A 1000-year record of vegetation change and wildfire from maar lake Erlongwan in northeast China

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A high-resolution (every 20 y) pollen and charcoal record from Erlongwan maar lake (EML) documents the vegetation history and fire activity of the Long Gang region (northeast China) over the past millennium. The age–depth model is based on $^{137}$Cs, $^{210}$Pb measurements, and one calibrated $^{14}$C-AMS date at the base of the core. For much of the record, vegetation was dominated by a mixed conifer-hardwood forest. Pollen and charcoal concentrations reveal considerable variability during the past 1000 years. Between 980 and 1500 AD both pollen and charcoal reached maximum concentrations (~1100 AD and 1300 AD respectively). The high pollen concentration was indicative of prevailing moist conditions during the period commonly referred to as the Medieval Climatic Anomaly (MCA). The high concentration of charcoal indicated high frequency and intensity of wildfire during the MCA, probably linked to high biomass productivity and less snow in winter. Between 1500 and 1850 AD both pollen and charcoal concentrations were low, indicative of colder winters with higher snowfall, relative drier summers and less intensive wildfire, coincidence with the cold period commonly known as the Little Ice Age (LIA). During 1900–1950 AD year, the highest relative abundance of Artemisia and the lowest abundance of Pinus together with high concentration of charcoal indicated strong human activity. The pollen data are in broad agreement with a previous study from an adjacent lake, indicating regional rather than localized human impact.

**Abstract**

A high-resolution (~every 20 y) pollen and charcoal record from Erlongwan maar lake (EML) documents the vegetation history and fire activity of the Long Gang region (northeast China) over the past millennium. The age–depth model is based on $^{137}$Cs, $^{210}$Pb measurements, and one calibrated $^{14}$C-AMS date at the base of the core. For much of the record, vegetation was dominated by a mixed conifer-hardwood forest. Pollen and charcoal concentrations reveal considerable variability during the past 1000 years. Between 980 and 1500 AD both pollen and charcoal reached maximum concentrations (~1100 AD and 1300 AD respectively). The high pollen concentration was indicative of prevailing moist conditions during the period commonly referred to as the Medieval Climatic Anomaly (MCA). The high concentration of charcoal indicated high frequency and intensity of wildfire during the MCA, probably linked to high biomass productivity and less snow in winter. Between 1500 and 1850 AD both pollen and charcoal concentrations were low, indicative of colder winters with higher snowfall, relative drier summers and less intensive wildfire, coincidence with the cold period commonly known as the Little Ice Age (LIA). During 1900–1950 AD year, the highest relative abundance of Artemisia and the lowest abundance of Pinus together with high concentration of charcoal indicated strong human activity. The pollen data are in broad agreement with a previous study from an adjacent lake, indicating regional rather than localized human impact.
The pollen and charcoal record of a peat bog from Jinchuan (Fig. 1), which lies to the west of the Long Gang Mountains, showed the interaction between climate, vegetation, fire events and human activity during the Holocene (Jiang et al., 2008). Stebich et al. (2009) provided the first high-resolution palynological record based on an annually laminated sedimentary sequence from Sihailongwan lake (SHLW) in the Long Gang Volcanic Field (LGVF), which spanned the late glacial to the early Holocene period (16,700–10,600 cal BP).

However, vegetation history recorded over the past millennium in northeast China is scarce (Mingram et al., 2004). Pollen investigations of the past 900 years from Lake Sihailongwan (Fig. 1) revealed distinct evidence for human impact on the landscape during the past 150 years (Mingram et al., 2004). Prior to then, palynological data suggested the persistence of very stable vegetation communities, despite evidence for distinct climate changes associated with the MCA and the LIA (Bradley and Jones, 1992). For example, decadal to annual scale climatic variations were reconstructed from high-resolution geochemical and sedimentological analyses from lakes in the LGVF (Chu et al., 2009a, 2009b). Snow anomaly events determined from Korean and Chinese documents recorded that northeast China had lower winter snowfall during the MCA (Chu et al., 2008). A reconstructed decadal spring (April–June) drought index from Korean historical documents also showed significant climate changes in northeast China over the past 1000 years (Kim and Choi, 1987).

In addition, fires are recognized as an important agent in ecological systems (Cochrane et al., 1999; Haberle et al., 2001; Whitlock et al., 2003), controlling forest structure and vegetation composition (Heinselman, 1973; Zackrisson, 1977; Patterson and Backman, 1988). Human activities can also play an important role in the occurrence of fire (Tinner et al., 1998; Pitkänen and Huttunen, 1999; Jiang et al., 2008; López-Blanco et al., 2011; Zhou et al., 2011), although at some sites it can be difficult to differentiate human causes of fire from natural causes (Ssemmanda et al., 2005). One way to solve this issue is to use pollen data to obtain evidence of human impact on the landscape (Pitkänen and Huttunen, 1999; Jiang et al., 2008; López-Blanco et al., 2011; Zhou et al., 2011).

The objective of this study is to reconstruct vegetation communities and the intensity of fire events over the past 1000 years in northeast China, against a backdrop of complex hydrological variability associated with the MCA, LIA, recent warming and direct human impact.

2. Geographical background and site location

2.1. Location of study site

Erlongwan maar lake (EML) (724 m asl) is one of eight maar and crater lakes located in the Long Gang Volcanic Field (LGVF) in Jilin Province, northeast China (Fig. 1). EML is a small, closed, elliptical lake (surface area is approximately 0.3 km²) with a maximum water depth of 36 m. It is primarily fed by rainfall during the summer months, in conjunction with associated groundwater inflow, and it has no inflowing streams and also no outlet (Mingram et al., 2004; Liu et al., 2005b).

2.2. Climate

The modern climate in northeast China is temperate, strongly seasonal and influenced by the East Asian monsoonal system. Winters are dry, very cold and dominated by winds from the northwest. Summers are dominated by warm and moist air masses from the Pacific Ocean. The mean annual temperature of the Long Gang Volcanic Field is ±3.0 °C (1955–2001), observed at Jingyu meteorological station. Winter temperatures can be extremely cold, as low as −39 °C, whereas in summer temperatures can be as high as 37 °C. The rainy season lasts from June to September and accounts for at least 60% of the mean annual precipitation of ~766 mm.

Fig. 1. Study location, main geological formations, and lakes of the Long Gang Volcanic Field, NE China (after Mingram et al., 2004; Liu et al., 2005b).
2.3. Vegetation

The modern natural vegetation in the Long Gang Volcanic Field belongs to the temperate mixed-forest flora of Changbai Mountain. The virgin vegetation is characterized by a Pinus koraiensis mixed conifer and broadleaf forest zone, which now deteriorates to secondary broadleaved forest (Editorial Board for flora of China, 1995). The coniferous trees are dominated by P. koraiensis, and also include Abies holophylla, and few Taxus cuspidata var. latifolia, Thuja koraiensis. The deciduous trees mainly consist of Betula costata, Betula platyphylla, Juglans mandshurica, Quercus mongolica, Ulmus propinqua, Carpinus cordata, Tilia amurensis, Fraxinus mandshurica, many kinds of Acer, Populus davidiana, Corylus mandshurica, Eleutherococcus senticosus and Syringa reticulate var. mandshurica.

3. Materials and methods

3.1. Chronology

A 66.5-cm-long sediment core was obtained using a UWITEC gravity corer in 2001 at 36 m water depth from the central part of EML (42°18’N, 126°23’E) (Fig. 1). The lower sediments (between 51 cm and 66.5 cm depth) were composed of a graded layer of slumped sedimentary deposits (Frank, 2007) and are not considered further. This study focuses on the upper 50 cm of laminated sediments, which were sectioned into 1 cm intervals for pollen analyses. The laminations are likely to be of a varved nature (You et al., 2008) although this has not been confirmed for this particular core. The age model was therefore developed using a combination of radiometric techniques. The activities of $^{137}$Cs, $^{210}$Pb, and $^{226}$Ra in the upper 23 samples were measured by gamma spectrometry using a low-background well-type germanium detector (EGPC 100P-15R) (Fig. 2). $^{210}$Pb is a naturally-produced radionuclide from nuclear weapons testing. Dates for the lower sediments were secured by dating a macrofossil taken at 49.5 cm core-depth by AMS $^{14}$C at the Poznan Radiocarbon Laboratory. The radiocarbon date was calibrated using the OxCal 4.1 program (Bronk Ramsey, 2009) and the IntCal09 radiocarbon calibration curve (Reimer et al., 2009). An age–depth chronology was developed by combining results of the $^{14}$C dating, $^{210}$Pb and $^{137}$Cs techniques (Fig. 2). The Pinus macrofossil was dated at 1045 ± 30 $^{14}$C yrs BP (Fig. 2), which after calibration gave an age range of 900–1030 AD. The ages of the samples between the lower most samples dated with $^{210}$Pb and the radiocarbon date at 49.5 cm were linearly interpolated. Furthermore, the age-model was extended to date the base of the core at ~980 AD (Fig. 2). The resolution of this record is ~20 years/cm.

3.2. Pollen and charcoal preparation

Dried sub-samples, ~1 g, were processed at the Micro-paleonotology Laboratory of China University of Geosciences, using standard palynological methods (Moore et al., 1991). Each sample was treated with 10% hydrochloric acid (HCl), 10% potassium hydroxide (KOH), hydrofluoric acid (HF) and then HCl again. Lycopodium spores were added as an exotic marker to the samples before acid maceration in order to facilitate the calculation of absolute pollen and charcoal concentrations. Slides, made with glycerin jelly with a wax seal, are stored in the Micro-paleonotology Laboratory of China University of Geosciences.

Pollen and spores were identified and counted with a Leica light microscope at ×400 magnification, with ×1000 magnification employed for critical identifications. For each sample 400–500 terrestrial pollen grains were identified and counted, plus other spores. In addition to pollen grains, charcoal particles in pollen slides were counted and used as a proxy of palaeofire history, providing a linkage between climate and vegetation (Whitlock and Larsen, 2001). Opaque, black charcoal fragments with irregular angles and elongate forms greater than 10 μm of the maximum length, were identified and counted and divided into three size classes: 10–50 μm, 50–100 μm and >100 μm.

The percentages of each pollen type were calculated based on the sum of total land pollen. Stratigraphic data were plotted using

![Fig. 2. The Erlongwan maar lake short core $^{137}$Cs–$^{210}$Pb, age–depth model diagram. a–b. Concentration of $^{137}$Cs and $^{210}$Pb. c. $^{137}$Cs, $^{210}$Pb and $^{14}$C age model. d. Sediment accumulation rate.](image-url)
the program C2, version 1.4.3 (Juggins, 2003). Pollen and charcoal concentrations were also calculated (grains g\(^{-1}\)) in order to circumvent the statistical interdependence of percentage data.

4. Results

A total of 44 pollen and spore types were identified from 48 samples from EML sediments, which the age model dates between 980 and 2001 AD. The relative frequencies of the most abundant and palaeoecologically most indicative pollen taxa record are shown in Fig. 3.

Relative pollen frequencies show only subtle changes (Fig. 3). The pollen assemblage reflects a mixed coniferous-hardwood and deciduous forest around the Erlongwan lake region. The assemblage is dominated by tree pollen, averaging almost 80% of total land pollen (TLP). *Pinus* is the dominant conifer, while major broad-leaved deciduous trees (accounting for almost 50% of TLP) include *Quercus, Betula, Juglans, Ulmus, Carpinus, Corylus, Tilia* and *Fraxinus.* Shrubs and herbs account for approximately 20% of TLP and included *Artemisia, Chenopodiaceae, Poaceae* and *Humulus.* Spores were not common in the samples, but those that did occur included *Polypodiaceae* and *Selaginella.*

Pollen and charcoal concentration stratigraphies are given in Fig. 4 and Fig. 5, respectively. The biostratigraphical record was divided into three pollen assemblage zones based on pollen concentration using CONISS cluster analysis (Fig. 4) (Grimm, 1987).  

4.1. Zone A: depth 50–26 cm; 980–1500 AD

Tree pollen concentrations are the highest in the total pollen sum, averaging up to 142 \(\times\) 10\(^4\) grains g\(^{-1}\), in which coniferous and deciduous pollen concentration averaged 59 \(\times\) 10\(^4\) grains g\(^{-1}\) and 83 \(\times\) 10\(^4\) grains g\(^{-1}\) respectively. Coniferous pollen was mainly composed of *Pinus,* averaging up to 50 \(\times\) 10\(^4\) grains g\(^{-1}\). *Quercus, Betula, Juglans, Ulmus* and *Carpinus* were the main types of broad-leaved deciduous pollen, with average concentrations of 29 \(\times\) 10\(^4\) grains g\(^{-1}\), 21 \(\times\) 10\(^4\) grains g\(^{-1}\), 13 \(\times\) 10\(^4\) grains g\(^{-1}\), 11 \(\times\) 10\(^4\) grains g\(^{-1}\) and 5 \(\times\) 10\(^4\) grains g\(^{-1}\) respectively. Herbaceous pollen is consistently present in lower concentrations, and is mainly composed of *Artemisia* (average 22 \(\times\) 10\(^4\) grains g\(^{-1}\)). This zone also contained the highest charcoal concentrations, averaging up to 2.5 \(\times\) 10\(^6\) grains g\(^{-1}\), with a peak value of 5.5 \(\times\) 10\(^6\) grains g\(^{-1}\).

4.2. Zone B: depth 26–10 cm; 1500–1850 AD

The most striking feature of this zone is the decline in total pollen concentration caused by declines in both tree and herb and shrub pollen. Tree pollen concentrations fell from approximately 142 \(\times\) 10\(^4\) grains g\(^{-1}\) to 49 \(\times\) 10\(^4\) grains g\(^{-1}\), caused especially by the decline in broad-leaved deciduous pollen concentrations, including *Quercus, Betula, Juglans* and *Ulmus,* which fell from approximately 83 \(\times\) 10\(^4\) grains g\(^{-1}\) to 28 \(\times\) 10\(^4\) grains g\(^{-1}\). The herb and shrub pollen concentrations also decrease to an average of approximately 12 \(\times\) 10\(^4\) grains g\(^{-1}\), caused mainly by the decrease in *Artemisia* and *Chenopodiaceae* values. Charcoal concentrations in this zone also show marked declines with an average of only 1.2 \(\times\) 10\(^6\) grains g\(^{-1}\).

4.3. Zone C: depth 10–0 cm; 1850–2001 AD

This zone begins with a marked increase in concentrations of almost all pollen taxa. Tree pollen concentrations rise to an average of 93 \(\times\) 10\(^4\) grains g\(^{-1}\). However, this increase in concentration is mainly due to broad-leaved, deciduous pollen including *Quercus, Betula, Juglans* and *Ulmus,* averaging from 28 \(\times\) 10\(^4\) grains g\(^{-1}\) to 50 \(\times\) 10\(^4\) grains g\(^{-1}\).
Herbs & Shrubs

45 × 10^4 grains g⁻¹, while coniferous pollen concentrations decline slightly in comparison to zone B. Herb and shrub pollen concentrations increase to an average of 25 × 10^4 grains g⁻¹, due mainly to Artemisia which sharply increases to an average of 16 × 10^4 grains g⁻¹, similar to values observed in Zone A.

Herbaceous pollen relative abundance also increases, reaching a maximum of 27.9%, the highest for the whole sequence, due mainly to Artemisia (averaging 18.5%). Concomitant with these increases is the simultaneous decline in coniferous trees, especially Pinus. Deciduous tree pollen exhibited a small increase (averaging 51.2%) in the proportion of the pollen sum, most notably Betula, Juglans and Carpinus, reaching the highest percentage of the total pollen sum.

Charcoal concentrations in this zone show a rapid rise above 10 cm, reaching highest concentrations of 2.6 × 10^6 grains g⁻¹.

5. Discussion

5.1. Vegetation history

During the study period, the extent of forest did not decline over the past ~1000 years. However, some pollen taxa did show subtle changes between 980 and 1850 AD. For example, thermostophilous taxa such as Juglans, Alnus, Carpinus, Thalictrum, Oleaceae and Rosaceae were present in higher abundances between 980 and 1500 AD than between 1500 and 1850 AD. In contrast, Pinus showed a small increase in values between 1500 and 1850 AD, perhaps linked to cooler temperatures associated with the LIA (Bradley and Jones, 1992). During this period Pinus was also recorded in higher abundances from Sihailongwan maar lake, which lies 7 km east of EML, indicative of a regional response (Mingram et al., 2004).

However, pollen concentrations exhibit much more variability during the past 1000 years, especially declining pollen concentrations from the base of the core to ~1500 AD. A key question is whether or not these changes are real and linked to changes in vegetation cover, or are a result of changing sedimentation rates in the lake. This study assumes a constant sediment accumulate rate between the timescales dated using 210Pb and AMS 14C, and therefore this issue cannot be resolved directly. A previous core taken from EML was reported to be varved, spanned the whole of the Holocene and sedimentation accumulation was relatively constant (e.g. You et al., 2008). You et al. (2008) report that dinocyst varves dominate their sequence down to 63 cm, dated to 1016 varve years. This gives an approximate sediment rate of c. 0.06 cm y⁻¹ which is very similar to the sedimentation rate estimated in this study (c. 0.05 cm y⁻¹) (Fig. 2d). Sedimentation rates were also similar to constant rates determined by a varve chronology from nearby Sihailongwan maar lake (Mingram et al., 2004). It is likely therefore that the changes in pollen concentrations observed are real.

Plant cover and biomass are positively associated with precipitation (Nearing et al., 2005; Buis et al., 2009). The maximum pollen concentration values were observed between 50 and 26 cm (980–1500 AD), therefore likely reflect high density plant cover and pollen production in this region of northeast China, associated with the warm and relative humid climate conditions during the MCA. Moreover, increasing frequencies of fern spores, also indicative of prevailing moist conditions, point to an increase in humidity. The drought index from historical documents suggest relative high moisture in northeast China during the late spring indicated by the length of the no precipitation period from April to June (Kim and Choi, 1987). Therefore, pollen data from EML and Sihailongwan maar lake (Mingram et al., 2004) are consistent with elevated moisture in northeastern China during the MCA caused by a strong summer monsoon (Yang and Tan, 2009).

In contrast, the relative abundance of pollen did not show significant changes in vegetation composition during the LIA, perhaps indicative that of the decline in precipitation because of a weak summer monsoon was limited or that low temperatures during this cold period resulted in decreasing evaporation, hence little change in effective moisture.

Temperature could be another important factor affecting pollen concentrations. Previous studies show that temperature changes also affect biomass production levels and rates in complex ways (Rosenzweig and Hillel, 1998; Nearing et al., 2005). Pollen
concentrations decline sharply between 26 and 10 cm (1500–1850 AD), indicative of lowest density of plant cover and pollen production. Many proxy records highlight that this region was cooler during the LIA than the preceding MCA, including variations of $\delta ^{18}O$ in peat cellulose from Jinchuan peat in northeast China (Hong et al., 2000); historical documents and stalagmite records from eastern China (Ge et al., 2003; Tan et al., 2003), and the tree-ring records from the Changbai Mountains (Shao and Wu, 1997). Snow anomaly index from detailed historical documents suggest that snow cover was heavier during the LIA than that during MCA, reaching its maximum extent around 1700 AD (Chu et al., 2008). Several studies show that plant biomass production declines when the temperatures decline (Rosenzweig and Hillel, 1998; Nearing et al., 2005). Cold climate causes the decline of plant cover because the length of growing season shortens with the increase duration of snow and ice cover in soils. The cold climate therefore likely results in overall low pollen concentrations observed, together with increased concentrations of Pinus pollen from Erlongwan and Sihailongwan lake (Mingram et al., 2004) linked to the expansion of cool coniferous forest. Diatom proxy recorded from EML also show a decline in aquatic productivity, indicating a shorter growing season at this time (Wang et al., 2012).

The period after the LIA is characterized by post industrial warming (Mann and Jones, 2003), which was likely responsible for the observed increases in EML pollen concentration, especially those associated with deciduous trees. However, there is also a notable increase in Artemisia and decline in Pinus, similar to observations from Sihailongwan lake (Mingram et al., 2004). These changes may be indicative of human impact on the regional vegetation. Historical documents show that northeastern China was sparsely populated prior to 1860 AD; only since 1861 AD did the government of the Qin dynasty repeal the command that previously forbade people to go into northeast China. On repeal, populations migrated into northeast China, which undoubtedly had an impact on the landscape (Editorial Board for Flora of China, 1995). Furthermore, low Pinus and maximum Artemisia during the 1930s–1940s AD tie in well with the Japanese invasion of northeast China. During that time Pinus koraiensis trees were selectively cut (Liu, 1989). The area of the original mixed coniferous–deciduous forest was reduced and the vegetation became deciduous forest, mixed with shrub and grassland (Editorial Board for Flora of China, 1995).

5.2. Fire history

Charcoal records from lake sediment cores are an excellent tool for studying fire intensity and fire frequency (MacDonald et al., 1991; Clark et al., 1998; Whitlock and Larsen, 2001). In general, charcoal particle sizes less than 100 μm are indicative of regional fires, whilst charcoal particles greater than 100 μm are indicative of local fires (Pitkänen et al., 1999; Whitlock and Larsen, 2001). A few studies have found that charcoal particles larger than 50 μm may also suggest short transport distances and record local fires or fires within a few kilometers (Tinner et al., 1998; Pitkänen et al., 1999), and the abundance of smallest charcoal particles also suggest increased burning in large regions (Clark and Royall, 1995; Clark and Hussey, 1996; Pitkänen et al., 1999). In most cases, pollen and charcoal data are used to examine the relationships among vegetation, fire, climate and sometimes anthropogenic activities in the past. Fire exhibits a strong relationship with climate change, such that charcoal influx values of small size classes increase during the warmer periods of climate (Pitkänen and Huttunen, 1999). Drier climatic conditions also may result in more frequent fires (Andreev et al., 2007; Jiang et al., 2008) and fire of course also has a strong relationship with human activity (Pitkänen and Huttunen, 1999; Andreev et al., 2007; Jiang et al., 2008; López-Blanco et al., 2011; Zhou et al., 2011).

In northeast China, e.g. in the Changbai Mountains, wild fires are more likely to occur during spring and at the end of the autumn due to generally drier conditions (Li and Zhang, 2011). Elsewhere, the intensity of fire events is closely associated with dry spring conditions, e.g. in the Southwestern United States between 1700 and 1905 AD (Swetnam and Betancourt, 1990). In Finland, fire history corresponded to temperature variation over the past 1300 years (Pitkänen and Huttunen, 1999). Forest fire activity in the Western United States has also increased in recent decades, which
is strongly associated with increased spring and summer temperatures and an earlier spring snowmelt resulting in a dry early spring (Westerling et al., 2006). Therefore, winter snowfall is an important factor influencing the occurrence of fire. In addition, some studies found the increasing accumulation of dead biomass also plays a very important role in raising the fire risk (Tinner et al., 1998).

The charcoal data recorded from EML showed that concentrations were high during the MCA and the 20th century, but low during the LIA. Several studies have reported that in north and northeast China, climate was generally warmer during the MCA and the 20th century but colder during the LIA (Liu et al., 2005a; Wang et al., 2007; Tan et al., 2009; Wang et al., 2012). At EML, pollen concentrations indicate higher biomass during these two warm periods (Fig. 4). The charcoal data from EML therefore suggest that temperature and biomass were important factors leading to strong intensity fire events on a century time scale.

However, fire events indicated by charcoal data show more complex relationships with climatic changes when the charcoal data at decadal time scale are compared with total snow events per decade from historical documents (Chu et al., 2008) and the decadal late spring drought index from historical documents of Korea (Kim and Choi, 1987). In addition, human activity also would play some role in leading to fire events during the 20th century. The charcoal data from EML show that there are two long periods of high fire intensity between 1200 and 1400 AD of the late MCA and the period of post industrial warming, and one short period with relatively high intensity fire event at ~1600 AD during the LIA (Fig. 6).

The relative low concentration of charcoal particles between 980 and 1200 AD suggest a period of relatively low intensity fire events when compared with the following periods. The early part of this period (980–1050 AD) had low intensity fire events possibly linked to low biomass (Tinner et al., 1998). Even though low snow events (Chu et al., 2008) suggest a relative arid climate condition during autumn, winter, and early spring, and the drought index (Kim and Choi, 1987) indicates a relative arid climate during late spring (Fig. 6), favoring fire events. However, the late part of this period (1050–1200 AD) was marked by low intensity fire events, possibly linked to relatively high snow events (Chu et al., 2008) and humid late springs (Kim and Choi, 1987), even though the high biomass indicated by the pollen during this period would favor fire events. Between 1200 and 1450 AD, concentrations of charcoal particles increase to peak values, indicating high intensity fire events (Fig. 6). Peak charcoal concentrations occur during periods with relatively little snow, that result in long dry periods at the end of autumn, winter and early spring (Chu et al., 2008) (Fig. 6). In addition, the pollen data indicate higher biomass productivity due to relative high precipitation during summer (Fig. 6) which provided enough materials for greater fire intensity. The abundance of smaller (10–50 μm) and large sized (50–100 μm and >100 μm) charcoal particles (Fig. 6) indicate both increased local and regional burning.

Between 1450 and 1750 AD, relatively low charcoal concentrations (Fig. 6) are indicative of low fire intensity during this cold period. Low fire intensity is likely linked to increased moisture at the end of the autumn, winter period and the early part of the spring indicated by the increase of snow cover (Chu et al., 2008) (Fig. 6), and the decrease in biomass inferred by low pollen concentrations. However, during this time there was a short period of relative high intensity fire events at ~1600 AD, likely related to observations of less snow cover in winter and increased aridity in late spring on a decadal time scale (Fig. 6). Between 1750 and 1850 AD, the lowest charcoal concentrations (Fig. 6) cannot be explained by increased aridity and less snow cover, so it is possible that low biomass may be the main reason leading to the lowest frequency of fire events during this period (Fig. 6).

After the LIA (from ~1850 AD), the concentrations of small charcoal particles increased rapidly, indicative of elevated levels of

![Fig. 6. Pollen and charcoal results from Erlongwan maar lake compared with snow events (Chu et al., 2008) and drought index (Kim and Choi, 1987) over the last millennium.](image-url)
6. Conclusions

This study used pollen concentrations from the Erlongwan maar lake to reconstruct pollen assemblages and biomass in northeast China over the past ~1000 years. Generally higher temperatures and increased summer monsoon rainfall during the MCA resulted in higher terrestrial pollen and spore concentrations and higher biomass than during the LIA. Interestingly, the pollen data did not show any substantial change in forest composition associated with climate change during the studied period. The fire events indicated by charcoal concentration were highly variable over the past 1000 years. The data suggest that warm climate with less snow and large biomass production were the key factors which controlled the intensity of fire events. In a warmer world, persistent, dry conditions caused by less snow during late autumn, winter and early spring may result in an increase in wildfire frequency, which will entail the adoption of new forest management practices in the very near future.

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References


Bradley, R.S., Jones, P.D., 1992. When was the increase in regional burning (Fig. 6). However, unlike the record during the MCA, this recent increase in charcoal occurs alongside a rapid increase in Artemisia and decline in Pinus (Fig. 6). This may suggest that high intensity fire events are related to human impacts, such as increased migration after 1860 AD and war-associated forest clearance since 1931 AD (Liu, 1989; Editorial Board for flora of China, 1995).

Furthermore, the charcoal data show that the fire event pattern was different from that during the MCA. The fire events between 1200 and 1450 AD show high frequency and short duration, but the fire events during the past 150 years were of longer duration, which may be related to human activity. During the past 50 years, the concentration of charcoal declined and the relative abundance of Pinus increased (Fig. 6), which are a result of government policy to restore the reclaimed land to natural forest since 1980 AD.


