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Understand the resilience and regime shift of the wetland ecosystem after human disturbances

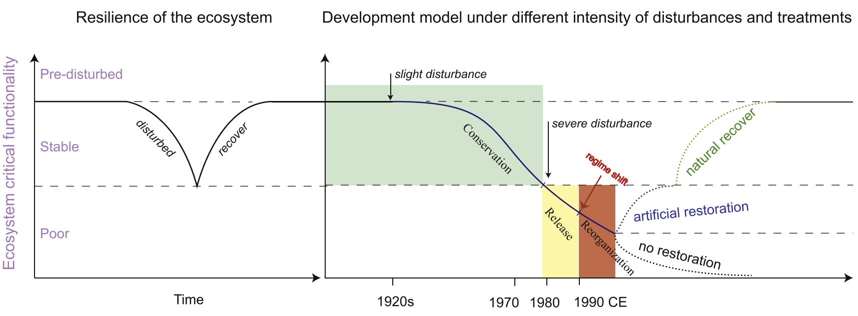
Hanxiang Liu [a,b], Chuanyu Gao [a,*], Guoping Wang [a,*]

[a] Key Laboratory of Wetland Ecology and Environment, Northeast Institute of Geography and Agroecology, Chinese Academy of Sciences, Changchun 130102, China
[b] University of Chinese Academy of Sciences, Beijing 100049, China

HIGHLIGHTS

- Geochemical records reflect human disturbance intensity.
- Ecological communities reflect ecosystem regime shifts.
- Time gap between severe disturbance and regime shift is due to strong resilience.
- Using ecological status before release phase to construct reference conditions

GRAPHICAL ABSTRACT



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ABSTRACT

Wetland protection and restoration are important for human's sustainable development, and assess the resilience and regime shift of wetland ecosystem under human disturbances is necessary for this purpose. Geochemical records, including nitrogen (N), phosphorus (P), heavy metals and polycyclic aromatic hydrocarbons (PAHs) from seven wetland cores dated by ^{210}Pb and ^{137}Cs analysis were used to identify the historical background of human disturbances on wetlands in the Sanjiang Plain. We also carried out paleoecological analysis (including plant macrofossils and diatoms) in one core (Honghe wetland) to reconstruct the successions of wetland ecological communities. The resilience and regime shift of ecosystem were evaluated based on autocorrelation and the Sequential *t*-test analysis of regime-shifts algorithm. Our results show that enrichment factors (EFs) of N, P and heavy metals (Cu, Zn, Pb etc.), and the concentrations of PAHs experienced slight increases from the 1920s but dramatic increases from the late 1970s. The dominant species of plant community began to change from *Drepanocladus aduncus* to *Carex lasiocarpa* from the late 1970s, and the diatoms began to change from wet-indicator to dry-indicator species from the 1950s in Honghe wetland. The regime shift of the wetland ecosystem occurred around 1990 CE, which due to a drop in water level caused by human activities, such as wetland drainage for the reclamation and the excessive use of groundwater for irrigation purpose, rather than climate moisture variations. There is a time gap between the severe disturbances and regime shift due to the stronger resilience of wetland ecosystem. The ecological characteristics (e.g. water level, biological compositions, and EFs of nutrient elements and heavy metals) of Honghe wetland before the late 1970s (release phase) were used as reference conditions for wetland restoration.

1. Introduction

With the development of science and technology and the dramatic increase in population, human activities have made substantial impacts

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* Corresponding authors.
E-mail addresses: gaochuanyu@iga.ac.cn, (C. Gao), wangguoping@neigae.ac.cn (G. Wang).

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on the environment in the last several decades. It has gradually become the leading factor that affects the structure and function of the terrestrial ecosystem. Global environmental issues, such as pollution, desertification and biodiversity loss, which are raising concerns about the viability of human civilization. Wetland ecosystem is the important component of the terrestrial ecosystem that has numerous beneficial services and functions (e.g. regulating runoff, purifying water quality, beautify the environment, and maintain regional ecological balance) (Dieleman et al., 2015; Woodward and Wui, 2001). The structure and function of wetland ecosystem would deteriorate sharply if wetlands are not protected or restored under the current intensity of human activities. In order to restore and protect ecosystem services and functions, it is necessary to document and understand past dynamic of these wetlands, especially the resilience and regime shift of ecosystem, to construct the reference conditions for wetland restoration.

Wetland sediments are readily and economically accessible geological archives for the study of climate changes or human activities. Main human activities events can produce some chemical or physical constituents, and transfer to the wetland ecosystem via atmosphere deposition and surface runoff. Some geochemical compounds, such as total nitrogen (N) (Saunders and Kalff, 2001), phosphorus (P) (Richardson, 1985), heavy metals (Gao et al., 2014), and polycyclic aromatic hydrocarbons (PAHs) (Cong et al., 2016) derived from fertilizer, industrial activities and mining can be used to reflect the intensity of human disturbances on the wetland. Early increasing concentrations of geochemical compounds cannot cause obvious changes to ecological balance at first due to the resilience of the ecosystem. Resilience determines the persistence of relationships within the ecosystem and is an ability to absorb changes and still persist (Fig. 5) (Holling, 1973). Barbieri et al. (2013) presented a comparison of geochemical data between 2002 and 2012 from a coastal wetland system and found that the system functions have no substantial alterations in the face of the slight increase of water resource contamination because of system resilience. However, the resilience has a threshold in the ecosystem adaptive cycle in moving through processes of exploitation, conservation, release, and reorganization. The severe disturbances will break the resilience and cross the threshold of the ecosystem (regime shift occurs) with the increasing enhancement of human activities (Walker and Salt, 2006). The term "regime shift" means a 'catastrophic shift' (abrupt shift) from one dynamic regime to another (Scheffer et al., 2001; Beaugrand, 2004). We hypothesize that the resilience will be disappeared and regime shift will occur immediately when the severe disturbances appear in the wetland ecosystem. The hypotheses will be tested using the collected ecological proxy data. The rapid changes in the composition of ecological communities have potentially serious consequences in the resilience of ecosystem functions (Oliver et al., 2015), and the critical resilience transition can be an early warning signal of approaching threshold in the ecosystem (Li et al., 2018). Paleoecological indicators, such as plant macrofossils are used to reflect the historical changes of vegetation compositions, diatoms are used to infer past changes in nutrient status, temperature or water level, etc. in the lacustrine, palustrine or riverine wetlands (Fritz et al., 2016; Hang et al., 2008; Krawiec, 2017). We can understand the historical dynamics of wetland ecosystem under human disturbances based on the changes in ecological communities and the reconstructed environmental characteristics (e.g. water level, nutrient elements, pH).

The anthropogenic activities have increased significantly during the last century in the Sanjiang Plain, Northeast China. As a result, more than 3/4 wetland areas have disappeared since the 1950s, and remaining wetlands were almost degraded or worsened (Wang et al., 2009), and the consequent worse of soil and water erosion, the increase of local desertification, the destruction of biodiversity, and the falling of groundwater level (Liu and Ma, 2000). Cong et al. (2016) found biomass burning residuals in the wetland influenced by regional human activities nearly a thousand years ago. Human activities growing intensely were reflected by the increasing heavy metals enrichment factors (EFs) (Gao et al., 2014) during the recent 150 years. The potentially toxic elements began to increase in the period of 1900–1930 CE (Common Era), and the key elements clearly increased in all of the wetland from 1950 CE which could be set as the start of the Anthropocene of the Sanjiang Plain (Liu et al., 2018), afterwards the environmental risks of wetland appeared from 1980 CE (Gao et al., 2018). However, most of these studies in the Sanjiang Plain did not assess the dynamics of wetland ecosystem under the influence of human activities. Some other studies in our study region have produced some interesting results about wetland initiation and developing history, and wetland carbon dynamics during the Holocene (Xing et al., 2015a, 2015b; Zhang et al., 2015a, 2015b), but these studies neither focus on human activities nor cover the last 150–200 years. Especially, the resilience and regime shift of wetland ecosystem under the human disturbances were not covered.

Here, we assess the resilience and regime shift of the wetland ecosystem under the background of human disturbances based on geochemical records and paleoecological indicators in the Sanjiang Plain, Northeast China. Our study fills an important data gap of wetland ecosystem dynamics and its sensitivity to human disturbances over the past century. The goals of this study are to (1) understand the historical intensity of human disturbances on the wetland ecosystem in the Sanjiang Plain, (2) to detect the succession and regime shift of ecological communities in a wetland ecosystem, (3) to evaluate the resilience of the wetland ecosystem, (4) and then to construct the reference conditions for wetland restoration based on the environmental characteristics before the phase of release.

2. Materials and methods

2.1. Study area and sampling sites

All sites are located in the Sanjiang Plain (130°–135° E, 45°–48° N), which is a low and flat alluvial plain of Heilongjiang province in the northeast of China (Fig. 1). The region experiences a temperate monsoon, with short, wet and warm summers and long, dry and cold winters. The annual temperature is 1.4–4.3 °C, with an average maximum of 22 °C in July and an average minimum of −21 °C in January, and the frost-free period is 120–140 days. The annual precipitation is 500–550 mm, and more than 80% rainfalls occur from May to September. There was a large amount of wetland developed in this area due to the low topography (the average elevation is 50–60 m).

In order to contain a variety of wetland types, and to make the wetlands as evenly distributed, seven wetlands along with rivers and one wetland nearby cities were found on the Sanjiang Plain (Table 1). In the central region of each wetland, one main core was obtained using Russian corer (Eijkelkamp, Netherlands). The length of each core is 50 cm, and cores were sectioned on-site at 1-cm intervals with a stainless steel hand saw. The collected samples were sealed in polyethylene plastic bags for bringing to the laboratory and stored at 4 °C in a refrigerator.

2.2. ^{210}Pb and ^{137}Cs dating

Sub-samples were dried in an oven at 105 °C for 12 h and ground into powder, and then filled in the plastic quasi-cylindrical bottle. Three weeks after samples stored in sealed plastic bags to balance the radioactivity, the radioactivities of ^{210}Pb (46.5 keV) and ^{137}Cs (661.6 keV) were measured using low background gamma spectroscopy (ORTEC Instruments Ltd., USA). Counting times were typically in the range 50,000–86,000 s. The standard sources and sediment samples of known activity provided by the National Institute of Metrology in China were used to calibrate the absolute efficiencies of the detectors.

The dating model was constructed by applying the constant rate of supply (CRS) model based on the specific radioactivity of ^{210}Pb (Appleby and Oldfield, 1978). The CRS model is to assume that the

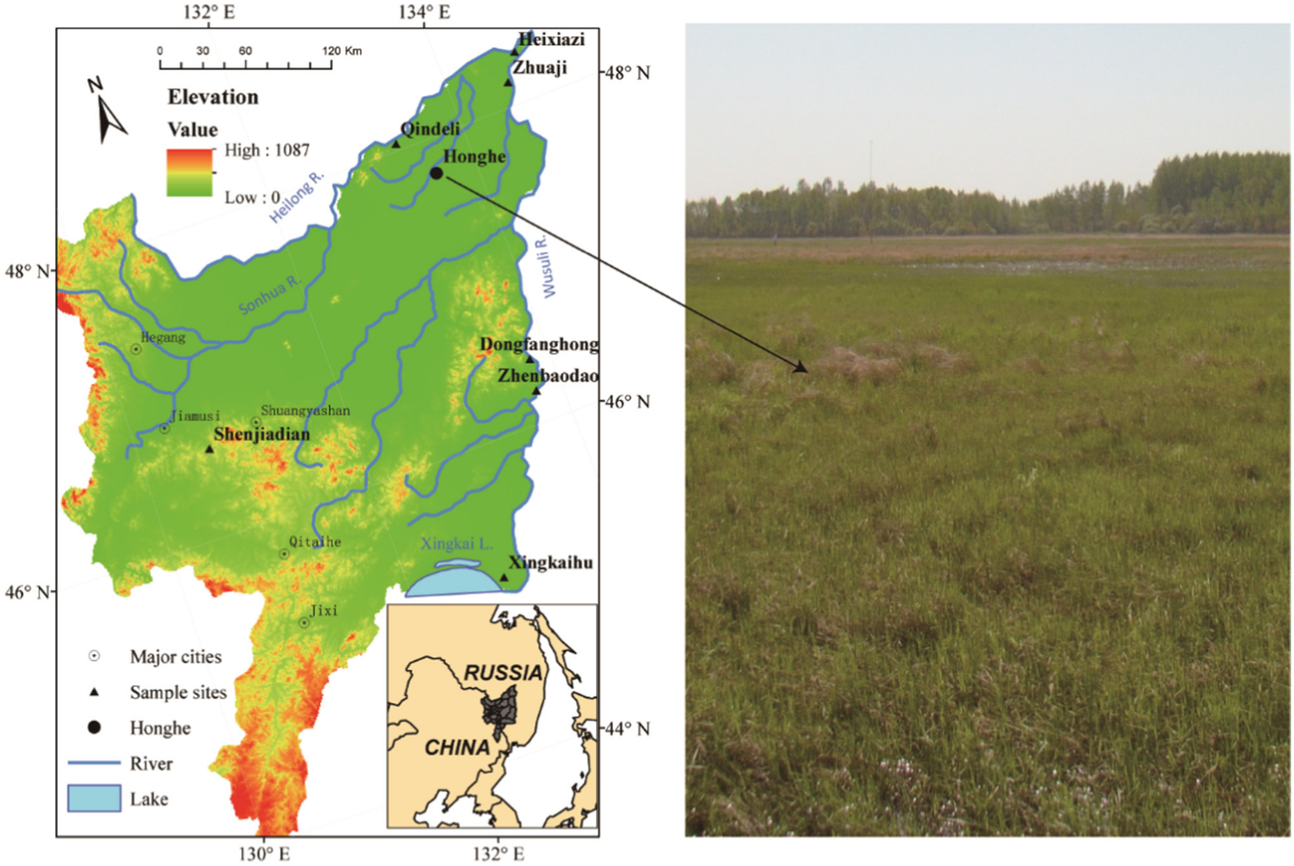

Fig. 1. Location of eight wetland sites in the Sanjiang Plain, Northeast China and the photo of Honghe (HH) wetland.

supply of ^{210}Pb to the sediment is the same for each time interval. The time was calculated using the radioactivity and half-life of ^{210}Pb. The radionuclide ^{137}Cs reflects the events of nuclear tests and nuclear leaks around the world, there will be high peaks in 1954, 1963, 1975, 1986 or 2011 CE (Bolsunovsky and Dementyev, 2011; Robbins and Edgington, 1975; Xu et al., 1999). The specific radioactivities of ^{137}Cs were plotted against depth to calibrate the CRS dating model.

2.3. Geochemical features analyses

Sub-samples were dissolved in the distilled water and analyzed the N concentrations of sediments using a segmented continuous flow analyzer (Futura, Alliance, France). The concentrations of P and heavy metals (including Al, Ti, V, Cr, Fe, Ni, Cu, Zn, Cd, Zr, Sb, and Pb) were determined using an inductively coupled plasma atomic emission spectroscopy (ICPS-7500, Shimadzu, Japan), and arsenic (As) was measured by a thermal decomposition-atomic absorption spectrometer (AA-6300C, Shimadzu, Japan). The EFs of a certain element is calculated as:

$$El_{EF} = \frac{(El/X)_{sample}}{(El/X)_{predisturbed}} \quad (1)$$

where El stands for the concentration of a given element, and X is the concentration of the conservative element. Ti, V, and Zr were commonly used as conservative elements because they are stable during natural weathering and have no significant anthropogenic source in the peat bog (Gallego et al., 2013; Shotyk et al., 1996, 2001). Other elements such as Al and Fe have been used due to Al is a major constituent of clay minerals and Fe is associated with surfaces (Barbieri et al., 2014). However, iron elements are susceptible to oxidation and reduction reactions in wetlands. The variations of Al, Ti, V, and Zr contrast with depth were shown in the supplementary data, and Ti always had a similar pattern to Al, V or Zr in all the wetlands (see Section 3.2). So we normalized the element concentrations to El/Ti ratios and compared the depths at which persistent low ratios appeared. The depths with persistent low ratios were considered as the boundary of disturbed and pre-

Table 1
Summary information for the eight study sites in the Sanjing Plain.

Site	Location	Wetland type[a]	Sediment type	Dominant plant
Xingkaihu (XKH)	132.8583° E; 45.1389° N	Lacstrine	1–40 cm: peat; 41–50 cm: silt and clay	Carex
Zhenbaodao (ZBD)	133.7594° E; 46.2169° N	Riverine	Silt and clay	Calamagrostis angustifolia
Dongfanghong (DFH)	133.6261° E; 46.3956° N	Riverine	Silt and clay	Carex
Zhuaji (ZJ)	134.6286° E; 48.1600° N	Riverine	Silt and clay	Calamagrostis angustifolia
Heixiazi (HXZ)	134.7458° E; 48.3308° N	Riverine	Silt and clay	Calamagrostis angustifolia
Qindeli (QDL)	133.3419° E; 48.0336° N	Riverine	1–18 cm: peat; 19–50 cm: silt and clay	Carex
Honghe (HH)	133.6275° E; 47.7886° N	Riverine	Peat	Carex
Shenjiadian (SJD)	130.6644° E; 46.5811° N	Palustine	Peat	Carex

[a] Wetland types are based on Cowardin et al.'s (1979) classification system.

disturbed sediments, and the background values for El/Ti were taken from the average of the persistent low ratios.

Sub-samples from DFH, HXZ and SJD were dried in the air and ground to 80 mesh using agate mortar, and then combined with 20 g sodium sulfite anhydrous. The following extraction procedure for PAHs was referenced from Khim et al. (1999) and Maruya et al. (1997). The mixtures of acetone and hexane (v/v = 1/1, 20 ml) were added into samples, and the ultrasonic-assisted extraction was used for extracting the sample two times (every 10 min). After that, the extracting solution was concentrated to 2 ml then added by hexane and concentrated to 1 ml in a rotary evaporator. The concentrated extraction was transferred to a glass column for cleanup and fractionation. The fraction was eluted with 25 ml dichloromethane-pentane (v/v = 2/3), and PAHs were contained in the eluent. PAHs were quantified using GC/MS system (QP5050A, Shimadzu, Japan) by following the step below: firstly, the start temperature of column oven was 50 °C (1-min hold); secondly, the temperature increased to 200 °C at a rate of 25 °C/min (1-min hold); then to 280 °C at a rate of 10 °C/min (30-min hold).

1-Year internal spline interpolation was used in the geochemical features data to calculate the average values which represent the values of the EFs of N, P and heavy metals, and PAHs of the Sanjiang Plain region using R function "*interp.dataset*".

2.4. Ecological communities structure analyses

The changes of plant community structure were reflected by plant macrofossils of the sediments which can be identified using the Quadrat and Leaf Count protocol proposed by Barber et al. (1994). Sub-samples were undertaken on 5 cm^3 slices from each sample and then washed with a strong jet of water over a 125 μm sieve. The residues were viewed through a stereo microscope. The peat components, composing moss, herbs, and shrub, etc. were estimated from 15 averaged quadrat counts using a 10 × 10 square grid salver (Wang et al., 2016). Diatom community was identified using an optical microscope, the details of sample preparation and analyses can be seen in Ma et al. (2018).

The diagrams of plant macrofossils and diatoms were created by R function "*strat.plot*" using rojia and vegan packages. The ecological communities' zones were determined by constrained incremental sum of squares cluster analysis (CONISS) (Grimm, 1987) using the R function "*chclust*". Detrended correspondence analysis (DCA) was applied to the plant and diatom community data, respectively to define the latent environment gradients (Barber et al., 1994) using the R function "*decorana*", and the axis 1 (DCA1) and axis 2 (DCA2) scores of both samples and species were plotted together to compare temporal variations in ecological communities (Nelson and Hu, 2008). Principal component analysis (PCA) was used to reduce the dimensionality of the ecological dataset using SPSS statistics, and the principal component factor 1 (PC1) scores represent the most important information from plant and diatom. The Sequential *t*-test Analysis of Regime-shifts algorithm (STARS) (Seddon et al., 2014) was used to detect statistically significant shift which is performed as regime shift index (RSI) in the mean level of fluctuations in PC1 using the R function "*stars*". Autocorrelation is a mathematical tool for finding repeating patterns. When a degraded system with declining resilience, the system recovers more and more slowly and tends to become more similar to its own past. The first autocorrelation (lag-1) were identified using the R functions "*ar.ols*" to indirectly represent resilience, and the lag-1 autocorrelation should show increasing trend before the ecosystem regime shift (Dakos et al., 2008).

3. Results

3.1. Chronologies

The age frameworks of eight wetlands in the Sanjiang Plain are shown in Fig. S1 (Supplementary figures). The bottom depth of the age-depth framework in HH is the longest (44 cm, 1835 ± 6 CE), and the bottom depth in XKH is the shortest (12 cm, 1899 ± 9 CE). The ^{137}Cs specific radioactivities of DFH, HXZ, ZJ, SJD, HH and QDL were plotted against the depth to calibrate the ^{210}Pb CRS dating model, while the ^{137}Cs activities of ZBD and XKH were not matched or undetected. However, not all peaks of ^{137}Cs will be recorded by the wetland due to the different surrounding topography features or rainfall erosion conditions (McHenry and Ritchie, 1977).

3.2. Geochemical characters

The concentrations and EFs of elements in all the wetlands were shown in the supplementary data, as well as the concentrations of PAHs in the three wetlands. The alternative conservative element Al had a different change pattern to the others in XKH, Zr was different from others in HXZ, and V was different from others in QDL. Only Ti always showed similar variation to other alternative conservative elements in all the wetlands (Supplementary data). The maximum, minimum, mean values, standard deviations and background values of elements (except Al, V, Zr, and Fe) at the depth of 0–50 cm in all wetlands were summarized in Table S1. The mean concentration of Sb was the lowest in all wetlands and N was the highest, so their background values were.

The EFs of nutrient elements and heavy metals of the Sanjiang Plain which were evaluated by the average of seven wetlands (exclude HH) are shown in Fig. 2, as well as the concentrations of PAHs which were represented by the average of SJD, DFH, and HXZ. The EF variations of nutrient elements that N and P ranged from 2.0 to 26.4 and from 1.4 to 10.5, respectively. The heavy metal EFs in the range of 1.0–2.7, and Ni reached the maximum value of EFs. The concentrations of PAHs ranged from 0.1 to 1.2 mg/kg with an average of 0.4 mg/kg.

3.3. Plant macrofossils and diatoms

Fig. 3 shows the percentages of plant macrofossils in the HH wetland sediments during the past 120 years (0–42 cm depth), the species of diatoms with clear environmental indicator significance were brought together, and three phases of ecological communities (zone A, B, and C) were divided according to the result of CONISS. The whole diatom species compositions of the core in HH wetland can be seen in Fig. S2 (Supplementary figures). These data allowed for a detailed reconstruction of local ecological communities changes during last hundred years.

Zone A, from the 1900s to the early 1950s, the plant community was dominated by *Drepanocladus aduncus* and *Carex lasiocarpa*, with low abundances of *Menyanthes trifoliate*, *Equisetaceae*, *Carex pseudo curaica* and other carex. The moisture loving diatom species of *Pinnularia brevicostata*, *Eunotia incisa* v. *incisa* and *Eunotia formica* were prevailing in this period, and almost no dry-indicator species, except *Navicula gallica* v. *perpusilla*.

Zone B, from the late 1950s to the 1980s, there was an increase of *Drepanocladus aduncus* and a decrease of *Carex lasiocarpa* in the 1950s, and then reached their highest value and lowest value in the 1960s, respectively. *Drepanocladus aduncus* showed a quick decrease, and *Carex lasiocarpa* experienced a sudden increase from the 1970s to the 1980s. The wet-indicator diatom species decreased quickly, and dry-indicator species began to dominate this period.

Zone C, from the 1990s to the 2010s, the abundances of *Drepanocladus aduncus* was low by historical standards, and *Carex lasiocarpa* had higher values, with more other Carex and unidentified organic matters (UOM). All the wet-indicator diatom species were almost disappeared, and the dry-indicator species had the highest abundances in this period.

4. Discussions

4.1. Historical human disturbances in wetlands of the Sanjiang Plain

To evaluate the historical intensity of human activities disturbances within the study region, the EFs variations of N, P and heavy metals

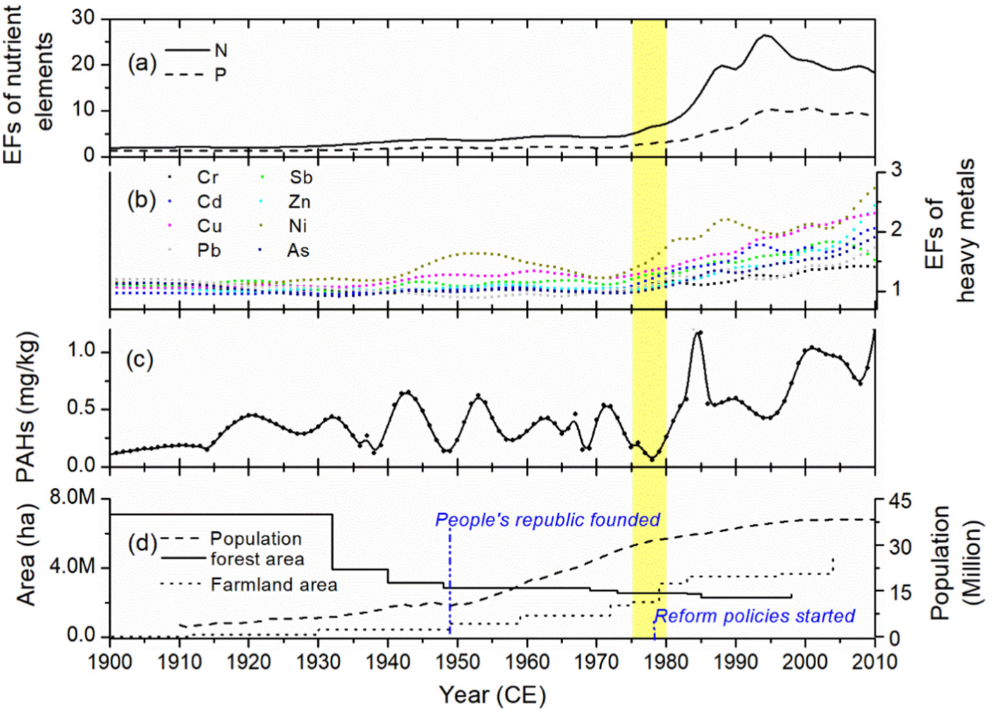

Fig. 2. The variation of human activity disturbance as indicated by 1-year interpolated geochemical data of wetland ecosystem in the Sanjiang Plain. (a) (b) The EFs of nutrient elements (N and P) and heavy metals (Cr, Sb, Cd etc.). (c) The concentrations of PAHs. (d) Historical population (dash line) of Heilongjiang province which the Sanjiang Plain belongs to were showed at the bottom, also compared with farmland area (dot line) and forest area (solid line) of the Sanjiang Plain. The spontaneously increases of these geochemical data are marked by a yellow band.

were used to reflect the agricultural and industrial activities, as well as the concentrations of PAHs. The agricultural activities were reflected by chemical fertilizers, such as N and P, which could be accumulated in the wetland with the surface runoff flows (Saunders and Kalff, 2001). The accumulated amount of heavy metals in the wetland sediments are mainly influenced by pesticide application or mine exploration (Olid et al., 2010). PAHs come from biomass or fossil fuel burning residuals, which reflect both agricultural and industrial human activities (Edwas, 1983; Goldberg, 1985).

After the Manchurians became the ruler in China, it practiced the prohibition policy to Northeast China for a long time, forbade the people to migrate to this region (Gao, 2008), especially in the Jilin and Heilongjiang Province. The agriculture and town development was very few and far below that of inside Shanhaiguan Pass, in terms of both quality and quantity (Xue and Li, 1993). The EFs of N, P, and heavy metals, and the concentrations of PAHs were low before the 1920s, indicating a low development level in agriculture and industry. Even though the Qing Dynasty lifted the ban gradually after the Opium War in 1841 CE, immigrants migrated into the Sanjiang Plain and reclaimed farmland, the farmland area of the Sanjiang Plain increased from 1.33×10^4 ha before 1795 CE to 44×10^4 ha in 1930 CE (Liu and Ma, 2002), the rate of land reclamation only increased from 2% to 7% (Research group, 1998) due to the vast territory with a sparse population and political and social unrest during this period. The degrees of the anthropogenic influence on wetland sediments in the Sanjiang Plain were low before the 1920s.

The political and social were stable under the control of Fengxi warlord after the Russo-Japanese War 1904–1905, the 1911 Revolution and some other wars. The business and a lot of cities developed along the Chinese East Railway since the 1920s (Fang et al., 2005). There were also some mining activities developed in this area (Li, 2005), while some wetlands began to be influenced by the development of the social economy (Gao et al., 2018). The EFs of N, P, and heavy metals experienced slight increase after the 1920s, as well as the concentrations of PAHs showed little higher variations. Along with the development of industry and agriculture, the massive forest was chopped down along Heilong and Wusuli Rivers. The deforestation in the Sanjiang Plain decreased the forest area from 710.9×10^4 ha before 1896 CE to 394.1×10^4 ha in 1932 CE (Liu and Ma, 2002). The forests and minerals (e.g. coals, fossil oils, metals) were exploited more frequently during the period of northeastern China occupied by the Japanese army from 1931 to 1945 CE (Liu, 1987), and more than 300 thousand Japanese immigrated to Northeast China and more lands were cultivated (Ren and Chen, 2004). For this reason, the EFs of N, P, and heavy metals, the concentrations of PAHs continued to increase during this period. What's more, a large number of farmers, demobilized military, and educated youth had moved to this area in succession since the foundation of the People's Republic of China in 1949 CE (Wang et al., 2008). The population had a sharp increase, and the land reclamation rate doubled to 13.9% (Research group, 1998). These growing population and land exploitation caused the increase of N, P, heavy metals and PAHs.

The state macroscopic agricultural policies play an important role in the increase of farmland in China (Song et al., 2008), and the land reclamation rate of the Sanjiang Plain increased to 27.3% (Research group, 1998) with the further development of agriculture after the China's reform policies since the late 1970s. Most of the traditional farming methods were gradually replaced by mechanized and automated agricultural practices. Meanwhile, large amounts of fertilizers and pesticides were widely used to increase production. The EFs of N, P, and heavy metals, and the concentrations of PAHs all showed a dramatic increase since the late 1970s, which increased the potential environmental risks to the wetland ecosystem (Gao et al., 2018).

In total, due to the Sanjiang Plain was protected by the government during the Qing Dynasty, the degree of development in agriculture and industry was much lower compared to other areas in southern China. The human activities were gradually increased from the 1920s to the 1970s with population growth and land reclamation, and the human activities increased rapidly with further industrial and agricultural development after China's reform and opening up in the late 1970s.

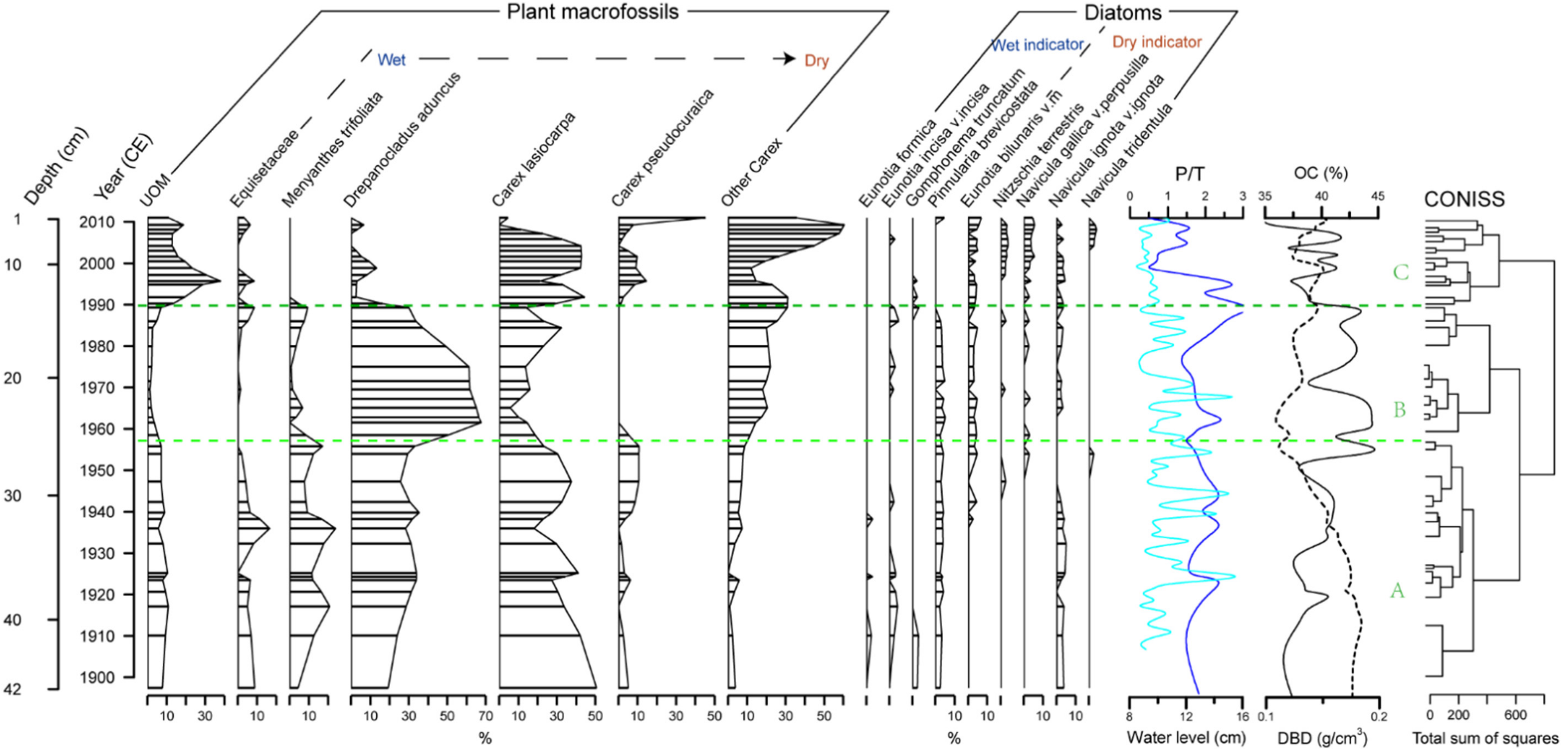

Fig. 3. Plant macrofossils and diatoms diagram (percentage) of HH wetland along with depth, age, water level (blue line), P/T (cyan line), OC (solid line), and DBD (dash line). Biological indicator diagram only shows the diatom species with clear environmental indicator significance. The water level was reconstructed using a diatom-based inference model. The total sum of squares is the result of CONISS and three main zones (A/B/C) were identified in the combined plant macrofossils and diatoms data.

4.2. The succession of wetland ecological communities

Ecological communities are the reflection of the wetland ecosystem state, such as nutritional and hydrological status (Palmer et al., 1997), which can be influenced by various natural and artificial factors. The successions of a plant community can result from dryer climate or wetland drainage for farmland reclamation, damming and water diversion etc. (Marques et al., 2004). Diatom community also sensitive to water level (Weilhoefer and Pan, 2007) or nutrition elements changes (Birks et al., 1990; Hall and Smol, 1992), and the significant relationships between water level and diatoms were identified based on the diatom-inferred transfer function during the Holocene in the Sanjiang

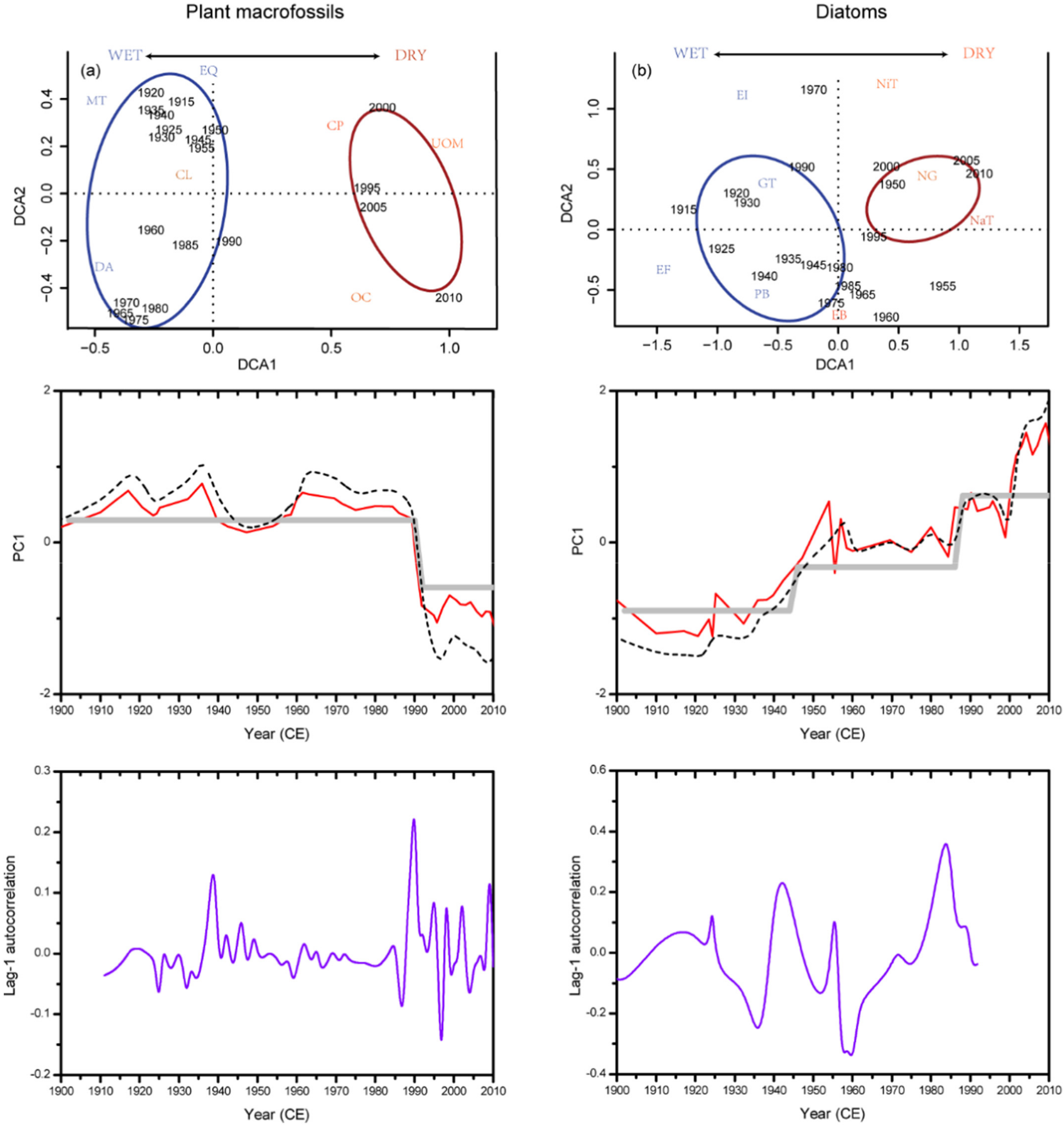

Fig. 4. The wetland ecosystem regime shift and resilience detection in the plant macrofossils and diatoms assemblages. (a) (b) DCA results of the ecological communities, the data points are plotted and labeled in 5-yr intervals, abbreviations of plant species and diatom species with clear environment indicator significance are shown to explain the DCA ordination; Plant macrofossils: *Menyanthes trifoliate* (MT), *Drepanocladus aduncus* (DA), *Carex lasiocarpa* (CL), *Equisetaceae* (EQ), *Carex pseudo curaica* (CP), other carex (OC) and UOM; Diatoms: *Eunotia formica* (EF), *Eunotia incisa* v. *incisa* (EI), *Gomphonema truncatum* (GT), *Pinnularia brevicostata* (PB), *Eunotia bilunaris v.m* (EB), *Nitzschia terrestris* (NiT), *Navicula gallica* v. *perpusilla* (NG) and *Navicula tridentula* (NaT). (c) (d) PC1 scores of plant macrofossils and diatoms plot against time (red line), the dash lines represent the standardized, 2-yr binned PC1 data, the thicker gray lines indicate the changes of PC1 in mean identified by the STARS algorithm. (e) (f) Lag-1 autocorrelations of plant macrofossils and diatoms based on the residuals of PC1 under half-time series moving window size.

Plain (Fig. 3) (Ma et al., 2018). The plant macrofossils and diatoms are reliable and good indicators of ecological and palaeoecological research on wetland ecosystem.

With the increasing enhancement of human activities in the Sanjiang Plain, the water level of the remaining wetlands declined in the face of wetland drainage for the reclamation and subsoil water use for agriculture were accelerated after the China's reform since the late 1970s (Jiang et al., 2011; Wang et al., 2009). However, the decline of wetland water level also could be influenced by climate moisture index. Due to the history of meteorological observations is short in the Sanjiang Plain, Northeast China (Fujin weather station, from 1953 CE to the present), we combined the meteorological records of Russian Far East (Six weather stations, 1911–1952 CE, Fig. S3). The annual climate moisture index was represented by the ratio of annual precipitation (P) to temperature (T) after 0–1 normalization (Fig. 3). The P/T was lower in the periods of 1911–1926, 1930–1941, 1948–1955, 1961–1968, 1974–1980, and 1988–2016, but the wetland water level reconstructed by diatom was almost stable before the late 1970s. This might be due to the functional role of healthy wetland in water conservation and the ability to withstand floods and droughts (Gilman, 1994). The wetland water level increased significantly after a climate wetting period (1969–1973), indicating that the water conservation function was damaged and the wetland ecosystem began to be unstable. There was a sharp decline of wetland water level after 1990 CE, even though the P/T had a lightly increase. Therefore, the main influence factor of the hydrological processes in HH wetland was dominated by human rather than natural climate change since the late 1970s.

Some functionalities began to get worse after a serious human disturbance, such as water conservation, but the regime shift of wetland ecosystem didn't happen immediately. Plant macrofossils assemblages showed that drought-tolerant plants (*Carex*) began to replace moisture-loving plants (including *Drepanocladus aduncus* and *Menyanthes trifoliata*) from the late 1970s and completed by 1990 CE. Simultaneously at the same time, the wet-indicator diatom species (*Pinnularia brevicostata*, *Eunotia incisa* v. *incisa*, *Eunotia formica* and *Gomphonema truncatum*) were replaced by the dry-indicator diatom species (*Eunotia bilunaris v.m*, *Nitzschia terrestris* and *Navicula gallica* v. *perpusilla*) after the 1990s (Fig. 3). This indicated that the transformation of wetland ecological communities occurred around 1990 CE. DCA results confirmed this pattern (Fig. 4). The DCA1 scores (the proportion of variance explained was 41%, DCA2: 34%) of 1995–2010 CE were higher than that of 1915–1990 CE, accompanying with dry-liked plant species on the right side of the DCA ordination diagram, which indicated that the remarkable change occurred between 1990 and 1995 CE in the plant community. There were almost increasing trends of DCA1 scores in the plant macrofossils from the 1970s to the 2010s, supporting the start time for dryer hydrological condition was the 1970s. DCA result of diatoms (the proportion of variance explained, DCA1: 64%; DCA2: 16%) is a little complex, but the dryer trend from left to right is clear that the remarkable dryer changes occurred during the periods of 1945–1950 and 1990–1995 CE. Results from the STARS algorithm on PC1 of plant macrofossils and diatoms complemented the cluster analysis and DCA ordination. PC1 explained 41% and 30% of the variations in the plant macrofossils and diatoms, respectively. PC1 transition point of plant macrofossils was identified at ~1990 CE (RSI: 0.123), while in diatoms the transition points were identified at ~1950 CE (RSI: −0.296) and ~1986 CE (RSI: −0.439) (Fig. 4) due to diatoms were more sensitive to the disturbances. Diatoms could be influenced by water level, nutrient elements, pH, salinity, and so on. As pressure increases, diatoms respond quickly and show small-scale shifts in composition and structure (Zhang et al., 2018). At the whole ecosystem level, the ecosystem was still stable in 1950 CE, while plant community didn't show big change due to their wide ecological amplitude (Lou et al., 2013). The synchronized regime shifts of wetland plant and diatom communities occurred around 1990 CE.

Generally speaking, DBD and UOM should gradually increase with depth, and OC decreases with depth due to the decomposition of organic matter. The abnormal sediment attributes also shown the big difference between 1900–1990 and 1990–2010 CE. The regime shift of HH wetland ecosystem occurred around 1990 CE owing to the falling of water level caused by the heavily human disturbances rather than climate moisture variations since the late 1970s.

4.3. The resilience and adaptive cycle of wetland ecosystem

The dynamically increased patterns of lag-1 autocorrelations in both plant community and diatom community, which indicated that the resilience of wetland ecosystem declined and reached its minimum (regime shift occurred) around 1990 CE (Fig. 4). The lag-1 autocorrelation in plant community also had a peak in the late 1930s, and diatom community had peaks in ~1924, ~1942 and ~1955 CE. As indicated by geochemical features, human activities began to affect Sanjiang Plain's wetland ecosystem from the 1920s. In response, there were some subtle fluctuations in the resilience of the ecosystem, and diatoms were more sensitive to the disturbances than plants. The human activities increased rapidly from the late 1970s, but the minimum resilience did not happen immediately. The maximum lag-1 autocorrelations of both plant and diatom communities showed that there was a substantial decline in ecosystem resilience and function around 1990 CE. The time gap between the severe disturbances and regime

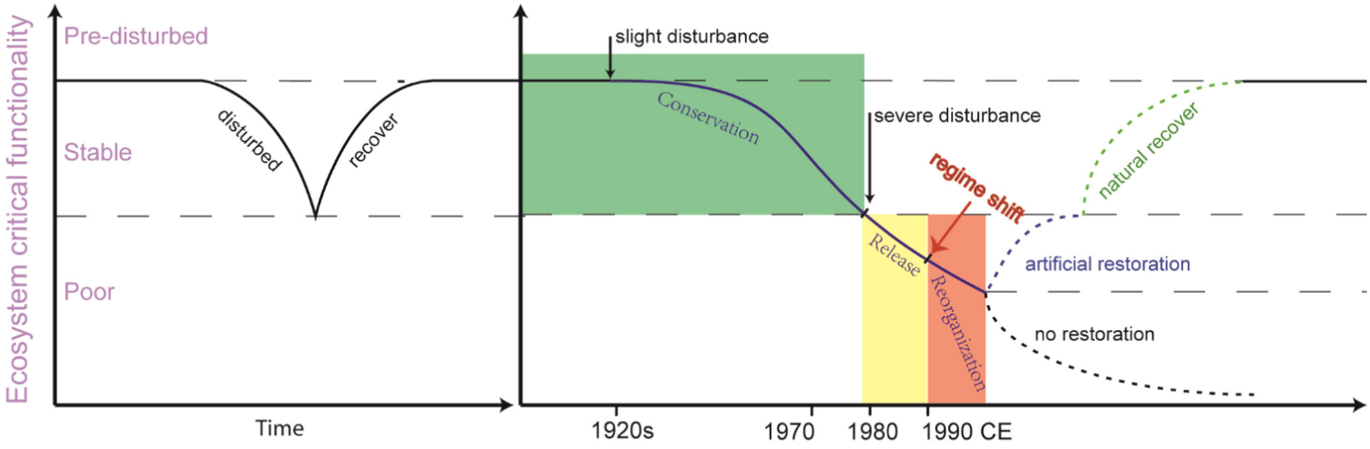

Fig. 5. Resilience theory of ecosystem (left) and the development model of wetland ecosystem critical functionality under the different intensity of disturbances and then different treatments (right). The green square, the yellow square, and the orange square represent the phases of conservation, release, and reorganization of the wetland ecosystem adaptive cycle, respectively.

Table 2
The reference conditions for HH wetland restoration.

Vegetation composition	Diatom community	Water level (cm)	Nutrient elements EFs		Heavy metal EFs			
			N	P	Cu	Zn	Pb	…
Drepanocladus aduncus community	*Pinnularia brevicostata* community	11–13	5.5	2.6	1.3	1.1	1.2	…

shift, indicating that the resilience of wetland ecosystem is stronger than some other ecosystem, such as lake ecosystem. The regime shift of wetland ecosystem didn't appear directly when the severe disturbances happened, while the regulating services of lake ecosystem have markedly declined when the heavily human activities appeared (Xu et al., 2017).

Wetland ecosystem is composited of multiple variables with complex interactions, such as biological species composition, hydrological condition, and nutrient status. The water level began to decrease and the composition of plant species began to dominate by dry-liked species after the late 1970s. That is, the ecosystem entered a phase of collapse or release in the adaptive cycle (Holling and Gunderson, 2002), and the linkage that bound the system in the former phase were broken, the *Drepanocladus aduncus* and wet-indicator diatom species fail to recolonize. In the subsequent reorganization phase of 1900 CE to the present, the resilience reached its minimum, with the result that a transfer of species occurs and a start of new cycle sets up (Fig. 5). The ecosystem critical functionality was poor and the ability of the wetland to recover spontaneously was lost after the phase of release.

4.4. Construct the reference conditions for wetland restoration

Wetland restoration is usually to recover an ecosystem to a close approximation of its condition prior to disturbance (Nation research council, 1992) in the past researches and practices. On account of restoration and management degraded wetland are expensive and strenuous, and the slight disturbance would not change the whole stability of the wetland ecosystem, we don't need to restore the ecological conditions to the pre-disturbed status. We propose that the reference conditions for wetland restoration are constructed by the ecological characteristics before the release phase of the wetland ecosystem. The wetland will recover naturally based on ecosystem resilience when the ecological status reaches the reference conditions, it could save the cost of artificial restoration (Fig. 5). Therefore, the ecological characteristics (vegetation composition, diatom community, water level, N, P and heavy metal EFs) of HH wetland before severe disturbance (release phase) in the late 1970s can be used as the references for wetland restoration.

The reference conditions for HH wetland restoration are listed in Table 2. The plant species *Drepanocladus aduncus* and other wet-indicator diatom species were almost disappeared since the late 1970s, biodiversity loss (the remaining vegetation is almost all carex), and the trend may accelerate if the water level still lower. To reconstruct the wet-liked ecological communities, the drainage ditches should be filled and provide a more suitable environment for aquatic species. The reference water level before the heavy disturbance was 11–13 cm which is higher than now. The referred EFs of N and P should be under 5.5 and 2.6, respectively, so there is a need to consider changes in management in relation to farming, such as fertilization patterns. The EFs of heavy metals Cu, Zn and Pb, etc. should be limited under 1.3, 1.1 and 1.2, etc. To reach that goal, the pesticide management should be strict or more pest-resistant plants created to reduce pesticide use. All in all, the aim of restoration is increasing biodiversity, rewetting and purifying water quality, and improving system resilience.

5. Conclusions

The anthropogenic activities have increased significantly during the last century in the Sanjiang Plain, Northeast China. The human disturbances experienced a slight increase from the 1920s but a dramatic increase in the 1970s. Owing to the sharp increase of human disturbances, the plant community began to dominate by dry-like species from the late 1970s, and completed around 1990 CE in HH wetland. The dominant diatoms changed from wet-indicator species to dry-indicator species from the 1950s, and also completed around 1990 CE. Therefore, the regime shift of wetland ecosystem occurred around 1990 CE, which mainly due to a drop in water level caused by human activities rather than climate moisture variations. The time gap between the severe disturbances and regime shift, indicating that the resilience of wetland ecosystem is stronger than lake ecosystem. In order to save the artificial recovery costs, the ecological characteristics of HH wetland before the late 1970s (release phase) were used as the reference conditions for wetland restoration. To reach the reference conditions, the drainage ditches should be filled and provide a more suitable environment for aquatic species. What's more, there is a need to consider changes in management in relation to farming, such as fertilization patterns. The pesticide management also should be strict or more pest-resistant plants created to reduce pesticide use. The ecosystem will recover to its original state based on self-recovery capability when the ecological characteristics reach the reference conditions we set.

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Declarations of interest

None.

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