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REVIEW ARTICLE

Ecological significance of common pollen ratios: A review

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Abstract Pollen ratios have been commonly used to indicate landscape change and climate variation. However, the reliability of these indicators needs to be verified by studies on modern pollen process. Here, we synthesized the major pollen ratios used in previous studies and found that pollen ratios are valuable indicators for the change of vegetation types and climate, e.g., precipitation and moisture. *Artemisia*/Chenopodiaceae (A/C) ratio could increase from desert to steppe and positively correlate with mean annual precipitation (MAP). *Artemisia*/Cyperaceae (A/Cy) ratio could be used to identify cool meadow and warm steppe, and it is positively correlated with temperature of July (T_{July}) and negatively correlated with MAP. Arboreal pollen/nonarboreal pollen (AP/NAP) ratio can be used as a semi-quantitative indicator for landscape and regional precipitation changes. In spite of the significant climatic and environmental implications of the pollen ratios, they were also questioned in some studies under various circumstances and thus caution is needed when using them to indicate climate in different vegetation zones.

Keywords pollen ratios, vegetation change, climate change

1 Introduction

Instrumental climate records show gradual warming during the 20th century in the Northern Hemisphere (IPCC, 2007). Therefore, climate change becomes one of the most urgent issues that people are facing today. To better understand our future climate, long-term past climate changes need to be understood first. Where, such as in lake sediment, peat, and loess, pollen and spores have accumulated over time, a record of the past vegetation of an area may be preserved. Generally, changes in the vegetation of an area may be due to changes of climate. Interpreting past vegetation through pollen analysis may therefore offer a form of palaeoclimatic reconstruction. The traditional interpretation of pollen records is usually based on the presence and abundance of selected indicator taxa (e.g., Birks and Birks, 1980), and it is usually presented as concentration or percentage of single pollen type. However, in some regions, the absence and abundance of single indicative pollen types are not enough in the studies of climate change based on pollen assemblages. Palynologists found that vegetation and climate information can be indicated effectively by the ratios of various pollen types. Some ratios of different pollen types have been proved to be better in indicating the vegetation gradient than percentages and concentrations of single pollen types (Liu et al., 1999). The *Artemisia*/Chenopodiaceae (A/C) ratio was introduced first by El-Moslimany (1990), and since then, various pollen ratios studies were widely exploited in surface pollen samples to validate the reliability of pollen ratios. Such as the *Artemisia*/Cyperaceae (A/Cy) ratio (Herzschuh, 2007; Zhao and Herzschuh, 2009), the arboreal pollen/nonarboreal pollen (AP/NAP) ratio (Cour et al., 1999; Liu et al., 1999; Herzschuh, 2007; Xu et al., 2007), the *Ephedra* fragilis-type/*Ephedra* distachya-type (Ef/Ed) ratio (Herzschuh et al., 2004), the *Pinus*/*Artemisia* (P/A) ratio (Xu et al., 2007), the Poaceae/*Artemisia* (Po/A) ratio (Tang et al., 2009), the Cyperaceae/Poaceae (Cy/Po) ratio (Cour et al., 1999), the Cyperaceae/Poaceae plus *Artemisia* (Cy/(Po + A)) ratio (Tang et al., 2009), the *Artemisia*/*Betula* (A/B) ratio (Liu et al., 1999, 2006), the Poaceae/*Artemisia* plus Chenopodiaceae (Po/(A + C)) ratio (Fowell et al., 2003), and so on.

In this paper, we made a review of the implication and reliability of the pollen ratios mentioned above, which were used in previous studies. Our method is examining the reliability of pollen ratios based on the modern pollen studies. This work will provide a basis for the proper use of pollen ratios in the reconstruction of paleovegetation and paleoclimate.

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2 Pollen ratios and their significance

2.1 A/C ratio

Artemisia and Chenopodiaceae are the two taxa of the most important pollen types in arid and semi-arid region, and their pollen have high percentages in most sediments as well as surface samples. El-Moslimany (1990) pointed out that these two types have in common the need for open environments, the preference for continental conditions, and the ability to tolerate an intense summer drought but differ in their moisture requirements. Zhao et al. (2008) interpreted relative humidity as an approximate measure of water available to plants. It is commonly recognized that *Artemisia* needs more soil moisture than Chenopodiaceae, so the ratio can be used as an indicator of moisture within the region where both groups grow (El-Moslimany, 1982, 1987). Since the introduction of A/C ratio, it has contributed substantially to the reconstruction of paleovegetation and paleoclimate. These reconstructions largely depended on the verification of A/C ratios in the surface sample studies. A study in the Tibetan Plateau showed that A/C ratio is significantly positively correlated with mean annual precipitation (MAP) ($r^2 = 0.25$) (Herzschuh, 2007). Zhao et al. (2008) analyzed 50a pollen records at near-annual resolution from Gahai Lake in the Qaidam Basin on the north-eastern Tibetan Plateau and found that A/C ratio positively corresponds well to relative humidity observed at the nearby Delingha weather station (Fig. 1(a)). Similar results were also found by other studies (Cour et al., 1999; Liu et al., 1999, 2006; Herzschuh et al., 2004). Furthermore, A/C ratio could change when the landscape changed. Previous studies in the drylands of the Middle East indicated that *Artemisia* is a characteristic of steppe, while Chenopodiaceae is more frequent in desert vegetation (El-Moslimany, 1990). Studies exploited by Yu et al. (1998) suggested that *Artemisia* pollen is more abundant in steppe, while Chenopodiaceae pollen is most abundant in desert vegetation in China. Studies in the Xinjiang region indicated that A/C ratios were < 0.5 in desert, 0.5–1.2 in steppe desert, and > 1 in typical steppe (Yan, 1991). Yu et al. (1998), Cour et al. (1999), and Zhao and Herzschuh (2009) reported that Chinese desert areas yield A/C values below 0.5. Study along the regional transect and elevational transect in the north-eastern Tibetan Plateau suggested that the A/C ratio decreased from > 5 to < 1 with the vegetation changing from mea-dow, through steppe, steppe desert, and desert. (Fig. 1(b)) (Zhao and Herzschuh, 2009). Therefore, the A/C ratio is a valuable tool for reconstructing landscape change.

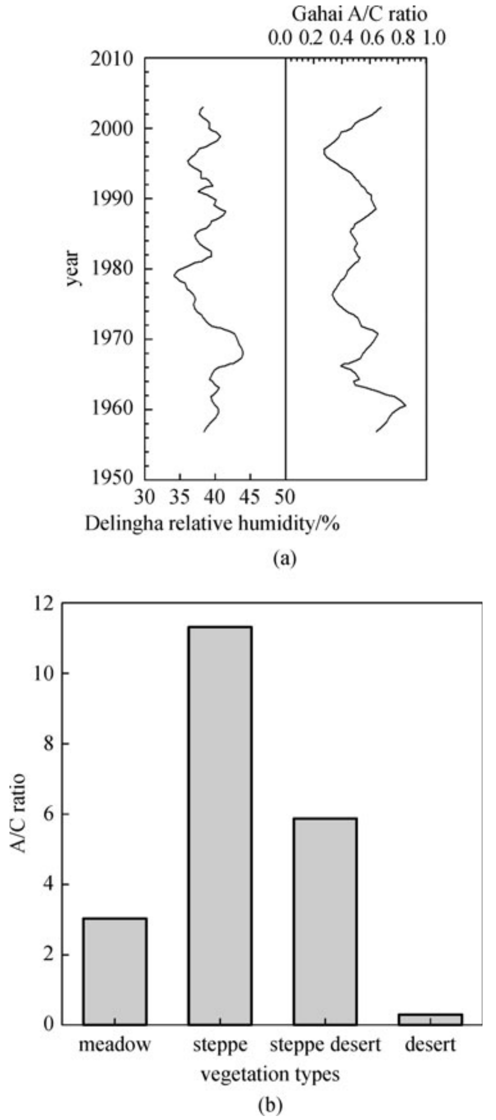

Fig. 1 Correlation of A/C ratio with selected factors. (a) A/C ratio versus relative humidity from Gahai Lake, in Qaidam Basin (Zhao et al., 2008); (b) A/C ratio in different vegetation types (Zhao et al., 2009)

However, in addition to the vegetation and climate, there are also other factors that influenced the value of A/C ratio. El-Moslimany (1990) stated the fact that nonclimatic influences affect the percentages of the two pollen types will make the climatic significance of A/C ratio less reliable. This is validated by Liu et al. (2006). They collected and analyzed surface pollen samples along moisture and human impact gradients in the steppe zone in East Asia and found that vegetation degradation in semiarid areas caused by human activities is indicated by the expansion of Chenopodiaceae plants (Liu et al., 2006). If the A/C ratio would also decrease in these circumstances, we could not absolutely attribute a decreased A/C ratio to either a decreased precipitation or human impact. Moreover, Ren (1999) inferred from pollen diagrams that an increase of Chenopodiaceae pollen following an increase of *Artemisia* pollen and a decrease of *Quercus* pollen indicated human-caused vegetation degradation. Therefore, if the human-induced vegetation degradation caused an increase on both *Artemisia* and Chenopodiaceae percentage, the situation will be more complicated. Cour et al. (1999) pointed out that the percentages of *Artemisia* were positively correlated with increasing altitude, whereas Chenopodiaceae was negatively correlated. In addition, this study found that the A/C ratio could significantly vary with the differences in topography. However, the application of the A/C ratio in parts of the Tibetan Plateau was ever questioned by Frenzel (2002). When A/C ratio is used to indicate the landscape change, Chenopodiaceae is considered to be true desert plants. However, both Chenopodiaceae and *Artemisia* in Tibetan Plateau have wide ecological range, which made the identification of the landscape change by A/C ratio become more difficult. The studies done by El-Moslimany (1990) also indicated that A/C ratio is probably not a valid indicator of moisture when comparing forested and nonforested sites or comparing sections of pollen diagrams with low and high arboreal pollen. Therefore, the vegetation type must be taken into consideration when A/C ratio is used to indicate landscape variation.

2.2 A/Cy ratio

Herzschuh (2007) introduced that the A/Cy ratio is significantly positively correlated with T_{July} and has a weak correlation with MAP on the central and eastern Tibetan Plateau based on the observation that Cyperaceae is abundant in high-alpine meadows and alpine steppe, which is also verified by Cyperaceae that has highest percentages ($>50\%$) in areas characterized by alpine meadows in eastern-central Tibet (Yu et al., 2001). Our study in the Zoige Basin in eastern Tibetan Plateau also agreed with this observation. In our field observation, we found that Cyperaceae is the most abundant taxa in meadow vegetation, especially in high-alpine meadows and marsh meadows. The former type is dominated by *Kobresia*, while the latter is mainly composed of *Carex.* It shows that Cyperaceae is adapted to living in cold-wet environment. Compared to Cyperaceae, *Artemisia* is more adapted to dry and warm steppe environment. Herzschuh (2007) suggested that the A/Cy ratio could be used to identify cool meadow and warm steppe, and it is positively correlated with T_{July} and negatively correlated with MAP (Fig. 2). A study in the eastern Tibetan Plateau showed that A/Cy values are less than 1 in surface samples from alpine meadow sites, while those sampled from temperate steppe and desert are more than 1. This study also indicated that A/Cy has a positive correlation with T_{July} but a negative correlation with MAP (Zhao and Herzschuh, 2009).

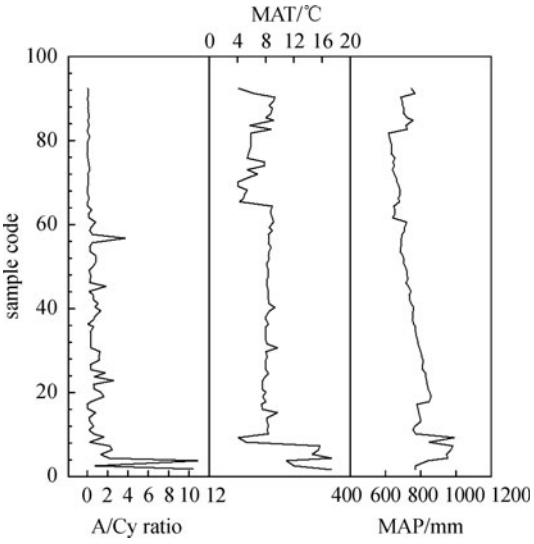

Fig. 2 Correlation of A/Cy ratio with selected climate variables (Herzschuh, 2007)

2.3 AP/NAP ratio

AP/NAP ratio is used to infer changes in the landscape openness of forest steppe and subalpine environments and as an indicator of moisture and temperature variability (Herzschuh, 2007). Study in the south-eastern edge of Inner Mongolia Plateau indicated that from dense forest, through open woodland, woodland–steppe to non-forested steppe zones, the AP/NAP ratio decreases from 8.5 to 0.2, which corresponds with the change of the vegetation (Fig. 3) (Liu et al., 1999). Studies from the modern pollen samples in Tibetan Plateau indicated that the arboreal pollen sum (AP) was highest in samples from forested areas and was significantly correlated with MAP ($r^2 = 0.44$), validating the applicability of the AP sum measure as a semiquantitative indicator for landscape and regional precipitation changes (Herzschuh, 2007). This study also supported that the increasing arboreal pollen percentages usually indicate the approaching tree-line, corresponding to the onset of wetter or warmer conditions. Another study in north China indicated that arboreal pollen account for more than 30% in temperate broad-deciduous forests region, while the AP/NAP is always <0.1 in temperate steppe, temperate desert, subalpine, and cold meadows (Xu et al., 2007).

However, some studies in north-western Tibet indicated that AP pollen percentage get their maximum value in spring and early summer (Cour et al., 1999). These results also showed that dust-trap samples contain much higher percentages of tree pollen than non-dust-trap samples, and many of the taxa present are exotic. In addition, the application of the AP/NAP ratio in parts of the Tibetan Plateau was ever questioned by Tarasov et al. (1998a), when the pollen samples are derived from lakes or mires as the pollen source area is regional rather than local. Herzschuh et al. (2004) tested his finding with modern pollen samples and reaffirmed that AP/NAP pollen ratio is not an appropriate method to infer moisture signal from the pollen record at Eastern Juyan, as it is a consequence of the low pollen production of the local plants due to

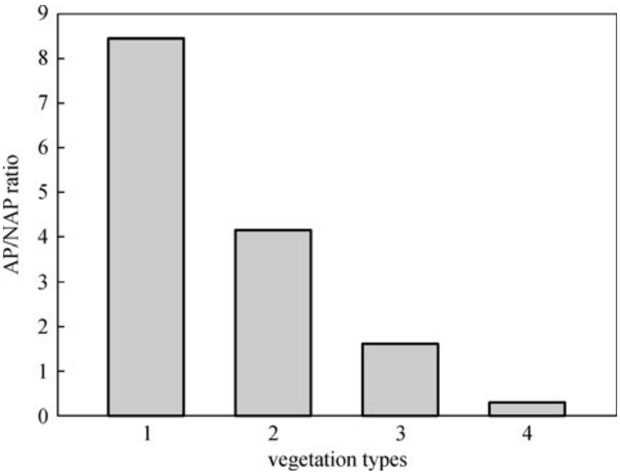

Fig. 3 Correlation of AP/NAP ratio with vegetation types (Liu et al., 1999). 1) Woodland; 2) woodland-grassland; 3) woodland-steppe; 4) steppe

pronounced aridity. In these situations, the AP value could neither be used as an evidence of the climate amelioration nor occurrence of trees. Therefore, the application of AP/NAP must be carefully adopted in different regions.

2.4 Other less used pollen ratios

Cy/Po ratio. The ratio of Cy/Po follows more or less the elevations (Cour et al., 1999). The value is higher in the montane areas (>1) and lower in the desert basins. It is due to the influence of both temperature and moisture, but it is difficult to determine which one is more responsible for this pattern.

(A + C)/Po. *Artemisia* and Chenopodiacae are the two most important pollen types in arid and semiarid regions. They are considered as the dominant types of desert-steppe, while the steppe and forest-steppe are dominated by the taxa of the family Poaceae. (A + C)/Po pollen was used as a semiquantitative index of aridity by Fowell et al. (2003) to distinguish dry steppe from moist meadow steppe and forest steppe vegetation in north-central Mongolia. The high values of the index (>5) are indicative of arid conditions that favor desert–steppe vegetation, whereas low values (<5) are interpreted as moist stages dominated by meadow– or forest–steppe.

Artemisia/*Ephedra* (A/Ep) and Ef/Ed ratio. Studies in north-western Tibet showed that the A/Ep ratio was likely affected by moisture level (Cour et al., 1999). However, Tarasov et al. (1998b) stated that among the *Ephedra* species, E. fragilis-type s.l. is often distinguished in the pollen spectra from arid climates with mean temperature of the warmest month above 22°C. Herzschuh et al. (2004) calculated Ef/Ed pollen ratios for each analyzed surface pollen assemblages and found that the Ef/Ed ratios are >10 in most samples from desert sites, while they are always <5 in most samples from the sites with more favorable climate (e.g., forest-steppe, steppe, and alpine meadows). Therefore, E. fragilis-type s.l. is thought to be a characteristic of desert vegetation, while the others mainly grow in the semidesert. High values of E. fragilis-type s.l. in the Ef /Ed ratio are supposed to indicate drier conditions.

P/A ratio. Surface pollen samples analyzed in north China showed that the Pinus/Artemisia (P/A) ratio in temperate broad-deciduous forests region always >0.1, while it is always <0.1 in temperate steppe, temperate desert, subalpine, and cold meadows (Xu et al., 2007).

Po/A ratio and Cy/(Po + A) ratio. It is well known that Poaceae demands more soil moisture than *Artemisia*, while Cyperaceae demands much more moisture than both of the former types. Therefore, both Po/A ratio and Cy/(Po + A) ratio can be used as a moisture indicator. Surface pollen records from steppe and alpine meadows in central Tibetan Plateau indicated that there existed good correlation between the ratios of Poaceae to *Artemisia* and moisture in July, and thus, the Cy/(Po + A) ratio is an indicator of moisture (Tang et al., 2009).

Poaceae/Asteraeae (Po/As) ratio. Based on the modern ecology and geographical distribution of Poaceae and Asteraeae, Betancourt et al. (2000) and Latorre et al. (2002) stated that Poaceae are typically shallow-rooted plants that tend to proliferate in wetter conditions, whereas the Asteraceae plants are xerophytic, deeply rooted shrubs that proliferate in drier environments. Liu et al. (2005, 2007) used the Po/As pollen ratio as an index of moisture availability in the Altiplano of South America.

B/A ratio. Pollen records analyzed in surface samples in Mongolia suggested that the ratio of A/B represented the precipitation as well as the vegetation gradients from deciduous broadleaved woodland to steppe vegetation (Liu et al., 1999, 2006).

3 Reliability of pollen ratios

3.1 Indicative function of pollen ratios

Precipitation and temperature are the two major climate variables that affect the values of pollen ratios. A/C ratio positively correlates with effective moisture and could change with difference vegetation types. A/Cy ratio shows positive correlation with precipitation and negative correlation with T_{July}. At the same time, it is a valuable tool to discriminate the high-alpine meadow from steppe vegetation. AP percentage shows positive correlation with MAP and varies with the vegetation zones. The B/A and P/A ratio also correlate well with mean annual precipitation and responds well to the vegetation change.

However, other nonclimatic variables could also influence the value of pollen ratios. For instance, A/C ratio variation could be caused by human disturbance. AP/NAP ratio could imply the proximity to tree-line, and Cy/Po ratio could reflect altitude.

3.2 Reliability of pollen ratios

As stated above, there are large quantities of factors influencing the value of pollen ratios as well as their relationship to vegetation and climate factors in different regions or under different circumstances.

Temperature and precipitation are the most important factors controlling the distribution of the vegetation. However, the integrative impact of the two works more on the vegetation distribution, which made the indications of the pollen ratios become more complicated. Moreover, the precipitation is not the direct factor that works on the plant; it is generally assumed that plant growth in arid and semiarid areas is limited by moisture availability rather than by absolute precipitation (Herzschuh et al, 2009). The moisture availability is a function of both precipitation and evaporation. The evaporation is influenced by many factors. Such as the topography, the soil texture, the slope aspect, and so on. In addition, it is the microclimate rather than macroclimate that worked more on the distribution of vegetation in small spatial scale. For instance, the Cyperaceae may prefer to live in the regions with high precipitation and low July temperature. However, it is also widely spread in catchment as well as marsh zones. In this circumstance, the A/Cy ratio would be less meaningful for indicating the precipitation. Therefore, the indicative function of pollen ratios to climate variable may be less reliable at small spatial scale.

Most pollen can be identified to family or genus; however, there are a large number of species under one family or genus. Many taxa from one family have wide ecological amplitude. For instance, the *Eperhera* type can always be classified to desert form, but there are still some hygrophilous types, similar with other species. Therefore, the pollen ratios may be less reliable in these circumstances.

The pollen ratios may be different in varied communities. Because the representation or percentage of one pollen type may affect the percentage of other pollen types, there may be differences in the same ratios calculated from different communities.

The exotic pollen transported by wind from a distant region may have more or less effect on the pollen ratios, especially to the AP/NAP ratio, the A/B ratio, and the P/A ratio. Hence, the factors, such as the size of the basin, the density of the vegetation, the wind, and the upstream of the sample sites related to the exotic pollen, influencing the pollen ratios must be taken into consideration. In addition, sampling season is also an important factor that influences the percentage of exotic pollen. For the season of bloom varies for different species, when the sampling time is in the season when there is less plant flowering, there may be more exotic regional pollen. Except the climate variables, other nonclimate variables could influence the value of pollen ratios, such as the human disturbance index and the topography.

In spite of the good indicative function of pollen ratios to climate and vegetation, the reliability of pollen ratios are restricted by the lack of verification executed in the modern pollen analysis, so more work needs to be carried out so as to verify the reliability of pollen ratios.

4 Summary

1) The various pollen ratios show reliable indicative function to climate and landscape change. AP and A/C positively correlate with MAP and could respond to the landscape change. A/Cy ratio shows a positive correlation to MAP and a negative correlation to T_{July}. Pollen ratio method is a useful tool in reconstructing paleovegetation and paleoclimate.

2) Pollen ratios may be influenced by many nonclimate factors that affect the reliability of indicative function of pollen ratios to vegetation and climate variation, which must be taken into consideration when using the pollen ratios in different circumstances.

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