The peatlands developing history in the Sanjiang Plain, NE China, and its response to East Asian monsoon variation

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Studying the peatlands accumulation and carbon (C) storage in monsoonal areas could provide useful insights into the response of C dynamics to climate variation in the geological past. Here, we integrated 40 well-dated peat/lake sediment cores to reveal the peatlands evolution history in the Sanjiang Plain and examine its links to East Asian monsoon variations during the Holocene. The results show that 80% peatlands in the Sanjiang Plain initiated after 4.7 ka (1 ka = 1000 cal yr BP), with the largest initiating frequency around 4.5 ka. The mean C accumulation rate of peatlands in the Sanjiang Plain exhibits a synchronous increase with the peatlands expansion during the Holocene. Such a peatlands expanding and C accumulating pattern corresponds well to the remarkable drying event subsequent to the Holocene monsoon maximum. We suggest that in addition to the locally topographic conditions, Holocene variations of East Asian summer monsoon (especially its associated precipitation) have played a critical role in driving the peatlands initiation and expansion in the Sanjiang Plain.

Peatlands as one of the largest biosphere carbon (C) reservoirs and CH₄ sources have played an important role in global carbon cycle and climate changes during geological past¹⁻³. Understanding the responses of these C-rich ecosystems to past climate changes could provide useful insights into projecting the fate of peatlands C in the future⁴⁻¹⁰. During last decades, numerous works have been done to reveal the peatlands dynamics to the local climate changes. It has been well documented that peat accumulates whenever the rate of organic matter production exceeds the rate of decay, and which is mainly controlled by the local temperature and moisture conditions⁷. Generally, a warmer condition in growing seasons will favor more primary production and in turn a higher peat accumulation rate in peatlands although it may cause more peat decomposition, and a much colder climate in winter will be more favorable to preserve more peat from being oxidized and decomposed⁸⁻⁹. In this sense, a higher degree of climatic seasonality generally leads to a higher peat accumulation rate. Such a contention is supported by a mid-high latitude distributing pattern of the northern peatlands, where the climate is characterized by the remarkable seasonality¹⁰.

In addition to temperatures, the local moisture conditions can also generate a significant influence on peat accumulation. Modeling experiments in wetlands show that a wetter condition is roughly more productive to peat accumulation with higher primary production but lower peat decomposition¹¹. While a few works have tentatively revealed the response of peat accumulation to past moisture conditions, the results show much different controls of the moisture conditions for peatlands expansion and C accumulation¹⁰,¹²,¹³. For example, the peat deposits in Alaska accumulate more quickly in much drier conditions¹⁹.

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and a considerable number of world peatlands initiated during the Last Glacial Maximum, a relatively cold and dry interval. Such an inverse correlation between the peat accumulation and moisture conditions seems to be inconsistent with the modeling results. So, the mechanisms of peatlands response to the moisture conditions may be more complicated than anticipated, and clarification of this issue will require high-quality records from more climatically sensitive locations.

The Sanjiang Plain known as the largest fresh-water wetland area is located in the northern monsoon marginal region, making it a particularly sensitive region to East Asian monsoon variations. In this paper, we integrated 40 well-dated peat cores to reveal peatlands initiation and C accumulation histories in the Sanjiang Plain, and discuss their relations to the East Asian monsoon circulations during the Holocene.

Results

Sampling and material. During May to September in 2012, a thorough investigation was performed in the Sangjiang Plain to ascertain the modern peatlands distribution, and 15 well-preserved peatlands were found and well studied in this paper. In the central region of each peatland, a deposit core was collected using a Russia peat corer and 15 peat/mud cores in total were gained (Fig. 1). According to lithologic properties, all these cores can be subdivided into two parts (Fig. 2): the typical brownish peat layers above and the grey-blackish mud deposits below. All samples were collected with 1-cm-thick interval from each core for laboratory analysis.

Lithology and chronology. We used 40 basal peat $^{14}$C ages including 15 dates in the present study (Fig. 2 and Table. 1) and 25 dates from published sources (Table. 2) across the Sanjiang Plain (site locations in Fig. 1) to assess the temporal and spatial pattern of peatlands initiation. According to visual
inspection and organic matter contents variation, most of the 15 collected peat cores can be subdivided into two parts: the lacustrine mud deposits with a lower organic content of ~20% in the lower part, and the overlying typical peat deposits with much higher organic contents of >50% (Fig. 2). The AMS dating results indicate that although the peatlands occurrences in the Sanjiang Plain cover a wide range of the Holocene, 80% of them concentrate in the last 4.7 ka (Fig. 3a,b) and the largest initiating frequency

Figure 2. Stratigraphy and organic matter content of 15 peat/mud cores from the Sanjiang Plain. The calibrated AMS ages are marked beside the organic matter curves with the solid rectangles indicating the depth of the dating samples. The solid arrow was used to indicate the basal age of peat accumulations for each core.
| Site# | Lab number | Depth (cm) | Dating material | δ¹³C (‰) | AMS ¹⁴C age (¹⁴C yr BP) |Calibrated ¹⁴C age (2σ) (cal yr BP) |
|-------|------------|------------|-----------------|----------|------------------------|----------------------------------|
| S2    | XA7553     | 27         | Plant residues  | −37.78   | 550 ± 24               | 520–560                           |
| S2    | XA7592     | 60         | Plant residues  | −38.64   | 1088 ± 24              | 940–1010                          |
| S2    | XA7542     | 84         | Plant residues  | −30.36   | 1381 ± 26              | 1280–1340                         |
| S2    | XA7543     | 107        | Plant residues  | −24.56   | 1673 ± 32              | 1520–1630                         |
| S2    | XA7570     | 165        | Plant residues  | −30.14   | 3542 ± 26              | 3810–3900                         |
| S1    | XA7561     | 44         | Plant residues  | −34.77   | 1733 ± 24              | 1590–1700                         |
| S1    | XA7562     | 67         | Plant residues  | −30.51   | 1847 ± 23              | 1710–1830                         |
| S1    | XA7540     | 92         | Plant residues  | −30.14   | 2173 ± 25              | 2220–2310                         |
| S1    | XA7563     | 100        | Plant residues  | −30.52   | 2446 ± 28              | 2360–25402                        |
| S1    | XA7541     | 135        | Organic matter  | −29.80   | 3268 ± 27              | 3450–3570                         |
| H2    | XA7572     | 29         | Plant residues  | −32.12   | 606 ± 23               | 580–650                           |
| H2    | XA7573     | 60         | Organic matter  | −30.91   | 1243 ± 24              | 1170–1270                         |
| H2    | XA7574     | 80         | Plant residues  | −31.54   | 2295 ± 25              | 2310–2350                         |
| H2    | XA7576     | 95         | Plant residues  | −29.89   | 2759 ± 28              | 2780–2930                         |
| H2    | XA7577     | 116        | Plant residues  | −30.40   | 3335 ± 25              | 3550–3640                         |
| H2    | XA7578     | 140        | Plant residues  | −31.76   | 5313 ± 33              | 5990–6190                         |
| H2    | XA7579     | 148        | Organic matter  | −29.89   | 5736 ± 28              | 6450–6570                         |
| Q3    | XA7583     | 65         | Plant residues  | −33.75   | 1021 ± 24              | 920–970                           |
| Q3    | XA7584     | 80         | Plant residues  | −36.03   | 1660 ± 24              | 1530–1620                         |
| Q3    | XA7593     | 92         | Organic matter  | −29.69   | 2188 ± 25              | 2330–2440                         |
| H3    | XA7580     | 26         | Plant residues  | −30.72   | 922 ± 25               | 790–920                           |
| H3    | XA7581     | 50         | Plant residues  | −30.86   | 1055 ± 23              | 930–990                           |
| H3    | XA7582     | 100        | Organic matter  | −30.16   | 5061 ± 28              | 5740–5900                         |
| Q4    | XA7587     | 57         | Plant residues  | −26.67   | 1852 ± 25              | 1720–1840                         |
| Q4    | XA7588     | 83         | Organic matter  | −29.51   | 3950 ± 26              | 4350–4450                         |
| Q1    | XA7589     | 11         | Plant residues  | −26.36   | 2244 ± 25              | 2160–2270                         |
| Q1    | XA7593     | 38         | Plant residues  | −27.43   | 4165 ± 28              | 4610–4770                         |
| Q1    | XA7590     | 69         | Organic matter  | −27.77   | 10223 ± 35             | 11820–12090                       |
| H1    | XA7567     | 30         | Plant residues  | −29.16   | 2066 ± 23              | 1990–2120                         |
| H1    | XA7568     | 60         | Organic matter  | −27.39   | 7830 ± 32              | 8540–8660                         |
| W4    | XA7534     | 36         | Organic matter  | −24.57   | 3606 ± 28              | 3840–3980                         |
| W4    | XA7533     | 60         | Organic matter  | −26.34   | 6277 ± 36              | 7160–7280                         |
| W6    | XA7538     | 30         | Plant residues  | −23.14   | 3528 ± 25              | 3720–3880                         |
| W6    | XA7537     | 53         | Organic matter  | −27.43   | 4165 ± 28              | 4610–4770                         |
| Z1    | XA7539     | 52         | Organic matter  | −26.01   | 3547 ± 26              | 3810–3910                         |
| Z1    | XA7528     | 90         | Organic matter  | −21.73   | 5476 ± 29              | 6260–6310                         |
| X2    | XA7564     | 24         | Plant residues  | −29.49   | 3005 ± 25              | 3140–3250                         |
| X2    | XA7560     | 40         | Organic matter  | −29.38   | 3983 ± 27              | 4460–4520                         |
| X1    | XA7558     | 60         | Plant residues  | −29.99   | 4194 ± 39              | 4610–4770                         |

Continued
occurs around 4.5 ka. Both the curves of the accumulating frequency of peat basal ages and mean C accumulation rate in the Sanjiang Plain exhibit a similar variation trend, as both of them show relatively low and stable values before 4.7 ka and gradually increasing trends thereafter (Fig. 3b,c).

**Discussion**

Generally, the peatlands initiation is marked by the appearance of peat layers in the geological past, and the peat deposits are defined by a high ratio of the organic matter contents. While such a definition varies largely among different countries with the organic matter contents changing from 40% to 70%24. Here, a median value of 50% was employed as an indicator of the peatlands initiation. With the peat basal

| Site# | Lab number | Depth (cm) | Dating material | δ13C (%) | AMS 14C age (1σ yr BP) | CALIB 14C age (2σ) (cal yr BP) |
|-------|-------------|------------|-----------------|----------|------------------------|-------------------------------|
| X1    | XA7559      | 76         | Organic matter  | −30.58   | 4278 ± 28              | 4830–4770                     |
| ZJ    | XA7569      | 44         | Organic matter  | −29.45   | 3797 ± 26              | 4090–4250                     |
| ZJ    | XA7591      | 80         | Organic matter  | −32.75   | 6308 ± 31              | 7170–7290                     |
| W2    | XA7529      | 32         | Organic matter  | −22.21   | 5258 ± 27              | 5930–6030                     |
| W2    | XA7530      | 45         | Organic matter  | −22.01   | 5937 ± 33              | 6670–6810                     |
| W2    | XA7527      | 62         | Organic matter  | −22.01   | 8062 ± 33              | 8970–9030                     |

Table 1. AMS radiocarbon dates of samples from 16 peat/mud cores in the Sanjiang Plain.

| Site No. | Site Names | Latitude (N) | Longitude (E) | Depth of peat (cm) | 14C date error | Basal age (Cal yr BP) | References |
|----------|------------|--------------|---------------|--------------------|----------------|-----------------------|------------|
| 1        | Xingkaihu  | 45°19′      | 132°9′        | 140                | 1486 ± 140     | 1733                  | 16         |
| 2        | Yangmu     | 45°36′      | 132°25′       | 145                | 3400 ± 340     | 4830                  | 17         |
| 3        | Huling     | 45°49′      | 132°56′       | 70–80              | 3775 ± 700     | 4188                  | 18         |
| 4        | Xinshugongshe | 45°55′    | 130°34′       | 55–60              | 3991 ± 3991    | 4443                  | 18         |
| 5        | Shuguang   | 46°10′      | 133°03’       | 320–330            | 1600 ± 1600    | 1487                  | 18         |
| 6        | Dongsheng  | 46°29′      | 132°28’       | 140–150            | 6955 ± 6955    | 6955                  | 18         |
| 7        | Dongsheng  | 46°32’      | 132°31’       | N/A                | 4417 ± 4417    | 4417                  | 19         |
| 8        | Jialong    | 46°33’      | 132°35’       | 136                | 4027 ± 4027    | 4503                  | 20         |
| 9        | Qinghe 1   | 46°35’      | 132°58’       | 85–90              | 1425 ± 1425    | 1350                  | 18         |
| 10       | Qinghe 2   | 46°35’      | 132°58’       | N/A                | 1585 ± 1585    | 1470                  | 18         |
| 11       | Baosong    | 46°36’      | 132°57’       | 120                | 1585 ± 1585    | 1585                  | 17         |
| 12       | Qinghe 3   | 46°36’      | 132°57’       | N/A                | 1610 ± 1610    | 1560                  | 18         |
| 13       | Shenjadian 1 | 46°36’    | 130°38’       | N/A                | 2470 ± 2470    | 2470                  | 21         |
| 14       | Shenjadian 2 | 46°36’    | 130°38’       | 195–200            | 2540 ± 2540    | 2541                  | 17         |
| 15       | Huachuan   | 46°37’      | 132°31’       | N/A                | 4417 ± 4417    | 2388                  | 17         |
| 16       | Bielahonghe 1 | 47°31’    | 130°43’       | 195                | 2375 ± 2375    | 5347                  | 22         |
| 17       | Bielahonghe 2 | 47°31’    | 134°04’       | 168                | 4615 ± 4615    | 6465                  | 22         |
| 18       | Bielahonghe 3 | 47°31’    | 134°04’       | N/A                | 5650 ± 5650    | 5650                  | 17         |
| 19       | Qindeli 1  | 47°55’      | 133°13’       | 196                | 9420 ± 9420    | 10651                 | 22         |
| 20       | Qindeli 2  | 47°58’      | 133°8’        | 84–89              | 1790 ± 1790    | 1727                  | 20         |
| 21       | Qindeli 3  | 48°00’      | 133°15’       | 225                | 9523 ± 9523    | 9525                  | 17         |
| 22       | Fuyuan     | N/A         | N/A           | 150                | 9300 ± 9300    | 9300                  | 17         |
| 23       | Yongfa     | 47°00’      | 130°15’       | N/A                | 5655 ± 5655    | 5655                  | 20         |
| 24       | Xingshu    | 47°04’      | 133°40’       | 60                 | 3990 ± 3990    | 3990                  | 17         |
| 25       | Tongjiang  | 48°05’      | 133°15’       | 80                 | 4917 ± 4917    | 4917                  | 23         |

Table 2. Radiocarbon dates and location of each site mentioned in this paper.
ages of 40 peat cores and high-resolution C contents of 15 cores, we tried to the peat initiation and C accumulation history of peatlands in the Sanjiang Plain.

As shown in Fig. 3b,c, both the accumulating frequency of peatlands initiation and the mean C accumulation rate exhibit much similar variations, implying the casual relations between the two records in the Sanjiang Plain. For the interval before 4.7 ka, only a few peatlands (~20% of the total peatlands) occurred in certain locations in the Sanjiang Plain, when most depressions in the plain were dominated by shallow lakes, which is indicated by the lacustrine mud deposits with relative low organic matter contents of ~20%. Comparing the peat layers, such widespread lacustrine deposits with lower organic matter contents and accumulation rates can only generate a low and stable mean C accumulation rate before 4.7 ka. Thereafter, most of the peatlands (~80% of the total peatlands) occurred, leading to the increase of mean C accumulation rate. The interval is highlighted by a rapid peatlands expansion stages spanning 4.7–3.8 ka.

The present climate in the plain belongs to the temperate humid or sub-humid continental monsoon climate with relative higher mean annual precipitations. In addition to the warm and wet climate, such a low-relief area with low slope grade is favorable for the development of wetlands. A recent survey shows that over 70% of the plain has been dominated by fresh-water wetlands, and thus it is known as the largest fresh-water wetlands area in China. While in the geological history, the lake-wetland which is so-called terrestrialization process as one of the three main peatland process with paludification, often depends on both allogenic (climate) and autogenic (ecological) processes. And in the Sanjiang Plain, such a transition was a quick process considering the sharp boundary between the lacustrine mud and peat sections. While the autogenic process (e.g. ecological evolution) is commonly accepted as much slow course of more than hundreds or thousands of years, thus it can hardly serve a dominant role in driving the rapid peatlands initiations within several decades.

Considering the prevalent monsoon climate in the Sanjiang plain, the peatlands occurrences and C accumulation pattern may be potentially linked with the monsoon variations during the Holocene. In the recent decades, numerous works have been done to reveal the monsoon evolution on different time scales, and most of the records indicate a much warmer and wetter interval during the early or early-mid Holocene, corresponding to the Holocene monsoon maximum. In low-mid latitudes of China, stalagmite δ18O has been widely employed as a climate-sensitive proxy for monsoon variation, as its values usually become lower when the Asian summer monsoon intensifies, and vice versa.
an anticorrelation is also observed in modern precipitation records near the cave site. In northeastern China, the alternations of sand accumulation and paleosol development in desert regions are regarded as the direct indicators for the monsoon variations in the geological past. As the soil development requires a much wetter/warmer climate and better vegetation cover comparing with the drier climate during the aeolian sand accumulation, in this context, the alternations of aeolian sand and paleosols are mainly controlled by the changes of summer monsoon strength. Here, we combined two high-resolution and absolutely-dated monsoon records from the Dongge Cave (DG) in southern China and the Hulun Buir Desert (HLB) in northeastern China respectively (site locations in Fig. 1), to discuss and reveal the relationships between peatlands development and monsoon variation in the Sanjiang Plain.

During the interval before 4.7 ka, the widespread shallow lakes in the Sanjiang Plain indicate a much wetter environment, and in turn a strong summer monsoon interval considering the prevalent monsoon climate in the study regions (Fig. 4b). The interval corresponds well with the well-developed soil sections in the HLB before 4.4 ka in spite of a 300 yr discrepancy, which is acceptable in view of the 400 yr error of the OSL dating at 4.4 ka, and relatively lower values of δ18O in the DG (Fig. 3). Furthermore, such a strong monsoon interval during the early and mid Holocene has been widely documented in lake sediments, eolian deposits, accretionary soils and peat accumulations in monsoonal regions. While with the gradual decline of the summer monsoon strength and its associated precipitation during the mid-late Holocene, the paleolakes in the Sanjiang Plain began to dry out and a number of peatlands initiated around 4.5 ka (Fig. 4a). Additionally, it is worthy to stress that the lacustrine mud layers were vitally important for the subsequent peatlands initiation, as they provided a nutrient-rich base for peatlands vegetation growing, and also a water-retaining layer for the subsequent peatlands developing. This might explain why few peatlands developed before 11.0 ka with the relative weak summer monsoon. As the weak monsoon before 11.0 ka would limit number of lakes on the landscape, and this is entirely different situation comparing to the change from abundant lakes during maximum monsoon intensity in the early Holocene to lake dry-up and conversion to wetlands in a dry mid-Holocene.

It worth noting that although 80% of the wetlands in Sangjiang Plain initiated after the remarkable monsoon decline at 4.7 ka, their initiations were not limited to that age but covered a wide range of 4.7–0.9 ka. Here, we suggest that the age discrepancies of the peatlands initiations should be attributed to the local site-specific conditions of topography, such as basin/lake depths and sizes. As deeper lakes/basins certainly take longer to respond to the same magnitude/speed of climate change than shallow lakes. While nowadays, the depths or sizes of the studied basins in geological past are hard to ascertain considering the natural landforms in the Sanjiang Plain have been seriously destroyed by human activities. In spite of this, we still accept the fact that there must be some discrepancies among the topographies of different basins, which should partly account for the responding discrepancies of the peatlands initiation to late-Holocene monsoon variations. Moreover, even during the late Holocene with the relative...

Figure 4. Schematic figures indicating the decline of East Asian summer monsoon plays a driving role in lake-peatland transition during Holocene. They were drawn by Zhenqing Zhang using Canvas 15.0.
weak monsoon strength, there is still a more rapidly monsoon weakening trend comparing the previous stage. Thus, in addition to local topographic conditions, the gradual declination of the summer monsoon would further strengthen the discrepancies of the peatlands initiations in the Sanjiang Plain during the late Holocene.

Methods
Regional setting. The Sanjiang plain (129°11′–135°05′E, 43°49′–48°27′N) located in NE China (Fig. 1) is a huge alluvial plain crossed by three major rivers: Heilong River, Wusuli River and Songhua River. It has a total area of 10.9 × 10⁶ ha, an altitude of < 200 m and a slope grade of < 1:10,000. The present climate of the plain belongs to the temperate humid or sub-humid continental monsoon climate. The mean annual temperature ranges from 1.4 to 4.3 °C, with average maximum of 22 °C in July and average minimum −18 °C in January. The mean annual precipitation is 500–650 mm and 80% of rainfall occurs between May and September.

In addition to the warm and wet climate, such an area of low-relief is favorable for the development of wetlands. A recent survey shows that over 70% of the plain has been dominated by fresh water wetlands developing in ancient riverbeds and waterlogged depressions. Peatlands with a total area of 3.3 × 10⁴ ha have developed in certain topographic conditions during Holocene or earlier.

Laboratory analysis. Subsamples with a volume of 3 cm³ were prepared for loss-on-ignition (LOI) with sequential combustion at 500 °C and 900 °C to estimate organic matter and carbonate contents respectively. Bulk density with 1 cm interval of each peat core was calculated with the dry weight and volume of each subsample. Ash-free (organic matter) bulk density was calculated from the measurements of bulk density and organic matter contents. Apparent carbon accumulation rates were calculated using calibrated AMS ¹⁴C ages, ash-free bulk density measurements and C contents of peat organic matter in peatlands (using 52% C in peat organic matter). The mean C accumulation rate (Fig. 4c) was calculated for each 400-year bin using time-weighted averaged C accumulation rates of 15 cores showed in Fig. 2.

Base on visual inspection and LOI analysis, only the samples with a dominant component of plant residues and organic matter contents > 50% were regarded as the peat deposits. While the grey-blackish mud with organic matter contents < 30% was regarded as lacustrine deposits (Fig. 2). Most of the subsamples for AMS dating were collected according to lithological changes, and they were all dated with an accelerator mass spectrometry system at the Institute of Earth Environment, CAS. The AMS ¹⁴C dates were calibrated into calendar ages using the program Calib 7.02 based on the INTCAL 13 calibration dataset (Table. 1).

Data analysis. To calculate the frequency of peatlands initiation, all the ages were grouped roughly into 500-year bins with additional considerations as follows: if a date in bin A has a discrepancy of no more than 100 yr with another date in bin B, we grouped the two dates in bin A (If A < B), otherwise we grouped the two dates in two different bins if the discrepancy > 100 yr, indicating the two peatlands initiation stage (Fig. 3). Such an improved grouping method could avoid grouping the two neighboring dates into much different peat expansion stages, as they are more likely within the same stage considering several decades dating error of the each date. Accordingly, an accumulating frequency curve can be drawn based on the frequency of the 40 peat basal ages from the Sanjiang Plain.
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Author Contributions
Z.Z. and W.X. designed and performed the research and wrote the paper; Z.Z. drew all the figures, G.W. and S.T. carried out the data analysis; X.L. and J.S. discussed the results and reviewed the manuscript.

Additional Information
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