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A paired marine-fluvial modern pollen dataset from the Bohai Sea and its inflowing rivers, China

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Abstract: Modern marine pollen records can be interpreted reliably only when the main source-to-sink processes between terrestrial vegetation, rivers, and marine depocentres are documented by comparable modern data. Here, we present and quality-assess a paired marine-fluvial pollen dataset for the Bohai Sea, China, consisting of 430 marine surface-sediment samples and 104 fluvial surface-sediment samples from 16 major inflowing rivers. The dataset includes sample coordinates, water depth for marine stations, river and regional identifiers, pollen and spore counts, pollen concentrations, and grain-size parameters. In total, 104 pollen and spore morphotypes were identified. Marine assemblages are dominated by arboreal pollen, especially *Pinus* (mean 59 %), whereas nearshore and river-influenced settings contain higher proportions of herbaceous taxa, particularly Chenopodiaceae/Amaranthaceae-type (mean 14 %), *Artemisia*, and Poaceae. Redundancy analysis after variance-inflation-factor screening indicates that water depth is the strongest retained predictor of marine pollen composition ($\lambda 1/\lambda 2$ = 0.303), followed by geographic position and sediment texture. In river samples, geographic position, water discharge, and pollen concentration together explain 20.53 % of the compositional variance. Along the 0-35 m depth interval, arboreal pollen and *Pinus* increase with water depth, whereas herbaceous taxa decrease, providing an internally consistent modern analogue for distinguishing nearshore fluvial influence from more distal aeolian influence. The dataset is intended primarily as a reusable calibration and quality-assessment resource for palaeoenvironmental studies in the Bohai-Yellow Sea region. The archived data are available at the National Tibetan Plateau Data Center (TPDC; Li and Yang, 2026; https://doi.org/10.11888/Paleoenv.tpdc.303516).

1 Introduction

Marginal seas at the land-ocean interface are important archives for Earth system research because their sediments integrate continental vegetation signals, fluvial sediment delivery, coastal hydrodynamics, and sea-level change (Sun et al., 2001; Chen et al., 2003; Wang et al., 2014). The Bohai Sea, a shallow and semi-enclosed epicontinental sea on the East Asian continental margin, is a particularly suitable setting for developing a modern pollen source-to-sink dataset. It receives sediment from several river systems, including the Yellow River (Huanghe), Liaohe River, Haihe River, and Luanhe River, and its surrounding catchments span a wide range of vegetation and

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land-use types across northern China (Qin et al., 1990; Liu et al., 2007; Wang et al., 2011; Yang et al., 2019a).

Pollen and spores preserved in marine sediments are widely used to reconstruct past terrestrial vegetation and climate, but marine pollen spectra do not represent source vegetation directly. Before burial, pollen grains are affected by differential production, atmospheric and fluvial dispersal, hydrodynamic sorting, sediment focusing, oxidation, and taxon-specific preservation (Müller, 1959; Havinga, 1984;, 1985; Heusser, 1988; Brush et al., 1994; Chmura et al., 1999). These processes may amplify some taxa, such as bisaccate *Pinus*, and underrepresent others, especially taxa with lower production or more restricted dispersal pathways.

A robust interpretation of fossil pollen from marginal seas therefore requires modern calibration data that document both the receiving basin and the terrestrial or fluvial pathways by which pollen reaches it. Such datasets allow users to separate ecological information from transport and depositional biases, to define modern analogues, and to evaluate the uncertainty attached to pollen-based environmental inference (Prentice, 1980; Overpeck et al., 1985; Davis et al., 2013). Large regional pollen databases have advanced quantitative palaeoecology, but paired modern datasets that connect marine surface sediments with the inflowing rivers of the same basin remain uncommon (Chmura and Liu, 1990; Luo et al., 2014; Yang et al., 2016a, 2019a, 2021).

Previous palynological studies of Bohai Sea surface sediments have shown that pollen distributions are structured by riverine input, basin circulation, sediment texture, and water depth, and that *Pinus* and herbaceous taxa often show opposite nearshore-offshore patterns (Wang, 1993; Yang et al., 2016a, 2016b, 2016c, 2019a, 2021). However, most earlier work focused on marine sediments alone. The pollen composition of the inflowing river systems, which constitutes a first-order control on the pollen delivered to the sea, has not been documented in a harmonized dataset with the marine samples. This gap limits the ability of users to assess fluvial filtering, aeolian input, and the degree to which river assemblages are transformed before final deposition in the marine basin.

Here we present an integrated modern pollen dataset that combines 430 marine surface-sediment samples from the Bohai Sea with 104 fluvial surface-sediment samples from 16 rivers that discharge into the basin. All samples were processed using comparable palynological and grain-size procedures, and the resulting records were harmonized taxonomically to facilitate reuse. The paired design is the principal added value of the dataset: it provides a modern reference from terrestrial and fluvial source areas to marine depositional sinks, rather than treating the marine signal in isolation.

The objectives of this data description article are to (1) document the sampling design, analytical procedures, variables, and metadata of the paired marine-fluvial dataset; (2) describe the main spatial patterns of pollen and spore assemblages in a way that helps future users evaluate data quality and representativeness; (3) quantify the dominant environmental gradients associated with pollen composition using exploratory ordination; and (4) provide usage guidance, uncertainty information, and limitations for palaeoenvironmental applications in the Bohai-Yellow Sea region.

2 Study region

The Bohai Sea (37-41° N, 117.5-122° E) is a shallow, semi-enclosed continental shelf sea in northern China. It is bounded by the Liaodong Peninsula to the east, the Shandong Peninsula to the south, and the North China Plain to the west. The sea covers approximately 7.7 × 10^4 km^2 and has a mean water depth of about 18 m, with the greatest depths occurring in the northern Bohai Strait (Qin et al., 1990; IOCAS, 1985). It is commonly subdivided into Liaodong Bay, Bohai Bay, Laizhou Bay,

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the Central Basin, and the Bohai Strait, which connects the Bohai Sea with the Yellow Sea (Fig. 1).

The regional climate is controlled by the warm-temperate East Asian monsoon system. Summers are warm and humid under southeasterly monsoon winds, whereas winters are cold and dry under the influence of the Siberian-Mongolian high-pressure system. Mean annual temperature is approximately 12.6 °C, and mean annual precipitation generally ranges from 500 to 900 mm, with more than 70 % of annual rainfall occurring during the summer monsoon season (June-August) (Zhang, 1991; Wang, 2013). This strong seasonality affects both terrestrial pollen production and the timing of fluvial sediment and pollen delivery to the sea.

The surrounding vegetation belongs mainly to the warm-temperate deciduous broadleaved forest biome, although natural vegetation has been extensively modified by long-term agriculture and urban development. Remnant natural and semi-natural vegetation includes *Pinus tabuliformis*, *Quercus acutissima*, *Quercus variabilis*, *Betula*ceae, Ulmaceae, shrub-grassland communities dominated by *Artemisia*, Chenopodiaceae/Amaranthaceae-type, Poaceae, and Asteraceae, and halophytic coastal communities on saline-alkaline plains (Wang, 1993; Meng and Wang, 1987; Zhang, 2007). The Yellow River catchment alone integrates pollen from temperate steppe, temperate deciduous forest, and warm-temperate deciduous forest zones (Ren and Beug, 2002; Li et al., 2020).

The Bohai Sea receives terrigenous sediment from several major rivers, including the Yellow River, Liaohe River, Haihe River, Luanhe River, and numerous smaller coastal rivers (Table 1). The Yellow River is the dominant sediment supplier and has historically contributed most of the suspended sediment entering the basin (Milliman and Meade, 1983; Wang et al., 2007, 2011; Milliman and Farnsworth, 2011). Because sediment and pollen are transported together during fluvial discharge and redistributed by marine circulation, river-borne pollen is expected to be especially important in nearshore and deltaic settings.

Marine circulation is driven by the Yellow Sea Warm Current intrusion through the Bohai Strait, wind-driven coastal currents, tidal forcing, and density gradients related to freshwater discharge (Guan, 1994; Fang et al., 1999). Fine-grained muds accumulate preferentially in the Central Basin, where low-energy bottom conditions favour deposition of suspended sediment, whereas coarser deposits occur near river mouths and in tidally energetic channels (Liu et al., 2009; Youn and Kim, 2011). This bathymetric and textural gradient provides a natural framework for assessing how pollen assemblages change from river-influenced shallow sites to more distal marine depocentres.

Together, the shallow basin geometry, strong monsoonal seasonality, heterogeneous catchment vegetation, large fluvial sediment supply, and complex circulation make the Bohai Sea a useful modern laboratory for documenting pollen production, transport, deposition, and preservation across the land-sea continuum.

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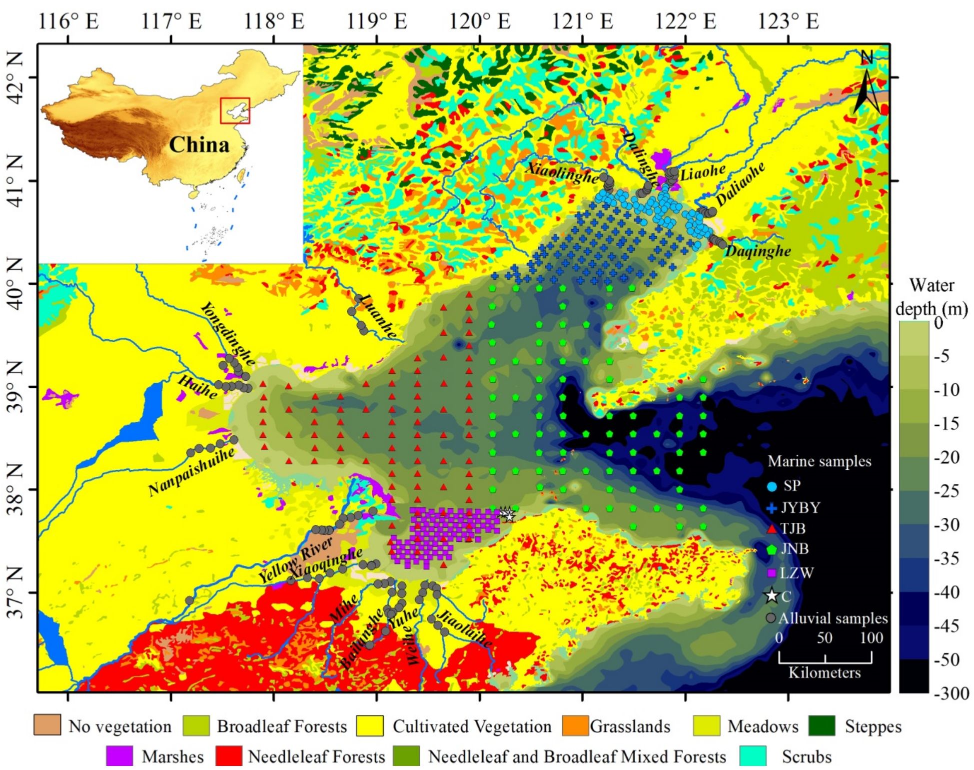

Figure 1. Sampling locations in the Bohai Sea and 16 inflowing rivers. Different color symbols denote different area code of sampling sites. The vegetation background was adapted from Zhang (2007).

Table 1. Hydrological characteristics and mean pollen concentrations of the main rivers discharging into the Bohai Sea. Values summarize the sources listed in the table; reporting periods differ among rivers and should be considered when comparing water discharge and sediment load.

River name	Length (km)	Area (km^2)	Water discharge ($10^8\ m^3\ a^{-1}$)	Mean pollen concentration (grains g^{-1})	Sediment load ($10^4\ t\ a^{-1}$)	Period	Reference
Liaohe	1396	13.65×10^4	29.35	1492	417	1987–2010	Ministry of Water Resources of China, 2011
Dalinghe	397	23549	19.63	1222	2740	1956-2000	Chen et al., 1998
Xiaolinghe	397.4	23549	4.03	1572	364	/	Chen et al., 1998
Daliaohe	768.4	25360	42.21	2355	899	1954-1979	Wang and He, 1993
Daqinghe	100.7	1482	2.82	5081	18.49	1959-2000	Yang, 2003
Luanhe	877	4.49×10^4	46.51	1143	1739	1950–1984	Chen et al., 1998
Haihe	1036	21.1×10^4	8.2	478	7.38	1990-2010	Ministry of Water Resources of China, 2011
Yongdingxinhe	61.9	8.3×10^4	0.939	19167	17.4	/	Zhu, 2007
Nanpaishuihe	99.4	13730	4	929	10	/	Editorial Committee of Encyclopedia of Rivers and Lakes in China, 2014
Yellow River	5465	75.2×10^4	313.3	1048	77800	1952–2010	Ministry of Water Resources of China, 2011
Weihe	242	6367	14.46	9174	92.44	/	Chen et al., 1998
Mihe	206	3847	4.3	6725	84.09	/	Chen et al., 1998
Xiaoqinghe	233	10498	8.78	2633	36.9	/	Chen et al., 1998

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Jiaolaihe	109	3793.5	2.33	5137	8.7	/	Chen et al., 1998
Bailanghe	120	1237	1.22	1538	1.16	/	Editorial Committee of Encyclopedia of Rivers and Lakes in China, 2014
Yuhe	75	301	0.05	4506	0.82	/	Editorial Committee of Encyclopedia of Rivers and Lakes in China, 2014

3 Materials and methods

3.1 Sample collection

Surface sediments were collected from the Bohai Sea and its major inflowing rivers during field campaigns between 2010 and 2012 to establish a spatially representative modern pollen dataset (Fig. 1). The term modern is used here to denote surface sediments that integrate recent depositional conditions; users should note that the upper centimetre of marine sediment may integrate multiple years to decades depending on local sedimentation, mixing, and bioturbation rates.

The study area encompasses diverse sedimentary environments, necessitating the use of different sampling methods according to sediment type and locality. In the coastal shallow water area (water depth <5 m), surface sediments were obtained using either a boat-deployed grab sampler or a manually operated seafloor sampling device. The grab sampler was required to retrieve no less than 1 kg (wet weight) of effective sediment, from which the upper 0–10 cm layer was carefully scraped from the central portion for subsequent laboratory analyses. In the deeper offshore areas (water depth >5 m), a box corer from research vessels was deployed to collect sediments with a depth of to 50 cm. The uppermost 10 cm mixed layer of each core was subsampled as the surface sediment fraction and stored in sample bags for further analysis. Along the inflowing rivers of the Bohai Sea, floodplain alluvium was collected as 5-cm-thick surface sediment samples using a pre-cleaned stainless steel scoop, with a sampling interval of 3–5 km. Where conditions permitted, surface sediments at a depth of 0–5 cm were additionally collected for palynological analysis.

A total of 430 marine surface sediment samples were collected. Sampling stations were more densely distributed in river-influenced areas, particularly across the Yellow River subaqueous delta and the estuarine transition zones of Bohai Bay and Laizhou Bay (Yang et al., 2016a, 2016b, 2016c). Fluvial surface-sediment samples (n = 104) were collected from 16 rivers entering the Bohai Sea: the Yellow River, Liaohe, Haihe, Luanhe, Daliaohe, Dalinghe, Xiaolinghe, Daqinghe, Yongdingxinhe, Nanpaishuihe, Xiaoqinghe, Mihe, Bailanghe, Yuhe, Weihe, and Jiaolaihe rivers. Samples were taken from lower reaches and estuarine zones, with each sample containing 100-150 g of wet sediment (Yang et al., 2019b). Floodplain and point-bar facies were targeted to capture integrated river-transported pollen, while avoiding obvious anthropogenic contamination where possible. All sampling locations were recorded using a differential GPS.

In addition, as a vast modern sink for fluvial sediments, multiple rivers, notably the Yellow River and the Luanhe River, transport enormous quantities of sediment into the Bohai Sea annually, which predominantly governs the sedimentary framework of the Bohai Bay. As a result, the surface sediments in this region are largely products of these riverine sediments that have been transported, sorted, and redeposited by marine hydrodynamic processes, rather than relict deposits, which distinguishes this region from the Yellow Sea and the East China Sea.

3.2 Pollen and grain-size analysis

Pollen analysis followed standard laboratory procedures (Berglund and Ralska-Jasiewiczowa, 1986; Moore et al., 1991). For each sample, 10-20 g of dry sediment was treated sequentially with 10 % HCl to remove carbonates, 40 % HF to dissolve silicates, and 10 % KOH in a heated water bath to

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remove humic material. Samples were rinsed and centrifuged between steps. Pollen and spores were concentrated by heavy-liquid flotation using $ZnBr_2$ at a density of approximately 2.0 g mL^{-1} (Nakagawa et al., 1998). One tablet of exotic *Lycopodium* spores (27 637±563 spores per tablet) was added before chemical treatment to calculate pollen concentration (grains g^{-1} dry sediment) (Stockmarr, 1971). Pollen was identified and counted using a Nikon Eclipse Ni transmitted-light microscope at 400× magnification, with difficult grains checked at 600× or 1000× under oil immersion. The target count was at least 200 terrestrial pollen grains per sample; samples that did not reach this target are retained in the dataset and should be treated as low-count samples during quantitative reuse. Taxonomic identifications were made using the reference collection at the Qingdao Institute of Marine Geology and published pollen atlases (Wang et al., 1995; IBSCIBAS, 1985; Tang et al., 2020). Pollen percentages were calculated from the terrestrial pollen sum, whereas fern spore percentages were calculated from the total palynomorph sum. The morphotype Chenopodiaceae/Amaranthaceae-type is retained in the manuscript to match the archived count table and common Quaternary palynological usage.

Grain-size distributions were measured by laser diffraction using a Malvern Mastersizer 2000 with a Hydro 2000G dispersion unit. Prior to measurement, samples were treated with 10 % H_2O_2 to remove organic matter and 10 % HCl to remove carbonates, dispersed with sodium hexametaphosphate ((NaPO3)6), and ultrasonicated. Sediments were grouped into clay (<4 μm), silt (4-63 μm), and sand (>63 μm) fractions following Wentworth (1922). Mean grain size (Mz), sorting, skewness, and kurtosis were calculated using the logarithmic method of moments implemented in GRADISTAT (Blott and Pye, 2001).

3.3 Numerical analysis

Exploratory statistical analyses were conducted in R (version 4.2.3; R Core Team, 2023), primarily with the vegan package (version 2.6-4; Oksanen et al., 2019). The purpose of these analyses was to evaluate internal pollen-environment consistency and to identify the main gradients represented in the dataset; the analyses are not intended as a formal transfer function for reconstructing past water depth or sea level.

Pollen counts were converted to relative abundances before ordination. Relative abundance data were Hellinger-transformed to reduce the influence of dominant taxa and to make the data suitable for linear ordination (Legendre and Gallagher, 2001). Detrended correspondence analysis (DCA; Hill and Gauch, 1980) was first used to evaluate gradient lengths. The first DCA axis was 0.98 standard deviation (SD) units for the riverine dataset and 1.25 SD units for the marine dataset, both below the 3-4 SD threshold generally used to justify linear response models (ter Braak and Prentice, 1988; ter Braak and Verdonschot, 1995). Redundancy analysis (RDA) was therefore used for both datasets.

Separate RDAs were performed for riverine and marine samples. For the riverine subset, the response matrix contained 21 pollen taxa with mean relative abundance greater than 0.2 %, and predictors included latitude, longitude, pollen concentration, watershed area, mean annual water discharge, and mean annual sediment load. For the marine subset, the response matrix contained 15 pollen taxa with mean relative abundance greater than 1 %, and predictors included latitude, longitude, water depth, sand, silt, clay, mean grain size (Mz), and pollen concentration.

Environmental predictors were screened using forward selection and variance inflation factors (VIFs) to reduce multicollinearity (Blanchet et al., 2008). Variables with VIF > 10 were removed iteratively until all retained predictors were below this threshold. Because latitude and longitude are spatial surrogates for several unmeasured environmental gradients, their effects should be interpreted

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cautiously and not as direct causal mechanisms.

Model significance was assessed with 999 unrestricted Monte Carlo permutations. Adjusted R2 was calculated to account for the number of explanatory variables. For each predictor, the ratio of the first constrained eigenvalue to the first unconstrained eigenvalue ($\lambda1/\lambda2$) was calculated as an exploratory indicator of predictive strength (Juggins, 2013). Marginal and conditional contributions were assessed to distinguish the variance explained by single predictors from their unique contribution within multivariable models.

Pearson correlation coefficients were calculated between selected pollen percentages and water depth for the 0-35 m marine depth interval. This restricted interval excludes the deeper and hydrodynamically distinctive Bohai Strait channel and is intended to describe the main basin-wide nearshore-offshore gradient. All statistical tests were two-tailed, with $\alpha = 0.05$. Ordination diagrams were produced using R software.

4 Data description

4.1 Sample characteristics and count quality

The dataset contains 534 samples, consisting of 430 marine and 104 riverine surface-sediment samples. Identified pollen grains per sample range from 59 to 1530, with a mean of 397. Four riverine samples and six marine samples contain fewer than 100 identified pollen grains. These low-count samples are retained because they document real low-pollen depositional settings, but they should be flagged during quantitative analyses and treated with caution when interpreting rare taxa. Mean pollen counts are similar in the two subsets, with 406 grains per riverine sample and 395 grains per marine sample.

Low pollen counts are concentrated mainly in Bohai Bay and the Luanhe River estuary (Fig. 2), where high sedimentation rates, coarser grain sizes, or oxidation may dilute or degrade palynomorphs (Yang et al., 2019a). Across the full dataset, 78 % of samples contain 300-600 identified pollen grains, providing stable percentage estimates for the dominant taxa and enabling comparison among regions (Heiri and Lotter, 2001). Users interested in rare taxa should, however, account for count-size effects.

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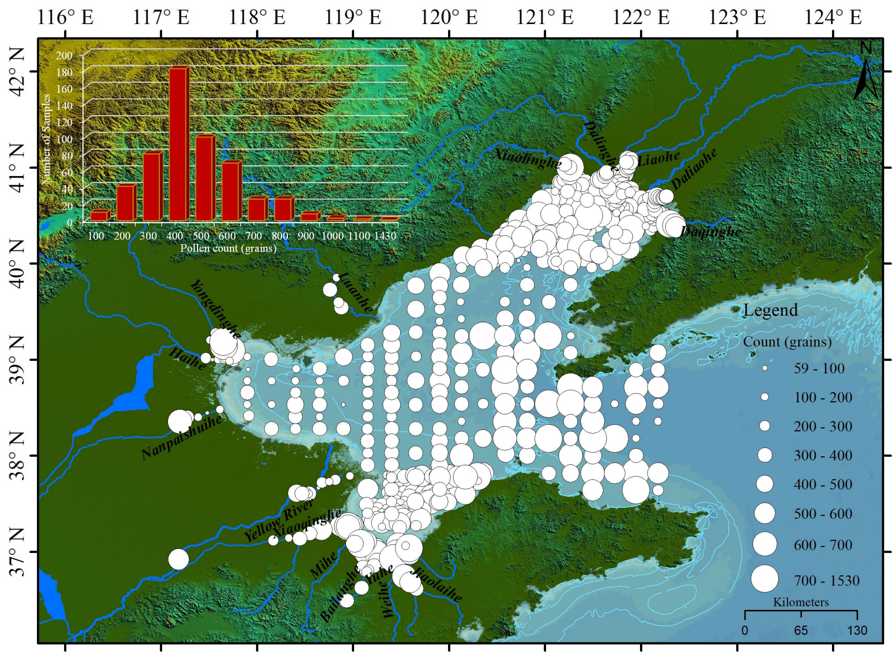

Figure 2. Spatial distribution of counted pollen grains per sample. Symbol size represents the pollen sum, and the inset histogram shows the frequency distribution.

A total of 104 pollen and spore morphotypes were identified. Riverine samples contain 87 morphotypes, whereas marine samples contain 95 morphotypes. Among the 16 rivers, the Daqinghe has the highest richness (52 morphotypes) and the Weihe the lowest (23 morphotypes) (Fig. 3a). The Yellow River contains 39 morphotypes despite its large drainage area and sediment load, possibly reflecting long-distance mixing and dilution by regionally sourced sediment and pollen (Chmura and Liu, 1990; Shen et al., 2006). Because richness values are not standardized by sample number or count size, they should be interpreted descriptively rather than as direct diversity estimates.

Arboreal pollen richness is lower in riverine samples (42 taxa) than in marine samples (50 taxa), whereas herbaceous pollen and fern-spore richness are broadly comparable between the two subsets (Fig. 3b). This pattern is consistent with the preferential atmospheric transport of buoyant bisaccate *Pinus* grains to offshore settings and with stronger local representation of herbaceous taxa in riverine and nearshore environments (Heusser, 1988; Dupont and Wyputta, 2003). Mean pollen concentration is higher in riverine samples (3531 grains g^{-1}) than in marine samples (2419 grains g^{-1}), consistent with proximity to terrestrial pollen sources and dilution by marine sediment accumulation.

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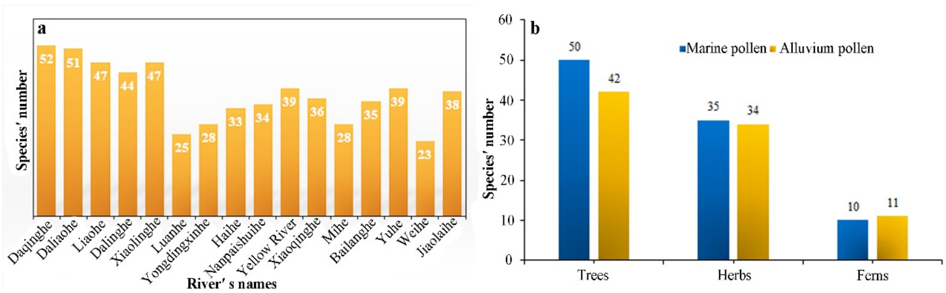

Figure 3. Recorded taxonomic richness in the riverine and marine subsets. (a) Number of pollen and spore morphotypes recorded in each inflowing river; (b) pooled numbers of arboreal, herbaceous, and fern-spore morphotypes in marine and riverine samples. Richness values are descriptive and are not standardized for sample number or count size.

4.2 Spatial distribution of major pollen taxa

Major pollen groups show clear spatial organization across the Bohai Sea and its inflowing rivers (Fig. 4). These patterns provide an internal plausibility check for the dataset because taxa expected to have different production, transport, and depositional behaviour occupy different parts of the land-sea gradient.

Arboreal pollen (AP) is abundant across most marine stations, except in Bohai Bay where non-arboreal pollen is more prominent. AP ranges from 12 % to 98 % and generally exceeds 50 % in offshore samples. The main arboreal components are *Pinus*, *Quercus*, and Betulaceae.

Pinus is the dominant arboreal taxon in marine sediments, with a mean abundance of approximately 59 % and a maximum of 98 %. Its distribution closely follows total AP, with the highest values in the deeper Central Basin and Bohai Strait. This pattern is consistent with the high production, buoyancy, long-distance atmospheric transport, and preservation potential of bisaccate *Pinus* pollen in marine environments (Heusser and Balsam, 1977; Heusser, 1988; Mudie and McCarthy, 2006). *Quercus* is common but subordinate, with a mean abundance of 1.7 % and a maximum of 10.6 %. Higher values occur mainly in the Laotieshan Channel and nearshore areas of northern Liaodong Bay and Laizhou Bay, where fluvial input and coastal currents may deliver non-saccate oak pollen from adjacent peninsulas. Betulaceae pollen is also relatively low, with a mean abundance of 3.3 % and a maximum of about 10.6 %. Its spatial pattern resembles that of *Quercus*, with somewhat higher values in nearshore zones of Liaodong Bay and Laizhou Bay.

Non-arboreal pollen (NAP) ranges from 1.5 % to 88 %. It is enriched in nearshore environments, especially northern Liaodong Bay, Bohai Bay, Laizhou Bay, and the northern Bohai Strait, and is depleted in the Central Basin. This pattern is consistent with local fluvial and coastal-plain inputs from salt marshes, grasslands, and agricultural areas bordering the Bohai Sea (Yang et al., 2016a, 2019a). Among herbaceous taxa, Chenopodiaceae/Amaranthaceae-type is the most abundant group (maximum 59 %, mean 14 %) and closely tracks the distribution of total herbaceous pollen. It is concentrated in nearshore and estuarine settings where halophytic communities occur on saline-alkaline coastal soils (Wang, 1993; Li et al., 2020). *Artemisia*, Poaceae, *Typha*, and Cyperaceae show broadly similar nearshore patterns, supporting the interpretation that nearshore environments are primary sinks for locally derived herbaceous pollen.

Fern spores are relatively abundant in the muddy Central Basin, Bohai Bay, and Liaodong Bay and reach a maximum of 84 % of total palynomorphs. The main spore groups are *Selaginella*,

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Osmunda, Monoletes, and Triletes, with *Selaginella* dominant. Their association with fine-grained depositional areas is consistent with hydrodynamic sorting and preferential settling in low-energy settings (Traverse, 2007).

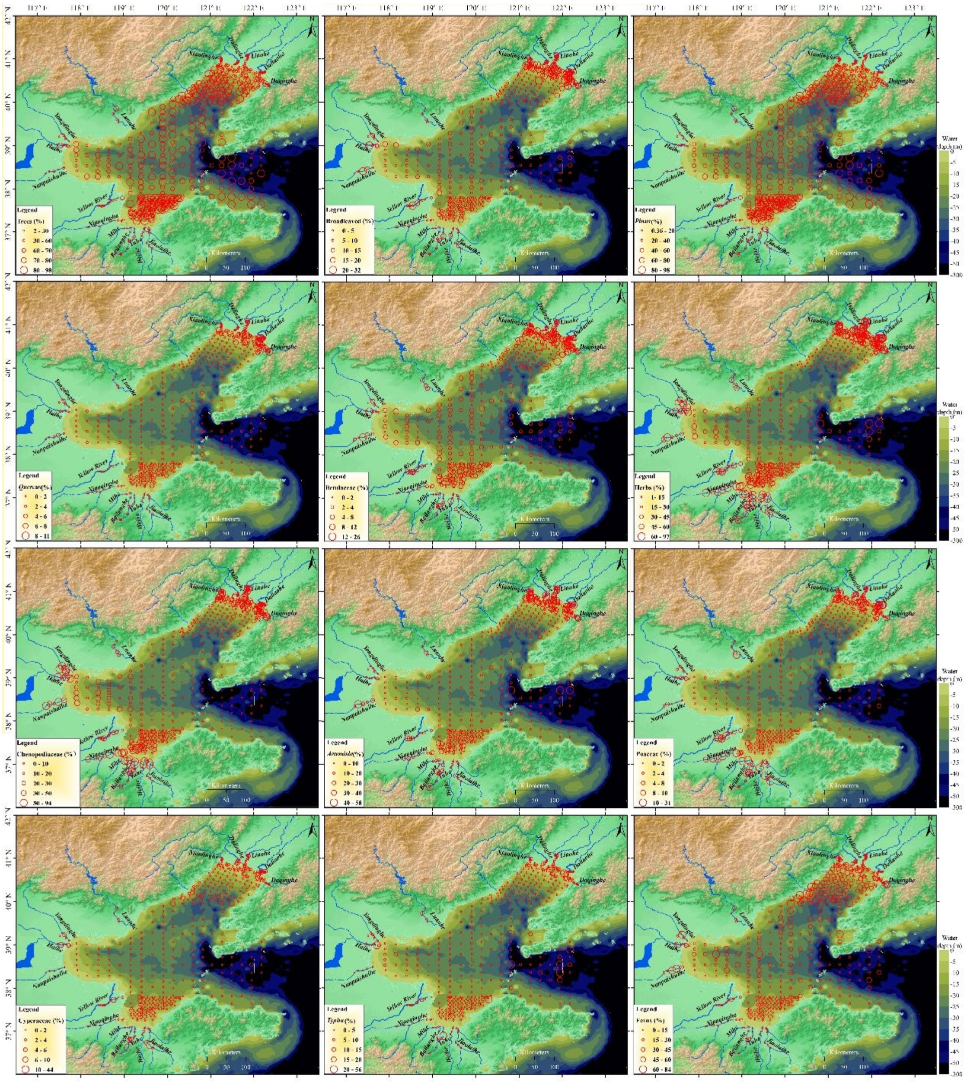

Figure 4. Spatial distributions of major pollen taxa, fern-spore groups, and ecological sums in the Bohai Sea and inflowing rivers.

4.3 Multivariate ordination and environmental controls

4.3.1 Riverine pollen assemblages

Initial VIF diagnostics for the six riverine predictors showed strong multicollinearity (Table 2; Fig. 5a). Sediment load had the highest initial VIF (92.41) and was removed first. Watershed area remained collinear after recalculation (VIF = 23.90) and was also excluded. The final RDA retained

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latitude (VIF = 2.02), longitude (2.08), pollen concentration (1.03), and water discharge (1.08).

The final riverine RDA was significant (pseudo-F = 6.393, permutation $p = 0.001$) and explained 20.53 % of the variance in pollen composition (adjusted $R^2 = 0.173$). The first two constrained axes accounted for 9.32 % and 6.09 % of total inertia, respectively, representing 75.1 % of the constrained inertia (Fig. 5b). These values indicate that the principal structured gradients are captured by the ordination, although most variance remains unexplained, as expected for multi-source pollen data.

RDA1 separates samples associated with positive latitude, longitude, and water discharge from samples with higher pollen concentration. RDA2 primarily contrasts latitude and longitude. *Selaginella*, *Corylus*, *Betula*, *Typha*, *Quercus*, and *Artemisia* plot toward positive RDA1 scores, whereas Chenopodiaceae/Amaranthaceae-type, Taxodiaceae, Monoletes, and Triletes plot toward negative RDA1 scores. Along RDA2, Monoletes, Taxodiaceae, *Selaginella*, *Typha*, and Liliaceae trend positively, whereas Poaceae, Aster, *Quercus*, *Artemisia*, and Cyperaceae trend negatively.

River groups are separated in ordination space. Yongdingxinhe, Haihe, and Nanpaishuihe plot in the upper part of the diagram; Daqinghe, Daliaohe, Liaohe, Dalinghe, and Xiaolinghe occur mainly on the positive side of RDA1; and Xiaoqinghe, Mihe, Bailanghe, Yuhe, Weihe, and Jiaolaihe occur mainly on the negative side. This pattern is consistent with a geographic gradient around the Bohai Rim, from the cooler Liaodong region to the warmer Shandong region.

The single-predictor λ1/λ2 ranking is longitude (0.234) approximately equal to latitude (0.234), followed by water discharge (0.129), pollen concentration (0.119), sediment load (0.115), and watershed area (0.112). The high ranking of latitude and longitude should be interpreted as evidence that spatially structured environmental and vegetation gradients are important, not that coordinates themselves are mechanistic drivers. Although sediment load and watershed area explain variance when fitted alone, they are redundant in the multivariable model because of collinearity with other basin-scale variables.

Table 2. VIF screening and exploratory RDA results. 'Explained alone' is the variance explained when a variable is fitted as the sole constraint; 'marginal contribution' is the unique contribution of the variable within the final multivariable model.

Subset	Environmental variable	VIF (initial)	VIF (final)	λ1/λ2	Sole predictor: explained variance (%)	Marginal contribution in final RDA: explained variance (%)	*p*-value
Rivers	Latitude	3.06	2.02	0.23	7.53	6.28	0.002
	Longitude	3.17	2.08	0.23	7.52	6.31	0.002
	Concentration	1.04	1.03	0.12	3.54	2.48	0.008
	Area	27.66	—	0.11	3.48	—	—
	Water discharge	79.70	1.08	0.13	3.89	3.53	0.002
	Sediment load	92.41	—	0.11	3.52	—	—
Marine	Longitude	3.52	3.49	0.21	10.92	4.53	0.005
	Latitude	2.45	2.43	0.10	5.18	1.92	0.005
	Depth	1.26	1.26	0.30	12.92	9.40	0.005
	Sand	513.78	—	0.02	1.22	—	—

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Subset	Environmental variable	VIF (initial)	VIF (final)	λ1/λ2	Sole predictor: explained variance (%)	Marginal contribution in final RDA: explained variance (%)	*p*-value
	Silt	344.96	2.46	0.03	1.62	1.32	0.005
	Clay	101.63	2.30	0.06	2.98	1.13	0.01
	Mz	22.91	—	0.03	1.61	—	—
	Concentration	1.24	1.23	0.03	1.39	0.26	0.295

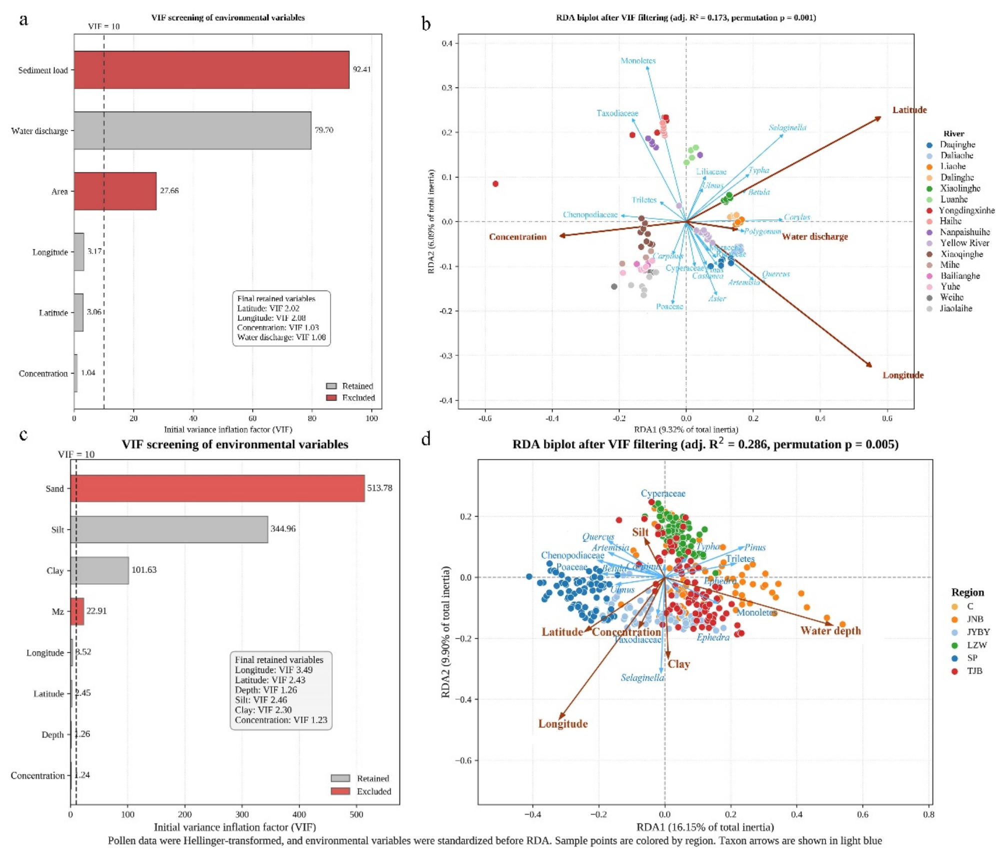

Figure 5. Variance inflation factor (VIF) screening and redundancy analysis (RDA). (a) Initial VIF values for river variables; (b) river RDA biplot using retained variables; (c) initial VIF values for marine variables; (d) marine RDA biplot using retained variables.

4.3.2 Marine pollen assemblages

The marine predictors also showed strong multicollinearity among grain-size variables (Table 2; Fig. 5c). Initial VIF values were high for sand (513.78), silt (344.96), clay (101.63), and mean grain size Mz (22.91), reflecting the mathematical dependence among textural fractions. Sand and Mz were therefore removed. The final marine RDA retained longitude (VIF = 3.49), latitude (2.43), water depth

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(1.26), silt (2.46), clay (2.30), and pollen concentration (1.23).

The final marine RDA was significant (R^2 = 0.296, adjusted R^2 = 0.286, pseudo-F = 30.167, permutation p = 0.005). The retained predictors together explained 29.6 % of the variance in marine pollen composition. RDA1 and RDA2 explained 16.15 % and 9.90 % of total inertia, respectively, corresponding to 88.08 % of constrained inertia (Fig. 5d). The explained fraction is substantial for a large modern surface-sediment dataset, but the residual variance indicates that additional unmeasured factors, including seasonal winds, episodic floods, resuspension, and preservation, also influence pollen assemblages.

Regional sample groups are partly separated in the RDA biplot. Bohai Strait samples plot mainly on the negative side of RDA1, Liaodong Bay samples plot mainly toward positive RDA1 scores, Laizhou Bay samples tend toward higher RDA2 scores, and southern Bohai samples tend toward lower RDA2 scores. Bohai Bay and Central Basin samples occupy more central positions (Fig. 5d), reflecting mixed influences from fluvial input, sediment texture, and basin circulation.

Water depth is aligned mainly with positive RDA1 and negative RDA2, whereas longitude points toward negative values on both axes. Latitude and pollen concentration are also associated with negative RDA1. Silt aligns with positive RDA2 and clay with negative RDA2. The λ1/λ2 ranking of retained predictors is water depth (0.303), longitude (0.214), latitude (0.099), clay (0.055), silt (0.033), and pollen concentration (0.029). Water depth is therefore the strongest retained gradient in the marine data, followed by geographic position and, more weakly, sediment texture. Pollen concentration has a low and non-significant marginal contribution (Table 2) and should not be overinterpreted as an independent predictor in the marine model.

Taxon positions support the spatial patterns described above. *Pinus* and Triletes plot toward deeper-water settings, whereas Chenopodiaceae/Amaranthaceae-type and *Artemisia* plot toward nearshore and river-influenced settings. *Quercus* and Poaceae occupy intermediate positions. This configuration is consistent with a mixture between distal aeolian inputs of buoyant bisaccate pollen and proximal fluvial or coastal inputs of herbaceous taxa.

5 Technical validation, uncertainty, and usage notes

5.1 Internal validation of pollen-environment relationships

The principal quality check for this dataset is the internal consistency between pollen assemblages, depositional setting, grain size, and water depth. In the marine subset, RDA identifies water depth as the strongest retained predictor (Table 2). Because most Bohai Sea depositional environments occur within 0-35 m water depth and deeper sites are concentrated in the hydrodynamically energetic Laotieshan Channel, the pollen-depth relationship was evaluated primarily within the 0-35 m interval.

Within this interval, AP and *Pinus* percentages increase significantly with water depth, whereas *Quercus*, total herbaceous pollen, Chenopodiaceae/Amaranthaceae-type, and *Artemisia* decrease (Fig. 6). The direction of these relationships is consistent with the expected transition from nearshore fluvial and coastal-plain inputs to more distal aeolian influence. The results therefore provide an internal plausibility test for the paired marine-fluvial design, rather than a direct calibration of absolute palaeo-water depth.

The shallow nearshore-estuarine end member (approximately 0-15 m water depth) is characterized by greater influence from rivers, floodplains, salt marshes, deltaic wetlands, and agricultural coastal plains (Yang et al., 2016a, 2016b, 2016c, 2019a). In this setting, *Quercus* and

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non-arboreal taxa such as *Artemisia*, Chenopodiaceae/Amaranthaceae-type, Poaceae, and Cyperaceae are relatively enriched because they are delivered mainly by short-distance fluvial and coastal transport.

The deeper central-basin end member (approximately 15-35 m water depth) has a larger proportional contribution from wind-transported pollen. With increasing depth and distance from major river mouths, the fluvial signal is diluted by transport, sorting, resuspension, and sediment focusing. High-production and buoyant bisaccate *Pinus* pollen is therefore increasingly overrepresented in distal offshore sediments (Heusser, 1983, 1988; Chmura et al., 1999; Dupont and Wyputta, 2003; Mudie and McCarthy, 2006).

The dataset agrees with marine palynological theory and previous Bohai Sea studies showing that *Pinus* and fern spores increase toward deeper waters and that river input, basin circulation, and fine-grained sediment deposition shape the spatial distribution of pollen assemblages (Wang, 1993; Yang et al., 2016c, 2019, 2021). Its added value is the explicit pairing of the marine samples with fluvial samples from the same source-to-sink system, which allows users to compare source-area assemblages with marine depositional assemblages directly.

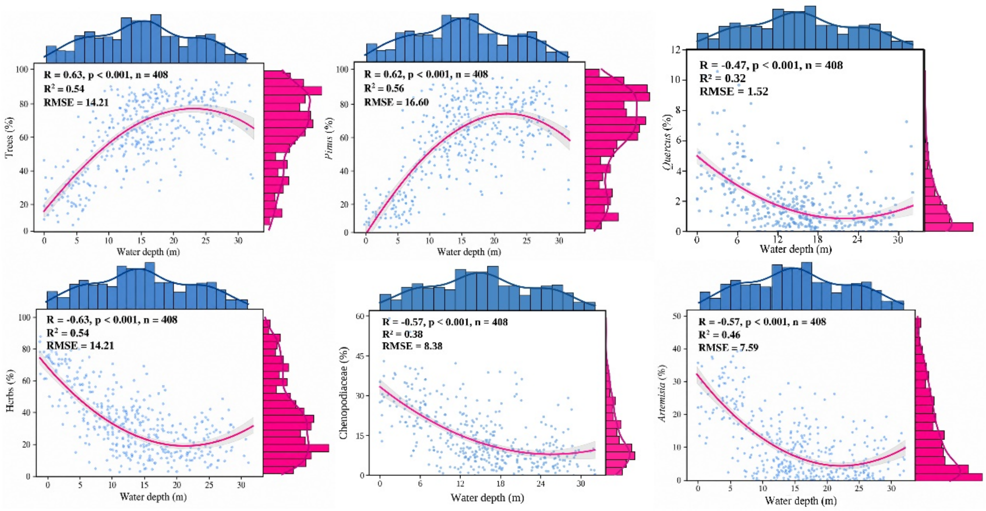

Figure 6. Relationships between water depth (0-35 m) and the percentages of total arboreal pollen, *Pinus*, *Quercus*, total herbaceous pollen, Chenopodiaceae/Amaranthaceae-type, and *Artemisia*. Reported r values are Pearson correlation coefficients.

5.2 Recommended applications and limitations

The dataset can be used as a modern analogue for evaluating how relative shoreline distance and river-mouth proximity influence pollen spectra in the Bohai-Yellow Sea region (Zheng et al., 2011, 2013; Li et al., 2022). Its strongest application is not the direct reconstruction of water depth but the identification of assemblage tendencies associated with fluvial-dominated nearshore settings versus more distal, aeolian-influenced marine settings.

Water depth in the modern dataset should therefore not be treated as a simple fossil sea-level variable. Instead, it is a spatial proxy for a suite of covarying factors, including distance from shore, distance from river mouths, sediment texture, depositional energy, and the relative balance between fluvial and atmospheric pollen transport. During lowstands, shorelines and river mouths move basinward and exposed shelf areas may contribute local herbaceous, wetland, and freshwater signals to marginal-marine deposits (Zheng et al., 2011, 2013). During highstands, greater source-to-sink distance generally reduces direct fluvial pollen delivery and increases the relative contribution of long-distance aeolian pollen.

In fossil records, intervals resembling the shallow nearshore end member may show lower *Pinus* percentages, lower AP/NAP, P/A, and PB/NAP ratios, and higher proportions of *Artemisia*, Chenopodiaceae/Amaranthaceae-type, Poaceae, Cyperaceae, aquatic pollen, and freshwater algae. Intervals resembling the deeper offshore end member may show higher *Pinus* percentages, higher AP/NAP, P/A, and PB/NAP ratios, lower herbaceous representation, finer-grained offshore muds, and more open-marine microfossil indicators. These criteria should be used together rather than individually.

Published records from the Okinawa Trough provide useful analogues for this interpretive approach. In core DGKS9602, P/A and PB/NAP ratios were used to infer changing shoreline distance, with lower ratios during MIS 2 and the Last Glacial Maximum and higher ratios during warmer high-sea-level intervals (Zheng et al., 2011). The MD982194 record similarly shows negative relationships between herbaceous pollen, freshwater algae, and sea level, whereas bisaccate taxa such as *Pinus* and *Tsuga* increase during interglacial or interstadial stages (Zheng et al., 2013). Organic geochemical evidence from the Okinawa Trough also records reduced terrestrial plant input as the shoreline retreated during deglaciation (Ujiié et al., 2001).

The Bohai Sea is especially sensitive to shoreline displacement because of its shallow bathymetry and large fluvial inputs. A glacial sea-level fall of approximately 120-130 m would expose the present Bohai Sea and much of the adjacent shelf (Yokoyama et al., 2000; Lambeck and Chappell, 2001; Lambeck et al., 2014). Consequently, down-core pollen records from the region should be interpreted as combined signals of vegetation change, climate variability, source-area migration, river routing, shelf exposure, and depositional environment.

For practical reuse, pollen-based shoreline-proximity indicators should be cross-checked against pollen concentration, grain size, sedimentary facies, freshwater algae such as *Pediastrum* and *Botryococcus*, dinoflagellate cysts, foraminifera, geochemical proxies, and independent chronological control. Samples with low pollen sums or strong evidence of reworking should be analysed separately or excluded from transfer-function development.

The main limitations of the dataset are that surface sediments integrate different time spans across settings; river sampling emphasizes lower reaches and estuaries rather than the full upstream catchment; coordinates and hydrological variables cannot represent all ecological gradients; and pollen percentages are compositional data influenced by both production and transport. Monsoon wind strength may also vary independently of sea level (An, 2000; Sun et al., 2012), potentially altering aeolian pollen flux. These limitations do not reduce the value of the dataset, but they define the conditions under which it should be reused.

6 Code and data availability

The dataset includes pollen count data of each sample, as well as geographic coordinate, water depth, as well as the grain size composition. The dataset is openly accessible from the National Tibetan Plateau / Third Pole Environment Data Center (TPDC; Li and Yang, 2026; https://doi.org/10.11888/Paleoenv.tpdc.303516).

7 Summary

We present a paired modern marine-fluvial pollen dataset for the Bohai Sea region, comprising 430 marine surface-sediment samples and 104 fluvial surface-sediment samples from 16 inflowing rivers. The dataset records 104 pollen and spore morphotypes, associated sample metadata, pollen concentrations, and grain-size variables. Marine pollen assemblages are dominated by *Pinus*, especially in deeper and more distal settings, whereas nearshore and river-influenced assemblages contain higher proportions of herbaceous taxa such as Chenopodiaceae/Amaranthaceae-type and *Artemisia*. Exploratory RDA shows that water depth is the strongest retained marine predictor, while riverine assemblages are structured mainly by geographic position, water discharge, and pollen concentration. The 0-35 m depth gradient provides an internally consistent modern analogue for distinguishing fluvial-dominated nearshore pollen assemblages from more aeolian-influenced offshore assemblages. The dataset is suitable for reuse in palaeoenvironmental research, especially for assessing source-to-sink processes and shoreline-proximity effects in Bohai-Yellow Sea sediment cores, provided that users account for the stated uncertainties and validate interpretations with independent proxies.

Author contributions

J.L. designed the pollen dataset, S.Ye, X.M., X.C., X.M., M.Gao., B.Chen. collected the samples, S.Y. performed pollen extraction and identification. S.Y., Q.H., S.Yi, and M.G. compiled the standardization for the dataset, performed numerical analyses, and organized the manuscript. All authors discussed the results and contributed to the final paper.

Competing interests

The corresponding author declares that none of the authors has any competing interests.

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