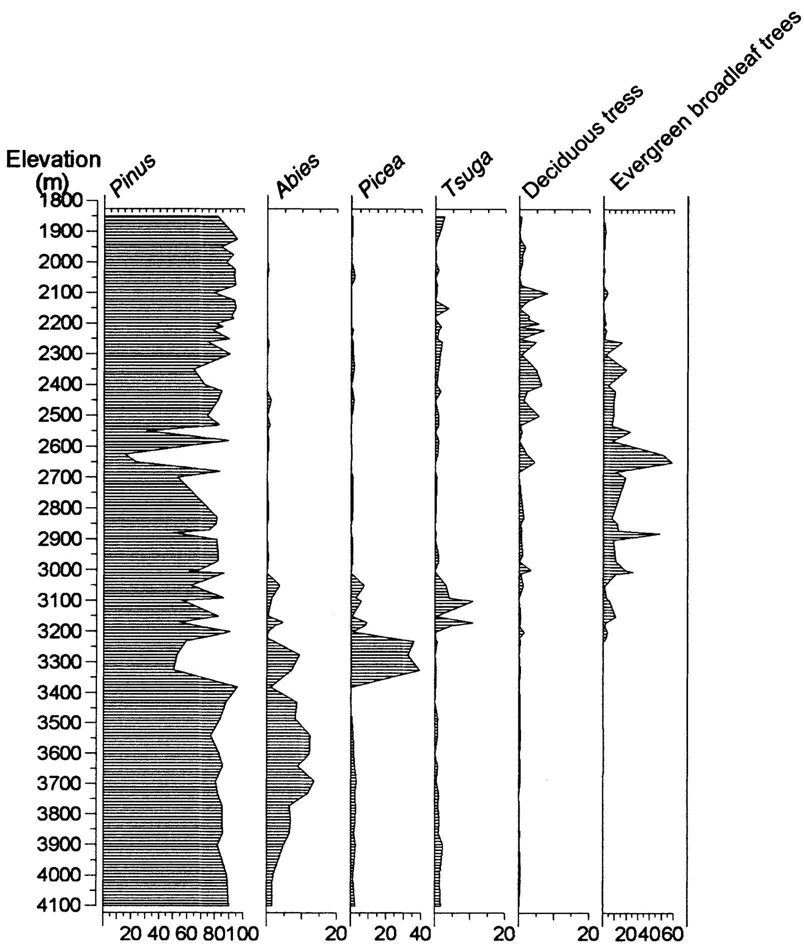

Figure 2 Modern vertical pollen spectra (percentages of total pollen) plotted against altitude in the Yulongshan mountains located to the north of Erhai. Redrawn and modified from Tong *et al.* (2003)

cautiously to infer past precipitation and temperature fluctuations.

Materials and methods

A 6.62 m sediment sequence was retrieved from the centre of the northern basin of Lake Erhai (Figure 1) in April 2001 using a UWITEC sampling system (sampling platform and piston corer: 2.0 m long PVC tubes with 60 mm inner diameter) in a water depth of 10.8 m. The core lithology changes from grey silty clay below 60 cm to yellowish brown clay above 60 cm, with a change to brownish red clay above 10 cm. The core was sampled at 1 cm intervals in the field to avoid disturbing the record during transportation.

Magnetic susceptibility was measured at 2 cm intervals, using a Bartington Instruments magnetic susceptibility meter with MS2B dual-frequency susceptibility sensor. Mass-specific magnetic susceptibility (χ_{LF}) and percentage frequency-dependent susceptibility (χ_{FD}%) were calculated following Walden *et al.* (1999). At this stage, the measurements are loosely interpreted in terms of the movement of eroded minerogenic material from the catchment. Unpublished measurements on catchment soils show that both χ_{LF} and χ_{FD}% are enhanced in the surface horizons of many freely drained soil profiles as a result of pedogenically formed magnetite/maghemite minerals. Pollen samples were prepared every 2–4 cm following Liu *et al.* (1986) with 5 g of wet sediment processed. *Lycopodium* spores were added to each sample for calculation of pollen concentration. A minimum of 300 grains was counted per sample, excluding Pteridophytes, aquatic taxa and Cyperaceae. The data are expressed both as a percentage of the total pollen sum (minus the excluded taxa) and concentration counts of pollen per gram, and graphed using TiliaGraph (Grimm, 1991). Pollen percentage data were subjected to cluster analysis using CONISS of TiliaGraph, and detrended correspondence analysis (DCA) using CANOCO (ter Braak and Smilauer, 1998). The taxonomy of pollen and spores was determined using guides compiled by the Institute of Botany, CAS (1960, 1976), the Institute of Botany and South China Institute of Botany, CAS (1982) and Wang *et al.* (1995).

Eleven AMS ^{14}C dates were obtained from seven bulk samples of lake sediment at the Radiocarbon Laboratory of Tokyo University, Japan (Table 1). Bulk sediment samples were used as no suitable terrestrial macrofossil material was recovered. Acid-alkaline-acid pre-treatment consisted of sequential washing with 1M HCl and dilute NaOH solutions to remove carbonates, fulvic acids and humic acids. Each sample was measured four times. Calibrated ages were calculated with reference to IntCal04 (Stuiver *et al.*, 1998). A continuous age–depth curve was then constructed by linear interpolation between dated depths (Figure 3).

The use of bulk sediment samples for dating raises the possibility that the resulting chronology could potentially contain an inherent hard water effect or be influenced by the inwash of old organic carbon from the catchment. However, there are several reasons to accept the timescale:

- the seven dated depths are ordered sequentially with no evidence of age reversals associated with deposition of 'old organic carbon' (Table 1);
- internal consistency is high as shown by duplicate ages of samples from the same depths (Table 1);
- the core is characterized by a fairly uniform lithologic composition and low contents of $CaCO_3$ (5–10% and declining to < 5% below 2 m sediment depth);
- the mean C_{total}, C_{org} and C_{inorg} contents of Erhai sediments are on average 2.05%, 1.79% and 0.27% of the bulk sediment, respectively, with C_{org} the dominant fraction (~ 88%) of C_{total} (Wan *et al.*, 2003);
- $\delta^{13}C_{org}$ values of − 25.0 to − 28.0‰ PDB in the upper 62 cm of a core taken to the south of the main core used in this study, stabilising at − 27.0 to − 28.0‰ PDB below 62–90 cm, are isotopically lighter than other carbon sources, suggesting that sediment organic matter originates from land-derived higher plants (Wan *et al.*, 2003);
- ratios of C_{org}/N_{org} indicate that the main component of sediment organic matter is non-cellulose plant detritus (Wan *et al.*, 2003);
- Wang *et al.* (1989), cited in Zheng *et al.* (2001), concluded that *n*-alkane ratios (C_{29}/C_{17}) suggested that land-derived hydrocarbons increased above 85 cm in a central core.

In the absence of no direct evidence for hard water effect or old organic carbon errors, we assume that the sediment carbon is dominantly contemporaneous terrestrial organic matter as reported elsewhere (eg, Whitmore *et al.*, 1994a,b) and as such the Erhai ^{14}C chronology is accepted.

Results

Pollen analysis

The results of the pollen and numerical analyses (DCA) are presented below and illustrated in Figures 4–6. The calculated χ_{LF} and χ_{FD} profiles are illustrated in Figure 7 and described below in relation to the local pollen zone scheme. The overall

Table 1 ^{14}C AMS ages and calibrated years in the Lake Erhai sediments

Laboratory number	Depth (cm)	^{14}C (yr BP)	Calendar age (cal. yr BP)	Average (cal. yr BP)
Tka-12195	60	1940 ± 70	2046–1710	1845
Tka-12217		1890 ± 70	1892–1733	
Tka-12196	120	2590 ± 80	2848–2452	2728
Tka-12218		2690 ± 80	2867–2746	
Tka-12197	230	5360 ± 130	6407–5890	6133
Tka-12001		5370 ± 110	6316–5920	
Tka-12198	360	6860 ± 80	7750–7615	7682
Tka-12199	480	8840 ± 90	10 186–9657	9930
Tka-12200	550	9300 ± 120	10 766–10 214	10 329
Tka-12220		9120 ± 240	10 787–9558	
Tka-12201	661	10 820 ± 80	12 990–12 917	12 950

Calibrated ages were derived from Stuiver *et al.* (1998), and both range values and average values are shown.

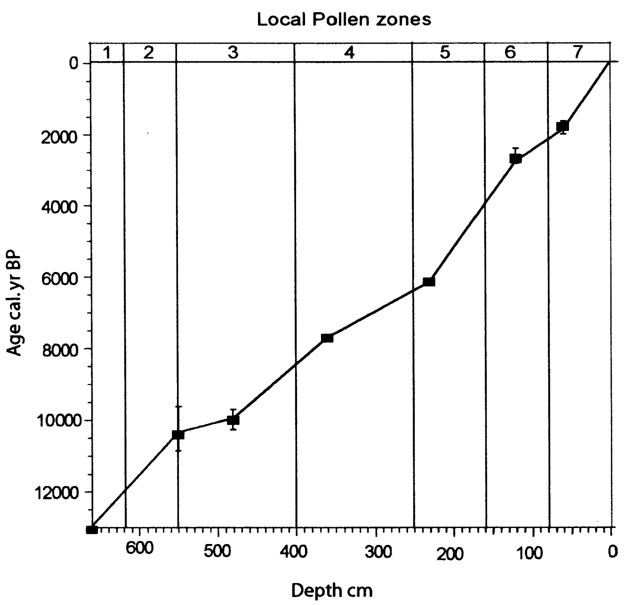

Figure 3 Age–depth curve for core Lake Erhai. Radiocarbon dates are listed in Table 1

pollen spectra from Erhai are characterized by abundant arboreal pollen (AP), with *Pinus*, *Tsuga*, *Cyclobalanopsis*/*Lithocarpus*, *Castanopsis* and sclerophyllous *Quercus* contributing 70–80% of the total pollen sum (Figure 4). *Abies*/*Picea*, *Betula*, Cupressaceae and broadleaved deciduous taxa including *Quercus*, *Ulmus*, *Juglans* and *Pterocarya*, are also present but are less dominant. The non-arboreal shrub and herb pollen (NAP) component is generally low ($\sim$20%) throughout the core. Seven local pollen zones (LPZ) have been identified with cluster analysis (Figure 4). Pollen concentrations are seen to fluctuate throughout the core from $<$10 000 grains/g to $>$50 000 grains/g with a marked decline in values towards the top of the core (Figure 5).

LPZ EH-1 (662–610 cm)

The basal zone EH-1 is dominated by arboreal taxa such as *Pinus* (30–40%), *Betula* (5–12%), *Quercus* (5–9%), *Cyclobalanopsis*/*Lithocarpus* (9–15%) and sclerophyllous *Quercus* (8–11%), with Cupressaceae, *Abies*/*Picea* and *Ulmus*, also recorded throughout the zone (Figure 4). Significant percentages in herbs are recorded for Poaceae, Cruciferae and Papaveraceae. *Tsuga* is poorly represented in the lower half of the zone ($<$5%) but is seen to increase above 635 cm. Total pollen concentrations for the zone average *c.* 56 000 grains/g. The basal sediments are weakly magnetic (average $\chi_{LF} = 10 \times 10^{-8}$ m^3/kg) with little variation in the record detectable though the zone (Figure 7). χ_{LF} values are relatively very low, remaining below 30×10^{-8} m^3/kg for the entire zone and into LPZ EH-2.

LPZ EH-2 (610–550 cm)

Zone EH-2 is characterized by increasing values for *Tsuga* and sclerophyllous *Quercus*, with values rising to *c.* 20%. Values for *Abies*/*Picea* remain low throughout the zone although there is a slight increase towards the top (up to 3%). Percentages of both *Betula* ($<$5%) and *Quercus* ($<$6%) decline and concentration values drop to an average of *c.* 38 000 grains/g. The curve for *Cyclobalanopsis*-type shows no obvious changes, while *Castanopsis* is seen to increase in frequency with values gradually rising through to the end of the zone. There is a relative increase in NAP% in this zone, characterized by increasing values for *Spiraea*, Actinidiaceae type, Papaveraceae and *Viola*.

LPZ EH-3 (550–400 cm)

Zone EH-3 is characterized by an overall increase in AP%. *Tsuga* reaches its maximum values ($>$25%) between 485 and 420 cm, with *Castanopsis* also experiencing a marked increase. There is a slight increase in *Cyclobalanopsis*/*Lithocarpus* whilst the frequency of evergreen *Quercus* remains constant. Cupressaceae and other deciduous tree pollen are present at low levels. *Pinus* has low percentage values in the lowest part, but rapidly increase thereafter – a trend also observed in the total pollen concentration curve (Figure 5). *Spiraea*, Actinidiaceae-type and Cruciferae continue to dominate the NAP taxa, with *Rosa*, Verbenaceae and *Eomecon*, amongst others, also increasing in significance. Euphorbiaceae, a winter drought-tolerant herb plant (Li and Walker, 1986; Wu *et al.*, 1987) is present throughout the zone from the onset. Zone EH-3 also records the first occurrence of *Caragana*. χ_{LF} remains slightly elevated throughout the zone with a slight peak in value centred on 500 cm. Occasional spikes in χ_{FD}% are recorded but these are all below 2% and not deemed significant.

LPZ EH-4 (400–250 cm)

Zone EH-4 is characterized by high total pollen concentrations (average *c.* 68 000 grains/g) and high percentages for broadleaved taxa. Both *Cyclobalanopsis*/*Lithocarpus* and *Castanopsis* show a marked increase with values peaking at 25% and 15%, respectively. *Tsuga* declines slightly in comparison with EH-3 with values fluctuating around 10–20% and a concentration of *c.* 12 500 grains/g. *Pinus* values are seen to fall varying from 40 to 17%. Sclerophyllous *Quercus* initially drops dramatically before values rise again between 290 and 330 cm. This rise corresponds with a period of reduced values for *Cyclobalanopsis*/*Lithocarpus* and *Castanopsis*. A number of shrub and herb taxa significant in previous zones (ie, *Spiraea*, Actinidiaceae-type, *Viola*, Cruciferae and Papaveraceae) are seen to decline and even disappear, replaced by taxa such as *Rosa*, Euphorbiaceae, Verbenaceae and *Eomecon*, which record an increase in values. A pronounced spike in Euphorbiaceae (25%) is recorded at 330 cm. χ_{LF} values remain roughly constant through this zone with a small spike in values centred on 320 cm. Spikes in χ_{FD}% are more common although the majority are still below 2%. Significant spikes over 5% are recorded at 380 cm and 300 cm.

LPZ EH-5 (250–160 cm)

The onset of Zone EH-5 is characterized by a marked decrease in broadleaved tree pollen and an increase in several herb taxa. A marked drop in *Cyclobalanopsis*/*Lithocarpus* just before the transition to zone EH-5 is followed by a reduction in *Castanopsis* at 240 cm and a decline in *Tsuga* at 226 cm, accompanied by rising percentage values for *Pinus*. Percentage values for deciduous trees such as *Ulmus*, *Juglans*, *Betula* remain low. Poaceae, *Artemisia* and aquatic plants, mainly *Myriophyllum*, increase for the first time. Several other pollen taxa appear for the first time and increase in frequency (eg, *Olea*, *Lonicera*, *Viburum*, Chenopodiaceae, *Porana*, *Plantago* and Labiatae), albeit often with low values. The average total pollen concentration for the zone is seen to decline (*c.* 50 000 grains/g), with values fluctuating throughout. All evergreen broadleaf tree taxa experience a drop in pollen concentration whilst *Pinus* pollen concentrations are seen to increase. χ_{LF} values begin a gradual rise up through the zone with a peak in values *c.* 50×10^{-8} m^3/kg recorded at 220 cm.

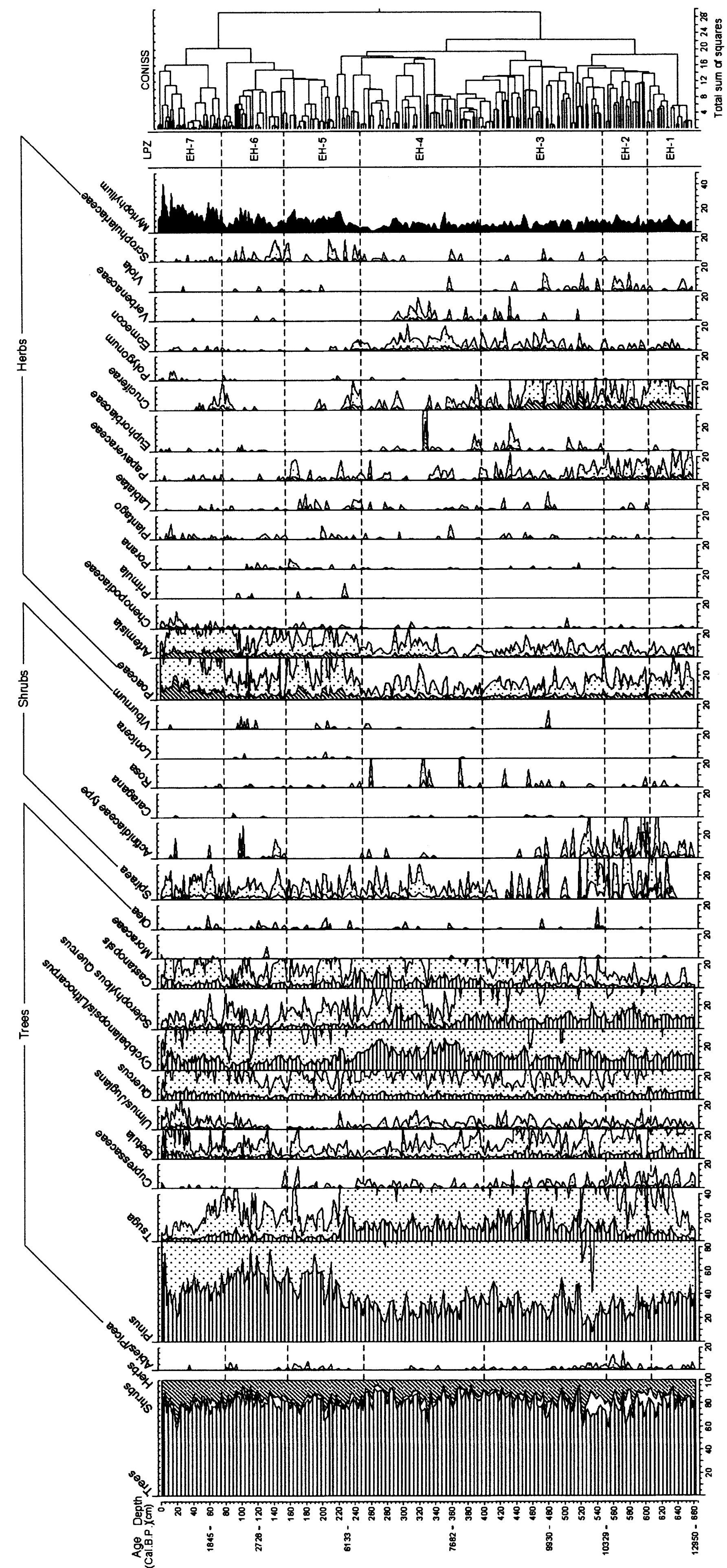

Figure 4 Percentage diagram of selected pollen taxa from a 6.62 m Lake Erhai sediment sequence

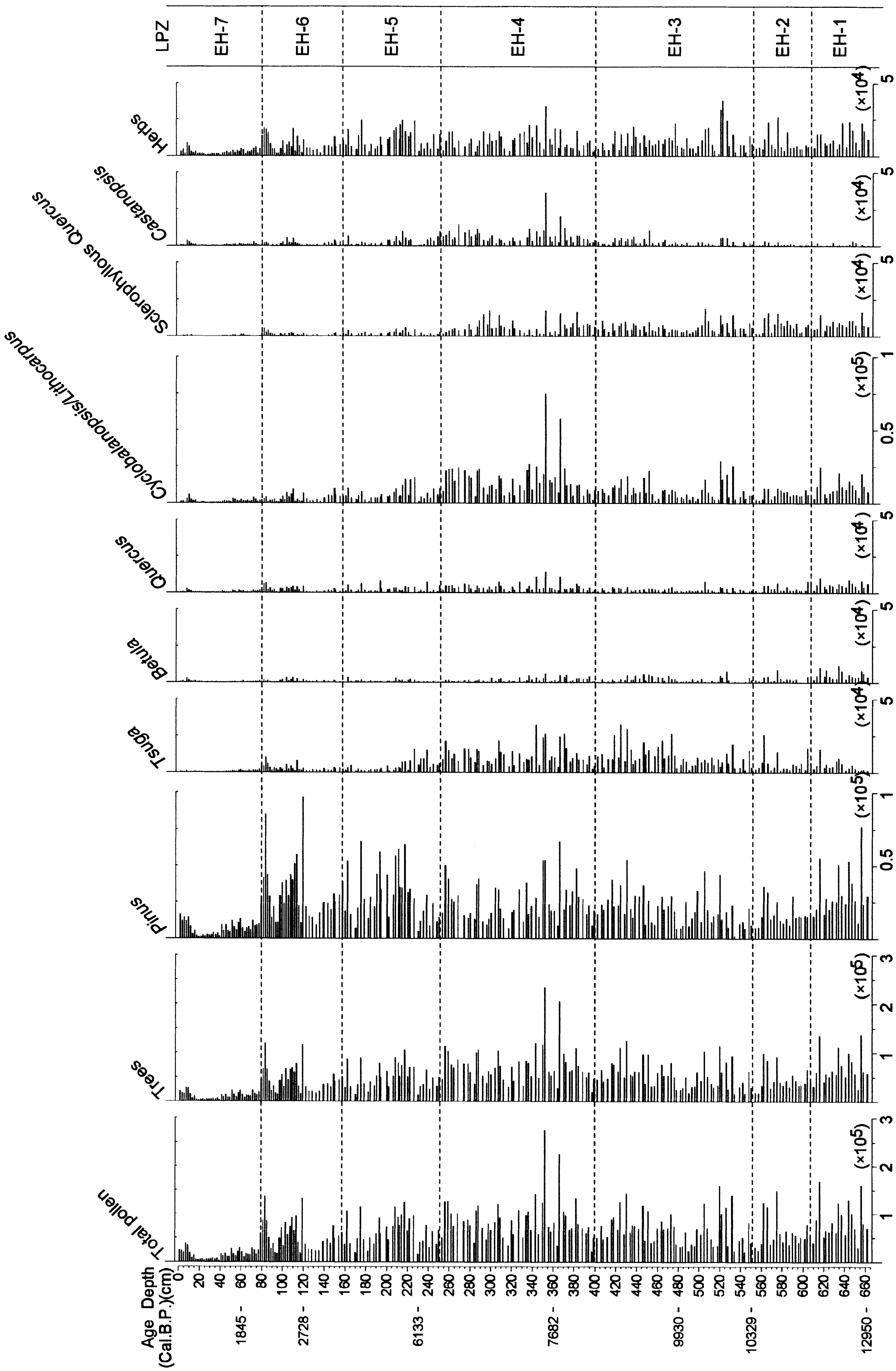

Figure 5 Pollen concentration diagram of selected tree and herb taxa from a 6.62 m Lake Erhai sediment sequence

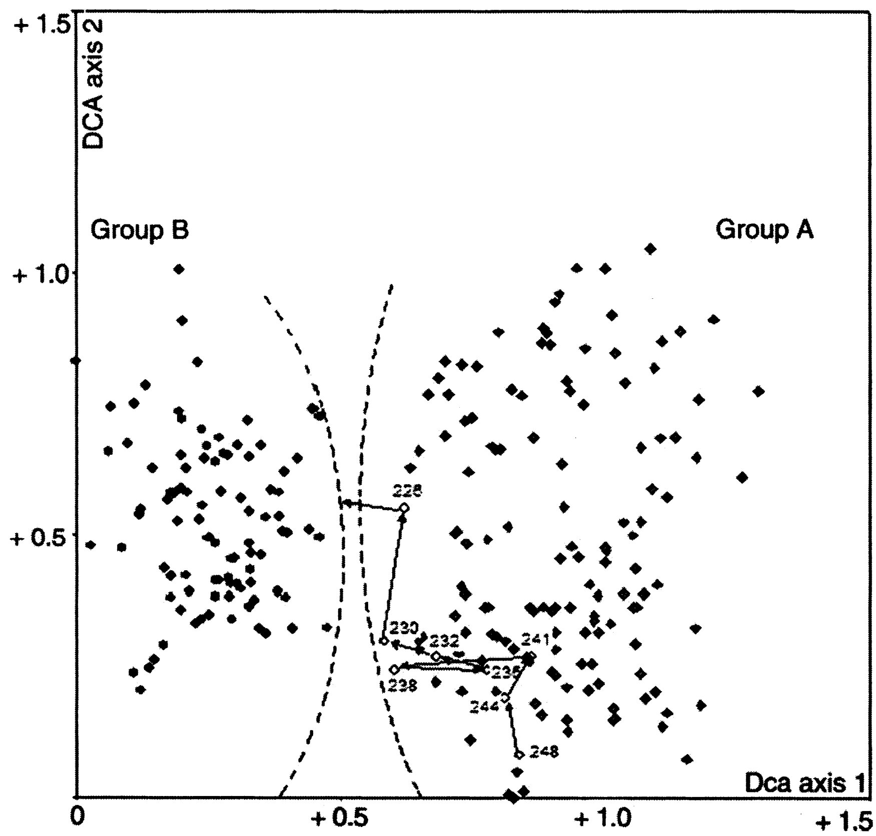

Figure 6 DCA ordination of the pollen percentage data showing sample distributions in the first two axes. Numbers are depths (cm) of selected samples. Group A includes samples within the range 226–662 cm depth, and Group B within the range 0–226 cm depth

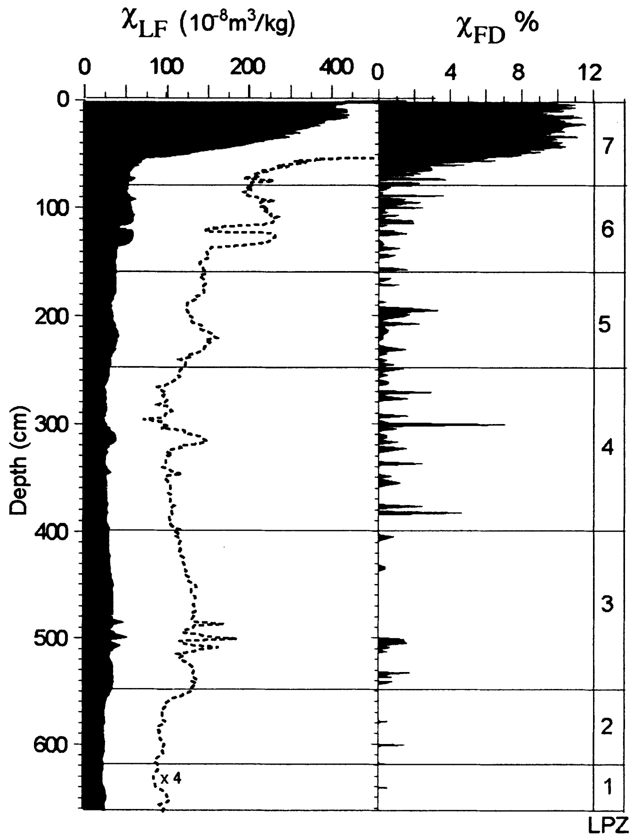

Figure 7 χ_{LF} and χ_{FD}% profiles for core Lake Erhai

LPZ EH-6 (160–80 cm)

Within zone EH-6, *Pinus* continues to be the dominant arboreal taxon with rising values continuing the trend of the previous zone. Values for evergreen broadleaved trees decline to a minimum, whilst some deciduous pollen such as *Juglans*, *Ulmus*, *Quercus*, *Olea*, *Betula* and Moraceae increase in percentages, particularly towards the upper part of the zone. Overall the values of NAP% decline with most of the herbs that expanded in the previous zone declining markedly or disappearing altogether. χ_{LF} continues to rise with values increasing beyond 50×10^{-8} m^3/kg for the first time. χ_{FD}% is still negligible although values are recorded throughout the zone.

LPZ EH-7 (80–0 cm)

The beginning of zone EH-7 is characterized by a marked decline in *Pinus* percentage and a sudden drop in total pollen concentration. *Pinus* declines from 50% to 30%, followed by an abrupt rise to more than 63% above 8 cm. Pollen concentrations also increase slightly above this point. Almost all the broadleaved pollen taxa are seen to increase from the beginning of this stage with a further increase recorded above 39 cm. Values for NAP % increase upwards, following the trend of the broadleaved trees. The dominant herb taxa include *Artemisia*, Poaceae, Chenopodiaceae, *Plantago* and *Polygonum*. A sharp rise in pollen of aquatic plants particularly *Myriophyllum* is noted towards the top of the zone, with values peaking at 40% by 8 cm. The χ_{LF} record is characterized by a significant increase in values to over 400×10^{-8} m^3/kg. Values for χ_{LF}% also experience a marked increase, rising above 8% within the upper 50 cm.

Numerical analysis

Seventy-five pollen taxa with a maximum abundance > 1% and at least two occurrences in 195 samples were included in the data set, from which 55 common taxa were selected for the final DCA analysis. The final DCA result provides eigenvalues for the first two axes of 0.128 and 0.063, respectively, accounting for 29.5% variance in species data. The result is identical to the primary DCA result for the whole data set ($\lambda 1 = 0.128$ and $\lambda 2 = 0.063$, 27% of cumulative variance for the first two axes), suggesting that the deleted taxa can be considered as noise (Poska and Saarse, 2002). The DCA result separates the data into two groups, notably those along the first axis (Figure 6), with Group B and A comprising samples above and below 226 cm, respectively. Seven samples located at the base of zone EH-5 cannot be separated easily from group A owing to the higher percentages of *Tsuga* and *Castanopsis* recorded. Nevertheless, the DCA ordination provides critical evidence for a change in the vegetational ecosystem across the LPZ EH-4 and EH-5 (226 cm) boundary. No further environmental information can be obtained from the DCA result.

Discussion

The results described above provide a detailed record of vegetation development in the Erhai catchment spanning from the end of the Lateglacial through to the present day. The following interpretation of the data set is based on the result of the DCA analysis and the use of key climatic indicators identified within the fossil pollen data set outlined above, following Li and Walker (1986) and Jarvis (1993):

- *Tsuga* forest, today restricted to an altitudinal range of 2800–3200 m a.s.l., is strongly associated with moist temperate habitats, and a dominance of summer rainfall (Jarvis, 1993). Within this study it is therefore used as a proxy for summer monsoon rainfall (Jarvis, 1993).
- *Betula* and deciduous oaks in Yunnan are typically viewed as assemblages tolerant of cold drought. There is no modern analogue for *Betula* in the Erhai catchment.
- Previous work by Li and Walker (1986) suggests that the semi-humid evergreen broadleaved forest (including *Cyclobalanopsis*, *Lithocarpus* and *Castanopsis*), which today grows on the hilly terrain and foot-slopes below 2800 m, can be used to infer periods of relatively high summer temperatures and precipitation with dry and relatively temperate conditions in winter.
- Sclerophyllous *Quercus* has been used before as an indicator of climates with dry (late) winters (Jarvis, 1993).
- Owing to the difficulties in differentiating Poaceae at sites in southwest China (Song *et al.*, 1994), particularly rice pollen, Poaceae was simply recorded as two class sizes < 37 µm and > 37 µm. Future attempts to investigate the transition from wild to domesticated rice at Erhai will be undertaken using phytolith analysis, which has proved successful at other sites in China (Lu *et al.*, 2002).

The magnetic susceptibility record is used to provide information on the concentration, grain-size and mineralogy of sedimentary magnetic mineral assemblages, which at Erhai reflects changes in the source and composition of detrital materials in the lake sediment record. It is therefore used as an indirect proxy for long-term catchment stability (Thompson and Oldfield, 1986; Thouveny *et al.*, 1994; Creer and Morris, 1996; Dearing, 1999). χ_{FD}% is also used as a proxy for the presence of topsoil in the sediment record as it is known to be sensitive to magnetic material of a 'pedogenic' origin (eg, Dearing *et al.*, 1996).

Lateglacial/early Holocene transition (LPZ EH-1 and older part of EH-2: *c.* 12 950–11 750 cal. yr BP)

The ^{14}C AMS date of *c.* 11 750 cal. yr BP for the upper boundary of LPZ EH-1 places it within the later stages of the Younger Dryas chronozone as defined in China (eg, Wang *et al.*, 1994). A marked altitudinal vegetation gradient appears to have existed within the catchment during this period, which persisted through into the early Holocene. *Betula* and deciduous *Quercus* together with Cupressacea (ie, *Sabina*) and the occasional stands of *Tsuga* dominated the upper mountain zones, whilst Sclerophyllous *Quercus* and *Cyclobalanopsis*/*Lithocarpus* occupied the lower slopes and valley floors. *P.* (possibly *P. densata* and *P. yunnanensis*) was most likely scattered across the catchment at all altitudes. The presence of *Betula* and deciduous oaks coupled with the low values for *Tsuga*, *Castanopsis* and *Cyclobalanopsis* is a characteristic Lateglacial assemblage in Yunnan, reflecting the dominance of cool climatic conditions and weak summer rainfall. A very similar climatic pattern is recorded at Eryuan Lake, 30 km to the north of Erhai (Walker, 1986; Li and Walker, 1986).

The expansion of conifer-rich forest (*Tsuga* and, to a lesser extent, alpine *Abies*/*Picea*) that defines LPZ EH-2 is thought to reflect a shift towards a much warmer and wetter climate, heralding the onset of the early Holocene. Sclerophyllous *Quercus* and *Cyclobalanopsis*/*Lithocarpus* continued to occupy the lower slopes, with *Castanopsis* also present. Shrubs such as *Spiraea* and Actinidiaceae types formed the understorey, with herbs such as Cruciferae and Papaveraceae also common. Comparable shifts have been recorded at several sites across Yunnan: Eryuan basin (Walker, 1986; Lin *et al.*, 1986), Dianci Lake (Sun *et al.*, 1986), Jilu Lake (Song *et al.*, 1994) and Shayema Lake in Sichuan (Jarvis, 1993). Despite the colder climatic conditions during the Lateglacial there is no evidence for significant catchment instability during this period. Indeed the climatic transition from the Lateglacial to the early Holocene is not recorded in the χ_{LF} record (Figure 7).

The early Holocene (LPZ EH-2 and EH-3: *c.* 11 750–8430 cal. yr BP)

The gradual expansion of *Tsuga* across the upper slopes after 10 320 cal. yr BP reflects the onset of rising temperatures and increasing seasonality in precipitation. *Castanopsis* becomes a common forest taxon although the overall forest composition is still mixed, with broadleaved oak forest common on the lower slopes and *Pinus* present throughout. The increased presence of dry valley herbs (Euphorbiaceae, *Eomecon* and *Caragana*) at this time is interpreted as a reflection of increased drought stress during the winter, presumably because of the failure of the winter frontal system to reach the catchment from the north. This pattern of warm, wet summers and drier winters is mirrored in other records from across the region (eg, An *et al.*, 1991; Jarvis, 1993; Shi *et al.*, 1994; Zhou *et al.*, 1994; Hodell *et al.*, 1999). The slight rise in χ_{LF} recorded at the transition to LPZ EH-3 is thought to reflect an increase in sediment flux to the lake as a result of the increase in summer precipitation.

From 8400 cal. yr BP (LPZ EH-4) evergreen broadleaved forest appears to have extended over much of the lower slopes. *Tsuga* continues to dominate the higher altitude slopes, possibly even expanding its range as hinted at by the increasing pollen concentration. The observed expansion in sclerophyllus *Quercus* after *c.* 7200 cal. yr BP may be a reflection of an intensification of winter drought conditions as proposed by Jarvis (1993).

The mid-Holocene (LPZ EH-4 and EH-5: *c.* 8430–3970 cal. yr BP)

The mid-Holocene is characterized by continuing warm climatic conditions, which appear to persist through to at least *c.* 6000 cal. yr BP. Pollen records from Lake Shayema and Lake Jilu also indicate that the highest annual average temperature appeared in this period (Jarvis, 1993; Song *et al.*, 1994). This warm phase is thought to correspond to the Holocene optimum as recorded in sites across China between 7500 and 5600 BP (Shi *et al.*, 1994). At this time annual average temperatures, inferred from pollen-assemblage data, were about 2–3°C higher than those of the present in south China.

The first evidence for anthropogenic modification of the landscape is detected within the pollen record during the mid-Holocene, with the onset of forest clearance *c.* 6100 cal. yr BP (Figure 4). A decline in evergreen broadleaved tree pollen (*Cyclobalanopsis*/*Lithocarpus*, *Castanopsis*) is followed by a sharp drop in *Tsuga*, reflecting the selective removal of forest trees, first from the foothills and then from the upper slopes around the catchment. This initial clearance phase is most likely linked to early shifting agricultural practices in the catchment. The observed increase in the number and frequency of disturbance taxa within the record – *Plantago*, Libiata, *Artemisia*, Chenopodiaceae and Poaceae (including cultivated crop pollen) – supports the view that the observed changes are being driven by early pastoralism rather than climatic change. Given the relative speed of the shift, the decline in selected arboreal taxa is unlikely to have been successional, indeed under the warm/humid conditions that prevailed in the catchment at this time, *Tsuga* would be expected to outcompete *Pinus*. A similar pattern of change has been recorded at sites in Yunnan (Song *et al.*, 1994) and other regions (Yasuda *et al.*, 2000).

The removal of selective taxa appears to have resulted in a collapse of the vertical vegetation gradient that persisted in the catchment since the start of the record. *Pinus* expands rapidly across the vertical gradient, favouring the disturbed environmental conditions. This human-induced vegetational change is clearly reflected in the DCA analysis and never returned to undisturbed conditions.

The onset of clearance activity in the catchment pre-6000 cal. yr BP is significantly older than the earliest dated archaeological data currently available for the catchment, although hunter-gathering/slash-and-burn agriculture is likely to have been prevalent in the catchment during this time (The Museum of Yunnan Province, 1981). Previous work on the Erhai sediment record by Zhang *et al.* (2000) dates the onset of agricultural activity in the catchment to *c.* 5500 cal. yr BP whilst Xu (1987) reports a marked decrease in oak (*Quercus*) at *c.* 4500 cal. yr BP in the northern part of the catchment associated with clearance for charcoal burning.

A recent investigation of the Wanhua alluvial fan on the western lake shore (G. Foster, unpublished data, 2006) has provided an AMS ^{14}C date of 8780±40 BP (9570–9900 cal. yr BP) just below the base of the oldest cultivated layer within the fan. If correct this pushes the onset of human activity in the catchment back well into the early Holocene. Such an early date for the onset of human activity within the catchment is not implausible: indeed Yunnan has long been considered one of the possible centres for early rice cultivation (eg, You, 1995; Lu, 1999) with a number of archaeological sites providing evidence for agricultural activity during the early Holocene (Lu, 1999).

The late Holocene (LPZ EH-6 and EH-7: *c.* 3970 cal. yr BP–present)

Archaeological records for the Late Holocene indicate that the Erhai catchment and the surrounding area rapidly developed into an important population centre. By *c.* 4000 cal. yr BP a number of Neolithic settlements had been established, including a major site located at Baiyangcun, in Bingchuan, 40 km away from the east bank of Lake Erhai (The Museum of Yunnan Province, 1981). Finds at this site include farm tools, rice and numerous pottery items. Similar remains have also been found on the west bank of the lake (The Museum of Yunnan Province, 1977; Elvin *et al.*, 2002). Settlement in the catchment continued to develop through into the Bronze Age and by the beginning of the Warring States at *c.* 256 BCE, several Bronze Age sites (*c.* 3100–2300 yr BP) in the region testify to a prospering culture (Tong, 1980; Fan, 1989; Institute of Archaeology, Yunnan Province, 1990). Local records reflect the rapid development of agriculture in the catchment during this period, with Chinese-style irrigated agriculture introduced *c.* 2000 years ago. This intensification of human activity in the catchment is clearly reflected in the pollen record by a sharp increase in agricultural indicators, particularly Poaceae. The occurrence of *Juglans*, *Olea* and Moraceae during LPZ EH-6 are particularly important as they are thought to reflect the development of arboriculture in the catchment for the first time. Rising χ_{LF} values point to increased instability within the catchment as a result of clearance activities. The long-term trend of increasingly high pollen percentages of the aquatic *Myriophyllum* from the beginning of EH-5 may be a reflection of the increased nutrient supply to the lake, although they could equally be associated with deeper water levels (cf. Kim and Rejmánková, 2001).

An interesting feature of the pollen record during the mid–late Holocene is the pronounced increase *Pinus*. Although pine would be expected to benefit from increased catchment disturbance, particularly if fire was a common agent of clearance, the apparent magnitude of the *Pinus* rise is also likely to be in part an artefact of long-distance pollen transport, a common palynological problem in heavily forested regions such as Yunnan. Palaeoenvironmental and archival data from across China point to a significant climatic shift *c.* 3200 cal. yr BP to a cooler and/or drier climate (Zhu, 1973; Tang and Shen, 1992). Such a climatic shift would certainly be beneficial to *Pinus*, providing it with a competitive edge over other more temperature-sensitive taxa. Indeed it could be argued that if the downturn in temperature was significant enough to limit agriculture much of the more marginal areas of farm land in the catchment could have been abandoned and quickly colonized by secondary pine woodland. Agricultural activity would continue but only in the more sustainable areas of the catchment floor and lower slopes.

A second, more pronounced phase of deforestation begins *c.* 2140 cal. yr BP, characterized by a rapid decline in *Pinus*. Poaceae experiences a marked increase along with other disturbance taxa including fireweed herbs. A more muted increase in selected deciduous trees (*Betula*, *Ulmus*, *Juglans*, *Pterocarya* and *Quercus*) parallels the decline in pine, which is thought to reflect the development of grazing and the expansion of settlements. The planting of deciduous taxa around settlements was also commonplace during this period for a mixture of aesthetics, fuel, fodder cropping and shelter (The Museum of Yunnan Province, 1977). Pine values continue to fall, culminating in a particularly severe decline recorded at *c.* 1100 cal. yr BP. In contrast, Poaceae continues to expand, with a disproportionate number of large Poaceae grains (> 37 μm) hinting at widespread cereal production.

The environmental impact of this pronounced phase of deforestation appears to have been very severe. A *c.* 10-fold increase in χ_{LF} values combined with sustained values of over 8% for χ_{FD}% points to severe catchment instability and the onset of intense soil erosion. The sharp decline in pollen concentration recorded across the entire pollen spectrum during this period points to a rapid increase in sedimentation diluting the pollen input. A similar acceleration in sedimentation rates has also been recorded at several sites across the province, with a 15-fold increase relative to natural erosion rates recorded in recent centuries (Whitmore *et al.*, 1994b, 1997).

Analysis of the documentary records clearly pinpoints economic pressure as the main driver of change in the catchment during the last millennium. By 1000 cal. yr BP a major administrative centre had been developed in the catchment at Dali on the western shore. Large-scale pastoral and irrigated agricultural economies were established by the end of the Tang dynasty ~900 CE with mining also prevalent across the catchment (Elvin *et al.*, 2002). As the catchment developed as an economic hub, so increased immigration prompted accelerated urbanization and an inevitable increase in demand for local resources (Zhou and Miao, 1989; Zhang *et al.*, 2000; Elvin *et al.*, 2002). As rates of soil erosion accelerated so did the incidence of flooding, as increased sediment loads regularly blocked drainage channels and raised the bed of the Miju river. By the mid–late Ming period (1368–1644 CE), the high rates of sediment transport to Erhai led to the formation of the Miju delta, a feature that had not previously been recorded on maps from the early Ming period (Elvin *et al.*, 2002).

The environmental state of the catchment appears to have deteriorated steadily over the last few centuries, reaching a nadir in the eighteenth and nineteenth centuries (Elvin *et al.*, 2002). A forest management regime initiated by the local government during the late twentieth century proved particularly effective leading to widespread reforestation and increased catchment stability. This reforestation trend can be clearly identified by the sharp rise in arboreal pollen, principally pine, at the top of the record.

Conclusions

(1) A 6.62 m pollen record from Lake Erhai, Yunnan, China, dating back to 12 950 cal. yr BP provides the first complete Lateglacial/Holocene pollen record for the province. The record reveals a long history of climate changes and human influence in the catchment area.

(2) An early cold and wet phase, characterized by *Betula* and *Quercus* forest in the upper mountain zones indicates that Erhai was located at the polar front position before 11 750 cal. yr BP, a period synchronous with the Younger Dryas cold oscillation.

(3) The transition to the early Holocene is characterized by the expansion of *Tsuga*, a consequence of an enhanced summer southwest monsoon. The progressive expansion of evergreen broadleaved oaks forest (*Cyclobalanopsis*/*Lithocarpus* and *Castanopsis*) and *Tsuga* forest also reflects the onset of warmer climatic conditions. The climatic optimum occurred at *c.* 8400 cal. yr BP, which lasted to at least 6370 cal. yr BP. The early to mid-Holocene warm and wet climate regime represents a regional climate signal across the Yunnan Plateau.

(4) The most significant statistical change in the pollen record occurs at *c.* 6370 cal. yr BP with a decrease in the natural altitudinal vegetation gradient that existed in the catchment from the Lateglacial. This development is attributed to selective forest clearance as part of an early phase of shifting agriculture.

(5) The strongest effects of human activities occur from *c.* 2150 cal. yr BP onwards in response to increased population immigration and probably the widespread expansion of irrigation farming. The pollen record over the last millennium parallels the documented changes in environmental degradation and remediation.

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