A Late Holocene record of vegetation and fire from the Amur Basin, Far-eastern Russia

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Abstract:

The Amur Basin, on the border of Russia and China, has accumulated substantial quantities of peat that have allowed the reconstruction of past vegetation and environments, especially during the Holocene. In this paper, a detailed pollen record from the Basin has been constructed for the last 3800 years and interpreted with the assistance of 40 surface pollen samples taken from vegetation types representative of a broader region. In addition, fossil microcharcoal counts were undertaken to explore variation in fire frequency and the role of fire in peat development and landscape disturbance. The record can be divided into four periods. (1) A period of deciduous broadleaved forest dominated by *Betula* and *Quercus* accompanied by thriving sedge-dominated wetlands indicating relatively warm and wet conditions between about 3800 and 2000 cal BP. (2) Coniferous and broad-leaved mixed forest domination between about 2000 and 680 cal BP indicating a shift to a cooler climate. (3) *Betula*-dominant deciduous forest, reduced sedge-dominated wetlands and increased burning between about 680 and 250 cal BP indicating further drying and

cooling during the Little Ice Age. (4) Secondary pine forest combined with a large increase in fire activity as well as a further reduction in the swamp environment signaling substantial human impact in the last 250 years.

Keywords: Amur Basin, Pollen record, Modern pollen samples, Microcharcoal analysis, Wetland history

1. Introduction

The northern latitude wetlands are the most important terrestrial carbon sink in the world and have an obvious feedback to climate change and the carbon cycle (Yu et al., 2009; Korhola et al., 2010). Consequently, with increasing concern about global climate change, increased attention including palynological research, is being paid to these wetlands. Most research, to date, has been concentrated on the wetlands of western European and northern America (Van der Linden et al., 2008; Mancini, 2009; Schellekens et al., 2011; Cai and Yu, 2011) while relatively few studies have been undertaken on the Quaternary history of the extensive wetland areas in northeastern Asia (eastern Siberia and northeastern China). In the Russian Far East, the research efforts show that pollen analysis has been the major means for determining the floristic variability of Quaternary forests and for describing the spatial shifts in vegetation zones associated with climatic fluctuations (Korotky, 2002). Both fossil and modern studies indicate that past and present vegetation responds to changes in both temperature and effective moisture. In recent years, some pollen records from the Sea of Okhotsk region, such as the Kamchatka Peninsula (Dirksen et al., 2013), Sakhalin, Primorye and Kuril islands (Korotky et al., 1997, 2000; Bazarova et al., 2008a; Razzhigaeva et al., 2008, 2009, 2013) have been produced, while a long pollen record from Lake Baikal has revealed a broad regional picture of high latitude vegetation and climate changes (Bezrukova et al., 2005; Bazarova et al., 2011b). However, the lower basin wetlands of the Amur-Heilong River have tended to be

relatively poorly studied despite possessing thick Holocene peats that have great potential for paleoenvironmental reconstruction as well as assessment of human activities and recent climate change (Lozhkin et al., 2011).

This paper attempts to help redress perceived imbalances by focusing on the late Holocene history of a site within the lower basin of the Amur-Heilong River, one of the longest rivers in the Russian Far East, flowing thousands of kilometres from the steppes of Mongolia through China and Russia and ending at the Amur Liman and Okhotsk Sea where it empties into the Pacific Ocean. The lower Amur River basin, about 1000 km in length, is located at the Russian – Chinese border, between 48 °N and 54 °N. It is covered by about 58000 km² of wetlands that contain the largest accumulation of peat in the Russian Far East. Some palaeoecological studies (Klimin et al., 2004; Han et al., 2007; Bazarova et al., 2008b, 2011a) have been undertaken in the catchment that, although showing some general consistency in temperature variation in relation to northern hemisphere orbital forcing, do exhibit marked variation in patterns of precipitation change.

In the broader Siberian region, there is evidence for peatland recession in the late Holocene because of cold and dry conditions in the far north after peaks around 4000 years ago in a number of sites (Borren et al., 2004; Kremenetski et al., 2010), while data from sites across West Siberia show a large variation in total carbon accumulation in recent millennia (Peteet et al., 1998). In addition to adding to the sparse evidence for environmental change in this extensive region, this study attempts to refine interpretation of past vegetation and climate by application of a novel modern vegetation/surface pollen sample transfer method and assessment of the role of fire, both natural and human-induced, through detailed charcoal analysis.

2. Regional setting

The study area incorporating the fossil site and modern pollen samples covers the Heilong-Amur River region bordering Heilongjiang Province in China and Amur areas of Blagoveshchensk, Russia (50°N to 55°N, 125°E to 133°E) (Fig. 1b). Surface pollen samples were collected from a variety of altitudes between the river and the surrounding mountain ranges: the Great Hinggan Range in the north that contains the upper tributaries of the River, the Small Hinggan and Bureya Ranges in the centre of the basin, and the Changbai Mountains located in the southern part of the study area with the Tukuringra-Dzhagdy Ranges along the northern border with China (Fig. 1b). The study sediment core was extracted from the wetland in the lower reach of the Zeya River which flows through the Zeya Reservoir and joins the Amur River near Blagoveshchensk, in Russia's Amur Oblast (Fig. 1a). The wetland lies about 126 m above sea level.

The study area falls within the cold temperate zone. The climate of this region is controlled by continental influences from interior Asia, predominant during the dry winter, and monsoon influences from the western Pacific that bring precipitation to this area during the summer. The local climate is characterized by a short, warm to hot summer and a long, cold, dry winter. The coldest month is January (-22 to -27°C) and warmest is July (16-18°C). The average annual temperature observed in Blagoveshchensk is around 1°C. About 80-90% of annual precipitation occurs in summer. Average annual precipitation ranges from 450 to 550 mm (Simonov and Dahmer, 2008).

The vegetation of the basin can be described in relation to a Boreal zone, a Temperate zone and Daurian steppe (Fig. 1b). The vegetation of the northern Boreal zone, embracing the upper reaches of the Zeya and Amur-Heilong Rivers, belongs to the coniferous continental taiga. It is mainly dominated by *Larix sibirica*, *L. dahurica*, and *L. gmelini* with patchy representation of *Pinus sibirica*, *Picea obovata* and *Abies sibirica* and some *Betula* and *Populus* in the south. The temperate mixed forest of the

area is located in the central and south east areas, with broadleaf deciduous species such as *Quercus mongolica*, *Betula schmidtii*, *Ulmus laciniata*, *U. propinqua*, *Juglans mandshurica* and *Acer spp.* conspicuous and with *Pinus koraiensis* as the most prevalent conifer. The southern-central part of the region is mostly farmland, which was previously covered by deciduous broadleaf forest containing *Quercus mongolica*, *Betula dahurica*, *Lespedeza bicolour*, *Corylus heterophylla* and some thorny shrubs like *Rhamnus dahuricus* and *Rosa dahurica*. The steppe and mires including *Carex*-Gramineae meadow steppe, Composite-Gramineae herb steppe and sandy versions of salt marsh-tussock steppe are sparsely distributed in the middle and lower parts of the Amur-Heilong River basin (Hou, 2001; Kolbuket al., 2003; Simonov and Dahmer, 2008; Pelankova and Chytry, 2009).

3. Material and Methods

3.1. Collection of surface pollen samples

The surface pollen sites were selected in relation to regional representation of natural vegetation types using GPS altitude, latitude and longitude positioning and their locations are shown on Fig. 1b. At each site a single surface soil grab sample was collected for pollen analysis from within an open area away from any canopy trees (Davis, 1984). A vegetation survey was conducted at every location and included the amount, height and coverage of each community, and the nature and extent of human impact. Forty samples were collected which can be divided into 5 groups according to their vegetation defined by dominant species. The vegetation communities of the groups are deciduous coniferous forest, evergreen coniferous forest, coniferous and broad-leaved mixed forest, deciduous broad-leaved forest and wetlands (Ni et al., 2003). All except the coniferous and broad-leaved mixed forest are illustrated photographically in Fig. 2. Descriptions of each surface sample are provided in Table 1.

3.2. Sediment core

The sediment core, located at 50°41'55"N, 127°42'12"E, was collected from the mire of Zeysko-Bureinskaya Plains (Fig. 1a) which formed around the lower reaches of two large tributaries, Zeya and Bureya, of the Amur-Heilong River. The Plains are about 43 km northwest of the city of Blagoveshchensk. Large natural wetlands still remain in this plain despite some patches having been ploughed up or burned for agriculture. The core is from a mire that is covered by meadow within which the graminoids *Carex lasiocarpa*, *C. myeriana* and *Deyeuxia angustifolia* are most conspicuous (Hou et al., 2004), and where the most notable surrounding forest species are *Pinus koraiensis* and *Quercus monolica* but a number of other trees such as *Larix gmellini*, *Juglans mandschurica* and *Mackie amurensis* are also present.

The sediment core, 3.15m in length, was extracted with a Russian corer at a water depth of 90 cm. Three bulk organic samples from the core sediment were dated by radiocarbon accelerator mass spectrometry at either Beijing University (pretreated in Guangzhou Institute of Geochemistry, Chinese Academy of Science), or the Institute of Earth Environment, Chinese Academy of Science in Xi'an. The acquired dates were calibrated to calendar years using the program Calib Rev 6.0.

3.3. Humification

Research from the northern wetlands has found that humification, or the degree of decomposition, reflects climate to some extent (Chambers et al., 1997) and has been used widely to infer variation in peat surface wetness (Anderson et al., 1998). The degree of humification of the sediment was determined from absorbance values using a spectrophotometer. We used the 722s instrument which can be applied in measurement of transmittance, absorbance and direct concentration readout of transparent material. Initially samples were dried, pulverized and sieved through a

60mesh sieve. An alkali-extraction method was utilized to treat the sieved samples, and the supernatant was used for the measurement of absorbance values (Ma et al., 2009) at the wavelength 540. The average value of three measurements for each sample was used.

3.4. Pollen analysis

Sixty-four pollen samples taken at 5 intervals (approximately 1 gram every sample) from the core together with the surface samples were prepared for pollen analysis following standard techniques (Davis, 1963; Tweddle and Edwards, 2010). A known quantity of *Lycopodium* spores was added to each fossil sample as an exotic tracer. All extracted pollen and spore samples were mounted in silicon oil on microscope slides. At least 200 pollen grains were counted for each sample. The percentage of each taxon in pollen spectra was calculated based on a sum of total pollen excluding aquatics and spores.

3.5. Charcoal analysis

Charcoal analysis was undertaken on the pollen slides. Charcoal was counted from more than 30 photos of every slide. In addition to total abundance, charcoal particles were also grouped according to size and morphology with size classes less than 10µm, 10-50µm, 50-100µm, 100-120µm or >120µm and morphologies cubic (small), surrounded, elongated, reticular or cubic, respectively. Determination of the amount and size of charcoal can allow assessment of dispersal and deposition as well as preservation (Patterson et al., 1987; Clark and Hussey, 1996; Li et al., 2010). The type of charcoal can be influenced by source of the plant material such as whether it is derived from woody or herbaceous plants and, with the former, the hardness and compactness of the wood, and hence provide an indication of vegetation type (Umbanhowar and Mcgrath, 1998; Zhang and Lu, 2006). The concentration of

charcoal particles, regardless of size and shape, was calculated by the particle-concentration formula:

$$GC = \frac{G \cdot L}{I \cdot V}$$

Where GC is the concentration of charcoal particles; G is the sum of charcoal particles counted; L is the number of *Lycopodium* spores added to the samples; I is the number of *Lycopodium* spores counted; and V is the weight of the samples.

4. Results

4.1. Modern pollen rain

From the 40 surface pollen samples, 35 taxa including 16 arboreal types, 4 shrubs and 15 herbs as well as a few taxa of ferns have been identified. The dominant arboreal taxa in general are the conifers *Larix* and *Pinus* and the broad-leaved trees *Betula* and *Quercus*. The major herbs are Cyperaceae and *Artemisia* (Fig. 3).

As the surface pollen samples were collected in relation to specific communities, the description of pollen assemblages is accompanied by that of their corresponding vegetation type: deciduous coniferous forest, evergreen coniferous forest, coniferous and broad-leaved mixed forest, deciduous broad-leaved forest, and wetland.

4.1.1. Deciduous coniferous forest (DCF)

Three surface samples were collected in this forest biome. The most important pollen taxa recorded are *Betula*, *Larix* and Cyperaceae, accompanied by some less abundant trees such as *Pinus*, *Alnus*, *Salix*, *Carpinus*, *Quercus*, and *Picea*. *Larix* achieves highest values in the data set, reaching a maximum of about 20% while *Betula* values are consistently high, averaging around 40%. The shrub and herb pollen taxa are Cyperaceae, *Artemisia*, *Sanguisorba* and Ranunculaceae with the percentage of Cyperaceae reaching as high as 30 %, while *Artemisia* varies between 5 and 10%.

4.1.2. Evergreen coniferous forest (ECF)

All 3 samples from this biome were collected in Russia, where *Pinus sibirica* has the greatest cover within the communities. Other trees include *Betula platyphylla* and *Larix gmelini*. Rosaceae, Compositae and Ranunculaceae are the most common herbs. *Pinus*, reaching 50-60 %, is the predominant pollen type in all samples of this community while *Betula* has secondary importance, achieving 25-35%. All other taxa have low representation with *Picea* and Cyperaceae being the only ones consistently present.

4.1.3. Coniferous and broad-leaved mixed forest (CBLMF)

The largest number (15) of surface samples was collected in this biome of which 10 are from Russia and the others from Heilongjiang Province of China. The most abundant trees are *Pinus gmelini*, *Betula platyphylla*, *Quercus mongolica*, *Carpinus*, *Acer*, and *Picea*. The most notable shrubs and herbs include Compositae, Polygonaceae, *Artemisia*, *Spiraea* and *Thalictrum aquilegifolium*.

Within the pollen spectra, *Betula* generally has the highest values with percentages averaging around 40% while *Pinus*, although having an occasional high value, is much more variable. Of other tree taxa, the conifers *Larix*, *Picea* and *Abies*, have notable representation in a number of samples. Within the herbs, Cyperaceae and *Artemisia* are consistently present although generally with low values and other taxa have only spasmodic occurrence.

4.1.4. Deciduous broadleaved forest (DBLF)

Ten surface samples were collected in this biome; half of them from Russia and the other half from Heilongjiang. The vegetation is dominated by *Quercus* and *Betula* with coverage greater than 60%, and other trees such as *Pinus*, *Populus*, *Salix*, *Acer*

and *Juglans* have sparse coverage. There is a variety of shrubs and herbs, with Rosaceae, *Rhododendron*, *Artemisia*, *Polygonum*, Cyperaceae and *Sanguisorba* being most notable.

Variation in the pollen percentages is significant with the overall dominant *Betula* varying from about 20 to 60% and *Quercus*, which is absent or almost absent in some samples, achieving over 20% in others. Apart from *Pinus*, other tree taxa are only occasionally present or, in the case of Cupressaceae, total absent. Within the herbs, Cyperaceae and *Artemisia* are consistently present and achieve relatively high percentages in some samples.

4.1.5. Wetlands (WT)

All samples were collected from wetlands distributed in the lowland valleys of Russia except one that was from Heilongjiang province. The dominant plant type in this community is Cyperaceae, existing in association with herbs of *Polygonum*, Compositae, Umbelliferae, Ranunculaceae and Leguminosae. The pollen diagram shows similar dominance of herbs, especially Cyperaceae, in most samples, although *Betula* is also well represented and dominant in a few samples.

4.2. Core lithology, humification and dating

These core attributes are shown diagrammatically on Fig. 4. The results of radiocarbon dating are also presented on Table 2.

The basal sediment (315-300 cm) is medium-grained sand with little organic material. This is succeeded by dark-grey silty-clay with a peat component (300-180 cm) that shows low humification levels, although these do increase gradually through the unit. The succeeding sediment is black silty-clay with high quantity of organic matter (180-140cm) that shows generally higher and more variable humification especially in

the lowest 15 cm. This variation intensifies through the peat in the top 140 cm of the core that contains an increasing proportion of plant roots towards the surface.

Radiocarbon ages are derived from near the base and near the top of the dark-grey silty-clay sediment and close to the top of the black silty-clay. The age- depth curve, interpolated and extrapolated from the radiocarbon ages, suggests average sediment accumulation rates of 0.79 mm/y (290-205cm), 1.41mm/y (205-135 cm) and 1.24 mm /y (135-0 cm) although the humification values would suggest that accumulation rates would have been rather variable, especially after about 2000 years ago. The age model suggests that the study core covers a time span from ~3800 cal BP to the present-day.

4.3. Pollen results of core AM32

A total of 36 pollen taxa have been identified from the core; they include 16 arboreal types, 3 shrubs, and 13 herbs as well as a few taxa of ferns. The dominant arboreal taxa are the conifer *Pinus* and the broad-leaved trees *Betula* and *Quercus*. The major herbs are Cyperaceae, *Artemisia* and Ranunculaceae. The frequencies of all taxa are shown on the pollen diagram of Fig. 5 that has been divided into four pollen zones with the aid of the CONISS dendrogram. This zonation has also been applied to results on Fig. 4 and 6, to facilitate comparison between all proxies.

4.3.1. Zone 1 (315-165cm; c. 3800 - 2000 cal BP)

The zone corresponds mainly with the dark-grey silty-clay layer that displays consistently low humification values but the sediment does change to black-silty clay that is accompanied by a peak in humification towards the top of the zone. Pollen from arboreal taxa is dominated by the broad-leaved trees *Betula* and *Quercus* with *Pinus* achieving about 8%-10%. *Carpinus*, *Corylus* and *Salix* are the only other arboreal taxa with a more or less constant presence. Herb pollen is consistently dominated by Cyperaceae with *Artemisia* maintaining a steady 10% of the pollen sum.

Sanguisorba, Umbelliferae and Gramineae are the only other notable herbs. Monolete spores, with an average value of about 3%, are the only consistent fern group while algae have occasional representation.

4.3.2. Zone 2 (165-55 cm; c. 2000 - 680 cal BP)

The sediment shows little variation in humification through much of the zone despite the change in sediment from black silty-clay to peat around 135 cm. However, there is a sharp peak to the highest humification value in the record around 80 cm followed by an equally sharp decline to levels around lowest for the diagram at the top of the zone. Within the arboreal taxa, *Betula* and *Quercus* maintain their consistently high values but *Pinus* shows a significant increase from 5-7% to 15-20%. The only other notable changes in arboreal taxa are a reduction in occurrences of *Salix* and an increase in those of *Ulmus*. Cyperaceae maintains dominance of the herbaceous taxa though it gradually declines from about 40% to 30% through the zone while *Artemisia* maintains its 10% average. There is little change in other herbs except for Ranunculaceae and Chenopodiaceae that become consistently represented from the base of zone, although Gramineae disappears in the basal few samples. Values for both monolete spores and algae are also higher.

4.3.3. Zone 3 (55-20 cm; c. 680 - 250 cal BP)

This zone shows a continuation of variation in humification with an early sharp peak followed by much lower values. There is no apparent reflection of this variation in the sediment description that remains peat although the roots continue to become larger and more numerous.

With the pollen, *Betula* values increase to over 30% of total pollen and *Betula* replaces Cyperaceae that falls from over 25% to 10% within the zone, as the major

taxon. The only other notable feature is highest percentages of Ranunculaceae for the record.

4.3.4. Zone 4 (0-20 cm; c. 250 - 0 cal BP)

The degree of the humification in this topmost zone is about average for the core and shows little variation.

The zone-3-4 boundary is marked by a small peak in *Carpinus* that represents the highest value for the taxon within the record. With respect to other arboreal taxa, *Betula* values fall back to about 20% but *Pinus* values, though variable, are generally highest for the diagram. *Larix* peaks for the diagram in the topmost samples while *Corylus* is completely absent from the zone. Within the herbs, Cyperaceae makes some recovery from zone 3 while Gramineae pollen achieves levels recorded through much of the diagram until late in zone 2. Compositae and Rosaceae have highest values for the record. There are no notable changes in pteridophyte and algal spore values.

4.4. Charcoal results

The charcoal diagram (Fig. 6) shows total concentrations and concentrations for all size and morphology classes in relation to the pollen zones. Charcoal concentrations vary substantially through the core and bear little relationship to pollen zones. Concentrations are very low in samples below 275 cm, with the only notable values occurring in the smallest, 0-10µm, category within the basal 15 cm. Concentrations then increase substantially from 270 cm with peaks in the three size classes below 100 µm, as well as in the total, centered on 270, 230 and 190 cm. There is some increase in charcoal particle size through this section most marked by a general decline in 0-10µm values and increase in >120 µm values. All shapes show low and sporadic representation in zone1 above 275 cm.

Charcoal concentrations are generally moderate and more consistent through the period represented by zone 2 but, as in zone 1, smaller particles (0-10 μ m and 10-50 μ m) are more prominent in the lower part and larger particles (>50 μ m) more abundant towards the top of the zone. Elongated particles are major shape throughout the zone and increase substantially towards the top with the increase in particle size. The most notable features of zone 3 are sharp and highest peaks in the record at 45 cm in all size classes except for 100-120 μ m. There is also a peak in elongated particles and these remain the most prominent shape throughout the zone. Overall, charcoal has its highest representation in zone 4 with consistently high values in all size categories except 100-120 μ m. All shapes are represented with cubic (small) equaling the abundance of elongated particles.

5. Discussion

5.1. Statistical analysis of modern pollen rain

In order to show major differences between, and variation within, vegetation types from the pollen spectra, box plots, showing median, maximum, minimum and interquartile values for major taxa within each community have been constructed using SPSS tools (Fig. 7). Box plots are also constructed for major climate parameter values in relation to vegetation types (Fig. 8) with data derived from climate estimates of all modern pollen sites (Table 1, Hijmans et al., 2005) in order to assess the nature and importance of climate controls over vegetation variation. Median, maximum, minimum and interquartile values are given for climate parameters of all communities except for deciduous coniferous forest and evergreen coniferous forest where, due to the limited number of samples, only maximum and minimum and maximum, minimum and median values are given, respectively. This statistical analysis of modern vegetation-pollen relationships that calculates the importance of major taxa in communities determined from a vegetation survey differs from the more conventional

biomization procedure (Prentice et al., 1992) that has been applied to both modern and fossil vegetation and climate analysis in the region to the east of this study area (Mokhova et al., 2009) where communities or biomes are generated from the ecological and geographical characteristics of taxa recorded in pollen spectra.

In the analysis undertaken here, several taxa, notably *Betula*, *Abies*, Cupressaceae and *Artemisia*, have fairly consistent pollen percentages between vegetation types and are limited in their contribution to community identification, but others, including *Larix*, *Pinus*, *Quercus*, *Picea* and Cyperaceae, allow characterization of specific communities. The deciduous conifer *Larix* is well represented in the deciduous coniferous forest, where it shows generally much higher values than in any other community. This vegetation community experiences generally the lowest annual average temperatures and clearly the lowest summer temperatures (Fig. 8). The evergreen conifers *Pinus*, *Picea* and, to a certain extent, *Abies*, with frequently highest values, and Cyperaceae with generally lowest pollen values of any community, allow the recognition of evergreen coniferous forest. This vegetation type is characterized by receiving lowest precipitation. There is no combination of taxa that allows clear identification of coniferous and broad-leaved mixed forest but samples generally have relatively high values for *Pinus*, *Betula* and Cupressaceae and low values for Cyperaceae. Similarly, the sample sites are not characterized by any distinctive climate parameter. Although they tend to embrace a range of climate conditions, values for all parameters are relatively high. The characteristic pollen taxon in broad-leaved forest is *Quercus*, which has clearly its highest abundance in a number of the samples from this vegetation type. The taxon indicates generally highest temperatures in the region. As expected, wetlands are indicated in most samples by high percentages of Cyperaceae and very low values of all arboreal taxa, except *Betula*. They are also not characterized by any specific combination of climatic parameter values.

5.2. Wetland history

Health or extent of wetlands might be positively related to the relative abundance of Cyperaceae that, from the surface samples, is shown to dominate herbaceous understories, achieve highest values in the wetland community, and is negatively related to the degree of humification, an indication of decomposition of organic matter. Fossil pollen results show that Cyperaceae values are highest and humification is lowest in the basal few samples, around 3800 years ago, suggesting high moisture levels. The dominance of sand in the sediment prevented further core penetration but may indicate that high moisture levels continued back in time with sand deposition, and perhaps erosion of deposited organic material, resulting directly from stream activity. It cannot be determined whether rainfall contributed to high moisture levels but records from other sites dominated by summer rainfall in the path of the summer monsoon (Xiao et al., 2004; Wang et al., 2005) do indicate that there was actually a reduction in precipitation with a weakening of the monsoon around 4000 years BP. Cyperaceae values then remained fairly constant through to around 2000 years ago although a gradual increase in humification suggests that there may have been some further drying, a trend consistent with some other regional records (Smith et al., 2004; MacDonald et al., 2006; Yu et al., 2009).

This drying trend accelerated around 2000 years ago, with a reduction in Cyperaceae through zone 2 and generally increased humification, although major oscillations in humification values suggest substantially increased variability. It is likely that the associated reduction in organic content of the sediment with a change from dark grey silty-clay to humified peat via a transitional black silty-clay is a result of decreased water flow or river incision that may have made the site more sensitive to moisture conditions and is not necessarily a reflection of climatic conditions.

One feature of the wetland record that does seem to suggest significantly changing climate conditions is the substantial reduction of Cyperaceae in zone 3 that, although estimated to cover the period 680 to 250 cal BP, could well relate to the Little Ice Age, formally defined as lasting between 1550 and 1850 AD (Lamb, 1972; Mann, 1998). This proposed relationship, illustrated in Fig. 9, suggests that the period was much drier as well as cooler in this region (Moberg et al., 2005). The peak in Ranunculaceae may provide some support for peat surface drying as such plants thrive under ephemeral swamp conditions. The recent fluctuations in Cyperaceae indicated in zone 1 suggest that, although the climate has become more favorable for wetland development, it has suffered instability as a result of anthropogenic activity.

5.3.Regional vegetation changes

The vegetation reconstruction based on pollen assemblages demonstrates that both late Holocene climatic variability and anthropogenic activities have influenced the local ecosystem. Vegetation changes are indicated by many AP and NAP pollen taxa particularly *Pinus*, *Betula*, *Carpinus*, and *Quercus*, and Cyperaceae, Gramineae, *Artemisia* and Ranunculaceae, respectively. The regional vegetation succession is outlined below:

(1) Period of deciduous broadleaved forest (pollen zone1)

The pollen record between approximately, 3800-2000 cal BP is dominated by the trees *Betula*, *Quercus* and *Carpinus*, of which the percentage of *Betula* is 15-20% with *Quercus* 20%, compared with *Pinus* at only 5%. This assemblage belongs to deciduous broadleaved forest that, from the regional modern pollen–vegetation study, is characterized by abundant *Quercus* (mean percentage is more than 10%) and low *Pinus* (less than 5%) (Fig. 7). The modern vegetation investigation shows that Mongolian oak (*Quercus mongolica*) is an important oak species with Daurian birch

(*Betula dahurica*) on the Northeast China plain and in the southern Russian Amur regions. This combination suggests relatively warmer conditions than at present. It is likely also that precipitation was relatively high with low variability as indicated from the wetland evidence.

(2) Period of mixed forest (pollen zone 2)

The percentage of *Pinus* increased to more than 15% at the beginning of the period about 2000-680 cal BP, while *Quercus* and *Betula* values remained relatively steady, up to 15% and 20% respectively. In comparison with the modern pollen assemblages, such pollen values suggest a change from the previous *Quercus-Betula* broadleaved forest to a coniferous and broadleaved mixed forest. This implies some temperature reduction from zone 1 to zone 2. Meanwhile, Cyperaceae shows a minor decrease but abundance is still sufficient to suggest the regional maintenance of wetlands in the river plain of Zeya.

(3) *Betula*-dominant deciduous forest (pollen zone 3)

This stage, approximately between 680 and 250 cal BP, is characterized by a high arboreal pollen proportion, which is illustrated in the diagram by *Pinus*, *Betula* and *Quercus*, especially the high abundance of *Betula*, up to 35%. The feature of high percentages of deciduous taxa accompanied by *Pinus* is comparable with the deciduous broadleaved and mixed forests from the modern pollen rain in northern Zeya areas (Fig.7). The sharp decrease of Cyperaceae to about 15% combined with generally high humification values indicates a reduction in wetland surface, possibly caused by a decrease of humidity or changes of the river channel.

(4) Secondary forest

During the latest 250 years or so, vegetation was marked by significant rises of *Pinus* and Cyperaceae, with pine reaching its highest level in the whole core. The increase of pines together with broadleaved birches may be the result of human disturbance. As the river plain was fertile and suitable for the development of human occupation, frequent burning of grass and forest would have favored the expansion of secondary pine forest.

5.4.Regional comparisons

Reconstructions and interpretations from this study are generally consistent with those of other pollen records within the lower Amur basin and adjacent areas of China and Japan. The previous works of longer records in the Russian Far East indicate that the maximum development of deciduous broadleaved forest occurred during wettest and warmest conditions of the mid Holocene, about 8000 to 4500 cal BP (Bazarova et al., 2008b, 2011a, 2011b). A quantitative biome reconstruction using modern and late Quaternary pollen data from the southern part of the Russian Far East demonstrated that the scores of temperate deciduous forest are high between 10.3 and 2.5 ka and become distinctly lower with a tendency to change to those of cool mixed forest during the late Holocene (Mokhov et al., 2009). In the South Kuril, a systematic study also shows the greatest northward movement of Kuril vegetation zones occurred during the Holocene Optimum (~6600–5000 ¹⁴C BP), and the reconstructed mean annual temperatures in the Islands were 2–3 C° higher than modern (Razjigaeva, et al., 2012). These authors also point out that there is evidence for a re-expansion of deciduous coniferous forest elements in the Amur regions from about 4000 to 2500 cal BP.

The above results indicate from Holocene shifts in vegetation zones that optimum climatic conditions occurred in the mid-Holocene and that cooler conditions commenced around 2500 years ago. This climate change is close to the timing of the

zone 1-2 boundary in core AM-23. The pollen record from Minamihama Mire in Rishiri Island in Japan shows that *Abies* become dominant and *Quercus* participation decreases under a cooling climate trend from ca. 3500 BP to several hundred years ago (Igarashi, 2006; 2013). The progressively cooler condition during the past 3500 years on Rishiri Island may have been caused by the weakening of the Tsushima Warm Current in the Sea of Japan. This could be one of the driving mechanisms of climate changes in the Amur River domains. Klimenko et al., (2000) suggest, from highest values of *Pinus* and *Betula*, that coolest conditions occurred between 1700 and 1500 years and around 250 cal BP (Klimenko et al., 2000). The latter period is consistent with the proposed Little Ice Age identified in AM-23. It has been suggested, from low pollen and also charcoal concentrations in a high-resolution pollen record from a Maar lake Erlongwan in northeast China, that there were coldest winters with high snowfall, relative drier summers and less intensive wildfire between 1500 and 1850 AD, coincident also with the Little Ice Age (Li et al., 2013). On Rishiri Island of Japan, a pollen record revealed that modern *Picea glehnii* forest might have been formed during the Little Ice Age (Igarashi, 2013).

The pattern of precipitation change is more difficult to determine than that of temperature from major dryland taxa and there may be regional differences in direction and synchronicity in humidity variation (Bazarova et al., 2011b), but there is a general positive relationship between the two climatic parameters with an overall decreasing trend from the mid-Holocene to around 250 years BP (Klimenko et al. 2000).

Overall, though, the degree of environmental change during the Holocene may have been limited. Application of the regional biome reconstruction system to the Gur pollen record from the lower reaches of the Amur River, suggests that the cool mixed forest biome was dominant through the whole of the Holocene (Mokhova et al., 2009). However, representation of the temperate deciduous forest was substantially higher

before 2.5 ka suggesting a marked reduction in extent of this biome after this time, in line with the major vegetation shifts elsewhere in the basin including those in the AM-23 record. The subdued vegetation variation in the Gur record in comparison to that in other records could be a feature of the definition of biomes that tend to incorporate greater ecological variation than vegetation communities or the more coastal and lowland location of the Gur site where the response to climate change has been stronger than the intracontinental sites of the Lower Amur Basin.

5.5.Relationship between vegetation changes and fire events

The charcoal counts show that the concentration of total charcoal is very low within the early part of the sequence, prior to about 3.2 cal ka BP, and then experiences a sudden increase after 3.2 implying a change from a low to moderately high fire frequency. Although there is no apparent change in the dryland vegetation reconstructed from pollen data that was deciduous broadleaved forest existing under warm and wet conditions throughout the period represented by zone 1, it is suggested from the wetland data that there may have been an initial change and then continuing trend towards drier conditions that may have created a more fire prone environment.

An alternative explanation for the charcoal pattern is a change in sediment source as the sediment fines upwards from the base, as has been recorded in other river basins and wetlands at this time, rather than climate change or even a change in fire activity (Li et al., 2007; Borisova et al., 2011). Once established, charcoal values display several discrete peaks in total and most individual size concentrations suggesting systematic oscillations in fire activity (Nelle et al., 2010). This pattern breaks down between 2000 and 680 cal BP when there is a general increase in the size of charcoal particles through the period and a shift in the record to high values for elongated types towards the top of the zone. However, the significance of these changes is unknown. By contrast, the increased values for reticular charcoals after this time are considered

to be meaningful in that some previous works have found that the most reticular charcoal particles are derived from broadleaved trees (Clark and Hussey, 1996; Zhang et al., 2006). This implies that past fires not only took place in grass and wetland biomes, but also in the forests. Associated higher concentrations of charcoal particles in zone 3 indicate frequent forest burning that resulted in the development of secondary forest and facilitated the expansion of *Pinus*. The simultaneous increases in fire activity, broadleaved trees particularly *Betula*, and *Pinus*, support the wetland evidence for a drier and colder climate during this interval that includes the Little Ice Age (Fig. 9) and are consistent with the results of (Karabanov et al., 2000). The most sustained increase of charcoal concentration is in the topmost zone, likely caused by anthropogenic fires within the last 250 to 150 years. Some deciduous forests of *Quercus* and *Betula* were replaced by secondary *Pinus* forest as a result of these fires, particularly in the vicinity of fertile plains where the land is suitable for farming. Data on historical population levels support the proposition of anthropogenic impact in that a major increase in immigration took place during the Jiaqing Period of Qing Dynasty (204-190 years ago) in the Heilongjiang-Amur region (Liu and Gu, 1983). However, historical records show that many broadleaved trees in the northern areas of the Amur forest zones remained intact after anthropogenic fires (Shimkin, 1988), because remaining forest localities are distant from cultivated land.

5. Conclusions

The present study reveals the relationship between regional modern pollen rain and vegetation, which is helpful for understanding the fossil pollen spectra and reconstructing the past vegetation. The pollen results from core AM-23 provide a history of vegetation for the past 3.8 ka. Firstly, the abundance of Cyperaceae of the record testifies to the fact that the wetlands of the lower Zeya basin had formed at least by 3.8 ka. Secondly, the regional forest changes surrounding the Zeya basin

indicate a succession of (1) deciduous broadleaved forest, (2) mixed forest, (3) birch-dominated deciduous forest, and (4) secondary pine forest. The evidence of forest changes from deciduous broadleaved forest to mixed forest at 2000 cal BP agrees with previous studies in the Russia Far East and in the adjacent areas of China and Japan, implying a cooling tendency in the late Holocene. This change may have resulted from the weakening of Tsushima Warm Current in the Sea of Japan. The charcoal concentrations show that fire events became more frequent or intense from 3.2 ka. A birch-dominated deciduous forest that largely coincides with the Little Ice Age may provide additional support for this event although, in this area, a reduction in wetlands as a result of a decrease in precipitation is the major feature. The vegetation of the last c. 250 years has been largely disturbed by anthropogenic activities, and secondary pine forest has been favoured by burning associated with agricultural activities and rapidly increasing population during the Jiaqing Period of the Qing Dynasty. The study contributes to a regional picture and understanding of late Holocene vegetation and environments but is limited in its contribution to a global assessment of carbon sequestration and future global atmospheric CO₂ levels, as the wetland may have been influenced as much by local fluvial activity as it has by regional climate change.

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Table captions

Table 1: List of surface samples showing their locations, dominant plant taxa within the communities (biomes) and their interpolated climatic values from WorldClim which is a set of global climate layers (climate grids) with a spatial resolution of about 1 square kilometer (Hijmans et al., 2005)

Table 2: AMS radiocarbon dating results for core AM-23

Figure captions:

Fig. 1. (a) Location of core AM-23 within the Amur-Heilong River Basin; (b) Location of surface sample sites in relation to core AM-23 with a background of vegetation types within the study area; (c) The AM-23 core site. Base map for (a) and (b) from Simonov and Dahmer (2008).

Fig. 2. Photographic views of principal vegetation types: (a) deciduous coniferous forest (DCF) dominated by *Larix dahurica*; (b) deciduous broad-leaved forest (DBLF) dominated by *Betula* showing burned trunks from fire events; (c) evergreen coniferous forest (ECF) of *Pinus koraiensis*; (d) wetland of Amur River.

Fig. 3. Diagram of modern pollen spectra (arranged by plant communities). Values of all taxa expressed as percentages of total pollen of the appropriate sample

Fig. 4. Lithology, degree of humification, AMS ^{14}C dates and age-depth plot for core AM-23. Zones derived from fossil pollen data.

Fig. 5. Core AM-23 pollen diagram. Values for all taxa are shown as percentages of total pollen of the appropriate sample. (All exaggerations are x5 except *Pinus*, *Quercus* and *Artemisia* that are x3 and *Betula* and Cyperaceae that are x2).

Fig. 6. Diagram of charcoal concentrations in AM-23 and their relation to particle length and shape. Zones derived from pollen data. (All exaggerations are x2)

Fig. 7. Box plots of values for major taxa shown for each vegetation type. Mean, maximum, minimum and interquartile ranges are shown in relation to percentages on the vertical scale while the different communities are aligned along the horizontal scale, where A=deciduous coniferous forest, B=evergreen coniferous forest, C=coniferous and broad-leaved mixed forest, D=deciduous broad-leaved forest, E=wetlands and marsh.

Fig. 8. Box plots of climate factor values shown for each vegetation type. Tann = annual average temperature, Tmin = minimum temperature in January, Tmax = maximum temperature in July, Pann = annual average precipitation. Mean, maximum, minimum and interquartile ranges are shown in relation to values on the vertical scale (except for communities A and B that are represented by 3 sites and by 2 and 3 climate records respectively) while the different communities are aligned along the horizontal scale, where A=deciduous coniferous forest, B=evergreen coniferous forest, C=coniferous and broad-leaved mixed forest, D=deciduous broad-leaved forest, E=wetlands.

Fig. 9. Comparative curves of percentages of Cyperaceae and *Betula* from AM-23 and reconstructed Northern Hemisphere temperature from tree rings (adapted from Moberg et al., 2005)

No.	Lab No.	Latitude (N)	Longitude (E)	Elevation	Community*	Dominant plant taxa	Pann (cm)	Tann (°C)	Tmin (°C)	Tmax (°C)
1	HLJ-06-1	48°43'18"	126°07'08"	380m	DCF	<i>Larix gmelinii</i> , <i>Betula platyphylla</i>	43.17	0.13	-29.8	25.8
2	Amur-18-1	54°01'15.96"	126°54'11"	350m	DCF	<i>Larix sibirica</i> , <i>Picea</i>	48.08	-4.77	-36	24
3	Amur-18-2	54°01'15.96"	126°54'11"	350m	DCF	<i>Larix sibirica</i>	48.08	-4.77	-36	24
4	Amur-04	51°21'	127°59'58"	138m	ECF	<i>Pinus sylvestris</i> , <i>Betula platyphylla</i>	46.08	-0.9	-32.3	26.4
5	Amur-13	52°39'23"	126°50'37"	301m	ECF	<i>Pinus koraiensis</i> , <i>Larix</i> , <i>Betula</i>	43.67	-2.88	-34.4	25.3
6	Amur-16	53°30'23.18"	127°00'25"	265m	ECF	<i>Pinus koraiensis</i> , <i>Rhododendron</i> , <i>Betula</i>	43.92	-2.88	-34.5	25.8
7	HLJ-15	47°21'51"	130°06'5"	226m	CBLMF	<i>Quercus mongolica</i> , <i>Betula davurica</i>	49.75	1.94	-27.1	26.8
8	HLJ-14	47°24'6"	129°43'1"	313m	CBLMF	<i>Betula platyphylla</i> , <i>Picea</i> , <i>Acer</i> , <i>Salix</i>	54.83	-0.058	-29.7	25.1
9	HLJ-11	47°26'02"	128°26'43"	390m	CBLMF	<i>Larix gmelini</i> , <i>Picea</i> , <i>Betula</i>	55.33	-0.033	-30.5	25.3
10	HLJ-12	47°42'09"	128°54'46"	283m	CBLMF	<i>Picea</i> , <i>Larix</i> , <i>Acer</i>	55.67	0.075	-30.8	25.6
11	HLJ-06-2	48°43'18"	126°07'08"	380m	CBLMF	<i>Betula davurica</i> , <i>Larix gmelini</i>	43.17	0.13	-29.8	25.8
12	Amur-23	50°41'55"	127°42'12"	130m	CBLMF	<i>Pinus koraiensis</i> , <i>Quercus mongolica</i>	46.75	-0.1	-29.9	26.3
13	Amur-23-2	50°41'55"	127°42'12"	130m	CBLMF	<i>Pinus koraiensis</i> , <i>Quercus mongolica</i> ,	46.75	-0.1	-29.9	26.3
14	Amur-22	50°55'54"	127°47'48"	132m	CBLMF	<i>Pinus koraiensis</i> , <i>Quercus mongolica</i> ,	45.83	-0.23	-30.6	26.5
15	Amur-12	51°45'53"	128°05'46"	115m	CBLMF	<i>Pinus koraiensis</i> , <i>Betula</i> , Gramineae	46.17	-1.76	-33.6	25.9
16	Amur-08	51°54'28"	129°20'44"	121m	CBLMF	<i>Betula</i> , <i>Larix gmelini</i> , <i>Artemisia</i>	48.08	-2.34	-36.1	26.1
17	Amur-21	51°54'55"	128°00'42"	285m	CBLMF	<i>Betula</i> , <i>Pinus koraiensis</i>	46.42	-2.18	-34	25.6
18	Amur-10-2	52°30'14"	130°02'41"	196m	CBLMF	<i>Larix sibirica</i>	48.58	-3.30	-38	25.8
19	Amur-20	52°58'21.54"	126°30'35"	350m	CBLMF	<i>Betula</i> , <i>Larix</i>	43.50	-3.12	-34.5	25.3
20	Amur-14-1	53°33'33.9"	126°43'01"	232m	CBLMF	<i>Betula</i> , <i>Larix</i>	43.58	-2.94	-34.4	25.7
21	Amur-15	53°44'59.02"	127°08'47"	265m	CBLMF	<i>Larix sibirica</i> , <i>Betula</i>	46.00	-3.77	-35.3	25
22	HLJ-17	46°03'12"	129°20'12"	135m	DBLF	<i>Juglans</i> , <i>Acer</i> , <i>Larix sibirica</i>	48.58	3.02	-26.3	27.3

23	HLJ-09	47°59'40"	126°45'33"	314m	DBLF	<i>Quecussibirica, Betula, Carpinus</i>	45.25	1.03	-28.4	26.2
24	HLJ-07	48°42'33"	126°07'15"	337m	DBLF	<i>Populus, Rosaceae</i>	43.17	0.13	-29.8	25.8
25	HLJ-04	50°19'01"	127°15'09"	235m	DBLF	<i>Betula, Quercus sibirica</i>	45.08	-0.24	-29.5	25.7
26	HLJ-03	50°35'02"	127°11'54"	205m	DBLF	<i>Quercus, Betula platyphylla</i>	44.75	-0.43	-29.9	25.8
27	HLJ-02	50°44'44"	127°12'24"	175m	DBLF	<i>Quercus</i>	43.75	-0.17	-29.9	26.3
28	Amur-01	50°48'37"	127°45'25"	118m	DBLF	<i>Betula, Salix, Asteraceae, Rosaceae</i>	45.83	0.05	-30.1	26.6
29	Amur-02	51°12'36"	128°07'03"	136m	DBLF	<i>Quercus, Betula, Populus</i>	46.75	-1.15	-32.2	26
30	Amur-07	51°40'49"	128°55'41"	181m	DBLF	<i>Betula, Quercus mogolian, Acer</i>	47.58	-1.79	-34.7	26.3
31	Amur-11-2	52°29'16"	130°01'32"	212m	DBLF	<i>Betula</i>	48.50	-3.27	-38	25.8
32	Amur-10-1	52°30'14"	130°02'41"	196m	DBLF	<i>Betula, Spiraea</i>	48.58	-3.30	-38	25.8
33	HLJ-01	50°32'23.43"	127°17'47.81"	123m	WT	<i>Cyperaceae, Artemisia</i>	44.00	0.46	-28.9	26.5
34	Amur-05	51°28'59"	128°16'31"	142m	WT	<i>Polygonaceae, Asteraceae, Umbelliferae.</i>	46.08	-1.07	-32.8	26.4
35	Amur-06	51°29'59"	128°21'22"	64m	WT	<i>Salix, Rosaceae, Artemisia, Umbelliferae</i>	46.58	-1.24	-33.1	26.3
36	Amur-08b	51°54'28"	129°20'44"	121m	WT	<i>Polygonaceae, Rosaceae</i>	48.08	-2.34	-36.1	26.1
37	Amur-10-3	52°30'14"	130°02'41"	196m	WT	<i>Ranunculaceae, Artemisia, Moss</i>	48.58	-3.29	-38	25.8
38	Amur-14-2	53°33'33.9"	126°43'01"	232m	WT	<i>Gramineae, Rosaceae, Asteraceae</i>	43.58	-2.94	-34.4	25.7
39	Amur-19	54°03'03.74"	126°54'30"	527m	WT	<i>Cyperaceae, Gramineae, Asteraceae</i>	48.92	-5.22	-36.4	23.6
40	HLJ-16	46°44'56"	132°25'27"	62m	WT	<i>Cyperaceae, Gramineae and rice field</i>	45.67	3.25	-24.2	27

Notes: * DCF=deciduous coniferous forest; ECF=evergreen coniferous forest; CBLMF=coniferous and broad-leaved mixed forest; DBLF=deciduous broad-leaved forest; WT= wetlands. Pann = average annual precipitation (cm); Tann = annual average temperature (°C); Tmin = the minimum temperature in January (°C); Tmax = the maximum temperature in July (°C).

Depth (cm)	^{14}C yr BP	Cal yr BP	Material	Lab.no.
135	1773 $\pm$ 25	1675.5 $\pm$ 65.5	Bulk sediment	GZ3972
205	2107 $\pm$ 39	2081 $\pm$ 35	Bulk sediment	GZ3973
290	3237 $\pm$ 29	3454 $\pm$ 53	Bulk sediment	XA6642

Table 2: AMS radiocarbon results for core Amur-23