Phytolith records of flourishing early Holocene Pooideae linked to an 8.2 ka cold event in subtropical China

Xinxin Zuo1,2,*, Houyuan Lu3,4,5, Zhen Li6, Bing Song7, Deke Xu3,4, and Jinqi Dai1,2

The grass subfamily Pooideae originated in a temperate niche during the late Cretaceous; it is the largest Poaceae subfamily, consisting of almost 4,000 species, which are distributed worldwide. Pooideae responses to climate changes at different time scales, and different ecological zones are thus important in understanding Poaceae evolutionary processes and their relationship with climate change. In the study described in this article, we reconstructed Pooideae variability during the early Holocene, as inferred by a phytolith sequence from the Lower Yangtze in subtropical China. The phytolith assemblage was marked by three increases in Pooideae phytoliths, dated to ca 8.4–8.0, 7.8–7.6, and 7.4–7.2 ka BP (before present, 1950 AD), with each representing pronounced increases in Pooideae extent and distribution. All these increases were within age ranges that agreed well with the timing of weak Asian Monsoon events, at 8.2, 7.7, and 7.3 ka BP. The first Pooideae flourishing period in subtropical China was the most significant, lasting for approximately four centuries and being characterized by a double peak, which equated with an event at 8.2 ka. This suggested that cold and/or dry conditions—which occurred over a period of several hundred years and were linked to weakening of the Asian monsoon—probably caused Pooideae to flourish in the Lower Yangtze region. Comparison of two diagnostic trapezoid phytolith types—namely wavy and wavy narrow—which showed different changes between ca 8.4 and 8.0 ka BP, suggested that they responded differently to the climate change represented by the 8.2 ka event. Our phytolith records have provided not only new data clarifying the detailed Pooideae response to the 8.2 ka event but also a reliable index for past cold climates in subtropical China.

Keywords: Response, Poaceae, Asian monsoon, Palaeo-vegetation, Phytolith, Holocene

Introduction

The 8.2 ka BP event was a most pronounced and abrupt cooling event, disrupting the relatively stable warm Holocene climate, as clearly shown in Greenland ice-core records (Alley et al., 1997; Thomas et al., 2007). Within accumulated high resolution and precise dating records, the timing, structure, and geographic distribution of the event have been well-documented. Based on annual layer counting chronology, Greenland ice-cores and monsoon region stalagmite records have shown that the 8.2 ka event lasted for 150–160 years, and was characterized by a double peak structure, with the most dramatic cooling of approximately 1–2 °C mainly concentrated between 8.2 and 8.1 ka BP (Alley and Agustsdottir, 2005; Rohling and Palike, 2005; Boch et al., 2009; Cheng et al., 2009; Liu et al., 2013; Morrill et al., 2013; Liu et al., 2015; Allan et al., 2018).

Such a centennial cold event has been regarded as a global climatic reversal during the early Holocene (Mayewski et al., 2004; Wanner et al., 2011); it was not restricted to Greenland (Alley and Agustsdottir, 2005) and other high-latitude northern hemisphere regions (Daley et al., 2011; Eddudöttir et al., 2018), but also occurred in many low- to mid-latitude regions (Wu et al., 2012; Dixit et al., 2014; Schemmel et al., 2016; Peckover et al., 2019), and even in some areas of the southern hemisphere.
fossil phytoliths as proxies, rather than pollen, to investigate the response of Pooideae to the 8.2 ka cold event, as subfamily level phytoliths can be used to distinguish Pooideae in most cases (Lu et al., 2006). Meanwhile, phytolith taphonomic patterns, such as resistance to decay, and in situ deposition (Madella and Lancelotti, 2012), indicate that they could be used as sensitive and reliable proxies by which to investigate how Pooideae responded to the 8.2 ka cold event.

Materials and methods
Regional setting
The HG01 core was extracted from the Yangtze River north bank, near Nanjing, in Jiangsu province eastern China (32° 17.35’ N, 118° 48.15’ E, 7.5 m ASL; Figure 1). The region enjoys a subtropical monsoon climate with mean monthly temperatures ranging from 14 to 18 °C, and approximately 1,100 mm mean annual precipitation (Jiang, 1991; Wang et al., 2016). The regional vegetation is mixed evergreen and deciduous broad-leaved forest, dominated by broad-leaved evergreen species, such as Cyclobalanopsis, Castanopsis/Lithocarpus, Pinus, Elaeagnus, Ligustrum, and Ilex, and deciduous broad-leaved trees, such as Quercus acutissima, Q. variabilis, Castanea, Liquidambar, Platycarya, Tilia, and so on (Wu, 1980).

Common herbaceous plants include Apiaceae, Artemisia, Poaceae, and Cyperaceae (Wang et al., 2019). According to a Jiangsu province flora study, there are 217 grass species, belonging to 103 genera, with Eragrostis (Eragrostioideae), Setaria (Panicoideae), Echinocloa (Panicoideae), Phyllostachys (Bambusoideae), Roegneria (Pooidae), and Digitaria (Panicoideae) making up the dominant genera.

Sedimentary facies
The 23.2 m-long sediment core consists of two main sections. The lower section (below 17.16 m depth) typically consists of Late Pleistocene sediments from the Lower Yangtze region, which have been categorized as “hard clay.” The section above 17.16 m consists of Holocene sediments and comprises three divisions of facies: (1) floodplain facies (17.16–5.38 m), (2) channel fill facies (5.38–3.50 m), and (3) flood plain to surface soil facies (3.50–0 m). It should be noted that the floodplain facies represents a sedimentary subsystem that included lacustrine deposits, crevasse splays, and marshes or sand bars on a floodplain (Millar, 1992; Collinson, 1996). The sediments from 17.16 to 5.38 m are either lacustrine or are from a comparatively stable sedimentary environment such as an oxbow lake. We chose, therefore, to conduct our phytolith analysis on the floodplain facies, from 17.16 to 5.38 m due to its relatively stable sedimentary environment. More detailed descriptions of the HG01 core sequence sedimentary facies and depositional environments have been published in Song et al. (2013).

Age model
Accelerator mass spectrometry 14C dates were used to construct the chronological model, and all dating processes were conducted on either plant residues or
charcoal. Eleven samples were sent to Beta Analytic Lab, for radiocarbon measuring, while conventional ages were calibrated to calendar years using Calib Rev 7.0.4 and IntCal13 calibration curves (Table 1; Reimer et al., 2013). Depth-to-age transformation was established with a Bayesian age-depth model, using the Bacon 2.2 software package (Figure 2; Blaauw and Christen, 2011; Song et al., 2017).

**Phytolith analysis and classification**
The sediment core was subsampled at 5 cm intervals for phytolith analyses, after which the subsamples were freeze-dried and homogenized. Phytoliths were extracted using the conventional wet oxidation method (Lu et al., 2009; Zhang et al., 2012) and then the recovered phytoliths were permanently mounted on glass microscope slides using Canada balsam. Phytolith identification and
counting were carried out at 400× magnification, using a Leica DM 500 microscope; at least 500 phytoliths were counted in each sample, and the relative abundances of individual morphotypes were presented as percentages of the total count. In this study, phytoliths were classified according to the system proposed by Lu et al. (2006) and described according to international phytolith nomenclature (ICPN1.0; Madella et al., 2005).

Table 1. Radiocarbon ages from core HG01. DOI: https://doi.org/10.1525/elementa.077.t1

| Lab ID (Beta-) | Depth (m) | Dating materials | Conventional age (±14C yr BP) 2σ | Calibration (Cal yr BP) Median age (Cal yr BP) |
|----------------|-----------|------------------|----------------------------------|-----------------------------------------------|
| 297107         | 4.75      | Plant fragments  | 5010 ± 40 BP                     | 5653–5774                                    |
| 287364         | 5.40      | Plant fragments  | 6270 ± 40 BP                     | 7154–7273                                    |
| 270343         | 5.87      | Plant fragments  | 6350 ± 50 BP                     | 7173–7337                                    |
| 270345         | 7.75      | Plant fragments  | 6730 ± 40 BP                     | 7560–7666                                    |
| 270346         | 8.35      | Plant fragments  | 6950 ± 50 BP                     | 7696–7869                                    |
| 270347         | 9.58      | Plant fragments  | 7010 ± 50 BP                     | 7723–7946                                    |
| 270348         | 10.58     | Plant fragments  | 7100 ± 50 BP                     | 7835–8012                                    |
| 270349         | 12.55     | Plant fragments  | 7300 ± 50 BP                     | 8000–8198                                    |
| 270350         | 13.90     | Plant fragments  | 7460 ± 50 BP                     | 8186–8373                                    |
| 270351         | 14.61     | Plant fragments  | 7680 ± 50 BP                     | 8390–8561                                    |
| 287365         | 17.10     | Charred plant    | 8070 ± 40 BP                     | 8931–9093                                    |

Figure 2. HG01 core age model, produced by Bacon 2.2, and sedimentation rates (as cm/yr, in red number on the right side). DOI: https://doi.org/10.1525/elementa.077.f2
Several phytolith types can be used to identify the Pooideae (Figure 3). Trapezoids (named trapeziform sinuate in ICPN1.0), including wavy trapezoid (Figure 3a, b, g, h) and wavy-narrow-trapezoid (Figure 3c, d, f, i, t) are unique to the Pooideae (Twiss, 1992; Wang and Lu, 1992). Rondel phytoliths (Figure 3j, k, m–p) are also wholly or largely specific to the Pooideae (Piperno, 2006; Rosen et al., 2019), while the Stipa type bi-lobates (Figure 3q, r), which appear bi-lobate in top view, but are actually trapezoid in side view, were found only in the Stipa (Fredlund and Tieszen, 1997). Another phytolith type (Figure 3s), which appears as a conic lateral shape with a bi-lobate base, was observed in several species of Festuca (Fernández Pepi et al., 2012).

Wang and Lu (1992) collected 15 Pooideae species from China and identified all phytolith morphotypes. DOI: https://doi.org/10.1525/elementa.077.f3

**Figure 3.** Several diagnostic phytolith morphotypes, produced by Pooideae: (a, b) wavy trapezoid, *Alopecurus japonicas*; (c, d) wavy-narrow-trapezoid, *Bromus japonicas*; (e) wavy trapezoid, *Poa annua*; (f) wavy-narrow-trapezoid, *Roegneria kamoji*; (g) wavy trapezoid, *Trisetum bifidum*; (h) wavy trapezoid, *Deyeuxia arundinacea*; (i) rondel, *Alopecurus japonicas*; (j) rondel, *Roegneria kamoji*; (k) rondel, *Phleum paniculatum*; (l) rondel, *Psammochoa villosa*; (m, n) rondel, *Triticum aestivum*; (o) rondel, *Bromus japonicus*; (q, r) stipa type bilobate, *Stipa sp.*; (s) truncated cones, *Festuca monticola*; (t) rondel and wavy-narrow trapezoid, *Festuca elata*. DOI: https://doi.org/10.1525/elementa.077.f3
produced. They found that the relative percentages of several diagnostic Pooideae phytoliths varied according to their tolerance to a cold or dry climate. Using *Poa annua* and *Festuca extremorientalis*, which are less dry-tolerant as examples, they demonstrated their production of a wavier trapezoid form (>50%), without finding any wavy-narrow-trapezoids and few rondels. However, several other species, such as *Bromus japonicas* and *Psammochloa mongachne*, produced more wavy-narrow-trapezoid forms, but no wavy trapezoids, while *Avena fatua* and three species of *Roegneria* produced over 70% rondel forms. Another study, on phytolith morphotypes in 19 species of Pooideae grasses from the Tibetan Plateau, showed that several species from the genera *Poa*, *Elymus*, and *Trisetum* were more likely to yield more wavy-narrow-trapezoid forms (Qin et al., 2008). In spite of a very small sample size (over 4,000 species in subfamily Pooideae), the preliminary results showed that an increase in wavy-narrow-trapezoid forms is indicative of relatively dry conditions, while a high abundance of wavy trapezoids indicated relatively less dry conditions (Wang and Lu, 1992).

**Results**

**Chronology and sedimentation rate**

As shown in Table 1, no chronological reverses occurred in the sedimentary sequence, indicating that a relatively stable and continuous sedimentary environment extended over the period 9.0–7.2 ka BP. According to the age–depth model generated by the Bacon software (Blauw and Christen, 2011), the sedimentation rates shown in the HG01 core ranged from 0.4 to 2.2 cm per year (Figure 2). The average resolution for phytolith samples between 9.0 and 7.2 ka BP was approximately 8 years, becoming as high as 5 years during the period of 8.3–8.0 ka BP.

**The diagnostic Pooideae phytolith assemblage in the HG01 core**

Thirty phytolith morphotypes were identified from the HG01 core; the major phytolith assemblages were investigated by Zuo et al. (2016) and have been illustrated in Figure S1. Among these, only three of the five principle phytolith morphotypes, including the wavy trapezoid, wavy-narrow-trapezoid, and rondel, were identified, while the other two types described in previous studies were absent (Figure 4). The total Pooideae phytolith percentage accounted for up to 18.5% of the total phytoliths, with the other two diagnostic Pooideae morphotypes contributing no more than 7% to the phytolith assemblages. Among those recorded, the wavy trapezoid was the main Pooideae morphotype, accounting for up to 4.9% of the total phytolith, with the wavy-narrow trapezoid occurring in relatively small amounts of up to only 2.0%.

It can be seen in Figure 5 that the presence of trapezoid phytoliths abruptly increased at ca 8.4 ka BP and maintained a high level of representation throughout the period of ca 8.4–8.0 ka BP, in what was the most prominent change in HG01 core trapezoid phytoliths during the period 9.0–7.2 ka BP. After 8.0 ka BP, the trapezoid phytolith percentages showed two further minor increases, with peaks at 7.7 and 7.3 ka BP.

Two trapezoid sub-morphotypes, wavy trapezoid and wavy-narrow-trapezoid, are unique to Pooideae, although they do exhibit slight form fluctuations. In our work, the marked increase of wavy-narrow-trapezoid phytoliths began at ca 8.2 ka BP, with the pattern of change characterized by a double peak between 8.2 and 8.0 ka BP, with the second peak at ca 8.2 ka BP, which was slightly higher than the first, at ca 8.1 ka BP. However, wavy trapezoid phytolith representation began to increase approximately 200 years earlier than the wavy-narrow-trapezoid, at ca 8.4 ka BP. The wavy-narrow-trapezoid peak was characterized by multi-fluctuations during the period ca 8.4–8.1 ka BP. We also noted that rondel phytoliths varied greatly, at the beginning of the profile, peaking between ca 8.4 and 8.2 ka BP, before decreasing dramatically after 8.2 ka BP. Only slight changes took place throughout the rest of the profile, apart from two minor peaks at ca 7.7 and 7.3 ka BP.

**Discussion**

Sample resolution and dating accuracy have long been recognized as important issues associated with understanding the timing, duration, and structure of centennial-scale climate events, such as the 8.2 ka cold event referred to here (Alley et al., 1997; Jin et al., 2007). This is why many of the studies on the 8.2 ka event have focused on stalagmites and ice cores, as they usually have high resolution and are considered to be precisely dated climatic proxies. Although several vegetation change reconstructions have been performed for subtropical China, spanning as long as the entire Holocene (Yi et al., 2003; Chen et al., 2009; Yue et al., 2012; Zhou et al., 2012; Meng et al., 2017; Zhong et al., 2017; Wang et al., 2019), few recorded the 8.2 ka event, and thus, detailed vegetation responses to climate changes at ca 8.2 ka BP have been unavailable.

Among 11 published dating results, 6 have covered the period between 8.4 and 7.8 ka BP. These high-resolution analyses allowed the 8.2 ka event to be identified, together with at least three or four dates before and after the anomalies of the 8.2 ka event, as noted by a previous study (Jin et al., 2007). Our sedimentary facies results showed that more than two thirds of the HG01 core sediments were deposited between 9.0 and 7.2 ka BP, indicating that high sedimentation rates, ranging from 0.4 to 2.2 cm per year, were occurring over this period. Each sample prepared for phytolith review covered an average of 8–10 years, over the period 9.0–7.2 ka BP, while the samples that spanned the period 8.3–8.0 ka BP, had resolutions as high as 5 years. Well-dated controls, together with the high sedimentation rates at approximately 8.2 ka BP in the HG01 core, allowed us to clearly identify the 8.2 ka event, and enabled us to work out the vegetation response to the climate change that took place then in some detail.

All diagnostic Pooideae phytoliths showed similar increases between ca 8.4 and 8.0 ka BP (Figure 6); this indicated that cold-tolerant Pooideae flourished during the period which closely matched the weak Asian summer monsoon interval, at 8.2 ka BP, recorded by oxygen isotopes in Chinese stalagmites (Dykosi et al., 2005; Wang et al., 2005; Dong et al., 2015; Liu et al., 2015). We have
interpolated these phytolith increases as representing a shift to drier, colder conditions, and hypothesized that this was caused, in turn, by the weakening Asian monsoon at that time—as indicated by pollen assemblage changes in the same core (Song et al., 2017).

Although Greenland ice cores and stalagmites from Europe showed events around this time, covering the period 8.25 to 8.0 ka BP (Rasmussen et al., 2007; Boch et al., 2009; Allan et al., 2018), a trend of Asian summer monsoon weakening has been reported as beginning at 8.3 ka BP (Cheng et al., 2009). This onset time is in agreement with the sudden increase in trapezoid phytoliths after ca 8.4 ka BP, allowing for reasonable dating uncertainty. The dramatic decrease in trapezoid and rondel phytoliths at ca 8.0 ka BP indicated that a decline of Pooideae might have been caused by the renewed strengthening of the Asian monsoon which followed the 8.2 ka cold event. Accordingly, we have been able to conclude that the timing of the Pooideae rise and fall in the Lower Yangtze of subtropical China generally coincided with the Asian monsoon weakening and strengthening associated with the 8.2 ka event.

Although belonging to the trapezoid phytoliths that are diagnostic to the Pooideae, the wavy trapezoid and wavy-narrow-trapezoid forms from the HG 01 core exhibited fluctuations in response to the 8.2 ka BP climate change event, implying that these two phytolith morphotypes may represent separate dry and cold climates. As suggested by Wang and Lu, the Pooideae which produced a high amount of wavy-narrow-trapezoid phytoliths may favor drier and colder conditions than Pooideae which produced more wavy trapezoid phytoliths (Wang and Lu, 1992), suggesting that the form variations shown by the trapezoid and wavy-narrow-trapezoid phytoliths might indicate different responses within the Pooideae to climate change.

The marked increase in wavy-narrow-trapezoid HG 01 phytoliths suggested the driest and coldest climate conditions occurred from ca 8.2 to 8.0 ka BP, which was consistent with the 8.2 ka event recorded in the Greenland ice core (Alley and Agustsdottir, 2005; Rasmussen et al., 2007; Thomas et al., 2007). The wavy-narrow-trapezoid peaks at ca 8.2 and 8.1 ka BP showed the same timing as two Asian monsoon plunges revealed by isotopic records in China (Cheng et al., 2009). Of these, the higher peak at ca 8.1 ka BP, which saw flourishing cold/dry-tolerant Pooideae, might correspond to the weakest Asian monsoon (Liu et al., 2013), and to the lowest temperature recorded in the Greenland ice core (Thomas et al., 2007).

Wavy trapezoid phytolith fluctuations provided evidence to support a multistage response of some Pooideae to the climate change represented by the 8.2 ka cold event. Other studies from the Northern Cuba also identified a multistage 8.2 ka event in the northern tropics.
which is likely consistent with multiple freshwater pulses deduced for Agassiz and Ojibway lakes (north America) at higher northern latitudes. In conclusion, the Pooideae assemblage in the Lower Yangtze may have varied in response to changes in the Asian monsoon over the period of the 8.2 ka event, which were themselves closely linked to the North Atlantic climate.

Two other Pooideae phytolith pulses were observed, centered at ca 7.7 and 7.3 ka BP (Figure 5), suggesting that Pooideae probably increased at these times—although these peaks were shorter and weaker than those of the 8.2 ka event. These two weak Pooideae peaks matched two weak Asian Monsoon intervals identified in Chinese stalagmites (Dykoski et al., 2005; Wang et al., 2005; Feng et al., 2020), which suggested that Pooideae were capable of responding to these weaker cold events, which have also been documented in many palaeo-climate reconstructions for both Europe (Constantin et al., 2007), and for areas influenced by the East Asian Monsoon (Liew et al., 2006; Tao et al., 2006; Jo et al., 2011; Selvaraj et al., 2011; Li et al., 2015).

The Pooideae that flourished during the dry and cold period centered at 8.2 ka BP might have been distributed across the exposed floodplain due to the decreasing Yangtze River flows that resulted from the weakening Asian monsoon (Figure 7). This concept was also supported by the very fine median sediment grain size at ca 8.2 ka BP, which probably represented the decreased flow velocities and volumes that existed over that period. At the same time, the HG01 core pollen assemblages included a relatively high herb pollen content, which probably reflected the increased occupation of the exposed floodplain by grasses and other herbs during this dry period (Song et al., 2017). In contrast to this, during wetter periods, higher water levels might have covered much of the floodplain that had been exposed during the dry period, resulting in the loss of the best Pooideae habitat from the Lower Yangtze.

The three marked cold events that occurred at 8.2, 7.7, and 7.3 ka BP were reflected in the Pooideae phytolith assemblages in the Lower Yangtze of subtropical China, suggesting that although grasses accounted for a very small portion of the plant community, they were still able to vary in response to regional and global climate events. Unfortunately, due to the data resolution being lower than that of both ice core and stalagmite records, construction of a direct causal relationship between Pooideae and the Asian monsoon has not been possible. Future research
Figure 6. Comparisons of Pooideae changes reconstructed by the diagnostic Pooideae phytolith assemblages with HG01 core grain sizes, stalagmite-based Asian Monsoon strength, and Greenland ice core-based northern hemisphere temperature. A, the median grain-size of the HG01 core (Song et al., 2017; WD represents the water dynamic); B, percentage of trapezoid phytoliths; C, percentage of wave-narrow phytoliths; D, percentage of wave trapezoid phytoliths; E and F, Dongge cave stalagmite oxygen isotopes (Dykoski et al., 2005; Wang et al., 2005; AM refers to the Asian monsoon); G, Greenland ice core oxygen isotopes (Rasmussen et al., 2007). Red dots represent the median calibrated $^{14}C$ age; the gray area indicates the period when Pooideae flourished in response to the 8.2 k event; the yellow area indicates changes to the most cold-tolerant Pooideae in response to the 8.2 k event; the blue Ps represent the two Pooideae peaks; the black Ps represent two Asian monsoon plunges, recorded in Chinese stalagmites. DOI: https://doi.org/10.1525/elementa.077.f6
that focuses on developing a higher resolution record of Pooidae, allowing genus-level reconciliation of some Pooidae species through phytoliths, would be beneficial.

The Pooidae flourished during the 8.2 ka cold event but declined during the warm and wet period in the early to mid-Holocene, suggesting that hydrothermal conditions in subtropical China during the cold period might have been more favorable for the growth of Pooidae, as well as for the most cereal crops, than the conditions in temperate China, where severe dry and cold conditions probably limited the growth of Pooidae. The large amount of historical cold periods, such as the Little Ice Age, which spanned from 0.75 to 0.25 ka BP, strongly affected human society, even causing changes in dynasties (Zhang et al., 2020). The finding that Pooidae flourishing is linked to the cold event during the early to mid-Holocene provides a deeper insight into climate change and human adaptation in historical cold periods. Although such cold periods disrupted the harvest in Northern China, subtropical China provided a good habitat for temperate cereal crops belonging to the Pooidae, which probably reduced the impact of the agricultural crisis on society.

Conclusions
To our knowledge, the study described here has provided the first record of Pooidae change in response to the 8.2 ka cold event experienced in subtropical China. Our phytolith assemblages indicated that Pooidae flourished between ca 8.4 and 8.0 ka BP, which within age uncertainty allowed us to suggest that it occurred simultaneously with the 8.2 ka event identified in Greenland ice cores. Fluctuations in the wavy-narrow-trapezoid phytolith representation suggested that some Pooidae, which were more tolerant to dry and cold conditions, began to increase at ca 8.4 ka BP and showed a multistage response to the climate changes that took place during the 8.2 ka event.

Overall, differences in the timing of the success of two trapezoid phytolith forms might represent a distinct response within the Pooidae to climate changes in the 8.2 ka event. Future work should focus on retrieving high-resolution sediment, as well as using phytoliths identifying Pooidae to genus or even species level, in order to better understand the Pooidae response to cold events such as that occurred at ca 8.2 ka.

Data Accessibility Statement
The presented results are based on the original data sets provided as a summary in one sheet of a supplementary Excel file. This file is called “Supplemental data,” and it is uploaded with the manuscript.

Supplemental files
The supplemental files for this article can be found as follows:
Data S1. Supplemental Data. Excel.

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Competing interests
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

Author contributions
Conceptualization, methodology, investigation, writing—review and editing: XXZ, HYL.
Writing—resources, review, and editing: ZL.
Data curation, software: BS.
Visualization: DKX, JQD.

Figure 7. Schematic showing the relationship between Pooidae distribution and two different climatic conditions in the Lower Yangtze. The mountain regional forest distribution aspects were based on arboreal pollen assemblages (Song et al., 2017). DOI: https://doi.org/10.1525/elementa.077.f7
References

Allan, M, Fagel, N, van der Lubbe, HJL, Vonhof, HB, Cheng, H, Edwards, RL, Verheyden, S. 2018. High-resolution reconstruction of 8.2-ka BP event documented in Père Noël cave, southern Belgium. *J Quat Sci* **33**: 840–852.

Alley, RB, Agustsdottir, AM. 2005. The 8 k event: Cause and consequences of a major Holocene abrupt climate change. *Quat Sci Rev* **24**: 1123–1149.

Alley, RB, Mayewski, PA, Sowers, T, Stuiver, M, Taylor, KC, Clark, PU. 1997. Holocene climatic instability: A prominent, widespread event 8200 yr ago. *Geology* **25**: 483–486.

Blaauw, M, Christen, JA. 2011. Flexible paleoclimate age-depth models using an autoregressive gamma process. *Bayesian Anal* **6**: 457–474.

Boch, R, Spötl, C, Kramers, J. 2009. High-resolution isotope records of early Holocene rapid climate change from two coeval stalagmites of Katerloch Cave, Austria. *Quat Sci Rev* **28**: 2527–2538.

Chen, W, Wang, WM, Dai, XR. 2009. Holocene vegetation history with implications of human impact in the Lake Chaohu area, Anhui Province, East China. *Veget Hist Archaeobot* **18**: 137–146.

Cheng, H, Fleitmann, D, Edwards, RL, Wang, X, Cruz, FW, Auler, AS, Mangini, A, Wang, Y, Kong, X, Burns, SJ, Matter, A. 2009. Timing and structure of the 8.2 kyr B.P. event inferred from δ18O records of stalagmites from China, Oman, and Brazil. *Geology* **37**: 1007–1010.

Collinson, JD. 1996. Sedimentary environments: processes, facies and stratigraphy, in Reading, HG ed., *Alluvial sediments*. Oxford: Blackwell Scientific Publications: 37–82.

Constantin, S, Bojar, A-V, Lauritzen, S-E, Lundberg, J. 2007. Holocene and Late Pleistocene climate in the sub-Mediterranean continental environment: A speleothem record from Poleva Cave (Southern Carpathians, Romania). *Palaeogeogr Palaeoclimatol Palaeoecol* **243**: 322–338.

Daley, TJ, Thomas, ER, Holmes, JA, Street-Perrott, FA, Chapman, MR, Tindall, JC, Valdes, PJ, Loader, NJ, Marshall, JD, Wolff, EW, Hopley, PJ, Atkinson, T, Barber, KE, Fisher, EH, Robertson, I, Hughes, PDM, Roberts, CN. 2011. The 8200 yr BP cold event in stable isotope records from the North Atlantic region. *Global Planet Change* **79**: 288–302.

Dixit, Y, Hodell, DA, Sinha, R, Petrie, CA. 2014. Abrupt weakening of the Indian summer monsoon at 8.2 kyr B.P. *Earth Planet Sci Lett* **391**: 16–23.

Dong, J, Shen, C-C, Kong, X, Wang, H-C, Jiang, X. 2015. Reconciliation of hydroclimate sequences from the Chinese Loess Plateau and low-latitude East Asian Summer Monsoon regions over the past 14,500 years. *Palaeogeogr Palaeoclimatol Palaeoecol* **435**: 127–135.

dos Santos-Fischer, CB, Weschenfelder, J, Corrêa, ICS, Stone, JR, Dehnhardt, BA, Bortolin, EC. 2018. A drowned lagunar channel in the southern Brazilian coast in response to the 8.2-ka event: Diatom and seismic stratigraphy. *Estuar Coast* **41**: 1601–1625.

Dykoski, CA, Edwards, RL, Cheng, H, Yuan, D, Cai, Y, Zhang, M, Lin, Y, Qing, J, An, Z, Revenaugh, J. 2005. A high-resolution, absolute-dated Holocene and deglacial Asian monsoon record from Dongge Cave, China. *Earth Planet Sci Lett* **233**: 71–86.

Eddudottir, SD, Erlendsson, E, Gisladóttir, G. 2018. An Icelandic terrestrial record of North Atlantic cooling c. 8800–8100 cal. yr BP. *Quat Sci Rev* **197**: 246–256.

Feng, XX, Yang, Y, Cheng, H, Zhao, JY, Kong, XG, Zhang, P, He, ZL, Shi, X, Edwards, RL. 2020. The 7.2 ka climatic event: Evidence from high-resolution stable isotopes and trace element records of stalagmite in Shuiming Cave, Chongqing, China. *Holocene* **30**: 145–154.

Fernández Pepi, MG, Zucol, AF, Arriaga, MO. 2012. Comparative phytolith analysis of Festuca (Pooidae: Poaceae) species native to Tierra del Fuego, Argentina. *Botany* **90**: 1113–1124.

Filoc, M, Kupryjanowicz, M, Szeroczyńska, K, Suchocha, M, Rzokiewicz, M. 2017. Environmental changes related to the 8.2-ka event and other climate fluctuations during the middle Holocene: Evidence from two dystrophic lakes in NE Poland. *The Holocene* **27**(10): 1550–1566.

Fredlund, G, Tieszen, L. 1997. Calibrating grass phytolith assemblages in climatic terms: Application to late Pleistocene assemblages from Kansas and Nebraska. *Palaeogeogr Palaeoclimatol Palaeoecol* **136**: 199–211.

Ghilardi, B, O’Connell, M. 2013. Early Holocene vegetation and climate dynamics with particular reference to the 8.2 ka event: Pollen and macrofossil evidence from a small lake in western Ireland. *Veget Hist Archaeobot* **22**: 99–114.

Hede, MU, Rasmussen, P, Noe-Nygaard, N, Clarke, AL, Vinebrooke, RD, Olsen, J. 2010. Multiproxy evidence for terrestrial and aquatic ecosystem responses during the 8.2 ka cold event as recorded at Højby So, Denmark. *Quat Res* **73**: 485–496.

Jiang, D. 1991. *Climate on the Yangtze Delta*. Beijing, China: Meteorological Press.

Jin, Z, Yu, J, Chen, H, Wu, Y, Wang, S, Chen, S. 2007. The influence and chronological uncertainties of the 8.2 ka cooling event on continental climate records in China. *The Holocene* **17**: 1041–1050.

Jo, K-n, Woo, KS, Lim, HS, Cheng, H, Edwards, RL, Wang, Y, Jiang, X, Kim, R, Lee, JI, Yoon, HI. 2011. Holocene and Eemian climatic optima in the Korean Peninsula based on textural and carbon isotopic records from the stalagmite of the Daeya Cave, South Korea. *Quat Sci Rev* **30**: 1218–1231.

Li, X, Jian, Z, Shi, X, Liu, S, Chen, Z, Wu, Y, Shi, F. 2015. A Holocene record of millennial-scale climate changes in the mud area on the inner shelf of the East China Sea. *Quat Int* **384**: 22–27.

Liew, PM, Lee, CY, Kuo, CM. 2006. Holocene thermal optimal and climate variability of East Asian
monsoon inferred from forest reconstruction of a subalpine pollen sequence, Taiwan. *Earth Planet Sci Lett* **250**: 596–605.

Liu, D, Wang, Y, Cheng, H, Edwards, RL, Kong, X. 2015. Cyclic changes of Asian monsoon intensity during the early mid-Holocene from annually-laminated stalagmites, central China. *Quat Sci Rev* **121**: 1–10.

Liu, YH, Henderson, GM, Hu, CY, Mason, AJ, Charnley, N, Johnson, KR, Xie, SC. 2013. Links between the East Asian monsoon and North Atlantic climate during the 8,200 year event. *Nat Geo* **6**: 117–137.

Lu, H, Zhang, J, Liu, KB, Wu, N, Li, Y, Zhou, K, Ye, M, Zhang, T, Zhang, H, Yang, X, Shen, L, Xu, D, Li, Q. 2009. Earliest domestication of common millet (*Panicum miliaceum*) in East Asia extended to 10,000 years ago. *Proc Natl Acad Sci USA* **106**: 7367–7372.

Lu, HY, Wu, NQ, Yang, XD, Jiang, H, Liu, KB, Liu, TS. 2006. Phytoliths as quantitative indicators for the reconstruction of past environmental conditions in China I: Phytolith-based transfer functions. *Quat Sci Rev* **25**: 945–959.

Madella, M, Alexandre, A, Ball, T. 2005. International code for phytolith nomenclature 1.0. *Ann Botany* **96**: 253–260.

Madella, M, Lancelotti, C. 2012. Taphonomy and phytoliths: A user manual. *Quat Int* **275**: 76–83.

Mayewski, PA, Rohling, EE, Stager, JC, Karlen, W, Maasch, KA, Meeker, LD, Meyerson, EA, Gasse, F, van Kreveld, S, Holmgren, K, Lee-Thorp, J, Rosqvist, G, Rack, F, Staubbawer, M, Schneider, RR, Steig, EJ. 2004. Holocene climate variability. *Quat Res* **62**: 243–255.

Meng, Y, Wang, W, Hu, J, Zhang, J, Lai, Y. 2017. Vegetation and climate changes over the last 30,000 years on the Leizhou Peninsula, southern China, inferred from the pollen record of Huguangyan Maar Lake. *Boreas* **46**: 525–540.

Miall, AD. 1992. Facies models: Response to sea level change, in Walker, RG, James, NP eds., *Alluvial deposits*. Waterloo, Ontario: Geological Association of Canada: 119–139.

Miao, Y, Jin, H, Liu, B, Wang, Y. 2014. Natural ecosystem response and recovery after the 8.2 ka cold event: Evidence from slope sediments on the northeastern Tibetan Plateau. *J Arid Environ* **104**: 17–22.

Morrill, C, Anderson, DM, Bauer, BA, Buckner, R, Gille, EP, Gross, WS, Hartman, M, Shah, A. 2013. Proxy benchmarks for intercomparison of 8.2 ka simulations. *Clim Past* **9**: 423–432.

Nicolussi, K, Schlüchter, C. 2012. The 8.2 ka event—Calendered-glacier response in the Alps. *Geology* **40**: 819–822.

Peckover, EN, Andrews, JE, Leeder, MR, Rowe, PJ, Marca, A, Sahy, D, Noble, S, Gawthorpe, R. 2019. Coupled stalagmite–Alluvial fan response to the 8.2 ka event and early Holocene palaeoclimate change in Greece. *Palaeogeogr Palaeoclimatol Palaeoecol* **532**: 109252.

Peros, M, Collins, S, G’Meiner, AA, Reinhardt, E, Pupo, FM. 2017. Multistage 8.2 kyr event revealed through high-resolution XRF core scanning of Cuban sinkhole sediments. *Geophys Res Lett* **44**: 7374–7381.

Piperno, D. 2006. *Phytoliths: A comprehensive guide for archaeologists and paleoecologists*. Lanham, MD: Altamira Press.

Qin, L, Li, J, Wang, L, Lu, H. 2008. The morphology and assemblages of phytolith in Pooideae from the Qinghai-Tibetan Plateau. *Acta Palaeontologica Sinica* **47**: 176–184.

Rasmussen, SO, Vinther, BM, Clausen, HB, Andersen, KK. 2007. Early Holocene climate oscillations recorded in three Greenland ice cores. *Quat Sci Rev* **26**: 1907–1914.

Reimer, PJ, Bard, E, Bayliss, A, Beck, JW, Blackwell, PG, Bronk Ramsey, C, Buck, CE, Cheng, H, Edwards, RL, Friedrich, M, Groosme, PM, Guilderson, TP, Haflidason, H, Hajdas, I, Hatté, C, Heaton, TJ, Hoffmann, DL, Hogg, AG, Hughen, KA, Kaiser, KF, Kromer, B, Manning, SW, Niu, M, Reimer, RW, Richards, DA, Scott, EM, Southon, JR, Staff, RA, Turney, CSM, van der Plicht, J. 2013. IntCal13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal BP. *Radiocarbon* **55**: 1869–1887.

Rohling, EJ, Palike, H. 2005. Centennial-scale climate cooling with a sudden cold event around 8,200 years ago. *Nature* **434**: 975–979.

Rosen, AM, Hart, TC, Farquhar, J, Schneider, JS, Yadmaa, T. 2019. Holocene vegetation cycles, land-use, and human adaptations to desertification in the Gobi Desert of Mongolia. *Veget Hist Archaeobot* **28**: 295–309.

Sallun, AEM, Sallun Filho, W, Sugio, K, Babinski, M, Gioia, SMCl, Harlow, BA, Duleba, W, De Oliveira, PE, Garcia, MJ, Weber, CZ, Christofoletti, SR, Santos, C.D.S, Medeiros, VB, d Silva, JB, Santiago-Hussein, MC, Fernandes, RS. 2012. Geochemical evidence of the 8.2 ka event and other Holocene environmental changes recorded in paleo-lagoon sediments, southeastern Brazil. *Quat Res* **77**: 31–43.

Schemmel, F, Niedermeyer, EM, Schwab, VF, Gleixner, G, Pross, J, Mulch, A. 2016. Plant wax δD values record changing Eastern Mediterranean atmospheric circulation patterns during the 8.2 kyr B.P. climatic event. *Quat Sci Rev* **133**: 96–107.

Schubert, M, Marcusen, T, Meseguer, AS, Fjellheim, S. 2019. The grass subfamily Pooidae: Cretaceous–Palaeocene origin and climate-driven Cenozoic diversification. *Glob Ecol Biogeogr* **28**: 1168–1182.

Selvaraj, K, Arthur Chen, C-T, Lou, J-Y, Kotlia, BS. 2011. Holocene weak summer East Asian monsoon intervals in Taiwan and plausible mechanisms. *Quat Int* **229**: 57–66.

Sheng, M, Wang, X, Zhang, S, Chu, G, Su, Y, Yang, Z. 2017. A 20,000-year high-resolution pollen record from Huguangyan Maar Lake in tropical–subtropical South China. *Palaeogeogr Palaeoclimatol Palaeoecol* **472**: 83–92.
Song, B, Li, Z, Lu, H, Mao, L, Saito, Y, Yi, S, Lim, J, Lu, A, Sha, L, Zhou, R, Zuo, X, Pospelova, V. 2017. Pollen record of the centennial climate changes during 9–7 cal ka BP in the Changjiang (Yangtze) River Delta plain, China. Quat Rev 87: 275–287.

Song, B, Li, Z, Saito, Y, Okuno, J, Lu, A, Hua, D, Li, J, Li, Y, Nakashima, R. 2013. Initiation of the Changjiang (Yangtze) delta and its response to the mid-Holocene sea level change. Palaeogeogr Palaeoclimatol Palaeoecol 388: 81–97.

Soreng, RJ, Peterson, PM, Romaschenko, K, Davidse, W, Wang, W, Li, C, Shu, J, Chen, W. 2019. Changes of vegetation in southern China. Quat Sci Rev 204: 1497–1507.

Tinner, W, Lotter, AF. 1992. Predicted world distribution of C3 and C4 grass phytoliths, phytolith systematics, emerging issues, in Rapp, G, Mulholland, SC eds., Phytolith study and its application. Beijing, China: China Ocean Press.

Twiss, PC. 1992. Predicted world distribution of C3 and C4 grass phytoliths, phytolith systematics, emerging issues, in Rapp, G, Mulholland, SC eds., Phytolith study and its application. Beijing, China: China Ocean Press.

Voarintsoa, NRG, Matero, ISO, Railsback, LB, Gregoire, LJ, Tindall, J, Sime, L, Cheng, H, Edwards, RL, Brook, GA, Kathayat, G, Li, X, Michel Rakotondrazafy, AF, Madison Razanatseheno, MO. 2019. Investigating the 8.2 ka event in northwestern Madagascar: Insight from data–model comparisons. Quat Sci Rev 204: 172–186.

Wang, W, Li, C, Shu, J, Chen, W. 2019. Changes of vegetation in southern China. Sci China Earth Sci 62: 1316.

Wang, Y, Lu, H. 1992. Phytolith study and its application. Beijing, China: China Ocean Press.

Wang, Y, Xu, Y, Lei, C, Li, G, Han, L, Song, S, Yang, L, Deng, X. 2016. Spatio-temporal characteristics of precipitation and dryness/wetness in Yangtze River Delta, eastern China, during 1960–2012. Atmos Res 172–173: 196–205.

Wang, YJ, Cheng, H, Edwards, RL, He, YQ, Kong, XG, An, ZS, Wu, JY, Kelly, MJ, Dykoski, CA, Li, XD. 2005. The Holocene Asian monsoon: Links to solar changes and North Atlantic climate. Science 308: 854–857.

Wanner, H, Solomina, O, Grosjean, M, Ritz, SP, Jetel, M. 2011. Structure and origin of Holocene cold events. Quat Sci Rev 30: 3109–3123.

Wu, YJ, Wang, YJ, Cheng, H, Kong, XG, Liu, DB. 2012. Stable isotope and trace element investigation of two contemporaneous annually-laminated stalagmites from northeastern China surrounding the “8.2 ka event.” Clim Past 8: 1497–1507.

Wu, Z. 1980. Vegetation of China. Beijing, China: Science Press.

Yi, S, Saito, Y, Zhao, Q, Wang, P. 2003. Vegetation and climate changes in the Changjiang (Yangtze River) Delta, China, during the past 13,000 years inferred from pollen records. Quat Sci Rev 22: 1501–1519.

Yue, YF, Zheng, Z, Huang, KY, Chevalier, M, Chase, BM, Carre, M, Ledru, MP, Cheddadi, R. 2012. A continuous record of vegetation and climate change over the past 50,000 years in the Fujian Province of eastern subtropical China. Palaeogeogr Palaeoclimatol Palaeoecol 365: 115–123.

Zhang, J, Zhou, X, Jiang, S, Tu, L, Liu, X. 2020. Monsoon precipitation, economy and wars in ancient China. Front Earth Sci 8: 317.

Zhang, JP, Lu, HY, Gu, WF, Wu, NQ, Zhou, KS, Hu, YY, Xin, YJ, Wang, C. 2012. Early mixed farming of millet and rice 7800 years ago in the Middle Yellow River Region, China. PLoS One 7(12): e52146.

Zhao, L, Ma, C, Leipe, C, Long, T, Liu, K-b, Lu, H, Tang, L, Zhang, Y, Wagner, M, Tarasov, PE. 2017. Holocene vegetation dynamics in response to climate change and human activities derived from pollen and charcoal records from southeastern China. Palaeogeogr Palaeoclimatol Palaeoecol 485: 644–660.

Zhong, W, Cao, J, Xue, J, Ouyang, J. 2017. A 15,400-year record of climate variation from a subalpine lacustrine sedimentary sequence in the western Nanling Mountains in South China. Quat Res 84: 246–254.

Zhou, B, Zheng, H, Yang, W, Taylor, D, Lu, Y, Wei, G, Li, L, Wang, H. 2012. Climate and vegetation variations since the LGM recorded by biomarkers from a sediment core in the northern South China Sea. J Quat Sci 27: 948–955.

Zuo, X, Lu, H, Li, Z, Song, B, Xu, D, Zou, Y, Wang, C, Huan, X, He, K. 2016. Phytolith and diatom evidence for rice exploitation and environmental changes during the early mid-Holocene in the Yangtze Delta. Quat Res 86: 304–315.
