Characteristics of peat humification, magnetic susceptibility and trace elements of Hani peatland, northeastern China: paleoclimatic implications

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Abstract
A high-resolution peat humification record is obtained from Hani peatland, northeastern China to study climate change. An absorbance value time series from alkali-extraction is used as a peat humification indicator. In addition, Hani peat magnetic susceptibility and trace elements have also been investigated. There is a sensitive response to abrupt climate changes when comparing a high-resolution peat humification record with a Hani δ18O temperature proxy record and a drift ice record from the North Atlantic Ocean. Based on analyses of factors that affect peat decomposition, we suggest similar paleoclimate significance between the Hani and Dajiuhu peat on the degree of humification with a higher peat humification indicating colder and drier climate conditions. In contrast, a warm and moist climate provides a deoxidized condition that results in lower peat humification. Moreover, the Rb/Sr ratios and χlf in Hani peatland also indicate different climate conditions, especially in late Holocene. According to the Hani peat data, regional paleoclimate variations can be divided into the following five phases: 11.5–10.0 cal. kyr BP with warm climate conditions; 10.0–8.8 cal. kyr BP with sharply cooling and warming climate conditions; 8.8–4.8 cal. kyr BP with alternating cooling and warming climate conditions; 4.8–1.6 cal. kyr BP with warm climate conditions overall and 1.6–0 cal. kyr BP with cold climate conditions.

Keywords: peat humification; magnetic susceptibility; trace elements; abrupt climate changes; Holocene climate variations

1. Introduction
Since the late 1800s, researchers have explored different climate conditions by studying stratigraphic changes in peat layers and eventually made contributions to the classification of the Late Glacial and Holocene periods (Kylander et al., 2013). Materials from peat, including testate amoebae, pollen, elements, molecular biomarkers, carbon and oxygen isotopes, have proven to be good proxies for reconstructing paleoclimate and paleoenvironmental conditions (Booth and Jackson, 2003; Xie et al., 2004; Barber and Langdon, 2007; Daley et al., 2010; Wei et al., 2012). In addition, peat humification is one of the most extensively used paleoclimate proxies. In recent decades, there has been growth in the use of humification data as a tool for peatland paleoclimate analysis (Aaby and Tauber, 1975; Blackford and Chambers, 1993; Barber et al., 1994; Langdon and Barber, 2005; McCarroll et al., 2016). The relationship between peat humification and peat-surface wetness has been found, and lower humification generally indicates wet-shifts (Blackford, 2000; Wang et al., 2010). Observations from the blanket bog at Talla Moss indicate that decreasing temperatures or an increasing moisture supply can lead to decreases in humification; a close relationship between increasing mire surface wetness and the Little Ice Age had also been found (Chambers et al., 1997). Peat humification records also demonstrate good correlations with solar output variations through a comparison with other terrestrial paleoclimate proxies, which could be beneficial for confirming the precise timing (Baker et al., 1999). Although peat humification data may be species specific (Yeloff and Mauquoy, 2006), k-values have been used to adjust peat humification for different plant species (Hughes et al., 2012). However, humification results from many studies show a general agreement between sites and other proxy records (Baker et al., 1999; Charman et al., 2001; Hughes et al., 2006). Prior studies also suggest that a peat humification analysis is broadly reliable even though the underlying processes remain unclear (Payne and Blackford, 2008).

Organic paleoclimate proxies from peat, such as humification, pollen or isotope records, have been proven to be good indicators of environmental change. In addition, paleoclimate reconstructions have also been obtained from inorganic records. Numerous studies have reported magnetic and element properties in long-term sediments because of their important global environmental and climate change significance (Begét et al., 1990; Shotyk, 1996; Nieminen et al., 2002; Zaccone et al., 2007; Perez-Rodriguez et al., 2015).
However, researchers have explored new areas for environmental information that can be applied to paleoclimate reconstructions, especially loess sediments (Shotyk et al., 2002; Muller et al., 2008; Kloss et al., 2015; Jensen et al., 2016). Techniques can also be applied to peat sediment. By extracting magnetic data from the Chandra peat bog, Holocene monsoonal variability in the Northwest Himalaya was reconstructed, suggesting that the intensive Indian summer monsoon (ISM) increases the concentration of antiferromagnetic minerals while the maximum influx of antiferromagnetic minerals responded to optimum climate (Rawat et al., 2015). Elemental characteristics in peat can also reflect paleoclimate changes. Atmospheric mercury in the Penido Vello peat bog in Northwest Spain was proven to be a good indicator of paleoclimate evolution (Martinez-Cortizas et al., 1999). In addition, MgO/CaO and Rb/Sr ratios in peat samples from South China suggested that lower MgO/CaO ratios imply dryer climate conditions while higher Rb/Sr ratios imply relatively wetter conditions (Zhong et al., 2010).

Humidity and temperature are key factors affecting bog surface wetness and peat decomposition (Kylander et al., 2013). As the process of peat decomposition has a close relationship with local climate conditions, peat humification can potentially be used as a proxy indicator of the regional climate, variation which is intrinsically linked to peat decomposition (Wang et al., 2010). Therefore, to a certain extent, humidity and temperature changing processes reflect the performance of peat humification, which can be recorded by peat humification. To our knowledge, few works have been completed in the Hani peatland, northeastern China (Hong et al., 2005; Hong et al., 2009; Yang et al., 2014). The results regarding δ18O, δ13C, pollen and grain-size from Hani peat have helped to reconstruct 14 cal. kyr BP environmental changes, while the high-resolution peat humification record will provide a better understanding of paleoclimate changes in this area. Thus, the objectives of this study are to (1) investigate the variation of peat humification, magnetic susceptibility and trace element records in the profile of Hani peatland, Northeast China, (2) distinguish the paleoclimate significance and response to abrupt climate change from peat proxies, and (3) recover regional paleoclimate variations since the Holocene.

2. Materials and methods

2.1. Sample preparation

The Hani peatland is located at the western foot of the Changbai Mountain, Jilin Province, northeastern China with an altitude of 882–900 m (Figure 1). The Hani peatland is 1680 km² in area, with a maximum thickness of peat accumulation of approximately 9.6 m. It developed in the late Pleistocene Nanping period on a low-lying valley, dammed by an effusive volcano mass (Qiao, 1993). Genetically, this peatland is typical of a lava-dammed lake. The study area belongs to a temperate continental monsoon climate with an annual average temperature of 5.5 °C and precipitation of 743.3 mm with a freezing period of approximately 6 months (November to April). A modified Russia peat drill was used to core the peat in the central thick depositional layer area of the Hani peatland (42°12′50″N, 126°31′05″E); a 900-cm peat core was collected for analysis. The core was sliced into 1 cm sections using a stainless-steel knife, and peat samples were placed in sealed polyethylene film. All peat samples were marked with sampling locations, depths and stratigraphic sequence. Then, the peat samples were transported back to the laboratory immediately and stored in a walk-in freezer at −20 °C. The labeled peat samples were dried in a vacuum dryer dehumidifier at 10 °C for 48 h, and the modern grass root layer (from the ground to a 25 cm depth) was removed because it was considered potentially contaminated during sampling. Then, the dried peat samples were manually homogenized using an agate mortar and pestle, which was cleaned with deionized water between each sample. The homogenized powder samples were stored in plastic bags at +5 °C.

2.2. Analytical methods

The alkali-extraction method was used to determine the humification of the Hani peat (Blackford and Chambers, 1993). The experimental procedures were processed as in (Huang et al., 2013). The absorbance values of the solute were measured on a Shimadzu UV-VIS-3000 type spectrometer, all data were assessed four times and the mean values were calculated and presented as the results. Mass-specific magnetic susceptibility was measured using an AGICO MFK1-FA Multi-function Kappabridge at frequencies of 976 Hz (low frequency) with a sensitivity of 10−11 m3 kg−1 and an accuracy of 0.1% (Hrouda, 2011; Hu et al., 2013). Prior to measuring the concentrations of Ti, Fe, Rb and Sr with Inductively Coupled Plasma Time Of Flight Mass Spectrometry (ICP-TOFMS) (Opti-Mass 9500, GBC Inc.), 1 g of powdered sample was placed into a 100-mL beaker along with 6 mL HNO3 and 4 mL H2O2. Then, nano-pure water was added to the beaker up to the 50 mL line and stirred with a glass rod. Then, 10 mL water samples were filtered through 0.22 μm polycarbonate membranes for the ICP-TOFMS analysis. To obtain the peat age, a total of 13 subsamples were selected from the Hani peat core for 14C dating via accelerator mass spectrometry (AMS). Plant cellulose from the peat samples were used for dating, prepared using a modified sodium chlorite oxidation method (Hong et al., 2009). The CALIB4.3 software was used to calibrate the AMS14C data (Hughen et al., 1998).

3. Results

3.1. Chronology and stratigraphy

A total of 13 AMS14C data are identified and presented in Figure 2. The depth-age model via the linear
interpolation method was chosen to establish the \(^{14}\)C age framework for the Hani peatland. According to the texture and color of the peat profile, the core was divided into 10 layers (Ma et al., 2009). From top to bottom, the peat layers are described as follows: grass root layer (0–25 cm), light brown peat layer (26–66 cm), brown peat layer (67–127 cm), dark brown peat layer (128–248 cm), light brown peat layer (249–319 cm), dark brown peat layer (320–599 cm), dark brown peat layer containing tephra (600–625 cm), dark brown peat layer (626–726 cm), black brown layer (727–890 cm) and greenish-gray clay peat (891–900 cm). Combined with the AMS\(^{14}\)C dating data, the Hani peat stratigraphic column is presented in Figure 2.

3.2. Peat humification

The absorbance values at the 540-nm wavelength were chosen as the peat humification proxy (Ma et al., 2009; Kylander et al., 2013). The peat humification results (540 nm absorbance values in percentage) are shown in Table 1 and Figure 3. Very high values of peat humification were found at depths of 319–325, 461–486 and 497–553 cm in the Hani peat core, which corresponds to 4753–4853, 7137–7556 and 7741–8681 cal. yr BP, respectively. The humification values are higher in the middle than in the top or bottom of the peat core. As shown in Table 1, the mean values are 10.82 (top), 14.36 (middle) and 10.75 (bottom).

3.3. Magnetic susceptibility

The \(\chi_{\text{lf}}\) results are shown in Table 1. Almost all values are low, and the mean \(\chi_{\text{lf}}\) values from different locations follow the order of bottom (6.15) > top (5.46) > middle (3.98). Even the maximum \(\chi_{\text{lf}}\) value in the top (23.91) is higher than that in the bottom (19.17). From the \(\chi_{\text{lf}}\) distribution (Figure 3), the \(\chi_{\text{lf}}\) values are extremely high at the depths of 555–565 cm, corresponding to 8866–9034 cal. yr BP, suggesting a high level mineralization of peat in this layer.

3.4. Trace elements

The trace element results, including Ti, Fe, Rb and Sr, are presented in Table 1 and Figure 3. These results show that concentrations of Ti are lower at the core top with average concentrations of 137.56 mg kg\(^{-1}\), while the middle and bottom have similar levels with average concentrations of 237.81 and 240.44 mg kg\(^{-1}\), respectively. However, Ti values in the core middle vary over a large scale (78.10 to 2650.40) and have a high standard deviation (SD) value (369.83). Fe concentrations are similar to Ti as the average Fe concentrations follow the order of top (2.58 mg g\(^{-1}\)) < middle (3.09 mg g\(^{-1}\)) < bottom (4.72 mg g\(^{-1}\)). Extremely high Fe values are found at the depths of 720–750 cm, corresponding to 11468–11972 cal. yr BP. The Rb and Sr distribution curves are similar, and high Rb and Sr concentrations are found at the depths of 190–210, 300–320, 630–675 and 840–900 cm, which correspond to 2570–2906, 4417–4753, 9957–10713 and 13483–14490 cal. yr BP, respectively.

4. Discussion

4.1. Response of peat humification to the \(\delta^{18}\)O temperature record and abrupt climate changes

The absorbance value time series of the Hani peat is shown in Figure 4. To smooth the short frequency
fluctuations and highlight trends over longer periods, the 3-point moving average of the absorbance values was calculated based on the humification results (Figure 4(c)) (Ma et al., 2009; Castro et al., 2015). This value generally indicates the degree of peat decomposition variation, with a smaller absorbance indicating a lower humification (Wang et al., 2010). To reveal the paleoclimatic significance of Hani peat humification, the humification record is compared with the $\delta^{18}$O time series of Hani peat cellulose (Figure 4(b)). The comparison suggests that the Hani peat cellulose $\delta^{18}$O time series have recorded a temperature evolution that reflects the abrupt warm/cold climate changes in the Northwest Pacific Region in the middle latitudes during the last 14000 years (Hong et al., 2009). Variations in the Hani $\delta^{18}$O record have good correlations with nine ice-rafted debris (IRD) events in the North Atlantic Ocean (Bond et al., 2001), suggesting that nine abrupt climate changes were associated with the sudden temperature drops. In addition, the Hani $\delta^{18}$O record documents the sudden cooling events, including the Older Dryas (OD), Inter-Allerød (IA) and Younger Dryas (YD) (Hong et al., 2009). Hence, peat cellulose $\delta^{18}$O records can be used as a standard for estimating the response sensitivity of peat humification to abrupt climate variations.

Corresponding to the nine IRD events and sudden cooling events during the last deglaciation, the peat humification record shows rising in varying degrees. From 14.1 to 13.9 cal. kyr BP, peat humification values increased to a peak of 6 to 8, while the Hani $\delta^{18}$O suddenly decreased from 24 to 19.5, indicating the occurrence of the OD event. From 13.5–13.3 cal. kyr BP, humification values increased rapidly from 8 to

### Table: Calibrated age (cal. yr BP) vs. AMS$^{14}$C age (yr BP) vs. AMS sampling depth (cm) vs. Depth (cm)

| Calibrated age (cal. yr BP) | AMS$^{14}$C age (yr BP) | AMS sampling depth (cm) | Depth (cm) | Stratigraphy                  |
|----------------------------|-------------------------|-------------------------|------------|-------------------------------|
| 722                        | 807 ± 40                | 80                      | 0          | Grass root layer              |
| 1292                       | 1380 ± 88               | 135                     | 100        | Light brown peat layer        |
| 2673                       | 2455 ± 46               | 200                     | 200        | Brown peat layer              |
| 5383                       | 4674 ± 53               | 350                     | 300        | Dark brown peat layer         |
| 8171                       | 7354 ± 63               | 495                     | 500        | Light brown peat layer        |
| 8412                       | 7658 ± 64               | 570                     | 600        | Dark brown peat layer         |
| 9337                       | 8352 ± 76               | 600                     | 600        | Dark brown peat layer contain tephra |
| 10 745                     | 9604 ± 80               | 625                     | 600        | Dark brown peat layer         |
| 11 643                     | 10 102 ± 80             | 740                     | 700        | Black brown peat layer        |
| 12 336                     | 10 399 ± 89             | 745                     | 800        | Black brown peat layer        |
| 12 356                     | 10 446 ± 91             | 780                     | 800        | Black brown peat layer        |
| 13 135                     | 11 122 ± 90             | 820                     | 800        | Black brown peat layer        |
| 14 440                     | 11 930 ± 172            | 900                     | 900        | Greenish gray clay peat       |

**Figure 2.** Stratigraphy and $^{14}$C age of the peat core from Hani peatland.
Table 1. Data of absorbance (peat humification), $\chi_{lf}$ and trace elements in Hani peat core.

| Index | Location   | Max.  | Min.  | Mean  | SD   |
|-------|------------|-------|-------|-------|------|
|       | Absorbance (%) |       |       |       |      |
| Top   | 16.35      | 5.50  | 10.82 | 1.89  |
| Middle*| 19.13      | 6.80  | 14.36 | 2.21  |
| Bottom* | 16.75     | 1.20  | 10.75 | 3.65  |
|       | $\chi_{lf}$ (10^{-8} m^3 kg^{-1}) |       |       |       |      |
| Top   | 23.91      | 1.16  | 5.46  | 4.04  |
| Middle | 14.13      | 1.83  | 3.98  | 2.24  |
| Bottom | 19.17      | 3.24  | 6.15  | 3.90  |
|       | Ti (mg kg^{-1}) |       |       |       |      |
| Top   | 346.25     | 76.00 | 137.56| 55.77 |
| Middle| 265.40     | 78.10 | 237.81| 369.83|
| Bottom| 1016.05    | 74.60 | 240.44| 155.40|
|       | Fe (mg g^{-1}) |       |       |       |      |
| Top   | 4.98       | 0.77  | 2.58  | 0.84  |
| Middle| 5.17       | 1.98  | 3.09  | 0.76  |
| Bottom| 14.75      | 1.26  | 4.72  | 2.37  |
|       | Rb (mg kg^{-1}) |       |       |       |      |
| Top   | 31.55      | 3.61  | 7.02  | 6.14  |
| Middle| 44.90      | 2.50  | 6.27  | 5.34  |
| Bottom| 29.10      | 4.74  | 11.52 | 5.15  |
|       | Sr (mg kg^{-1}) |       |       |       |      |
| Top   | 496.00     | 80.50 | 236.01| 114.16|
| Middle| 528.00     | 120.00| 297.79| 105.01|
| Bottom| 982.00     | 224.50| 491.31| 193.56|

*Top, Middle and Bottom correspond to the depth of 0–299, 300–599 and 600–900 cm in Hani peat core, respectively.

16, corresponding to a drop in $\delta^{18}O$ and indicating the occurrence of the IA cold event (Hong et al., 2009). The YD event is the most notable cooling event of the last deglaciation, which is indicated by obvious drops in the GISP2 $\delta^{18}O$ record, corresponding to the time period 12.9–11.7 cal. kyr BP (Stuiver et al., 1995). In the YD phase, the Hani $\delta^{18}O$ record declined to the lowest value, approximately 18.2, at approximately 12.5 cal. kyr BP, and the peat humification varied, with increasing peaks until approximately 11.7 cal. kyr BP, which is the suggested end of the YD event (Stuiver et al., 1995). In addition, the peat humification record has obvious responses during the IRD event cooling patterns. At 11.6–11.0 cal. kyr BP, the peat humification values increased from 10 to 16, which was similar to the Hematite-stained grain record (Figure 4(a)), while the Hani $\delta^{18}O$ decreased from 21 to 19. At approximately 11.3–11.2 cal. kyr BP, the peat humification and Hematite-stained grains stayed at high values but $\delta^{18}O$ lowered. This result indicates that the climate condition in this phase was cold, corresponding to the IRD-8 cooling event. The IRD-5 event is known as the ‘8.2 cal. kyr BP’ event, which is a famous cooling climate change during the early Holocene, occurring in many regions of the globe. Evidence from the North Atlantic Deep Water (NADW) formation and reduced oceanic thermohaline circulation shows a sharp temperature decrease in the Northern Hemisphere at approximately 8.2 cal. kyr BP (Broecker, 2003; Alley and Ágústsdóttir, 2005). The Hani peat humification record also has a sensitive response to the ‘8.2 cal. kyr BP’ event, which provides an opportunity for the evaluation of this cooling event in the Western Pacific region, similar to the $\delta^{18}O$ record (Hong et al., 2009) as shown in Figure 4. During 8.7–7.1 cal. kyr BP, peat humification values

Figure 3. Distribution of absorbance (peat humification), $\chi_{lf}$ and trace elements in Hani peat core.
The paleoclimatic significance of peat

Figure 4. Comparison between Hani peat humification record (c) with Holocene record of drift ice for the MCS2-VM29-191 core in the North Atlantic (a) (Bond et al., 2001) and the $\delta^{18}$O temperature proxy record of Hani peat cellulose (b) (Hong et al., 2009). YD, IA, and OD denote the Younger Dryas, Inter-Allerod and Older Dryas cooling events, respectively. Numbers from 1 to 8 indicate each of the eight IRD events of the North Atlantic, number 0 indicates ‘Little Ice Age’ event. The vertical light gray bands trace the comparisons of temperature anomalies inferred from the Hani $\delta^{18}$O and peat humification with the cooling events.

increased from 7 to 19. Hematite-stained grains broadly increased, and $\delta^{18}$O largely decreased from 23 to 20. The period from 8.5 to 3.0 cal. kyr BP is called the Holocene Megathermal, corresponding to the IRD-4, IRD-3 and IRD-2 events. It has been suggested that this is the warmest phase in the Chinese mainland although there may have been regional differences in the warm period (Shi et al., 1994; Wang and Gong, 2000). At approximately 5.9 cal. kyr BP, all the curves shown in Figure 4 reach a peak as Hematite-stained grains and humification have an increasing peak, and $\delta^{18}$O had a decreasing peak, indicating the IRD-4 event. Staring from approximately 4.9 cal. kyr BP, the humification record increases quickly to a peak of approximately 4.8 cal. kyr BP and then decreases until 4.4 cal. kyr BP with few small fluctuations. It reaches a peak again at approximately 4.2 cal. kyr BP, corresponding to the IRD-3 event. Then, the humification values continue to rise until 3.9 cal. kyr BP. There are similar changes in the Hematite-stained grains, but opposite occurs in $\delta^{18}$O. However, all records have a good response to the IRD-3 event. All the curves shown in Figure 4 show obvious peaks at approximately 3.2–3.1 cal. kyr BP and 1.5–1.4 cal. kyr BP, corresponding to the IRD-2 and IRD-1 events. During 0.5–0.4 cal. kyr BP, peat humification shows two sharply rising peaks, while the $\delta^{18}$O record has a sharply decreasing peak, indicating the cooling IRD-0 event, which is called the ‘Little Ice Age’. The Hematite-stained grain record also has two peaks at approximately 0.4 and 0.2 cal. kyr BP, recording the fluctuating cooling climate conditions during that time.

Based on the comparison between the ice-rafted record (Figure 4(a)) and Hani peat humification (Figure 4(c)), the absorbance values show positive correlations with the Hematite-stained grains over long-time scales. In particular, during the time of the cooling patterns of the nine IRD events, the peat humification all have increasing peaks as recorded in the Hematite-stained grains. In general, the curves of Hani $\delta^{18}$O and humification have similar variations during the Holocene even though their values show an
inverse correlation. Therefore, the Hani peat humification record has a sensitive response to abrupt climate change, including the OD, IA, YD and nine IRD cooling events. In addition, the humification record has an inverse correlation with the Hani δ¹⁸O temperature record, which, along with the higher humification inferred from the absorbance, corresponds to a colder climate condition.

4.2. Environmental significance of peat humification

Peat humification, which reflects the degree of peat decomposition, is affected primarily by hydrothermal conditions, microbial activity, soil pH values, peat species and so on. The hydrothermal condition is the most important factor, which is controlled by humidity and temperature (Ma et al., 2009). Although the peat decomposition process is affected by plant species, which show different humification, peat humification can be used as a proxy reflecting past humidity changes (Caseldine et al., 2000). However, peat humification has different paleoclimate significance based on the results from China’s peatlands. The humification record of the Hongyuan peatland in the Eastern Tibetan Plateau was studied and used as a proxy of summer monsoon (Wang et al., 2010). This suggests that increases in temperature and humidity will strengthen microbial activity in peat soil, which will enhance the ability of microbes to decompose peat. In contrast, humid-warm climate conditions will promote vegetation production and provide more plant remains for decomposition. Both processes help increase humic acids in peat and the degree of humification. Thus, it has been suggested that high peat humification reflects warm and wet climate conditions; in contrast, low humification reflects cold and dry climate condition (Wang et al., 2010). According to research in the Dajiuhu peatland of Central China, peat humification shows the contrary paleoclimate significance (Ma et al., 2009). This indicates that for the peat in intermountain basins from middle latitude areas of the East Asia monsoon region, the dry, cold climate conditions would decrease the available surface humidity (precipitation–evaporation) and increase the peat decomposition intensity, which promote a higher degree of humification. In contrast, the warm and wet climate conditions increase the available humidity, and peat decomposes slowly under the waterlogged condition. Therefore, peat humification is lower.

The environmental conditions of the Hani peatland are similar to those of the Dajiuhu peatland, and they are all affected by the East Asia Monsoon (Zhou et al., 2010). The peat humification records of both peatlands show similar responses to abrupt climate change as increasing humification peaks correspond to cold events. At the Hani peatland the ground is perennially saturated with water, and the warm and wet climate conditions may bring in excessive precipitation, which works against plant growth, and thus, organic carbon and peat humification decrease (Ma et al., 2009). However, the Hongyuan peatland in the high-altitude mountain environment of the Tibet Plateau will be affected by alternating drying–rewetting and freezing–thawing events. All these processes will influence the soil structure (Willis, 1955; Birch, 1959), microbial activity (Stevenson, 1956), free amino acids and sugars (Ivarson and Sowden, 1970). Since the background temperature in the Hongyuan peatland is quite low, the warm and wet climate will promote stronger microbial activity and shorten the surface freezing time with plant growth increasing, which results in higher organic carbon contents and peat humification. Therefore, the peat humification record may have different proxy-climate significance because of different climate and geological environments. We suggest that the similar paleoclimate significance between the Hani and Dajiuhu peats on the degree of humification where there is higher peat humification indicates a colder and drier climate condition; in contrast, the warm, moist climate provides a deoxygenated condition, resulting in a lower peat humification.

4.3. Characteristics of peat humification, $\chi_f$, Rb/Sr and Fe/Ti ratio in the Hani peat core and regional climate variations since the Holocene

As a paleoclimate proxy, peat humification has successfully been used to reconstruct Holocene climate conditions in many regions (Baker et al., 1999; Booth and Jackson, 2003; Langdon and Barber, 2005; Ma et al., 2009; Wang et al., 2010). In this paper, the Hani peat humification record has been found to have paleoclimate significance where lower humification, inferred from absorbance, corresponds to warmer climate conditions. In most regions of the globe, the Holocene started at approximately 11.5 cal. kyr BP with a strong warm period. According to the Hani peat humification record, the decreasing peaks at approximately 11.5 cal. kyr BP indicate warm climate conditions. Combined with the grain-size record from the Hani peat, which reaches the lowest value (3.75%) at 11.5 cal. kyr BP, suggests that this is the beginning of the Holocene in the Hani region (Yang et al., 2014). Thus, the Holocene climate variations in this study area can be divided into five phases according to the peat humification and data from the Hani peatland.

4.3.1. Phase I: 11.5–10.0 cal. kyr BP, with warm climate conditions

Humification values start to decrease from approximately 11.6 cal. kyr BP and reach the decreasing peaks at approximately 11.5–11.4 cal. kyr BP, corresponding to the climate conditions at the beginning of the Holocene. Then, humification increased quickly, indicating a colder climate condition. At approximately 11.1 cal. kyr BP, it started to decrease sharply until 11.0 cal. kyr BP, suggesting a warmer condition during the period. Then, humification values increase within a small range until 10.7 cal. kyr BP and decrease to 10.6, indicating warm and cold fluctuations over this period.
Values increase until 10.1 cal. kyr BP but decrease sharply to 10.0 cal. kyr BP, suggesting a change from colder to warmer climate conditions. During this period, $\chi_H$ lowers, and values stay between 3 and 6. The Rb/Sr ratios have an increasing trend at approximately 11.5 cal. kyr BP, decreasing from 11.4 cal. kyr BP. Fe/Ti ratios have a tendency to decrease during phase I. The rapid decrease and increase of Fe/Ti ratios starts from 11.5 to 11.2 cal. kyr BP as shown in Figure 5; then, the Fe/Ti ratios decrease slowly until 10.3 cal. kyr BP.

4.3.2. Phase II: 10.0–8.8 cal. kyr BP, with sharp cooling and warming climate conditions

From 10.0 to 9.7 cal. kyr BP, Hani peat humification increases sharply and reaches a peak value. This was followed by values decreasing until 9.5 cal. kyr BP. Similar changes can be observed in the $\delta^{18}$O record and drift ice from the North Atlantic Ocean, which suggests the IRD-6 cooling event that occurred in this period. These data show that from 10.0 to 9.7 cal. kyr BP, climate conditions experience cooling first with the occurrence of IRD-6 event; then, it became warmer from 9.5 to 9.3 cal. kyr BP. After, there was a rapid cooling until 9.0 cal. kyr BP. In phase II, $\chi_H$ changes lowered until 9.1 cal. kyr BP, and then the values increased quickly from 4 to 15 in the period 9.1–8.8 cal. kyr BP, which is abnormal as the other values were constant between 3 and 6. The Fe/Ti ratios decrease to a small range in 10.0–9.2 cal. kyr BP but sharply increased similar to $\chi_H$ at approximately 9.2–8.8 cal. kyr BP. The Rb/Sr ratios are very low during phase II, and the value is approximately 2.

4.3.3. Phase III: 8.8–4.8 cal. kyr BP, with alternating cooling and warming climate conditions

This phase is within the Holocene Megathermal, from 8.5 to 3.0 cal. kyr BP in China (Shi et al., 1994; Hong et al., 2009). During 8.5–7.0 cal. kyr BP, peat humification and Hematite-stained grains show three decreasing peaks and two increasing peaks, indicating alternating warming and cooling climate conditions. However, this shows overall colder conditions during this period along with the occurrence of the ‘8.2 cal. kyr BP’ event. From 7.0 to 4.8 cal. kyr BP, peat humification stayed at a low stable level, suggesting warmer climate conditions. At approximately 5.9 cal. kyr BP, peat humification and Hematite-stained grains increased to a peak corresponding to the IRD-4 event. In phase III, $\chi_H$ sharply decreases at 8.8–8.5 cal. kyr BP, then it increases slowly at 8.5–7.6 cal. kyr BP followed by a small-scale decrease until 7.0 cal. kyr BP. After that it maintains a low level with a value approximately 1. Fe/Ti ratios change in a different way, showing two sharply decreasing and increasing peaks at 8.5–7.5 cal. kyr BP. Then, Fe/Ti ratios stay stable from 19 to 23 with some fluctuations at 7.5–4.8 cal. kyr BP. Rb/Sr ratios vary with regular fluctuations at 8.8–5.0 cal. kyr BP but the value is low overall.

4.3.4. Phase IV: 4.8–1.6 cal. kyr BP, with warm climate conditions overall

As shown in Figure 5, peat humification keeps decreasing at 4.8–4.4 cal. kyr BP, indicating warmer conditions. Then, it rises quickly until 4.2 cal. kyr BP, when both $\delta^{18}$O and Hematite-stained grains reach a peak value corresponding to the ‘4.2 cal. kyr BP’ event. From 4.8–3.5 cal. kyr BP, peat humification and Hematite-stained grains decrease while $\delta^{18}$O changes inversely. This suggests stable and warmer climate conditions, which may have contributed to the prosperity of civilization (Shi et al., 1994). These values decrease until humification reaches a low peak approximately 1.6 cal. kyr BP, which suggests a warmer climate condition at 3.2–1.6 cal. kyr BP. In phase IV, $\chi_H$ has low level variations until approximately 2.8 cal. kyr BP, increasing with large fluctuations including four rising peaks and reaches a maximum at 1.6 cal. kyr BP. The $\chi_H$ variation is similar to peat humification at 3.2–1.6 cal. kyr BP, which suggests that higher $\chi_H$ indicates a warmer climate condition. Results from the Chandra peat bog also proves that the maximum influx of antiferromagnetic minerals responded to optimum climate (Rawat et al., 2015). Fe/Ti ratios decrease with few small fluctuations from 4.8 to 1.8 cal. kyr BP following an increase until 1.6 cal. kyr BP. Rb/Sr ratios have two extreme values at 4.8 and 2.8 cal. kyr BP, corresponding to rising peat humification peaks. However, variations in Rb/Sr ratios contradict peat humification and $\chi_H$ at 2.8–1.6 cal. kyr BP, which may suggest that higher Rb/Sr ratios indicate a colder condition. Results of the Djuhu peat show that Rb/Sr ratios have an inverse correlation with peat humification, and lower Rb/Sr ratios are a response to drier conditions (Ma et al., 2009), which are consistent with the findings in the Hani, especially in phase IV.

4.3.5. Phase V: 1.6–0 cal. kyr BP, with cold climate conditions

At 1.6–1.3 cal. kyr BP peat humification increases with a few sharp fluctuations, suggesting cold conditions. Hematite-stained grains and $\delta^{18}$O variations also indicate the occurrence of the IRD-1 event in this period. Then, humification decreases until 0.6 cal. kyr BP. Hematite-stained grains and humification are stable and low, suggesting warmer climate conditions, a response to the Medieval Warm Period. At 0.6–0.4 cal. kyr BP, peat humification and Hematite-stained grains show sharply increasing peaks. This suggests a natural cooling after warmer conditions, which corresponds to the appearance of the Little Ice Age. In phase V, the $\chi_H$ curve varies similarly to peat humification; the increasing $\chi_H$ peaks also show a warm condition.

5. Summary and conclusions

Peat humification has been used as a climate proxy for studying paleoclimate variations in Europe for
Figure 5. Hani peat humification, \( \chi_f \), Rb/Sr and Fe/Ti ratio variations in the Holocene.

a long time. However, more information is required for China’s peatlands to understand the environmental significance of peat humification. In this work, a high-resolution peat humification record from the Hani peatland, northeastern China has been found to be sensitive to abrupt climate changes, including the Older Dryas, IA, YD and nine ice-rafted debris events. In the Hani region, dry and cold climate conditions decrease the surface available humidity (precipitation–evaporation) and increase the decomposition intensity of peat, which promote a higher degree of humification. In contrast, warm and wet climate conditions will increase the available humidity, and peat decomposes slowly in the waterlogged condition. Consequently, peat humification is lower. Therefore, it may have paleoclimate significance, with higher peat humification indicating a colder and drier climate condition, and warm and moist climate providing a deoxidized condition, resulting in lower peat humification. In addition, the Rb/Sr ratios and \( \chi_f \) in the Hani peatland can also indicate different climate conditions, especially in the late Holocene. Combined with Hani peat humification, regional paleoclimate variations can be divided into the following five phases: 11.5–10.0 cal. kyr BP with warm climate conditions; 10.0–8.8 cal. kyr BP with sharply cooling and warming climate conditions; 8.8–4.8 cal. kyr BP with alternating cooling and warming climate conditions; 4.8–1.6 cal. kyr BP with warm climate conditions overall; and 1.6–0 cal. kyr BP with cold climate conditions. As the environmental significance of peat humification could be different based on the climate and geological environments, further investigation at a global scale should be performed to identify applicability to different environments.

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