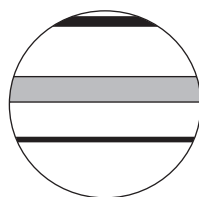


# Environmental history of the dry forest biome of Guerrero, Mexico, and human impact during the last c. 2700 years

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**Abstract:** Two lake sediment cores from Madre del Sur mountain range, Guerrero State, west-central Mexico were studied to examine the past dynamics of the dry forest biome. Pollen, spores of coprophilous fungi, cyanobacteria and lithological changes are presented. The 390-cm Tixtla core (17°30'N, 99°24'W, 1400 m altitude) represents the last 2700 cal. yr; the 340-cm Huitziltepec core (17°45'N, 99°28'W, 1430 m altitude) represents the last 2050 cal. yr. Pollen shows climate-dependent competition between dry deciduous forest (with Asteraceae, *Chamaesyce*-type, *Bursera*, *Euphorbia*, *Myrica* and *Lysiloma-Pithecellobium*-type as main components) and moister (mesophyllous) forest (with *Pinus*, *Quercus*, *Alnus* and *Juglans*). Human impact on the environment is apparent during the entire record, as evidenced by crop cultivation (*Zea mays*, *Amaranthus*, *Capsicum*, *Chenopodium*), coprophilous fungi (*Podospora*-type and *Sporormiella*-type), deforestation (at Tixtla in particular) and lake eutrophication, i.e. cyanobacteria blooms. Environmental change at both sites is summarized as follows. Period 1 (2700–2450 cal. yr BP): abundant dry deciduous forest and climate conditions drier than today. Period 2 (2450–1950 cal. yr BP): little change in proportions of dry deciduous and mesophyllous forest but floral composition of the forests differed between sites. Human occupation was low. Period 3 (1950–1550 cal. yr BP): dry deciduous forest decreased while mesophyllous forest increased, indicating more humid climatic conditions. Populations expanded significantly around 1950 cal. yr BP. Period 4 (1550–1070 cal. yr BP): maximum expansion of mesophyllous forest. Climate was more humid than today. Pre-Hispanic populations at Tixtla reached high numbers leading to deforestation and eutrophication. Period 5 (1070–c. 750 cal. yr BP): shows abundant mesophyllous forest and lowest proportions of dry deciduous forest. Climate continued to be humid. There is evidence of forest harvesting, crop cultivation and dense human population. Period 6 (c. 750–225 cal. yr BP): dry deciduous forest expanded and mesophyllous forest decreased. There was significant deforestation by pre-Hispanic people around Lake Tixtla. High population densities and frequent fires at both sites caused eutrophication of the lakes. Domesticated herbivores were introduced ~AD 1500 and the presence of dung is reflected in the record of coprophilous fungi. Period 7 (the last 225 calendar years): the basins were used intensively by local people and their cattle. Dry deciduous forest continued to increase while mesophyllous forest decreased.

**Key words:** Climate change, vegetation history, environmental history, human impact, coprophilous fungi, dry forest, Guerrero, Holocene, Mexico, pre-Hispanic occupation, pollen.

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## Introduction

Reconstruction of palaeoenvironments in Central America and Mexico are important to understand the dynamic character of natural ecosystems and evolution of pre-Hispanic cultures in Mesoamerica (Ben Brown, 1985). Fossil pollen is used to reconstruct regional vegetation changes that are often climate-driven. In this study we also use information from non-pollen palynomorphs. This proxy provides information on environmental change within and around lake basins and aids a better understanding of the pre-Hispanic occupation in the study area. Several authors related the collapse of pre-Hispanic cultures to climatic changes (eg, Hodell *et al.*, 1991, 1995; O'Hara *et al.*, 1994; Curtis *et al.*, 1996; Islebe *et al.*, 1996; Leyden *et al.*, 1998; Brenner *et al.*, 2001; Islebe and Sánchez, 2002; Haug *et al.*, 2003).

Phytogeographically, Mexico occupies an interesting position between the temperate vegetation of the USA and the tropical vegetation of Central America. Mexico possesses a large variety of biomes (Rzedowski, 1983); their dynamic historical ecology is still poorly known. In order of increasing dryness, the following biomes are most important: the evergreen tropical forest, conifer and oak forest, (montane) mesophyllous forest, tropical semi-deciduous forest, tropical deciduous forest, xerophytic bush ('matorral'), dry spiny forest ('bosque espinoso') and the grassy meadows ('pastizal'). Together these biomes represent a large floral diversity (Davis *et al.*, 1997).

This study deals with the tropical deciduous forest biome ('bosque tropical caducifolio') that covers a significant part of western Mexico and extends from north to south at relatively short distance from the Pacific coast. A study of the neotropical biomes by Marchant *et al.* (in review) generated continental-scale reconstructions of the vegetation distribution for selected time segments in the past. These vegetation maps represent snapshots of large-scale vegetation dynamics based on sites with good quality pollen data and chronological control in the Latin American Pollen Database (LAPD). Marchant *et al.*'s biome study presents the available pollen sites in a 'climate-space' diagram in which the 'average temperature of the coldest month' and the 'moisture index' form the two axes. The diagram illustrates how few sites from the tropical deciduous forest biome have been studied. As a consequence, there is a poor understanding of dynamic tropical deciduous forest under natural conditions. There is also little understanding of how tropical deciduous forest might grade into a different biome under climate forcing, eg, into 'tropical dry forest' under more arid conditions or into 'tropical evergreen forest' under more humid conditions. Improved understanding of ecosystem dynamics under changing environmental settings is relevant to reveal past vegetation location(s), elucidate the dynamic history and relevance for biodiversity of centres of high diversity and gain insights into new areas when environmental conditions change (Pennington *et al.*, 2000).

This study focuses on the 'tropical deciduous forest' biome in the state of Guerrero, west-central Mexico (Trejo and Rodolfo, 2002; Diego-Perez and Ludlow-Wiechers, 2003). The record covers the late Holocene, a period during which much of the area of central Mexico was occupied by pre-Hispanic cultures that caused significant impact on the natural vegetation. We anticipated that the microfossil records would show signals of natural change as well as evidence of human impact on the vegetation and landscape. Our objective was to use a variety of fossil taxa that are indicative of regional or local change to identify evidence of natural change and human

impact. Humans play an important role in landscape modification, by clearing forest (Bosch and Hewlett, 1982; Brujinzeel, 1990; Hornbeck and Swank, 1992, Stednick, 1996; Rosenmeier *et al.*, 2002), changing the local hydrological balance and promoting erosion.

In general, dry areas offer poor conditions for pollen preservation. Fossil pollen grains are easily damaged by corrosion (Anderson and van Devender, 1995). Diatoms and ostracods are less sensitive to corrosion and therefore play an important role in palaeoenvironmental reconstructions of dry areas (Metcalf *et al.*, 1997, 2000, 2002; Palacios-Fest *et al.*, 2002). Studies of the relation between modern pollen rain and the (potential) modern vegetation are complicated in areas where agriculture has disturbed the natural vegetation. In such situations, the modified remnants of original forest represent the only clue to such relations (Pope *et al.*, 2001; Wille *et al.*, 2001; Berrio *et al.*, 2002). Natural events, such as volcanism, also cause vegetation disturbance (Lozano-García *et al.*, 1993; Siebe *et al.*, 1995; Lozano-García and Ortega-Guerrero, 1998).

Pollen records from the Chihuahuan and Sonoran deserts in northern Mexico were published by Meyer (1973), van Devender (1990), and Anderson and van Devender (1995). The pollen record of Tetitlán (González-Quintero, 1980), recovered from a coastal lagoon ~100 km north of Acapulco, is close to our sites. González-Quintero (1980) reconstructed a climate curve that identified a warm-wet period before 2500 <sup>14</sup>C yr BP, a warm-dry period from 2500 to 1800 <sup>14</sup>C yr BP, temperate conditions from 1800 to 1000 <sup>14</sup>C yr BP, and increasing precipitation and temperature during the subsequent modern period (Bryant and Holloway, 1985).

An integrated analysis and interpretation of non-pollen palynomorphs in Quaternary deposits was started in Europe (van Geel, 2001 and references therein). A first record of non-pollen palynomorphs in Mexican deposits was worked out by Almeida-Lenero *et al.* (2005). Dung-inhabiting fungi and cyanobacteria appeared to be especially valuable environmental indicators. In the present study the most important palynomorphs that were recorded and interpreted are:

- Ascospores of *Gelasinospora* (fungi; spores illustrated by van Geel, 1978) occur mainly on dung but prefer to grow on burned ground or wood (Lundqvist, 1972).
- Ascospores of *Ustulina deusta* (fungi; spores illustrated by van Geel *et al.*, 1986). *Ustulina deusta* is a mild parasite causing soft-rot of wood. It occurs regularly on a variety of host trees, including *Quercus* and *Alnus* (Wilkins, 1934). Van Geel and Andersen (1988) found a positive correlation between fungal spores of *Ustulina deusta* and the pollen curves of host trees in Eemian deposits in Denmark, which is in agreement with the mild parasitic character of the fungus. Fructifications appear at the trunk base and therefore less ascospores will be released from a closed forest than from areas where people open the forest for agriculture.
- Ascospores of *Coniochaeta ligniaria* (fungi; spores illustrated by van Geel *et al.*, 1983). According to Munk (1957) *C. ligniaria* is common on dung and wood.
- Ascospores of *Sporormiella*-type, *Cercophora*-type and *Podospora*-type (fungi; spores illustrated by van Geel, 2001). These are the spores of coprophilous (dung-inhabiting) fungi. Increased frequencies of the spores may point to a higher population density of herbivores and humans (Davis, 1987; van Geel *et al.*, 2003).
- Chlamydospores of *Glomus* (fungi; spores illustrated by van Geel, 2001). The fungus grows on the roots of many plants.

The chlamydospores of *Glomus* may appear in lake deposits after erosion of soils in the catchment.

- Akinetes of *Anabaena* and heterocysts of the *Rivularia*-type (cyanobacteria, illustrated by van Geel *et al.*, 1994 and by van Geel, 2001). Increased cyanobacteria in lake deposits can be interpreted as the effect of intensified farming in the past, causing eutrophication of lakes. Phosphorus enrichment in the catchment may become so high that N-limited growth conditions may occur in the lake. Under such conditions, cyanobacteria can bloom as they are capable of nitrogen fixation.

This paper reconstructs late-Holocene vegetation and environmental change in the state of Guerrero, Mexico, where ‘tropical deciduous forest’ prevails. We used various proxies, such as downcore changes in the fossil pollen, coprophilous fungi and other non-pollen palynomorphs, and radiocarbon dates, to identify the contribution of natural environmental change versus human impact in this changing landscape.

## Environmental setting of the study area

### Geography and climate

The municipalities of Tixtla and Huitziltepec are within the Madre del Sur mountain range that crosses the state of Guerrero from east to west, separating the Balsas Depression from the coastal region (Figure 1). The Madre del Sur has an average width of 100 km and its crest an average altitude of 2000 m. In the western end of the state, the Madre del Sur is interrupted by the Balsas River that drains to the Pacific Ocean. In the vicinity of Chilpancingo the crest is only 1400 m high. The municipalities of Tixtla and Huitziltepec are located in valleys in the middle part of the mountain range that consist

of carbonate rocks of Cretaceous age. Both depressions have been defined as ‘poljés’ formed by rock dissolution.

Lake Tixtla (17°30’N, 99°24’W, 1400 m altitude) lies in the Balsas Depression of the Sierra Madre del Sur (Figure 1). It is located in a shallow depression some 500 m from the village of Tixtla and borders hills that rise to some 200 m above the lake (Figure 2). The water depth was about 50 cm at the time of coring, but evidence on the lake shores suggested that during the wet season the water level rises up to 1 m higher.

Lake Huitziltepec (17°45’N, 99°28’W, 1430 m altitude; literally translated as ‘hummingbird hill’) is located close to Eduardo Neri City (Figures 1 and 2). The distance between the lakes is about 40 km. Lake Huitziltepec is located in an area of softly rolling hills used intensively for agriculture. Part of the lake floor was dry during our visit in the dry season. We found a maximum water depth of about 30 cm. Both lakes were visited by cattle. The surrounding hills of both lakes have sandstone outcrops of Miocene and Cretaceous age (López, 1984). The main soil types in the study area are leptosols and vertisols (Secretaría de Programación y Presupuesto, 1981).

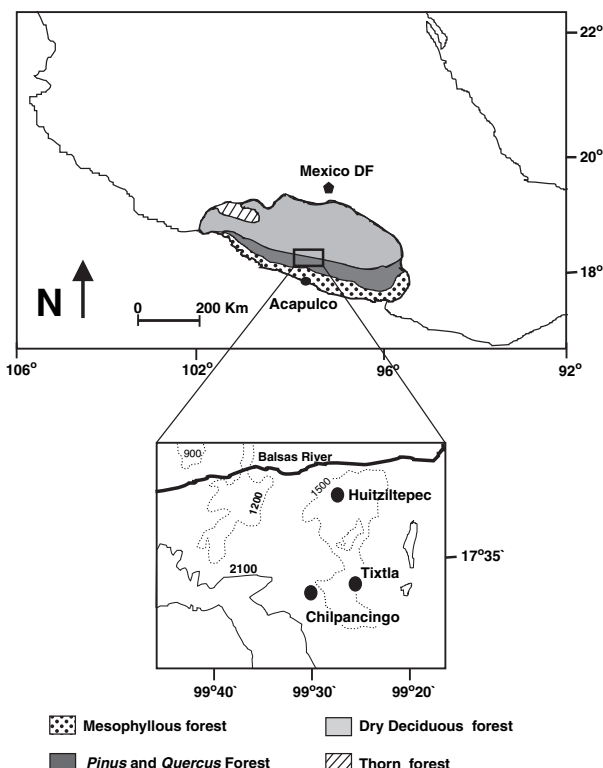
Annual precipitation in Tixtla is 1015 mm and in Huitziltepec 830 mm. The average annual temperature is 21°C at both sites. The deciduous forest of Guerrero is located in a ‘Cw’ climate (temperate warm rainy climate with a dry winter season) based on the Koeppen/Geiger classification system modified by García (1988). According to the Troll/Paffen classification, the climate is a ‘V3’ type (seasonal dry climate with raingreen dry forest and dry savannas; Müller *et al.*, 1983). The average monthly temperature is between 20° and 26°C, January being the coldest month. The average annual precipitation varies from 890 to 1300 mm, occasionally values may reach minima of 500 mm and maxima of 1500 mm/yr. The dry period is from February to April and the wet period from June to September. Low water conditions may persist for 8 to 9 months. Present-day seasonality is mainly driven by the annual migration of the Intertropical Convergence Zone (ITCZ) (O’Hara and Metcalfe, 1997).

### Present-day vegetation

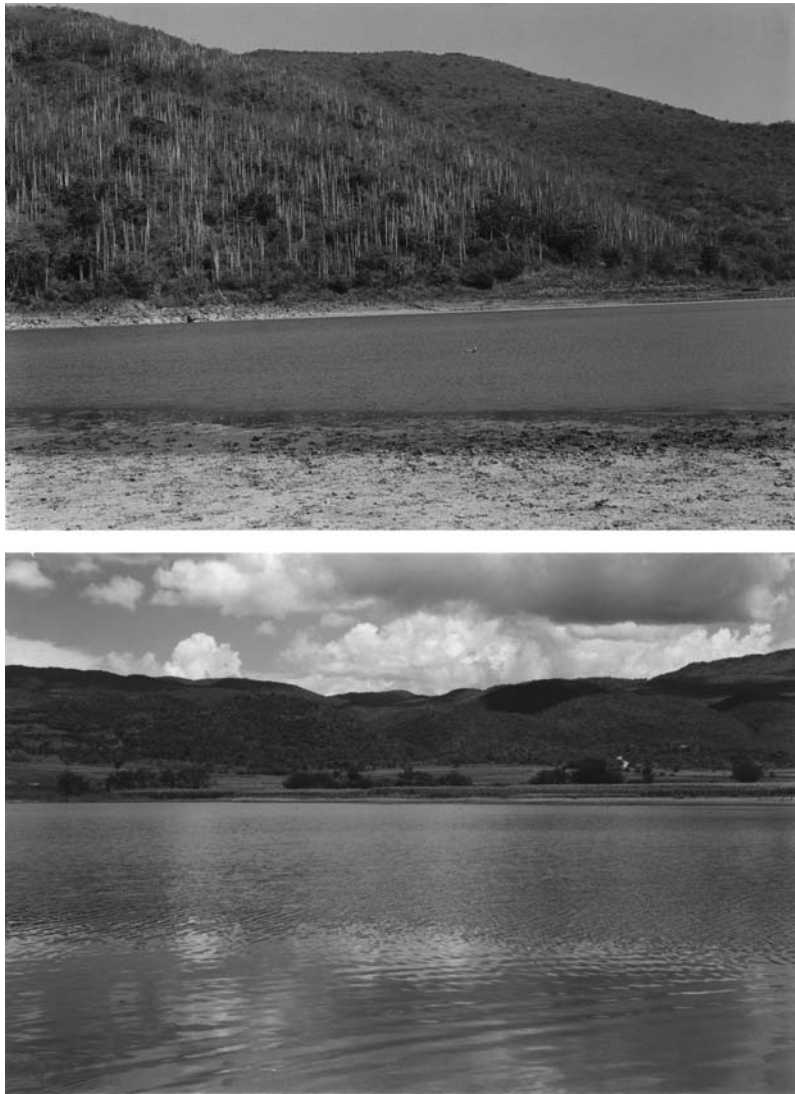
The present-day vegetation distribution in Mexico was presented by Rzedowski (1983). For our study area the following vegetation types (biomes) are relevant: montane mesic forest, coniferous forest and oak forest. Information from unpublished vegetation studies has also been incorporated into the following account. The tropical deciduous forest is dominated by tree species that lose their leaves during the dry season, which is of variable length but is generally about six months. In the state of Guerrero, tropical deciduous forest covers 17% of its surface, the highest cover for any vegetation type, exceeded only by farmland which now covers 25%. Between 1981 and 1992, 14% of the semi-deciduous forest disappeared (Flores and Gerez, 1994).

In the depression of the Balsas River, where Lake Tixtla is located, tropical deciduous forest is the most widespread vegetation type. It consists of a mixture of temperate and tropical trees and shows great floristic richness. In the study area, species of *Bursera* stand out, locally known as ‘cuajotes’ and ‘copales’. In Guerrero, tropical semi-deciduous forest is most abundant around Chilpancingo, in the lower parts of the Taxco Mountain Range, southeast of Ixcateopan and Taxco, and near Julianilla and the coastal area, mostly at altitudes below 1500 m. A large number of different associations were recognized in semi-deciduous forest, forming a complex mosaic (Toledo, 1982).

The most characteristic elements of the semi-deciduous forest are species belonging to the genus *Bursera*. Common



**Figure 1** Map of the main vegetation types near our study site in west-central Mexico (after Rzedowski, 1983). Lakes Tixtla and Huitziltepec, and other sites mentioned in the text, are indicated



**Figure 2** Photographs of lakes Tixtla (top) and Huitziltepec (bottom) in the Sierra Madre del Sur, state of Guerrero, México. Lake Tixtla is located at 1400 m a.s.l. Hills in the background are covered by thornbush and cactaceous vegetation. Lake Huitziltepec is located at 1430 m a.s.l.

tree taxa are: *Bursera morelensis*, *B. longipes*, *B. lancifolia*, *B. schlehtendahlia*, *B. submoniliformis*, *Lysiloma tergemina*, *Ceiba parviflora*, *Plumeria rubra*, *Jatropha* aff. *dioica*, *Acacia acatlenensis* and species of the Cactaceae: *Neobuxbaumia mezcalensis*, *Opuntia atropes* and *Stenocereus dumortieri*. Frequent taxa in the uppermost range of this forest, contiguous with the low-altitude oaks, usually include: *Bursera glabrifolia*, *B. copallifera*, *B. bipinnata*, *Pseudosmodingium perniciosum*, *Ipomoea* spp., *Mimosa* aff. *bentharii* and *Brahea dulcis* (Fonseca and Lorea, 1980; Toledo, 1982). In the Zopilote Canyon, in the Papalotepec and Venta Vieja areas, Peralta (1995) and Gual (1995) carried out floristic inventories in different ravines. In the tropical deciduous forest they recognized seven associations of which the floristic similarity varies from 22% to 65%. The best-represented families in terms of species numbers are Asteraceae, Fabaceae, Euphorbiaceae and Burseraceae.

The vegetation near Lake Tixtla is composed of tropical deciduous forest and oak forest. Tropical deciduous forest is present below 1500 m. In the uppermost range it may be found mixed with elements of oak forest. At many places below 1500 m the vegetation has been eliminated. In undisturbed areas the following taxa occur: *Stemmadenia tomentosa*, *Vallesia glabra*, *Bursera ariensis*, *B. bipinnata*, *B. submoniliformis*, *Merremia macdonaldii*, *Ceiba aesculifolia*, *Thevetia ovata*, *T. thevetioides*,

*Ipomoea arborea*, *Quercus glaucooides*, *Pistacia mexicana*, *Gliricidia ehrenbergii*, *Tecoma stans*, *Lysiloma acapulcensis*, *Comocladia mollissima*, *Tabebuia rosea*, *Lantana camara*, *Vitis berlandieri*, *Rhus nelsonii*, *Crotalaria tilifolia*, *Euphorbia dioica*, *Pinaropappus spatulatus*, *Nicotiana glauca*, *Mentzelia aspera*, *Porophyllum punctatum*, *Thalictrum pubigerum*, *Byrsonima crassifolia*, *Phitecellobium dulce*, *Psidium guajava*, *Guazuma ulmifolia*, *Russelia parviflora*, *Corchorus siliquiosus* and *Spondias purpurea* (Fonseca *et al.*, 2003).

*Quercus* and *Pinus* forest occurs between 1500 and 1900 m. It has trees with a layer between 3 and 6 m tall, some reaching heights of 15 m. Main taxa are: *Quercus castanea*, *Q. acutifolia*, *Q. conspersa*, *Q. elliptica*, *Q. magnoliifolia*, *Q. subspatulata*, *Pinus* spp., *Arbutus xalapensis*, *A. madrensis*, *Buddleia parviflora*, *Prunus brachybotrya*, *Oreopanax peltata*, *Ostrya virginiana*, *Cercocarpus macrophyllus*, *Acacia pennatula*, *Loeselia glandulosa*, *Stachys coccinea*, *Diastatea tenera*, *Asclepias glaucescens*, *Lobelia cardinalis*, *Euphorbia cyathophora*, *Dalea foliosa* (Velázquez *et al.*, 2003).

The vegetation near Lake Huitziltepec shows a mosaic of tropical deciduous forest between 1400 and 1700 m and oak forest. Main taxa are: *Bursera trimera*, *B. morelense*, *B. copallifera*, *B. aptera*, *Lysiloma setifera*, *Pseudosmodingium perniciosum*, *Ipomoea minutiflora*, *I. setifera*, *Neobuxbaumia*

*mezcalensis*, *Cordia elaeagnoides*, *Brahea dulcis*, *Lysiloma acapulcensis*, *Serjania triquetra*, *Agave cupreata*, *A. hirschmeriana*, *Hechtia mooreana*, *Alvaradoa amorphoides* (Escamilla, 1995). Oak forest has its range from 1700 to 2200 m, and the main taxa are: *Quercus magnoliifolia*, *Q. planipocula*, *Q. candicans*, *Q. acutifolia*, shrubs such as *Colubrina macrocarpa*, *Calliandra physocalix*, *Tecoma stans* and herbs such as *Asclepias curassavica*, *Coursetia madrensis* and *Habenaria jaliscana* (Escamilla, 1995).

## Methods

Sediment cores were collected close to the centre of these shallow lakes in March 1998 by H. Hooghiemstra and B. Ludlow. Sediment cores of 25 mm diameter were recovered in 25-cm increments using a hand-operated Dachnowsky Corer. The sediment cores were extruded into plastic bags and protected by PVC pipe. Sediment cores were transported to the laboratory in Amsterdam and stored in a dark room at 4°C.

Samples of 0.5 cm<sup>3</sup> were taken from both cores at 5-cm intervals for microfossil and charcoal analysis. Samples were prepared using standard pre-treatment techniques, including sodium pyrophosphate, acetolysis and heavy liquid separation by bromoform (Faegri and Iversen, 1989). Prior to processing, one tablet with exotic *Lycopodium* spores was added to each sample to calculate pollen concentration and pollen influx values. Pollen residues were mounted in glycerin gelatin and pollen grains were counted with a Zeiss microscope at 500× magnification. Non-pollen palynomorphs were enumerated in similar fashion.

Pollen grains and spores were identified using the morphological descriptions of Palacios-Chávez *et al.* (1991), Herrera and Urrego (1996), Hooghiemstra (1984), Roubik and Moreno (1991), and the modern pollen catalogues of recent vegetation of the state of Guerrero by Vázquez-Santana and Martínez-Mena (1991), Juárez-Jaimes and Martínez-Mena (1992), Vargas and Ludlow-Wiechers (1992), Zamudio and Ludlow-Wiechers (1993), Olvera (1997), Núñez and Ludlow-Wiechers (1998), and Olivera *et al.* (1998). The non-pollen palynomorphs were identified according to van Geel (1978, 2001), van Geel and Andersen (1988), van Geel and Grenfell (1996), and van Geel *et al.* (1983, 1986, 1994, 1996b, 2003). We also used the reference collection of modern pollen, spores and other non-pollen palynomorphs of the Institute for Biodiversity and Ecosystem Dynamics (IBED). Most samples were counted to a minimum of 300 pollen grains, excluding pollen of aquatic taxa. Taxa were assigned to the following ecological groups: (1) dry deciduous forest, (2) mesophyllous forest, (3) open vegetation, (4) indicators of human disturbance, (5) swamp vegetation, (6) aquatic vegetation, (7) bryophytes, (8) fern spores, (9) fungal spores and other non-pollen palynomorphs and (10) spores of coprophilous fungi.

Accelerator mass spectrometry (AMS) radiocarbon dates were obtained from 0.5 cm<sup>3</sup> bulk sediment samples of < 1-cm core interval. We dated six sediment samples from the Huitziltepec core and five samples from Tixtla core. Dating was carried out at the Van de Graaff Laboratory, University of Utrecht. We calibrated radiocarbon dates with Calib 4.3 software (<http://depts.washington.edu/qil/dloadcalib/>, last accessed 19 October 2005). In many cases, radiocarbon ages from the literature could not be calibrated because of insufficient data. Therefore, comparisons of our data with results from other sites are based on correlation of uncalibrated radiocarbon ages.

Palynological data are presented in pollen percentage diagrams and show temporal changes in the contribution of individual taxa and ecological groups to the regional vegetation. Changes in the relative pollen contribution reflect competition between the main biomes and basically reflect climate and other environmental changes. Taxa of local significance, such as swamp elements, aquatics, bryophytes, fern spores and fungal spores were calculated as percentages of the pollen sum. For calculation of pollen percentages, cluster analysis, and data plotting, TILIA, CONISS, and TILIA-GRAPH software were used, respectively (Grimm, 1987).

## Results

### Lithology

Based on the CONISS cluster analysis and visual inspection of the records, seven pollen zones were recognized in the Tixtla pollen diagram (see Figure 5) and six pollen zones in the Huitziltepec pollen diagram (see Figure 7).

Lithological sequence in core Tixtla:

0–25 cm	sandy clay (yellowish-grey) with small gravel
25–50 cm	no sample recovery
50–55 cm	coarse sand
55–80 cm	sandy clay (yellowish-grey)
80–125 cm	clay (compact; yellowish-grey, slightly mottled)
125–390 cm	clay (grey; at 355 cm with small gravel)

Lithological sequence in core Huitziltepec:

0–25 cm	clay (light brown; few rootlets)
25–75 cm	sandy clay (very compact; light brown; oxidation between 50 and 75 cm)
75–125 cm	clay (dark brown)
125–250 cm	sandy clay (dark brown)
250–325 cm	clay (little sand; dark grey)
325–350 cm	coarse sand (very compact, brown)
350–400 cm	coarse sand (light brown)

### Chronology

We show uncalibrated ages as <sup>14</sup>C yr BP' and calibrated ages as 'cal. yr BP' (Table 1). Oldest dates of 2013 ± 35 <sup>14</sup>C yr BP for core Huitziltepec and 1760 ± 50 <sup>14</sup>C yr BP for core Tixtla, indicate that both records span the last several millennia of the Holocene.

Ages from the Huitziltepec core show age–depth reversals between 280 and 100 cm core depth. This core interval shows sandy sediments. Re-deposition of older sediments might have caused an older than expected age. The data allow a general depth versus age relationship for Huitziltepec core (Figure 3). Radiocarbon ages from Tixtla core do not lead to a clear depth versus age relationship. Ages in the lower part of the core (at 290 cm and 387 cm) deviate from the ages in the upper part (from 215 to 35 cm core depth). Sediments show several characteristics indicative of re-deposition (sands, fine gravel) and water-level fluctuations (ie, mottling). The combination of dry climate conditions and high population pressure on the local landscape led to abundant erosional input to the basin, explaining inversions of radiocarbon ages. However, without rejecting any radiocarbon dates of the Tixtla core we arrive at similar depth versus time curves (Figure 4). Chronology and pollen zone boundaries for each core are based on linear regression of depth (cm) and age in cal. yr BP. Because we found the accuracy of the time control of both sediment cores insufficient, we have not graphed pollen concentration records.

**Table 1** AMS  $^{14}\text{C}$  ages of samples from the Tixtla and Huitziltepec sediment cores, State of Guerrero, Mexico. The last column shows the calibrated age intervals in calendar years BP ( $1\sigma$  probability; program Calib4)

Lab. number	Depth (cm)	Age ( $^{14}\text{C}$ yr BP)	$^{13}\text{C}/^{12}\text{C}$ ratio	Age (cal. yr BP)
<i>Huitziltepec core</i>				
UtC-11532	35	117 ± 27	-19.7	modern (263–240, 232–220, 140–126, 124–65, 38–27, 1–1)
UtC-11533	100	1003 ± 33	-20.3	958–912, 807–801
UtC-11534	160	1537 ± 42	-19.1	1512–1498, 1489–1430, 1422–1386, 1376–1374, 1361–1354
UtC-11535	215	1134 ± 47	-19.4	1166–1162, 1118–1113, 1074–968
UtC-11536	280	1546 ± 32	-18.1	1513–1497, 1491–1429, 1423–1407, 1399–1393
UtC-8370	345	2013 ± 35	-17.0	1989–1922, 1915–1895
<i>Tixtla core</i>				
UtC-11604	70	1583 ± 49	-22.0	1521–1417
UtC-7684	171	1307 ± 41	-21.8	1282–1176
UtC-11605	230	2064 ± 41	-21.4	2103–2082, 2066–1988, 1978–1971, 1959–1951
UtC-11606	290	1760 ± 50	-19.8	1730–1605, 1598–1595, 1581–1570
UtC-7685	387	1707 ± 41	-21.6	1690–1661, 1626–1540

### Pollen zones

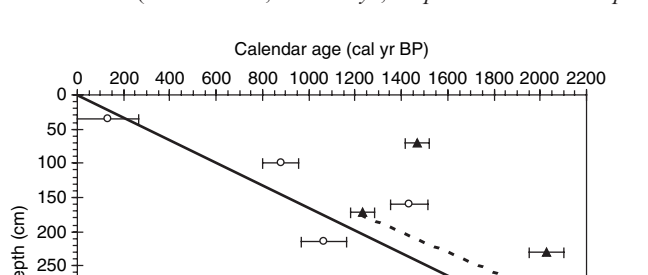
The most important pollen taxa in the Tixtla core are shown in Figure 4. The full list of pollen, spores and other microfossils is shown in Table 2. Downcore changes in the contribution of ecological groups, human impact indicators, pollen sum values, pollen zones and the CONISS dendrogram are shown in Figure 5. For the Huitziltepec core the data are presented in a similar way in Figures 6 and 7. Based on CONISS cluster analysis and visual inspection of the records, six pollen zones were recognized in the Huitziltepec pollen diagram and seven pollen zones in the Tixtla pollen diagram.

#### The Tixtla pollen record

In the following section, only taxa with a representation > 2% are mentioned by name. Non-pollen palynomorphs for environmental reconstruction are discussed later.

Zone TXA-1 (390–353.5 cm, 8 samples): taxa from dry deciduous forest dominate (Asteraceae (40–75%), *Bursera* (0–5%), *Chamaesyce*-type (3–8%) and *Protium*); mesophyllous forest is mainly represented by *Pinus* (9–16%) and *Quercus* (4–7%); taxa of open vegetation are represented by Poaceae (0–10%); indicators of human activity (*Zea mays*, *Amaranthus* and *Chenopodium*).

Zone TXA-2 (353.5–285 cm, 12 samples): the contribution of mesophyllous forest taxa decreases (*Pinus* (1–15%), *Quercus* (1–8%) and *Alnus*); taxa from deciduous forest remain at the same level (Asteraceae (55–80%), *Chamaesyce*-type (0–6%) and *Protium* (0–5%)); open vegetation is characterized by Poaceae (1–4%); representation of indicators of human disturbance (*Amaranthus*, *Zea mays*, *Capsicum* and *Chenopodium*).



**Figure 3** Depth versus age graph of the Tixtla sediment core (triangles and dashed line) and Huitziltepec sediment core (open circles and solid line)

*dium*) is low; swamp taxa (*Cuphea*, Cyperaceae, *Ranunculus*, *Polygonum* and *Isoetes*) reach lower values.

Zone TXA-3 (285–232.5 cm, 9 samples): there is a significant reduction of dry deciduous forest (Asteraceae decreasing from 50% to 20%, *Chamaesyce*-type (0–4%) and *Protium*); an increase of mesophyllous forest taxa (*Pinus* increase from 7% to 20%, *Quercus* (15–32%) and *Alnus*); an increase of open vegetation (Poaceae 10–17%); human disturbance indicators (*Amaranthus* and *Chenopodium*); pollen of swamp taxa (*Cuphea*, Cyperaceae and *Ranunculus*) show low values.

Zone TXA-4 (232.5–155 cm, 17 samples): the main change is a decrease of taxa of open vegetation (Poaceae 5–14%); an increase of aquatic taxa (*Isoetes*); main dry deciduous forest taxa are Asteraceae (25–48%), *Bursera*, *Chamaesyce*-type, *Crotalaria*, *Myrica* and Leguminosae; main mesophyllous forest taxa are *Pinus* (20–45%), *Quercus* (8–16%) and *Alnus*; human impact indicators are *Zea mays* (0–12%), *Amaranthus* and *Chenopodium*; swamp vegetation is represented by *Cuphea*, Cyperaceae, *Ranunculus*, *Polygonum*, *Typha* and *Hydrocotyle*.

Zone TXA-5 (155–121.5 cm, 5 samples): this zone is characterized by a rapid change in which dry deciduous forest taxa (Asteraceae decrease from 50% to 30%, *Bursera*, *Crotalaria*, *Euphorbia*, Leguminosae, *Myrica* and *Simarouba*) are replaced by mesophyllous forest taxa (*Pinus* (6–20%), *Quercus* increases from 3 to 48% and *Alnus*); open vegetation is represented by Poaceae (3–13%); human indicators (*Zea mays*, *Amaranthus* and *Chenopodium*) show low values; swamp vegetation is reflected by Cyperaceae and *Ranunculus*.

Zone TXA-6 (121.5–29 cm, 12 samples): this zone is characterized by a minimum of mesophyllous forest taxa (*Pinus* (0–30%), *Quercus* (8–20%) and *Alnus*); relatively high values of dry deciduous forest (Asteraceae 30–55%, *Bursera*, Cappariaceae, *Chamaesyce*-type, *Euphorbia*, *Piper*, *Simarouba* and *Triumfetta*); open vegetation (Poaceae 5–14%, *Borreria* and *Agave*); and in the upper part of this zone increased values of swamp and aquatic taxa (*Cuphea*, Cyperaceae, *Typha* and *Hydrocotyle*); human impact indicator taxa show highest values in the upper part of this zone and are represented by *Zea mays*, *Amaranthus* and *Chenopodium*.

Zone TXA-7 (29–0 cm, 5 samples): this zone is characterized by a decrease in dry deciduous forest taxa (Asteraceae 25–40%, *Chamaesyce*-type (0–5%), *Crotalaria* and *Euphorbia*); an increase of mesophyllous forest taxa (*Pinus* 28–32% and *Quercus* 4–6%); increasing values of human impact indicators (*Zea mays*, *Amaranthus*, *Capsicum* and *Chenopodium*); open vegetation is represented by Poaceae (6–10%); swamp vegetation by Cyperaceae (1–3%).



**Table 2** Identified pollen and spore taxa from the lake Tixtla (T) and Huitziltepec (H) cores. Taxa are grouped according to ecological preferences. Taxa marked by an asterisk are included in the pollen sum. Some rare types are not listed

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Dry deciduous forest

*Acacia* (H)\*  
 Aeschynomene-type (H)\*  
*Alvaradoa*-type (H)\*  
 Anacardiaceae (H, T)\*  
*Anacardium* (H)\*  
*Anoda*-type (H, T)\*  
*Annona* (T)\*  
 Apocynaceae (H, T)\*  
 Araliaceae (T)\*  
*Arrabidaea*-type (H, T)\*  
 Asteraceae subf. Asteroidea (H, T)\*  
 Bignoniaceae-1 (H, T)\*  
 Bignoniaceae-2 (H, T)\*  
*Bucida*-type (H, T)\*  
*Bunchosia*-type (H, T)\*  
 Bursera (H, T)\*  
 Cactaceae (T)\*  
 Cappariaceae (H, T)\*  
*Casearia* (H, T)\*  
*Ceiba* (H)\*  
*Celtis* (H, T)\*  
*Chamaesyce*-type (H, T)\*  
 Citrus-type (H)\*  
 Convolvulaceae (H)\*  
*Corchus*-type (T)\*  
*Cordia*-type (H)\*  
*Crotalaria*-type (H, T)\*  
*Croton* (H)\*  
*Cupania* (T)\*  
*Cydistia*-type (H)\*  
*Dalbergia*-type (H, T)\*  
*Daphnopsis* (T)\*  
*Desmanthus*-type (H)\*  
*Desmodium* (H, T)\*  
*Dodonaea* (H)\*  
*Erythroxylum* (T)\*  
 Euphorbiaceae (H)\*  
*Euphorbia* (H, T)\*  
*Gouania* (H, T)\*  
*Harpalyce*-type (H)\*  
 Ipomoea (H, T)\*  
 Leguminosae (H, T)\*  
*Lonchocarpus* (H)\*  
 Lysiloma/Pithecellobium-type (H, T)\*  
 Meliaceae (H)\*  
*Melothria* (H, T)\*  
 Menispermaceae-type (H, T)\*  
*Merremia*-type (H, T)\*  
*Mimosa* (H)\*  
 Moraceae/Urticaceae-type (H, T)\*  
*Myrica* (H, T)\*  
 Myrtaceae (H, T)\*  
 Palmae (H, T)\*  
*Piper* (H, T)\*  
*Phyllanthus* (H)\*  
*Portulaca* (H, T)\*  
*Pouteria*-type (H)\*  
*Psittacanthus* (H)\*  
*Psychotria* (H)\*  
*Rhus*-type (H)\*  
 Sapotaceae (H)\*  
*Sebastiania* (H)\*  
*Senna* aff. *pallida* (H)\*  
*Serjania*-type (H)\*  
*Simarouba*-type (H, T)\*  
*Solanum* (H, T)\*  
*Spondias* (H, T)\*

**Table 2** (continued)

*Struthanthus*-type (H, T)\*  
*Thouinia*-type (H, T)\*  
 Tiliaceae (H, T)\*  
*Trichilia* (H, T)\*  
*Triumfetta* (H, T)\*  
 Verbenaceae (H, T)\*  
*Vernonia*-(T)\*  
*Xylosma* (H)\*

Mesophyllous forest  
*Alnus* (H, T)\*  
*Hedyosmum* (H, T)\*  
*Juglans* (H, T)\*  
*Oreopanax* (H)\*  
*Pinus* (H, T)\*  
*Quercus* (H, T)\*  
*Salix* (H, T)\*  
*Thalictrum* (H, T)\*

Open vegetation  
*Agave* (H, T)\*  
 Apiaceae (H, T)\*  
*Borreria* (H, T)\*  
*Coriandrum* (H, T)\*  
*Gomphrena* (H, T)\*  
*Iresine* (H)\*  
 Lamiaceae (H, T)\*  
*Leonotis*-type (H)\*  
*Mimosa* aff. *pudica* (H)\*  
*Pancreatium*-type (H)\*  
*Philoxerus* (H, T)\*  
 Poaceae (H, T)\*  
*Sida* (H, T)\*

Swamp  
*Azolla* (T)  
 Cyperaceae (H, T)  
*Cuphea* (H, T)  
*Eichornia* (T)  
*Oenothera* (T)  
*Pinguicula* (H, T)  
*Polygonum* (H)  
 Pontederiaceae (T)  
*Typha* (H, T)

Aquatics  
*Anabaena* (T)  
*Botryococcus* (H, T)  
*Conochilus natans* (T)  
*Debarya* (T)  
*Isoetes* (H, T)  
*Pseudoschizaea circula* (H, T)  
*Rivularia*-type (H, T)  
*Spirogyra* (H, T)  
 Tetra-algae? (H, T)  
*Zygnema* (H)

Human impact indicators  
*Amaranthus* (H)\*  
*Capsicum*-type (H, T)\*  
 Chenopodium (H, T)\*  
*Cucurbita mixta* (H, T)\*  
*Ipomoea* aff. *batatas* (H)\*  
*Mangifera* (H)\*  
*Zea mays* (H, T)\*

Fern, fern allies and Bryophytes  
*Asplenium* (H, T)  
 Bryophyta (H, T)  
*Ceratopteris* (H, T)  
*Hymenophyllum* (H, T)  
*Lophosoria* (H)  
*Lycopodium curvatum* (T)  
*Lycopodium foveolate* (T)  
 Monolete psilate (H, T)

**Table 2** (continued)

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Monolete verrucate (H, T)
<i>Pityrogramma</i> (T)
<i>Polypodium</i> (H, T)
<i>Selaginella</i> (H, T)
<i>Thelypteris</i> (T)
Trilete baculate (H, T)
Trilete psilate (H, T)
Trilete reticulate (H)
Trilete verrucate (H, T)
Non-Palynomorphous type
<i>Assulina</i> (H, T)
<i>Cercophora</i> (H)
<i>Contiochaeta</i> cf. <i>Ligniaria</i> (H, T)
<i>Diporothea</i> (H, T)
Fruit body (H, T)
<i>Gaeumannomyces</i> (H, T)
<i>Gelasinospora</i> (H, T)
<i>Glomus</i> (H, T)
<i>Podospora</i> (H, T)
<i>Sporormiella</i> (H, T)
Testacea (H)
<i>Tetraploa aristata</i> (H, T)
<i>Ustilina deusta</i> (H, T)

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### Huitziltepec pollen record

Zone HTC-1 (340–317.5 cm; 4 samples): this zone is characterized by a high representation of dry deciduous forest taxa (Asteraceae (40–55%), *Anacardium*, Bignoniaceae, *Dicliptera* and *Lysilomal/Pithecellobium*-type); mesophyllous forest taxa are *Pinus* (15–25(50%)), *Quercus* (8–10%) and *Alnus*; Poaceae (8–25%) show a large variability; human impact indicators (*Zea mays*, *Amaranthus*) show 0–5%.

Zone HTC-2 (317.5–247.5 cm, 12 samples): this zone is characterized by a decrease in dry deciduous forest taxa (Asteraceae (25–40%), *Chamaesyce*-type, *Bursera*, *Euphorbia* and *Lysilomal/Pithecellobium*-type); an increase of mesophyllous taxa: *Pinus* (20–35%), *Quercus* (5–10%) and *Alnus* (1–4%); and higher values (1–10%) of indicators of human impact (*Zea mays*, *Chenopodium*, *Amaranthus*). Swamp taxa and aquatics display values similar to those of the previous zone.

Zone HTC-3 (247.5–172.5 cm, 15 samples): this zone is characterized by a further decrease in dry deciduous forest taxa (Asteraceae (18–32%), *Euphorbia* (1–8%), *Anacardium*, *Chamaesyce*-type, *Bursera* and *Lysilomal/Pithecellobium*-type); indicators of human impact (1–5%: *Zea mays* and *Chenopodium*); higher values of mesophyllous forest taxa (*Pinus* (15–35%), *Quercus* (10–22%) and *Alnus*); Poaceae reach 8–20%.

Zone HTC-4 (172.5–102.5 cm, 13 samples): this zone is characterized by a decrease of dry deciduous forest taxa (Asteraceae (15–25%), *Chamaesyce*-type, *Bursera*, *Euphorbia* and *Crotalaria*); lower values of human impact indicators; an increase of mesophyllous forest taxa (*Pinus* (30–42%), *Quercus* (10–17%) and *Alnus*); open vegetation and, in the last part of this zone, presence of 1–5% swamp taxa (Cyperaceae, *Pinguicula*, *Cuphea* and *Polygonum*).

Zone HTC-5 (102.5–32.5 cm; 13 samples): this zone is characterized by an increase in dry deciduous forest taxa (Asteraceae increasing from 25% to 40%), *Chamaesyce*-type, *Bursera*, *Desmodium*, *Arrabidaea*-type, Bignoniaceae-1 and Apocynaceae); a decrease of mesophyllous forest taxa (*Pinus* decreases from 30% to 20%), *Quercus* (decreases from 10% to 2%) and *Alnus*; taxa of open vegetation (Poaceae, *Leonitis*-type and Lamiaceae) continue to be stable; swamp taxa (Cyper-

aceae, *Cuphea* and *Polygonum*) decrease; aquatics are abundant; human impact indicators (*Zea mays*, *Chenopodium*, *Amaranthus* and *Capsicum*) increase rapidly in the uppermost part of the zone.

Zone HTC-6 (32.5–0 cm; 7 samples): this zone is characterized by a further decrease of taxa from mesophyllous forest (*Pinus* (10–18%), *Quercus* (1–9%), *Alnus* and *Thalictrum*); decrease of open vegetation; dry deciduous forest remains constant (Asteraceae (30–42%), *Arrabidaea*-type, *Bursera*, *Chamaesyce*-type, *Crotalaria* and *Senna* aff. *pallida*); human impact indicators increase significantly: *Zea mays* (1–4%) *Chenopodium* (1–13%) and *Amaranthus* (1–5%). Open vegetation is represented by Poaceae (12–20%). Main swamp taxa are represented by Cyperaceae and *Polygonum*.

## Interpretation of data and reconstruction of palaeoenvironmental change

We present an environmental reconstruction based on pollen results from the two basins and integrate the data into a regional synthesis. Ages were calibrated into calendar years (cal. yr BP) and the periods represented by the pollen zones were calculated assuming a linear accumulation rate between calibrated radiocarbon dates. The six periods of site Huitziltepec and the seven periods of site Tixtla are presented versus time (Figure 8).

### Period I, c. 2700 to c. 2450 cal. yr BP (zone TXA-1)

Deepest sediments are clays, indicating a low-energy environment. At Tixtla, presence of aquatics (*Isoetes*), algal colonies (*Botryococcus*) and swamp taxa (*Polygonum*, *Ranunculus*, Cyperaceae) indicate lacustrine conditions. At the end of this period (at 355 cm core depth) the presence of small gravel shows that coarse material was supplied to the basin; this material might have originated from the steep slopes bordering the lake basin and might indicate incomplete vegetation cover. Presence of chlamydo spores of the fungus *Glomus* indicate eroded soils and supports this interpretation. Presence of, among others, Asteraceae, *Bursera*, *Chamaesyce*-type and *Protium* show that dry deciduous forest was abundant around the lake. Low representation of the mesophyllous forest taxa *Pinus*, *Alnus* and *Quercus* indicates this type of forest was poorly represented in the area, possibly restricted to higher elevations where the vegetation receives more moisture by condensation. We infer conditions significantly drier than today; either lower annual precipitation values and/or a longer dry season. Perhaps this is comparable with the intensive seasonal droughts present-day across Guerrero State, locally called ‘canícula’ (O’Hara and Metcalfe, 1997).

Only few pollen grains of crops plants (*Zea mays*, *Amaranthus* and *Chenopodium*) were counted, and spores of coprophilous fungi were absent: pre-Hispanic settlements did not cause a strong impact on the natural vegetation at that time.

### Period II, c. 2450 to c. 1950 cal. yr BP (zones TXA-2 and HTC-1)

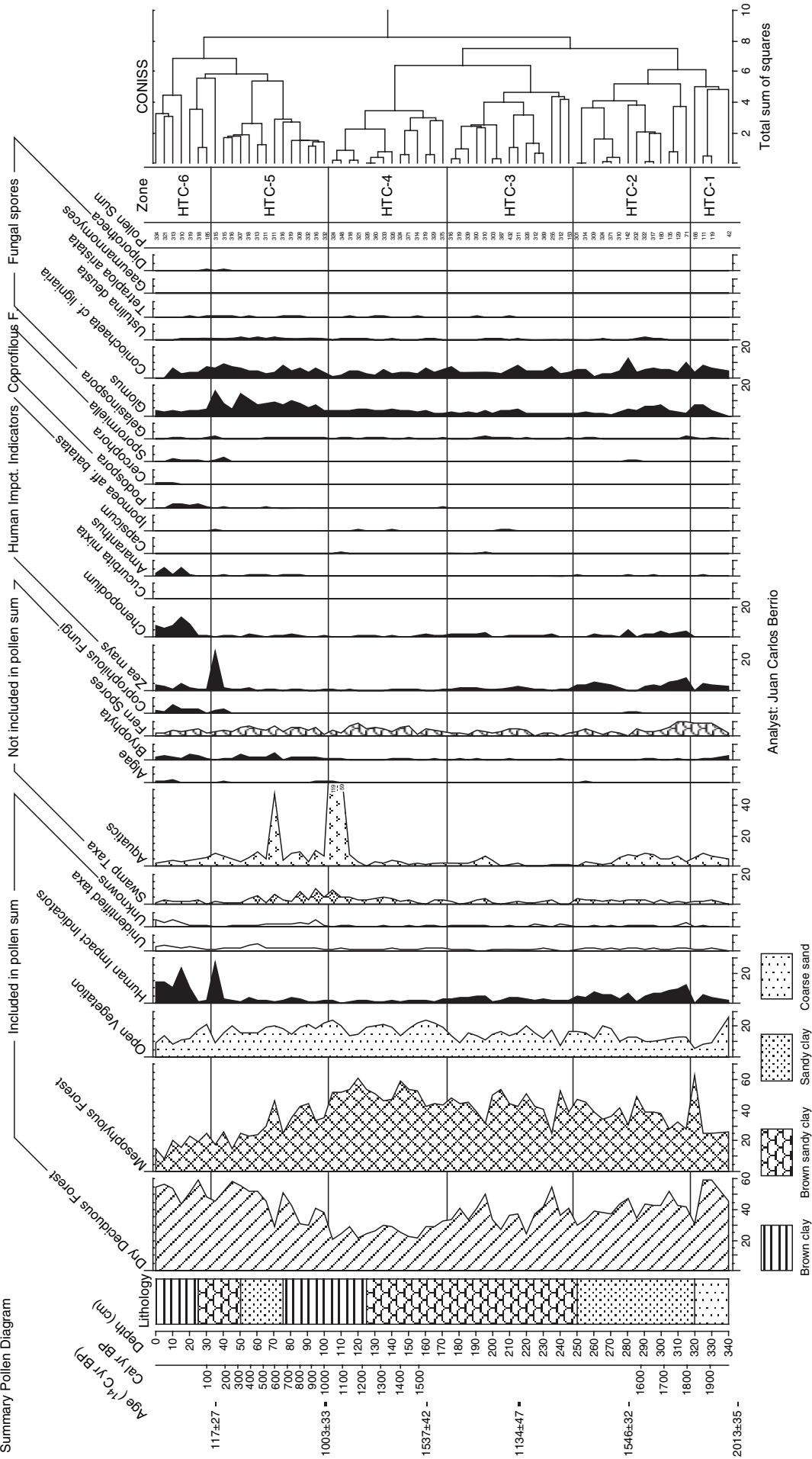
In the Tixtla basin, the accumulation of lacustrine clays continued, indicative of a quiet depositional environment. In the Huitziltepec basin, coarse sands accumulated during most of this period, but the record also shows presence of aquatics (*Isoetes*), algae and cyanobacteria (*Pseudoschizaea*, *Rivularia*) and swamp vegetation (Cyperaceae, *Cuphea*), indicating a lacustrine setting in a landscape with erosion and transport





# Huiziltepec

Summary Pollen Diagram



**Figure 7** Pollen diagram of the Huiziltepec core. From left to right: radiocarbon ages, depth, lithology, representation of ecological groups, sums of taxonomic groups not included in the pollen sum, human impact indicators, pollen sum values, pollen zones and the CONISS cluster dendrogram

of coarse material. Presence of algae, in particular, indicates that the basin was not part of a drainage system but rather an isolated water body. Presence of *Glomus* in the records of both basins also indicates eroded soils.

In the Tixtla basin, the proportions of dry deciduous forest and mesophyllous forest hardly changed compared with the previous period, but showed some fluctuations. In the Huitziltepec basin, the proportion of mesophyllous forest was larger but the floral composition (*Pinus* versus *Quercus*) was similar to the previous period. In both basins, the dry deciduous forest had a number of important taxa in common (Asteraceae, *Bursera* and *Chamaesyce*-type) but also showed a site-specific floral composition: *Crotolaria*, Leguminosae, *Protium* and *Solanum* at site Tixtla, and *Anacardium*, Bignoniaceae, *Dicliptera*, *LysilomalPithecellobium*-type at site Huitziltepec. Lake Huitziltepec is located near a mountainous area where mesophyllous forest might have been more abundant. At both sites open vegetation is mainly represented by grasses (Poaceae), which might have occupied open areas inside the dry and mesophyllous forests, a results of natural processes and/or low pressure of disturbance by the pre-Hispanic people. The proportion of human impact indicators is low in Tixtla (mainly *Amaranthus* and *Chenopodium*) and in Huitziltepec (mainly *Zea mays*), as is the presence of coprophilous fungi. Low population density is strongly suggested. We conclude that the dry climate conditions of period I continued in the area and the level of human occupation was low.

### Period III, c. 1950 to c. 1550 cal. yr BP (zones TXA-3 and HTC-2)

In the Tixtla basin the accumulation of lacustrine clays continued, indicating a quiet depositional environment. In the Huitziltepec basin, sandy clays accumulated on top of the coarse sands during this period, indicating a lower-energy depositional environment. The record also shows presence of aquatics (*Isoëtes*), algae and cyanobacteria (*Pseudoschizaea*, *Rivularia*) and swamp vegetation (Cyperaceae, *Pinguicula*, *Cuphea*, *Polygonum*) pointing to a lacustrine setting in a landscape with open sandy patches from where sand was still transported to the lake. Presence of algae points to an isolated water body, and *Glomus* in both basins indicate eroded soils.

In the Tixtla basin, dry deciduous forest decreased, Asteraceae and *Protium* in particular. Mesophyllous forest (*Quercus*, *Alnus*) increased significantly, pointing to more humid climatic conditions. At the same time, the proportion of open, grass-dominated vegetation (Poaceae) increased; this seems to be related to increased human impact on the landscape. The latter is indicated by an increase of crop plants (*Zea mays*, *Amaranthus* and *Chenopodium*) and coprophilous fungi (*Sporormiella*-type and *Coniochaeta* cf. *lignaria*). Domesticated herbivores were introduced by the Spanish some 500 years ago. Coprophilous fungi probably developed on human faeces, ‘guajolote’ (*Meleagris gallopavo*; turkey) and ‘xoloitzcuintle’ (*Canis* sp.; native dog) may have contributed substrate for these fungi.

During period III and later periods, ascospores of *Ustilina deusta* occur regularly in the Tixtla deposit. Fruit-bodies of this fungus appear at the base of host tree trunks and therefore less ascospores are released from closed forest than from forest that people opened for agriculture. We interpret the relatively high frequencies of *Ustilina deusta* in the Tixtla sequence as another indication of human impact.

Swamp and aquatic taxa decreased, suggesting lower water levels. This interpretation is supported by the increase in fungal spores that play an important role in the decomposition of

newly exposed organic material. This period constitutes the beginnings of the Huitziltepec record, it seems that here, too, dry deciduous forest was decreasing and floral composition was changing: *Chamaesyce*-type, *Euphorbia* and Myrtaceae increased while *Anacardium* and *Dicliptera* decreased in proportion; mesophyllous forest increased (the proportion of *Pinus* in particular). We again observed differences in the floral composition of the forest between the Tixtla and Huitziltepec basins. Nevertheless, it is plausible that vegetation changes were regional and coincided. The difference in time between pollen changes in Tixtla and Huitziltepec was only 60 calendar years, within the error of chronological control. The density of pre-Hispanic population in the study area apparently increased significantly ~1950 cal. yr BP.

### Period IV, c. 1550 to c. 1070 cal. yr BP (zones TXA-4 and HTC-3)

In the Tixtla basin, lacustrine clays continued to accumulate. An increase of *Zea mays* pollen shows intensified agricultural activities in the basin. In the Huitziltepec basin, sandy clays accumulated: apparently there were open (eroded) patches in the landscape that provided sandy material to the lake. Locally, there was also higher organic matter production, giving the sediments a brown colour. Both records show presence of aquatics (*Isoëtes*), algae and cyanobacteria (*Pseudoschizaea*, *Spirogyra*, *Rivularia*) and swamp vegetation (Cyperaceae, *Ranunculus*, *Polygonum*, *Pinguicula*, *Typha*, *Hydrocotyle*) pointing to lacustrine conditions. The presence of chlamydo-spores of the fungus *Glomus* in both basins indicates eroded soils in the catchment area.

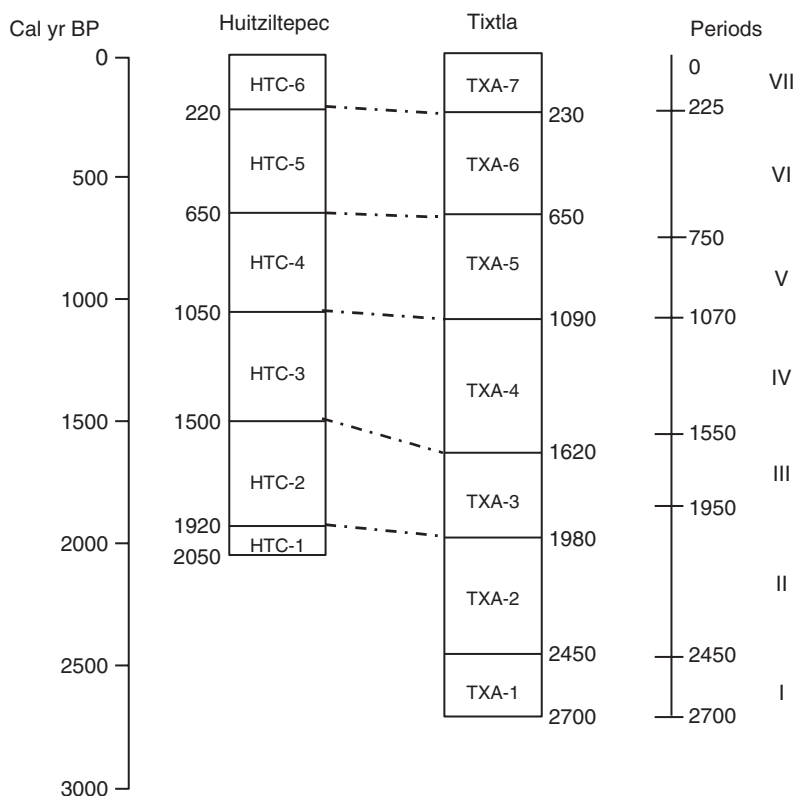
Dry deciduous forest continued to be scarce while mesophyllous forest reached maximal coverage during this period. At the Tixtla site, *Pinus* dominated whereas at Huitziltepec, *Pinus* was associated with a much higher proportion of *Quercus*, a common forest type in Mexico. *Alnus* and *Juglans* were associated taxa. Climate conditions remained more humid than today.

At the Tixtla site human impact indicators (*Zea mays*, *Amaranthus*, *Chenopodium*) reached their highest values, indicating important crop cultivation. The proportion of open vegetation (Poaceae) declined. According to O’Hara and Metcalfe (1997), moist climate conditions with a relatively short dry episode favours intensive crop cultivation. High proportions of spores of the coprophilous *Sporormiella*-type and *Coniochaeta* cf. *lignaria* also point to a high human population density. At the Huitziltepec site human occupation seems to have been less intensive than in the previous period. Presence of ascospores of *Gelasinospora* in both lake records may point to fires in the basins. Presence of *Rivularia*-type, belonging to cyanobacteria, points to phosphate eutrophication, indicative of intensive land use.

### Period V, c. 1070 to c. 750 cal. yr BP (zones TXA-5 and HTC-4)

In the Tixtla basin, lacustrine clays continued to accumulate in a quiet sedimentary environment. In the Huitziltepec basin, brown sandy clays changed to brown clays when swamp taxa (Cyperaceae, *Pinguicula*, *Polygonum*), aquatics (*Isoëtes*), algae and cyanobacteria (*Spirogyra*, *Rivularia*-type) became more abundant. Apparently, near the end of this period the Huitziltepec basin contained more water. The presence of *Glomus* indicates eroded soils.

At the Tixtla site, dry deciduous forest increased rapidly (accompanied by a strong increase in Asteraceae), while mesophyllous forest decreased. But soon proportions returned



**Figure 8** Comparison between time, on a linear calendar timescale, and environmental histories from the Tixtla and Huitziltepec cores, west-central Mexico (Guerrero State). Pollen zones in both cores are indicated. On the right, site-specific change is synthesized into six periods of regional change

to the situation of the previous period, ie, limited dry deciduous forest and abundant mesophyllous forest. This short oscillation seems characteristic of the Tixtla site, whereas the Huitziltepec site shows highest proportions of mesophyllous forest during this period, with abundant *Pinus*, *Quercus* and *Alnus*, and lowest proportions of dry deciduous forest. Thus, climatic conditions during this period seem as humid as during the previous period. At Huitziltepec the proportions of *Pinus* and *Quercus* are relatively stable while this is not the case at Tixtla. We interpret this difference as possible evidence of deforestation in the Tixtla basin.

At Tixtla, human impact indicators (*Zea mays*, *Amaranthus*, *Chenopodium*) showed lower values than during the previous period, suggesting that in this basin the use of forest products might have been more important than crop production. In the Huitziltepec basin crop production was still significant. Records of *Zea mays* and *Chenopodium* show only slightly lower values than during the previous period. High proportions of spores of coprophilous fungi in the Tixtla basin also point to a high pre-Hispanic population density. *Sporormiella*-type shows low values in the Huitziltepec basin and supports the interpretation that human occupation was less intensive here than in the Tixtla basin. Presence of *Gelasinospora* in the records of both lakes may point to fires. The presence of *Rivularia*-type during the last part of this period indicates phosphate eutrophication at both sites, reflecting intensive land use. Presence of *Glomus* at both sites indicates soil erosion.

#### **Period VI, c. 750 to c. 225 cal. yr BP (zones TXA-6 and HTC-5)**

The transition from period V to VI shows a discrepancy of 210 calendar years between the two basins. It is dated at 860 cal. yr BP in Tixtla and at 650 cal. yr BP at Huitziltepec. At this

transition, the most salient feature in the pollen records is the decrease of mesophyllous forest, while dry deciduous forest increased. This change is probably of regional significance. In both basins we can recognize three steps in the increase of dry deciduous forest and the corresponding decrease of mesophyllous forest. The age discrepancy between cores is probably due to insufficient chronological control, ie, inversions of radiocarbon dates. We use the average age of 750 cal. yr BP as the best estimate for the beginning of period VI.

In the Tixtla basin the lithological sequence showed several abrupt changes. There is a transition from grey clay to coarse sand, followed by a hiatus in sediment recovery of 20 cm. This hiatus is also seen from coarse sand that fell out of the coring device during core retrieval. The lithology at the Huitziltepec site also shows abrupt changes, from brown clay to coarse sand and back to brown sandy clay. Coarse sands in both basins are indicative of strong human disturbance in the immediate surroundings of the water body. This interpretation is supported by peaks in the record of *Glomus*, an indicator of eroded soils, and concomitant abrupt changes in the records of aquatics and swamp taxa.

At the Tixtla site, dry deciduous forest expanded again but became less abundant than during periods I and II. Mesophyllous forest decreased. At the Huitziltepec site a similar change in forest types is apparent and we conclude that the regional climatological conditions became drier. Dry forest was dominated by Asteraceae but relatively high proportions of *Celtis*, *Euphorbia*, *Gouania* and *Simarouba* show that the dry deciduous forest had a specific floral composition during this period. Mesophyllous forest consisted of mainly *Quercus*, *Pinus* and *Alnus*. During this period proportions of these taxa remained similar in the Huitziltepec basin, but changed appreciably in the Tixtla basin. We interpret this difference as

evidence for significant deforestation activities by pre-Hispanic people around Lake Tixtla. Presence of helophytic taxa, such as *Borreria* and *Agave*, and increased values of Poaceae, indicate open (deforested) areas. Intense human occupation in the Tixtla basin is also supported by presence of crops (*Zea mays*, *Amaranthus* and *Chenopodium*), and peak values of the erosion indicator *Glomus*. Presence of *Gelasinospora* may indicate frequent fires around the lake. The Spanish arrived in the study area during this period, some 500 years ago, and introduced domesticated herbivores. Ascospores of coprophilous *Podospora*, *Cercophora* and *Sporormiella*-type might indicate the density of human populations and reflect the contribution of dung by herbivores. Apparently the lakes became eutrophic, as indicated by blooms of cyanobacteria (*Anabaena* and *Rivularia*-type).

### Period VII, c. 225 cal. yr BP to present (zones TXA-7 and HTC-6)

In the Tixtla basin the lithological sequence changed from what was likely coarse sand in the hiatus, to sandy clay, indicating that erosion occurred widely around the lake. In the Huitziltepec basin sediments changed from brown sandy clay to brown clay, suggesting that the depositional environment was more quiet and stable during the last two centuries. Today the Tixtla basin is intensively used by local people and their cattle. The lake water is heavily polluted and the village of Tixtla, located at a few hundred metres from the lake, has a notable impact on the lake. In the Huitziltepec basin we observed people and cattle and signs of deforestation. Nevertheless, the nearest village is far from the shore, explaining the lower impact on this lake compared with Tixtla.

The Huitziltepec record shows that during the last few centuries dry deciduous forest increased (Asteraceae in particular, and *Arabidaee*-type, Bignoniaceae and *Senna* aff. *pallida* as specific components) while mesophyllous forest (with *Quercus*, *Pinus* and *Alnus* as main taxa) decreased. Much of the area must have been deforested and the high values of the human impact indicators (*Zea mays*, *Chenopodium*, *Amaranthus*) provide evidence that crop cultivation in open places was so intensive that grassy vegetation was limited. The record from Lake Tixtla shows an opposite trend, ie, decreasing dry deciduous forest and increasing mesophyllous forest. Because the Tixtla basin is so intensively used, the significance of this trend is puzzling. Recent plantations of *Pinus* in the area may bias the mesophyllous forest component. Similar to the Huitziltepec basin, the Tixtla basin has been deforested and the high values of human impact indicators (*Zea mays*, *Amaranthus*, *Capsicum*, *Chenopodium*) suggest that crop cultivation in open places was so intensive that open grassy vegetation could not expand.

## Discussion

Palaeoenvironmental reconstructions based on sediment cores from lakes Tixtla and Huitziltepec represent ecological change over the last c. 2700 cal. yr. It is unclear why the basins apparently do not possess sediments of earlier Holocene age. According to van Geel *et al.* (1996a) climatic conditions changed significantly at 2750 <sup>14</sup>C yr BP (c. 850 cal. yr BC). Van Geel *et al.* (1998) and van Geel and Renssen (1998) suggested that global climate changed and introduced drier conditions to the tropics after a decline in solar activity. In our study area, drier conditions might have led to significant input of sand into the lake basins, which prevented us from collecting

older sediments. Climate drying may also have led to the complete desiccation of the lakes, precluding lacustrine sedimentation.

There are clear signals of vegetation shifts related to climate change. In addition, there are also clear signals of human occupation in this area. The area around Lake Tixtla has experienced more intensive human occupation, in particular during the last 2000 years, and this record shows frequent anthropogenic perturbations on top of trends that are similar to those seen in the Huitziltepec record.

It is not surprising to see age–depth inversions in radiocarbon dates from lake basin sediments in an important agricultural centre. The record from the Huitziltepec basin includes only one age inversion, the date at 160 cm. The Huitziltepec basin had relatively little human impact and sediments have apparently accumulated in an orderly manner. The Tixtla basin, on the contrary, has for a long time been an important centre of human occupation, which began some 2400 cal. yr BP, a time when significant crop plants appeared in the record. The five radiocarbon dates from this record show three inversions. The ‘too old’ date at 230 cm is at a depth when intensified crop cultivation had just begun. In particular, maize culture had started. The second ‘too old’ age is at 70 cm depth. Just below this depth there was a sudden input of sands, possibly reflecting erosion of riparian soils. This inversion might be explained by the perturbations of the lake system by pre-Hispanic people. Notwithstanding problems with the radiocarbon dates, we were able to develop plausible chronologies for both basins that enabled us to interpret the timing of vegetation change over the whole study area.

In this study we used several lines of evidence to indicate human land use. Crop cultivation is documented by the presence of pollen grains of *Zea mays*, *Amaranthus*, *Capsicum* and *Chenopodium*. Human populations, and during the last 500 years also domesticated herbivores are indicated by ascospores of coprophilous fungi (‘dung fungi’) of *Podospora*-type, *Cercophora*-type and *Sporormiella*-type. Human activities around the lakes are further supported by deforestation of mesophyllous forest taxa (*Pinus*, *Alnus* and *Quercus*). Consequent soil erosion is shown by *Glomus*. Fires around the lakes are inferred from the presence of *Gelasinospora* spores. Finally, both water bodies became eutrophic by phosphate enrichment that induced nitrogen-limited growth conditions and caused blooms of cyanobacteria (*Anabaena*-type and *Rivularia*-type). The multiproxy approach in this study provides a detailed record of the local occupation history, and shows that pre-Hispanic populations were significant by ~2200 cal. yr BP. Archaeologists date the earliest sedentary Maya populations in southeastern Mexico to the Middle Preclassic period, c. 1000–300 BC (Turner, 1990; Rice and Rice, 1990; Brenner *et al.*, 2001). Our records from Guerrero show that sedentary land occupation was already present in the Huitziltepec basin by 2050 cal. yr BP. In the Tixtla basin, land occupation began even earlier, c. 2450 cal. yr BP, and expanded rapidly by around 1950 cal. yr BP.

Increasing climate drying during the first millennium AD may have contributed to the collapse of the Maya culture on Yucatan Peninsula around 1000 cal. yr BP (c. AD 950) (see the synthesis by Brenner *et al.*, 2001, and the literature therein). In our study area, the first millennium AD (periods III and IV; zones TXA-3 and 4; zones HTC-2 and 3) is characterized in both lake basins by a decreasing proportion of dry deciduous forest, a seemingly opposite trend to the Yucatan Peninsula. As the Guerrero records are the first on the dynamic character of the Mexican dry forest biome, is too early to speculate on the

climatological significance of this regional difference in signals. Our sites lie at ~1400 m elevation while the Yucatan sites are close to sea level. Wille *et al.* (2001) and Hooghiemstra and Van der Hammen (2004) showed that specific altitudinal intervals of the Andes respond differently to climate change. For example, in the Colombian Andes, the interval from 1000 to 1400 m altitude is less responsive to climatic change than higher and lower elevations.

The trend of increasingly drier climatic conditions at 20°N during the middle and late Holocene has been attributed to declining differences in seasonal insolation and to the southward migration of the Intertropical Convergence Zone (ITCZ), a phenomenon linked to the precession cycle of orbital change (Berger and Loutre, 1991; see also the synthesis by Brenner *et al.*, 2001). To which degree the migrations of the ITCZ play a role in explaining the moist and dry periods during the last two millennia we observed in central west Mexico is not clear and needs further exploration.

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