Pollen source areas of lakes with inflowing rivers: modern pollen influx data from Lake Baiyangdian, China

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ABSTRACT

Comparing pollen influx recorded in traps above the surface and below the surface of Lake Baiyangdian in northern China shows that the average pollen influx in the traps above the surface is much lower, at 1210 grains cm^{-2} a^{-1} (varying from 550 to 2770 grains cm^{-2} a^{-1}), than in the traps below the surface which average 8990 grains cm^{-2} a^{-1} (ranging from 430 to 22310 grains cm^{-2} a^{-1}). This suggests that about 12% of the total pollen influx is transported by air, and 88% via inflowing water. If hydrophyte pollen types are not included, the mean pollen influx in the traps above the surface decreases to 470 grains cm^{-2} a^{-1} (varying from 170 to 910 grains cm^{-2} a^{-1}) and to 5470 grains cm^{-2} a^{-1} in the traps below the surface (ranging from 270 to 12820 grains cm^{-2} a^{-1}), suggesting that the contribution of waterborne pollen to the non-hydrophyte pollen assemblages in Lake Baiyangdian is about 92%. When trap assemblages are compared with sediment–water interface samples from the same location, the differences between pollen assemblages collected using different methods are more significant than differences between assemblages collected at different sample sites in the lake using the same trapping methods. We compare the ratios of terrestrial pollen and aquicolous pollen types (T/A) between traps in the water and aerial traps, and examine pollen assemblages to determine whether proportions of long-distance taxa (i.e. those known to only grow beyond the estimated aerial source radius); these data suggest that the pollen source area of this lake is composed of three parts, an aerial component mainly carried by wind, a fluvial catchment component transported by rivers and another waterborne component transported by surface wash. Where the overall vegetation composition within the 'aerial catchment' is different from that of the hydrological catchment, the ratio between aerial and waterborne pollen influx offers a method for estimating the relative importance of these two sources, and therefore a starting point for defining a pollen source area for a lake with inflowing rivers.

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1. Introduction

Lacustrine pollen is an important proxy for reconstructing paleovegetation and paleoclimate, because pollen grains are usually well preserved in lake sediments (Sun and Wu, 1987; Gasse et al., 1991; Chen et al., 2006). Interpretation of the pollen signal and reconstruction of palaeovegetation is underpinned by assumptions about the spatial area reflected by the pollen signal and the taphonomy of different pollen types.

About thirty years ago, palynological researchers began to produce quantitative estimates of a pollen source area for basins of different sizes (Jacobson and Bradshaw, 1981). The Prentice model of pollen dispersal and deposition (Prentice, 1985) allowed simulation of aerial pollen taphonomy to be used to estimate quantitative source areas for individual pollen types (Prentice et al., 1987), defined as the radius around the basin from which a defined percentage of the pollen type originated. Sugita modified this taphonomic model to incorporate mixing of pollen across a lake surface, and defined a pollen source area for the whole pollen assemblage, the Relevant Source Area of Pollen or RSAP (Sugita, 1993, 1994). The RSAP is defined in terms of the Extended R-value approach, an iterative means of estimating the parameters of the pollen dispersal and deposition model from empirical data (Parsons and Prentice, 1981; Prentice and Parsons, 1983). Where

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vegetation data are available from multiple radii around the basin, the distance at which adding further vegetation data to the analysis leads to no improvement in the likelihood function score (a measure of goodness of fit between the fitted model parameters and the empirical data) is defined as the RSAP for the whole assemblage being studied. The Prentice–Sugita model of pollen dispersal and deposition is currently being used as the primary basis for various approaches to the quantitative reconstruction of past vegetation composition and abundance such as the Landscape Reconstruction Algorithm (Sugita, 2007a, b) and the Multiple Scenario Approach (Bunting and Middleton, 2009). Sugita (1994) explores the implications in terms of RSAP for lakes of different sizes, and demonstrates that large lakes (typically >500 ha in area) record regional vegetation as if it is homogenous, with no variations in response to the spatial organization of that vegetation. The REVEALS approach software (Sugita, 2007a; Hellman et al., 2008) uses this property to reconstruct vegetation for a region 100–200 km in radius around such large lakes, but assumes that aerial transport of pollen to the sampled basin is the main taphonomic route.

Most lakes have inflowing rivers, so waterborne pollen may also make a substantial contribution to the pollen influx to the lake (McAndrews and Power, 1973; Peck, 1973, 1974; Bonny, 1978; Sun and Wu, 1987; Traverse, 1992; Huang et al., 2004; Xu et al., 2005; Brown et al., 2007). In order to attempt quantitative reconstructions of past vegetation and paleoclimate from the sedimentary record in such lakes, it is important to understand the relative importance of the different components of the pollen taphonomy

and to characterize the spatial sensitivity of the record, the pollen source area.

Some empirical studies of pollen transport in rivers have been reported (e.g. Brush and Brush, 1972; Fall, 1981; Solomon et al., 1982). Flume experiments suggest that pollen grains will settle out into sediment when the water speed is lower than 0.3 m/s, and therefore that grains can remain in suspension and be transported long distance when the water speed is higher than 0.3 m/s (Brush and Brush, 1972). Pollen assemblages from the Yellow River and Luan River follow these trends (Xu et al., 1994, 1995, 1996).

In this paper, we present an empirical study of the airborne and waterborne pollen components which compares the pollen influxes of traps above and below the lake surface with samples from the upper layer of the water–sediment interface within the lake in order to investigate the possible pollen source area and pollen deposition dynamics of a lake with substantial inflows, Lake Baiyangdian in the North China Plain.

2. Study area

Lake Baiyangdian is the largest fresh water lake in the North China Plain (Fig. 1). It is located in Anxin County of Hebei Province (115°53′8.25″–116°6′9.64″E, 38°47′1.69″–38°59′22.78″N) and has a water area of 366 km^2 and maximum water depth of 5 m (Xu et al., 1988; Wang and Su, 2008). The lake has seven major inflowing rivers, the Baigou River (the longest at 275 km), Zhulong River, Tang River, Cao River, Xiaoyi River, Pu River and Fu River (the shortest at 62 km), which all originate in the Taihang Mountains
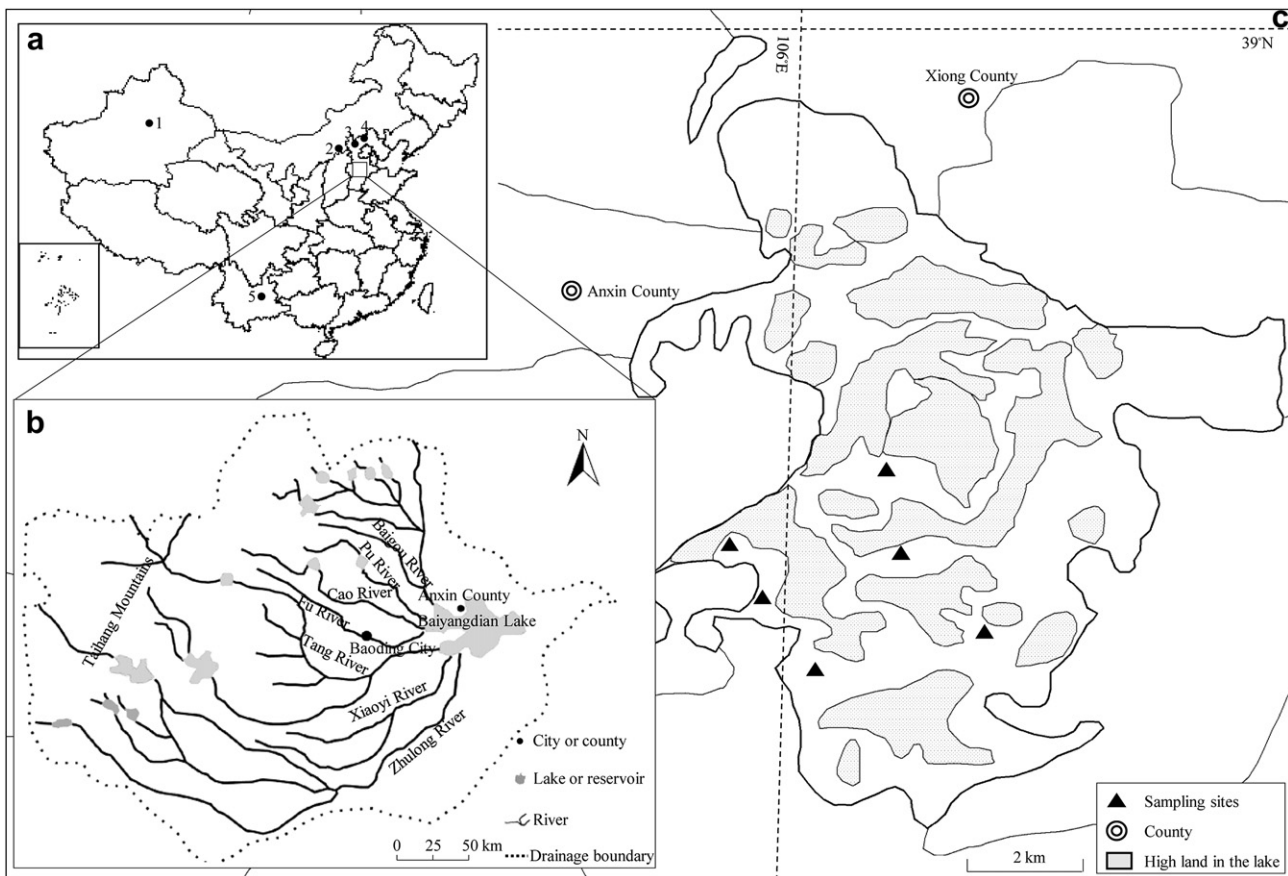

Fig. 1. Map of Lake Baiyangdian showing the locations of sampling sites. Inset a: the locations of study area and lakes mentioned in the text: 1, Lake Bosten; 2, Lake Daihai; 3, Lake Duikounao; 4, Lake Hulunnao; 5, Lake Dianchi. Inset b: the drainage area of Lake Baiyangdian modified from Liu et al., 2007. Insert c: map of Lake Baiyangdian, solid triangles show the trap sites.

(Fig. 1). The catchment of Lake Baiyangdian is about 31199 km^2 and drains about 34.46×10^8 m^3 of water annually; about one third of this volume of water actually enters the lake every year (Hebei Institute of Geography, 1983) (Fig. 1). Dense reedbeds of *Phragmites* grow on shallower areas within Lake Baiyangdian, and species of *Typha*, *Myriophyllum*, *Nelumbo*, *Nymphoides* and *Potamogeton* all colonise areas of open water (Xu et al., 1988).

Lake Baiyangdian lies in the warm temperate continental monsoon climate zone. The mean annual temperature is 12.1 °C with January means of −5.1 °C and July means of 26.3 °C. Mean annual precipitation is about 464 mm, about 55% of which falls between July and August. These climate data were calculated on the basis of the daily weather records from the year of 1981 and 2000 of the meteorological station of Gaoyang County, 20 km away from Lake Baiyangdian. During the sampling year, the total annual precipitation was 430 mm, >60% of which fell as rain in August of 2006 and July of 2007, and no recorded flooding occurred (climate data come from Hebei Province Meteorological Bureau), therefore it can be considered a representative year.

The potential vegetation of the area is temperate broad-leaved deciduous forest, but the area is heavily modified by human activity, with only small patches of plantation or secondary forests surviving in the western mountain areas. Most areas of the plain below 100 m altitude in the catchment of Lake Baiyangdian are cultivated. Planted *Populus*, *Salix*, *Ulmus*, *Sophora*, *Ailanthus* and other trees are scattered in the towns, the villages and along the roads (Fig. 2).

In the hilly areas and foothills between 100 and 800 m a.s.l., the main vegetation type is brushwood and grassland, dominated by *Vitex negundo*, *Ziziphus jujube*, *Bothriochloa ischaemum*, *Themeda triandra*, *Leapedeza bicolor* and *Spiraea salicifolia*. *Platycladus orientalis*, *Pinus tabuliformis*, *Cotinus coggygria* and *Robinia pseudoacacia* can be dominant in areas with high soil moisture whilst *Malus sieversii*, *Pyrus* spp., *Zizyphus jujube*, *Amygdalus persica*, *Juglans regia* and *Diospyros kaki* are often planted in and around villages. Between 800 and 1500 m a.s.l., mixed temperate forests still dominate, mainly consisting of *Pinus* and *Quercus*, with *Betula*, *Populus davidiana* etc., and are replaced between 1500 and 2000 m a.s.l. by mixed forests of *Betula* and *Picea meyeri*. Between 2000 and 2500 m a.s.l., coniferous forest dominated by *Larix principis-rupprechtii* forms the upper forested zone and above 2500 m a.s.l. by subalpine meadow dominated by *Kobresia bellardii*, *Carex tristachya*, *Ptilagrostis* spp., *Polygonum viviparum* and *Saussurea stella* (Editing Committee of Hebei Vegetation, 1988).

3. Methods

The study was designed on the assumption that pollen entered the lake by two main routes, via aerial and water transport. The pollen grains in the traps above the lake water level are assumed to be transported by wind, pollen grains in the traps below the water surface could have been transported by wind and water, and pollen assemblages in the surface sediment are assumed to be a mixture of pollen grains transported by both wind and water which has
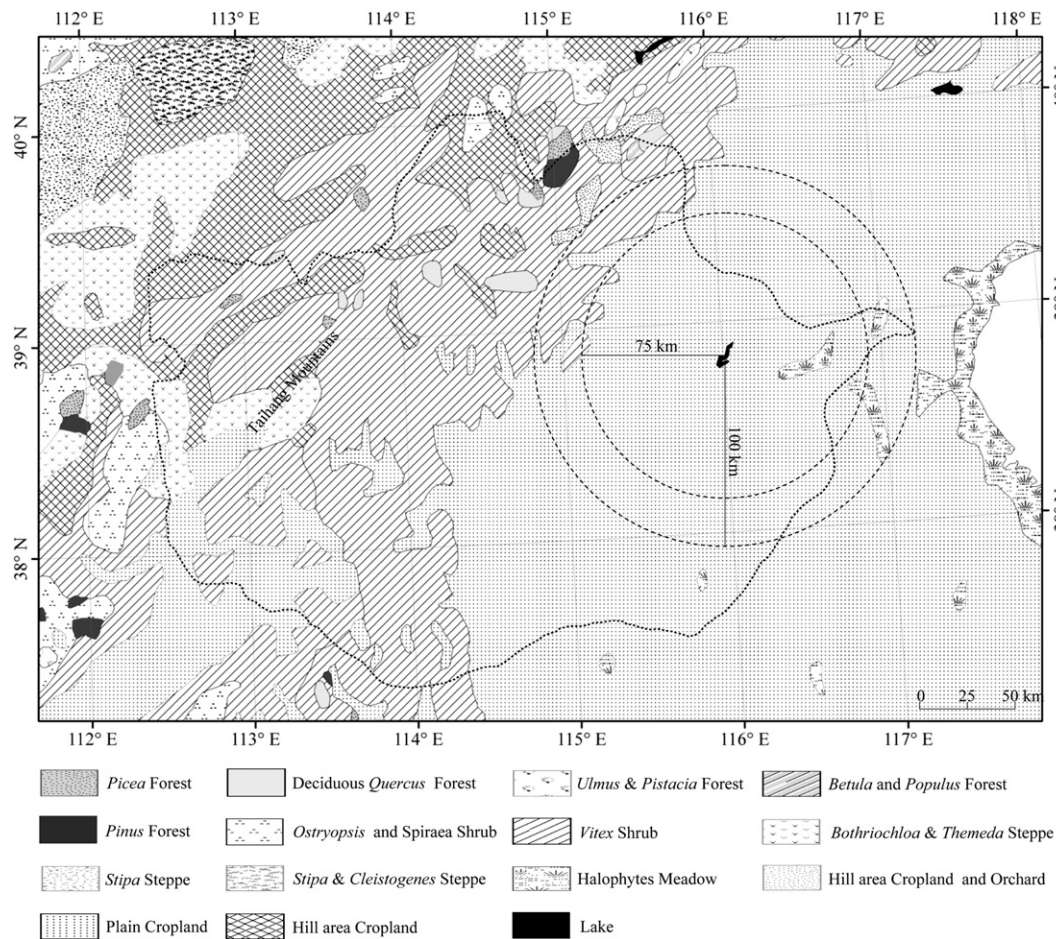

Fig. 2. Vegetation map of the study area (modified from Institute of Botany of the Chinese Academy of Sciences, 1979) and the locations of Lake Baiyangdian. Two concentric circles represent potential aerial pollen source radius.

accumulated over several years. Water transported pollen could either be carried in via the rivers or through overland flow.

3.1. Field work

In order to determine the contribution of airborne and water-borne pollen to the pollen assemblages of Lake Baiyangdian, tauber traps (Tauber, 1967) were placed in pairs. One trap was placed 30–40 cm above the water surface and the second trap was placed below the water surface in areas with water depth 1.5–2 m with the trap opening 60 cm above the lakebed to minimise contributions from resuspended lake sediment (Tian et al., 2008). A surface sediment sample (the top 2–3 cm) was collected near each trap pair using a specially-made sampler (with four holes in the top and a moving valve in the bottom). Ten pairs of traps were placed in July, 2006, but only six pairs were retrieved in July, 2007 (locations shown in Fig. 1). Data from these six locations are considered in this paper.

3.2. Laboratory work

Ten gram subsamples of lake surface sediment were treated to concentrate pollen as described by Faegri and Iversen (1989). The trap samples were first sieved through 200 μm mesh screens to remove insects, small animals (lizards) and coarse plant remains, and then one *Lycopodium* tablet (27637 ± 563 grains) was added as tracer to each sample. After that, samples were treated with 10% NaOH, washed with distilled water and acetolysis carried out using a mixture of acetate anhydride and sulphuric acid in the ratio 9:1. Finally samples were washed with distilled water and centrifuged before being mounted on slides in glycerine for counting. All samples were counted with a BX-51 Olympus light microscope at 400× magnification and more than 400 pollen grains were counted for each sample.

3.3. Calculation of pollen influx of trap sample

Pollen influx was calculated as following:

$$\text{Pollen influx of type } i \left(\text{grains cm}^{-2} \text{ a}^{-1} \right) = \left(P_{ij} \times N \right) / \left(C_j \times S \right) \quad (1)$$

Where P_{ij} = count of pollen type i in sample j; N = number of *Lycopodium* added to the sample; C_j = count of *Lycopodium* tracer in sample; S = opening area (cm^2) of Tauber trap. In this study, the diameter of the openings in traps above the water level was 5.2 cm, and of traps below the water level was 7.8 cm.

3.4. Statistical analysis

Discriminant Analysis and Cluster Analysis are effective methods of measuring the similarities and dissimilarities among pollen assemblages (Liu and Lam, 1985; Lynch, 1996; Reese and Liu, 2005). Here, Discriminant Analysis and Cluster Analysis were carried out on a dataset of pollen percentages of 15 major taxa, including *Pinus, Betula, Quercus, Populus, Salix, Ulmus*, Elaeagnaceae, *Ostryopsis, Artemisia*, Poaceae, Chenopodiaceae, Compositae, *Humulus, Urtica* and *Polygonum*. Discriminant Analysis was carried out in SPSS and grouping validity was analyzed via a stepwise method. The Bray Curtis coefficient was used to quantify the pollen assemblage dissimilarity between sample pairs (Bray and Curtis, 1957; Legendre and Legendre, 1998) in Cluster Analysis, which was carried out in MVSP 3.1 (Pei, 1990; Xu et al., 2007).

4. Results

4.1. Pollen source areas of Lake Baiyangdian

4.1.1. Source areas of airborne pollen

Pollen fall speeds were calculated according to the methods provided by Duffin and Bunting (2008) (Table 1). Percentage pollen source areas of major taxa were then calculated using the Sutton distance weighting model (Prentice et al., 1987) (Fig. 3). As the outline of Lake Baiyangdian is crescentic, we estimated the lake radius as half of the maximum lake width in the sampling area (4125 m). Wind speed is usually assumed to be constant in many studies (Sugita, 1994; Sugita et al., 1999; Broström et al., 2004; Bunting et al., 2004), but changes in modeled wind speed have obvious influence on model outputs (e.g. Mazier et al., 2008). Therefore, in this paper, percentage pollen source areas of 13 major pollen types (*Artemisia*, Chenopodiaceae, Poaceae, *Urtica, Pinus, Quercus, Salix, Betula, Ulmus, Populus, Elaeagnus, Ostryopsis* and Compositae) were calculated based on wind speed of 2.1 m s^{-1} (annual mean wind speed) and 3.2 m s^{-1} (mean wind speed in April, annual maximum) respectively and compared.

Percentage pollen source area decreases with increasing fall speed. If the pollen source area for the whole assemblage is defined as the distance where the rate of increase of pollen contribution of almost all pollen types no longer increases substantially with increasing distance, then these results imply that this distance is about 75 km when the annual mean wind speed 2.1 m s^{-1} is used, and 100 km with a wind speed of 3.2 m s^{-1}. Since 9 of the 13 pollen taxa originate from trees or shrubs, the corresponding plants usually flower in spring when the wind is stronger in the Baiyangdian area, and we suggest that 100 km radius is the better estimate of the airborne pollen source area for Lake Baiyangdian using this definition. 'Local' vegetation is therefore that found within 100 km, whilst vegetation beyond 100 km is considered regional. Most of the local area is the North China Plain. The border with the mountain area to the west occurs about 100 km from the lake (see Fig. 1). Pollen of *Populus, Salix, Ulmus* and *Ailanthus*, which are planted in towns, village and roads in the plains area, will mainly originate within the local pollen catchment, whilst *Pinus, Betula, Quercus, Elaeagnus* and *Ostryopsis* which grow in the mountain area are considered regional pollen taxa.

4.2. Pollen assemblages and pollen influx

69 pollen types were identified from the 18 samples (Figs. 4–6 show the main pollen types). Some entomophilous pollen types such as Caryophyllaceae, Leguminosae, Liliaceae, Iridaceae,

Table 1
Fall speed (m s^{-1}) of major pollen types.

Pollen types	Fall speed (m s^{-1})	Reference
Artemisia	0.015	This paper[a]
Chenopodiaceae	0.029	This paper[a]
Poaceae	0.035	a
Urtica	0.008	This paper[a]
Pinus	0.031	b
Quercus	0.042	This paper[a]
Salix	0.022	c
Betula	0.031	This paper[a]
Ulmus	0.032	c
Populus	0.020	This paper[a]
Elaeagnus	0.048	This paper[a]
Ostryopsis	0.025	This paper[a]
Compositae	0.051	d

a, Sugita et al., 1999; b, Eisenhut (1961); c, Gregory (1973); d, Broström et al. (2004).
[a] The pollen fall speed of each pollen type is calculated using the geometric method outlined in Gregory (1973) based on measurements of axis length for 100 pollen grains from samples collected in Lake Baiyangdian.
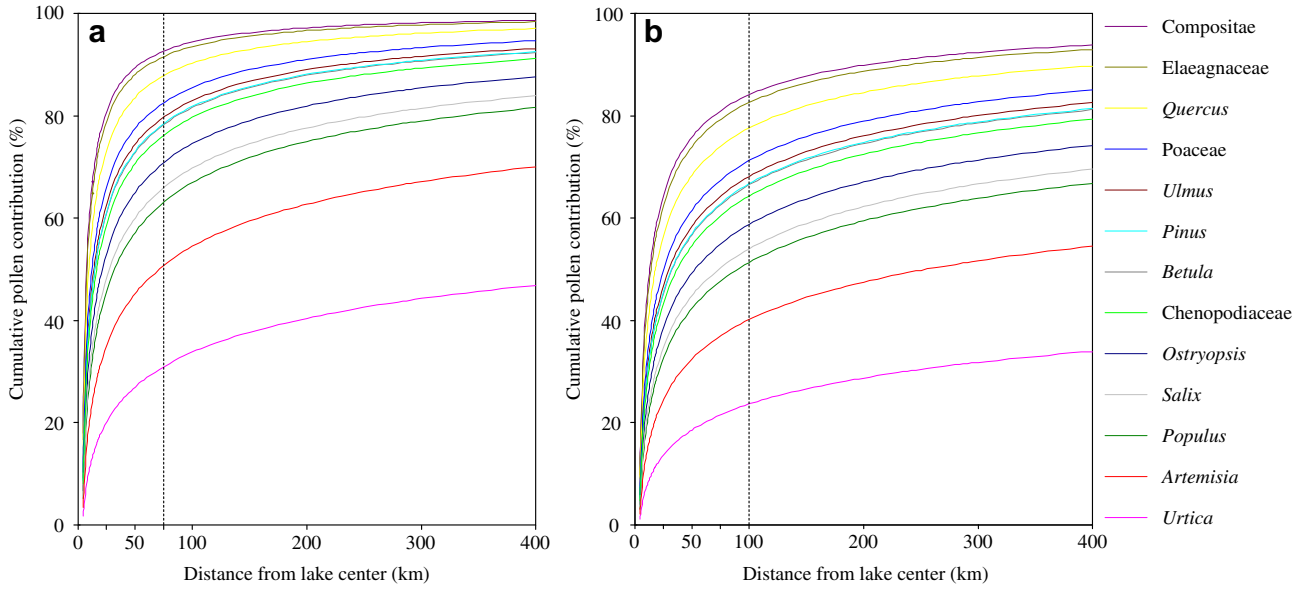
Fig. 3. The relationship between pollen source radius and the contributions of certain pollen taxon coming from the source distance to the overall pollen loading of that taxon. The dashed line indicates a potential pollen source radius for major pollen types of Lake Baiyangdian. a: wind speed, 2.1 m s^{-1}, b: wind speed, 3.2 m s^{-1}.

Malvaceae and *Spiraea* were not recorded in the traps below the water surface, whilst some large-grained taxa such as *Picea* and *Abies* only appeared in the traps below the water surface (Table 2). Proportions of mountain arboreal and shrubby pollen types are higher in traps above the water surface than the traps below the water surface (Table 2).

Traps positioned above the water surface record 56 taxa (Table 2), of which 36% are mountain types. The mean non-hygrophyte pollen influx is 470 grains cm^{-2} a^{-1} (range 170–910 grains cm^{-2} a^{-1}) and the mean hygrophyte pollen influx is 740 grains cm^{-2} a^{-1}, range 380–1860 grains cm^{-2} a^{-1}.

Traps positioned below the water surface record 52 types (Table 2), 24% of which are mountain types. The mean non-hygrophyte pollen influx is 5470 grains cm^{-2} a^{-1} (range 270–12820 grains cm^{-2} a^{-1}) and the mean hygrophyte pollen influx is 3520 grains cm^{-2} a^{-1} (range 160–9490 grains cm^{-2} a^{-1}).

Sediment-water interface samples contained 55 pollen types (Table 2), of which 13% are mountain types.

4.3. Comparison of pollen assemblages

The cross-validation process within the Discriminant Analysis shows that the accuracy rates are all higher than 80%, indicating credible results (Table 3, Fig. 7). The results show that the three types of samples were clearly distinguished, and suggest that location within the site is a less important control on pollen assemblage composition than sampling method. Results of Cluster Analysis are presented in Fig. 8, and Bray–Curtis dissimilarity
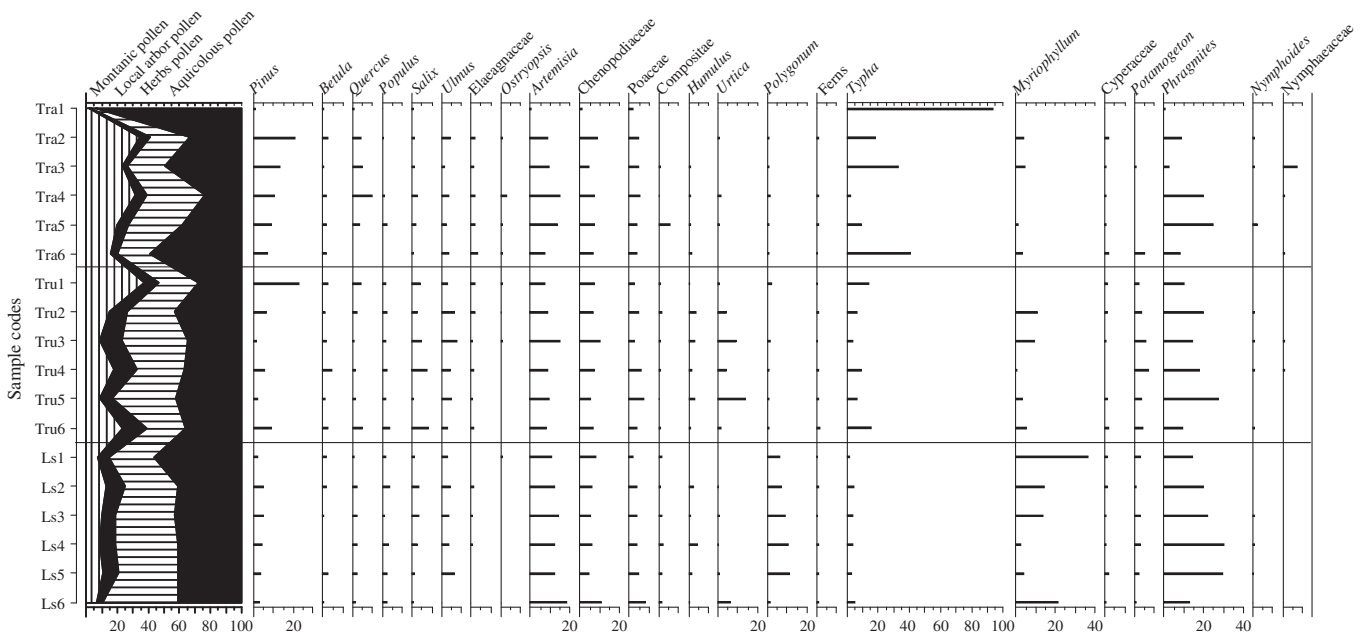

Fig. 4. Percentage pollen diagram (%) of the major pollen types recorded in samples from Lake Baiyangdian. Tra: Trap above water surface; Tru: Trap below water surface; Ls: Surface sediment.

Fig. 5. Pollen influx (×100 grains cm^{-2} a^{-1}) of the major pollen types recorded in samples from Lake Baiyangdian. Tra: Trap above water surface; Tru: Trap below water surface.

coefficients for all samples are shown in Table 4. The results of Cluster Analysis (Fig. 8) show that pollen assemblages from traps below the water surface are more similar to those from lake surface sediment than those from aerial traps.

5. Discussion

One striking characteristic of the pollen assemblages presented here is that some large-grained taxa such as *Picea* and *Abies* are only recorded in the traps below the water surface, whilst some entomophilous pollen types such as Caryophyllaceae, Leguminosae, Liliaceae, Iridaceae, Malvaceae and *Spiraea* were only recorded in traps above the water surface (Table 2). *Picea* and *Abies* plants are not found in the North China plain but do grow in the Taihang Mountains (Fig. 2). Both types are large grains, with fall speeds in excess of all the taxa modeled in Fig. 2 (see also Table 1) − Jackson and Lyford (1999) review the available literature and give median fall speeds of 0.100 m s^{-1} for *Abies* and 0.052 m s^{-1} for *Picea* − so the estimated aerial percentage pollen source area of these taxa is

less than 100 km. *Picea* pollen is usually interpreted as a water-transported pollen type in the sedimentary record (Li, 1991; Huang et al., 2004). The absence of *Picea* and *Abies* from the aerial trap pollen assemblages is in accordance with these data, since the large distance from the source in the Taihang Mountains means that their contribution to the aerial pollen signal will be very small and unlikely to be detected in a count of a few hundred grains. Their presence in the underwater traps and surface sediment samples supports our argument that these traps contain a substantial element transported by river from Taihang Mountains.

The presence of entomophilous taxa in only the aerial traps illustrates one of the disadvantages of using Tauber traps as a proxy for lake sediment records. Insects enter the traps in pursuit of food, shelter or to drink the water that accumulates, and either shed some of their pollen load or become trapped and die within the trap, leading to enhanced representation of both obligate and facultative entomophilous pollen taxa. The overall proportion of these types is not large, suggesting that in this case insect-borne pollen is only a minor component of the aerial trap assemblage.

Fig. 6. Percentage pollen diagram (%) of the major pollen types after excluding hydrophyte pollen of the major pollen types recorded in samples from Lake Baiyangdian. Tra: Trap above water surface; Tru: Trap below water surface; Ls: Surface sediment.

Table 2
Summary of pollen assemblages of three kinds of samples.

	Common taxa	Aerial trap	Trap below water	Surface sediment
Mountains trees and shrubs	*Pinus*, *Betula*, *Juglans*, *Quercus*, *Cotinus*, Rhamnaceae, Oleaceae, *Nitraria*, *Ostryopsis*, Elaeagnaceae	Moraceae, *Pteroceltis*, *Spiraea*, *Vitex*	*Picea*, *Abies*, *Acer*, *Alnus*, *Carpinus*, *Celtis*, *Pteroceltis*, *Tilia*, *Corylus*	*Alnus*, *Celtis*, *Picea*, *Carpinus*, Moraceae, *Corylus*, Cornaceae
Woods both in plains and mountain	*Populus*, *Salix*, *Ulmus*, *Ailanthus*, *Tamarix*			
Mountain herbs	*Thalictrum*, Ranunculaceae	Campanulaceae, Caryophyllaceae, Iridaceae, *Pedicularis*	Campanulaceae, *Sanguisorba*	Geraniaceae, Iridaceae, Scrophulariaceae
Herbs both in plains and mountain	*Artemisia*, Chenopodiaceae, Compositae, Convolvulaceae, *Humulus*, Labiatae, Poaceae, Rosaceae, Cucurbitaceae, *Urtica*, Solanaceae, *Polygonum*	Leguminosae, Liliaceae, Malvaceae	Cruciferae	Cruciferae, Leguminosae, Plantaginaceae, Umbelliferae
Plains Aquatic plants	Cyperaceae, *Myriophyllum*, *Phragmites*, *Potamogeton*, *Nymphoides peltatum*, *Typha*	Nymphaeaceae	Nymphaeaceae	

Discriminant Analysis reveals that the differences between pollen assemblages collected using different methods are more significant than differences between assemblages collected at different points in the lake (Fig. 7), and Cluster Analysis (Fig. 8) shows that the pollen assemblages in traps below the surface are relatively similar to those from sediment samples, but differ from the pollen assemblages trapped above the surface. The results of both analyses suggest that transport agents have significant effect on the lacustrine pollen assemblage.

5.1. Pollen transport mechanisms in Lake Baiyangdian

A simple model of the pollen sources for a lake with inflowing streams is given by:

$$L = A + W \tag{2}$$

Where L: lacustrine pollen; A: airborne pollen; W: waterborne pollen

In this study, aerial traps record the aerial component for the year July 2006 to July 2007, the A_{2006-7} component. Traps in the water column record both A_{2006-7} and W_{2006-7}, and sediment samples contain both A and W for an unknown number of years prior to sample collection in 2007.

Comparing aerial traps (mean pollen influx 1210 grains $cm^{-2} a^{-1}$) and traps in the water column (mean pollen influx 8990 grains $cm^{-2} a^{-1}$) allows calculation of an estimate of W_{2006-7} at 7490 grains $cm^{-2} a^{-1}$, suggesting that airborne pollen accounts for around 12% of the total pollen influx to Lake Baiyangdian in 2006–7. When hygrophyte pollen types are removed from the influx data, W_{2006-7} is estimated as 5470 grains $cm^{-2} a^{-1}$ and airborne pollen makes up only about 8% of the total influx into Lake

Baiyangdian in 2006–7. Peck (1973) reports that the waterborne component in Lake Oakdale is up to 97% of the total pollen count, and Bonny (1978) finds that 87% of the pollen assemblage in Blelham Tarn is probably transported by rivers; despite the size difference between the lakes studied, the findings are similar to those from Lake Baiyangdian. The primary control on the proportion of aerial to waterborne pollen is likely to be the ratio between river length/input and lake surface area (the aerial pollen 'trap'), rather than lake size directly.

Hydrophyte plants such as Cyperaceae, *Phragmites*, *Typha* and Nymphaeaceae grow in shallower parts of the lake basin (Fig. 1c) and in the lake margins, and can also be found in suitable habitats in the wider landscape and in ditches, albeit in much smaller numbers, and they produce pollen above the water allowing for aerial dispersal mechanisms. In the aerial traps, the ratio of pollen types from obligate dry-land plants to hydrophytic plants (T/H) will broadly reflect the vegetation in the local area since the hydrophytes mainly originate within and adjacent to the lake and the aerial pollen source area is estimated as confined to the North China Plain. This can be contrasted with the pollen assemblages from the underwater traps or the sediment, where the hydrophyte pollen could have originated from the same aerial sources, from overland flow (which will bring in both hydrophyte pollen and aerially transported pollen which has landed on the ground surface from the local area around the lake) or from river flow in the aerial pollen source radius (which will include some hydrophyte pollen from the river margins). If overland flow dominates the waterborne pollen signal, the T:H ratio is expected to be similar for aerial traps and underwater traps. If river-borne pollen is significant in the waterborne component we would expect the T:H ratio to be higher than in the aerial traps. For aerial traps, the mean T:H is 0.64, whilst for underwater traps it is 1.55, supporting the argument that river-borne pollen makes a significant contribution to the assemblages in the water column. However, the proportionate increase in terrestrial types is not as large as would be expected if no overland flow contributed to the pollen assemblages suggesting that overland flow from the local area might be an important fraction of the waterborne pollen assemblage and Eq. (1) should be written as:

$$L = A + W_o + W_r \tag{3}$$

Where L = Lacustrine pollen; A = airborne pollen; W_o = waterborne pollen from overland flow and W_r = fluvial waterborne pollen

Assuming that the T:H ratio from the aerial traps is also a good estimate for the overland flow component, it is possible to estimate constants for Eq. (3) for Lake Baiyangdian as:

$$L = 0.09A + 0.33\,W_o + 0.58\,W_r \text{ (see appendix for calculations)}$$

Table 3
Classification results of discriminant analysis of all samples.

		Sample codes	Predicted group membership			Total
			1	2	3	
Original	Count	1	6	0	0	6
		2	0	6	0	6
		3	0	0	6	6
	%	1	100	0	0	100
		2	0	100	0	100
		3	0	0	100	100
Cross-validated	Count	1	5	0	1	6
		2	0	6	0	6
		3	1	0	5	6
	%	1	83.3	0	16.7	100
		2	0	100	0	100
		3	16.7	0	83.3	100

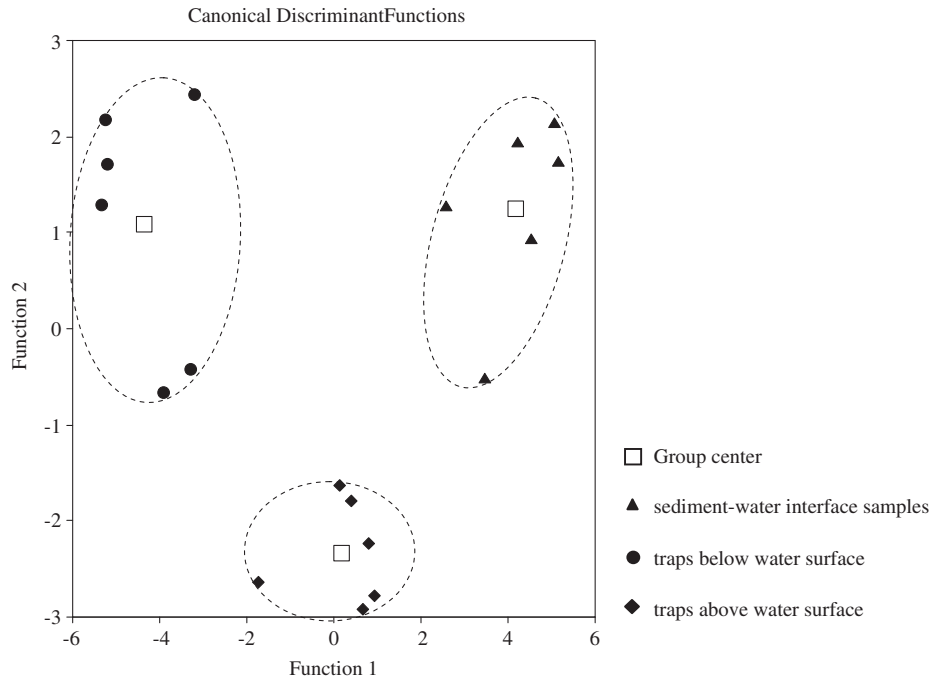Canonical DiscriminantFunctions

Fig. 7. Results of Discriminant Analysis of the three types of pollen sample.

These are crude initial estimates only. Overland flow is particularly tricky to investigate, and pollen transported by overland flow may have been exposed to oxidative degradation whilst lying on the ground surface for some months, leading to a reduction in proportions of less robust pollen types such as Cyperaceae. However, this equation sets up a useful hypothesis for testing in future research.

5.2. The source area of major pollen taxa in Lake Baiyangdian

Assumptions about pollen transporting agencies and pollen source areas are key components when reconstructing palae-ovegetation and palaeoclimate from lake sediment pollen records. Current pollen dispersal and deposition models seem to be able to estimate pollen source area quite effectively for lakes without inflowing rivers, but such sites are rare in nature. In this study, we

estimate the percentage aerial pollen source area of common pollen taxa in Lake Baiyangdian to be about 100 km radius. The Taihang Mountains lie beyond this distance, but inflowing rivers carry mountain pollen taxa which are incorporated into pollen traps placed below the water surface and into surface sediment pollen assemblages, but are absent from aerial pollen traps. In reconstructing palaeovegetation and palaeoclimate from lacustrine pollen records from sites with inflowing rivers, it is important to consider that the fossil pollen assemblages could contain a large portion of waterborne pollen, which has a source area of the entire drainage area, rather than aerially transported pollen, which is assumed to have a roughly circular source area.

The potential aerial pollen area of Lake Baiyangdian is occupied by the North China Plain which is vegetated with cultivated plants (mainly wheat and maize) (Fig. 2). These taxa typically have low pollen productivities compared to trees, the grains are
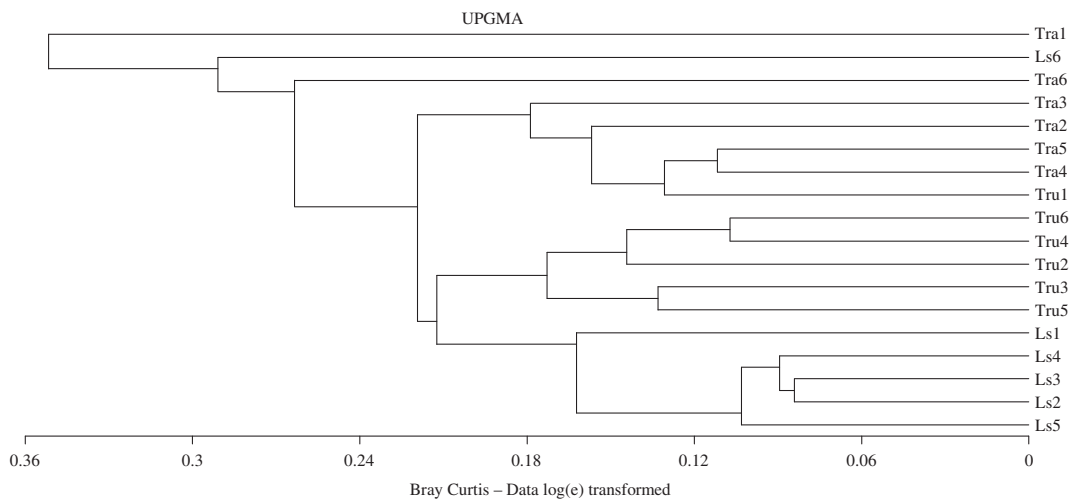
UPGMA

Fig. 8. Results of Cluster Analysis using the Bray Curtis dissimilarity coefficient using UPGMA clustering method on pollen data transformed by log(e). Tra: Trap above water surface; Tru: Trap below water surface; Ls: Surface sediment.

Table 4
Bray–Curtis dissimilarity of pollen assemblages between samples.

	Tra1	Tru1	Ls1	Tra2	Tru2	Ls2	Tra3	Tru3	Ls3	Tra4	Tru4	Ls4	Tra5	Tru5	Ls5	Tra6	Tru6	Ls6
Tra1	0																	
Tru1	0.320	0																
Ls1	0.375	0.231	0															
Tra2	0.270	0.133	0.274	0														
Tru2	0.365	0.205	0.280	0.224	0													
Ls2	0.356	0.171	0.164	0.232	0.172	0												
Tra3	0.295	0.190	0.316	0.197	0.226	0.215	0											
Tru3	0.432	0.211	0.226	0.285	0.158	0.186	0.316	0										
Ls3	0.359	0.197	0.155	0.258	0.190	0.084	0.203	0.212	0									
Tra4	0.306	0.127	0.264	0.162	0.181	0.185	0.150	0.211	0.197	0								
Tru4	0.322	0.199	0.264	0.217	0.121	0.145	0.250	0.156	0.180	0.200	0							
Ls4	0.428	0.245	0.182	0.304	0.191	0.086	0.225	0.236	0.093	0.240	0.214	0						
Tra5	0.349	0.134	0.209	0.175	0.143	0.171	0.178	0.222	0.186	0.112	0.178	0.196	0					
Tru5	0.410	0.273	0.311	0.267	0.148	0.205	0.291	0.133	0.230	0.237	0.142	0.235	0.241	0				
Ls5	0.371	0.218	0.148	0.253	0.199	0.101	0.240	0.221	0.085	0.211	0.186	0.123	0.197	0.203	0			
Tra6	0.361	0.264	0.294	0.201	0.258	0.248	0.228	0.268	0.296	0.209	0.261	0.325	0.246	0.291	0.283	0		
Tru6	0.297	0.121	0.273	0.173	0.167	0.139	0.196	0.216	0.194	0.132	0.107	0.218	0.125	0.217	0.203	0.280	0	
Ls6	0.357	0.336	0.268	0.363	0.263	0.305	0.307	0.258	0.259	0.314	0.244	0.287	0.272	0.218	0.259	0.409	0.293	0

comparatively large and therefore have a short aerial transport distance (Cerealia fall speeds are estimated at 0.060 m s^{-1} and *Zea mays* fall speeds around 0.100 m s^{-1}, Sugita et al., 1999), and Poaceae grains also have relatively poor pollen preservation (Ma et al., 2008; Zheng et al., 2008). These facts mean that these communities would be expected to be under-represented in a pollen record relative to the scrub and woodland vegetation of the Taihang Mountains which will probably have the effect of reducing the aerial contribution to the lake pollen record relative to the fluvial component. Whilst the numerical values for proportions of different components in the record are specific to the present-day landscape, climate and taphonomy of Lake Baiyangdian, the complexity of the pollen signal forming process illustrated by these data is widely applicable to lake records past and present.

5.3. Comparison with previous studies

The pollen influx of lakes with no inflow channel is lower than that of sites with an inflow (e.g. Pennington, 1979), which indicates that the pollen brought by river and stream contributes to lake pollen assemblages. Tauber traps are designed as empirical models of pollen assemblage formation in a lake, and this study's findings from aerial and submerged traps show, as expected, higher influx in traps affected by the inflow. Various studies find that inflowing rivers can be the main source of pollen in a lake system (Cross et al., 1966; Peck, 1973; Bonny, 1976, 1978; Vincens and Bonnefille, 1988; DeBusk, 1997). For example, surface sediment pollen studies of three large lakes (Lake Dianchi, Lake Daihai and Lake Bosten) and two relatively small lakes (Lake Duikounao and Lake Hulunnao) in China (see Fig. 1) show that pollen carried by the rivers has a clear effect on the lacustrine pollen assemblages (Sun and Wu, 1987; Huang et al., 2004; Xu et al., 2005; Tian et al., 2008). Pollen influx data from pollen traps allows better quantification of the relative contributions of waterborne and airborne pollen.

6. Conclusions

This paper presents results of a modern pollen taphonomic study at Lake Baiyangdian, a large fresh water lake with several inflowing rivers. Comparison of pollen traps above the water with those below implies that the pollen influx to the sediment is dominated by waterborne pollen; around 92% of the total terrestrial plant pollen influx is waterborne. When interpreting pollen records from lakes with inflowing streams, therefore, the pollen source area of the aerial component is a poor starting point, and

a more complex understanding of source area which takes into account the hydrological catchment as well as the aerial pollen source area needs to be developed and applied. Developing methods for estimating pollen source areas for such sites, then considering how (and indeed whether) they can be used to interpret past changes of vegetation and climate, will be a challenging work, but it is clearly necessary if Quaternary scientists are to extract meaningful reconstructions from the problematic but relatively abundant sediments of lakes with inflowing streams.

Appendix. Estimating the parameters for the pollen assemblage formation equation pollen influx data

	Aerial trap mean pollen influx (grains cm^{-2} a^{-1})	Underwater trap mean pollen influx (grains cm^{-2} a^{-1})
Terrestrial types (T)	470	5470
Hydrophyte types (H)	740	3520
T:H ratio	0.64	1.55

If hydrophytic pollen was purely transported via the aerial route, then the amount would be the same in aerial and underwater traps, and the underwater trap T:H ratio would be predicted to be 5470/740 = 7.4.

If the underwater traps received pollen from the aerial route and from overland flow, hydrophytic pollen would enter the system via two routes. Assuming that the overland flow picked up pollen deposited onto bare land surfaces through the aerial route, then we would predict that the ratio of terrestrial to hydrophyte pollen types should be the same in both types of traps, i.e. T:H = 0.64. If T:H = 0.64 in the underwater traps then, since an influx of 3520 hydrophyte grains is recorded, we would expect to see about 0.64 × 3520 aerial grains = 2250 aerial grains. Since a substantially larger number of terrestrial grains are recorded, this suggests that

another source of terrestrial pollen types is present; we infer that this represents the river-borne component of the assemblage.

Assuming that the hydrophyte component is sourced from aerial and overland flow only, the increase in hydrophytes in the underwater trap over the aerial trap reflects influx from overland flow, and the runoff component can be estimated as contributing about 2780 grains cm^{-2} a^{-1} to the hydrophyte part of the forming assemblage (influx estimated as $3520-740 \approx 2780$ grains cm^{-2} a^{-1}). Both of these components are assumed to have the same T:H ratio, estimated as 0.64 for the aerial component, which implies that the terrestrial pollen component entering the lake as part of the overland flow would be 0.64×2780 or about 1780 grains cm^{-2} a^{-1}.

The measured terrestrial pollen component in the waterborne traps is 5470 grains cm^{-2} a^{-1}, which we can now break down into three parts; roughly 470 grains from the aerial route, 1780 grains from the overland flow route and 3220 grains from the fluvial transport route.

On this basis, we estimate the sources of pollen entering the submerged trap (and, we infer, the lake sediment) in the study period as follows:

Taphonomic route	Hydrophyte pollen		Terrestrial pollen	
	Influx (grains cm^{-2} a^{-1})	Percentage	Influx (grains cm^{-2} a^{-1})	Percentage
Aerial	740	21%	470	9%
Overland flow	2780	79%	1780	33%
River transport	0	0%	3220	58%

The river transport component will include both grains of mountain types carried from the upper parts of the catchment and grains collected during travel through the lowland part of the catchment, therefore the proportion of mountain pollen types in the submerged traps and the sediment–water interface samples should be substantially lower than the total river transport proportion, which is seen in the data (24% and 13% respectively).

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