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Historical (1880s–2000s) impact of wind erosion on wetland patches in semi-arid regions: A case study in the western Songnen Plain (China)

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A R T I C L E I N F O

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A B S T R A C T

The western Songnen Plain, which is located in a semi-arid region, is one of the most important cultivated regions in China, and it is subject to constant threats from sandy desertification due to wind erosion. Wetland patches between the desert and cultivated regions in the western Songnen Plain capture dust from desert regions and are influenced by regional wind erosion. To evaluate the degree of historical wind erosion and the impact of wind erosion on wetland patches in the western Songnen Plain, we selected four regions along a wind erosion gradient and analyzed the geochemical properties of soils in wetlands and their surrounding typical ecosystems. The results indicate that more dust and sand are deposited in the western wetland patches than in eastern wetland patches and that more than 50% of the soils in the western wetland patches are comprised primarily of sand. Wetland patches in the wetland/desert transitional region act as natural buffers that impede wind-driven desertification, and only 20% of the soils in eastern wetland patches comprise sand. Additionally, increasing farmland area and residential water consumption caused by human activities have also increased wind erosion in the eastern region. Increased wind erosion has caused eastern wetland patches to start capturing dust from surrounding farmland and grassland since the 1920s, and the accumulation rates of typical elements (i.e., Cu, Pb, Zn, P) increased obviously after the 1960s.

1. Introduction

Wind erosion is one of the most important factors that causes land degradation in arid and semi-arid regions by removing silt- and clay-sized particles from the land surface; it is one of the processes that leads to sandy desertification (Zha and Gao, 1997). Wind erosion can have significant adverse impacts on soil productivity, and the estimated annual losses of the top layer of soil carbon (C) and nitrogen (N) due to wind erosion in northern China range from 53 to 1044 $kg\ ha^{-1}$ and 5 to 90 $kg\ ha^{-1}$, respectively (Wang et al., 2006). Furthermore, fine particles, which contain most of the cation exchange capacity, water-holding capacity, and fertility of the soil, can be lost from ecosystems due to wind erosion (Toy et al., 2002). Fine particles are deposited on the surface as dust and added to soils by infiltration (Reheis et al., 2009). Wind erosion and the wind-driven redistribution of sediment can also impact plant distribution patterns in most arid and semi-arid regions (Breshears et al., 2009). High-density vegetation patches in dry ecosystems serve as sinks for dust, which is transported by wind-driven processes from low-density vegetation patches (Field et al., 2012; Gillette et al., 2006). The loss of grass cover caused by desertification is a compounding problem that not only increases dust emissions but also decreases the capacity for dust capture (Field et al., 2012; Nandintsetseg and Shinoda, 2015).

The western Songnen Plain is located in the western part of Jilin Province in northeast China, and sandy desertification exerts a serious influence on the soils and plant patterns there (Qiu, 2007). Precipitation on the western Songnen Plain reaches an average of 350–450 mm per year (Statistics Office of Jilin Province, 2017), which means that the western Songnen Plain is located in a semi-arid region and is susceptible to wind erosion. At the end of the 19th century, the Qing government began to encourage people to move and settle in northeast China (Zhang et al., 2006). Many people moved to the Songnen Plain, and the area of cropland increased substantially. During the 1950s, several reservoirs in western Jilin Province were constructed, and more

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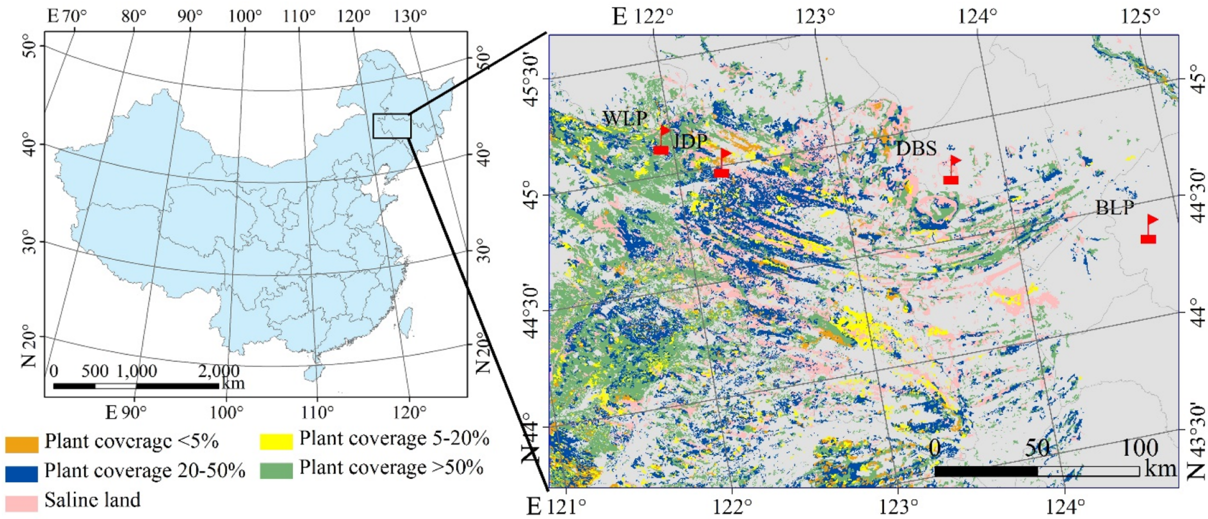

Fig. 1. Locations of sample sites on the western Songnen Plain in Northeast China and the distribution of deserts in the study region (the desert distribution data set is provided by "Environmental & Ecological Science Data Center of West China, National Natural Science Foundation of China", http://westdc.westgis.ac.cn). The grey areas mean other landscape in this region except desert and saline land.

water resources were allocated to the residents living there (Editorial Committee of Jilin chronicles, 2001). Due to improper land use and low precipitation, sandy areas increased 0.44% per annum from the middle of the 1980s, and covered 7.5% of the total western Songnen Plain in 2001 (Zhao et al., 2009). High degrees of sandy desertification and sandy areas caused the ecosystems in the western Songnen Plain to become more easily influenced by wind erosion. However, few studies have evaluated the historical variations in wind erosion in the western Songnen Plain or the influences of wind erosion on the surrounding ecosystems.

Because of the geological history of this region, several wetland patches are distributed in the western Songnen Plain (Bian et al., 2008). Wetland patches with high-density plant coverage and surface water have served as important ecosystem landscapes in this semi-arid region (Wang et al., 2004b). The plants in wetlands slow the wind speed and trap sands carried by the wind (Soons, 2006); furthermore, wetland patches, which are located at the margin of the desert, act as barriers to desert expansion (Yu et al., 2014). Similar to other ecosystems, wetlands are also strongly influenced by the input of dust from surrounding ecosystems (Yu et al., 2014). Wang et al. (2008) found that there were general differences in soil P that formed due to different degrees of the influence of wind erosion on wetland profiles. For example, residual P, one kind of stable P in soils that is influenced by regional fertilizer use and wind erosion, increased due to soil fertilization in the surrounding ecosystem (Wang et al., 2008). While, most wetlands researchers have tended to focus descriptions or analysis on short timescales, and long-term anthropogenic and climatic changes influencing wetland in the semi-arid region are poorly understand (Tooth et al., 2015). Wetland sedimentary records have been widely used to reconstruct the historical influence of regional climate change and human activities on natural ecosystems (Gao et al., 2014b; Wang et al., 2004a). To understand the historical impact of sandy desertification caused by the wind erosion on surrounding ecosystems, wetland patches in the western Songnen Plain can be used as sedimentary records to reveal the historical degree of wind erosion in this region and to reconstruct the influence of wind erosion on wetland ecosystems.

To achieve these aims, soil samples in a wetland and its surrounding ecosystem were collected in four regions along a wind erosion gradient on the western Songnen Plain, as was performed in a previous study (Wang et al., 2008). Based on a ^{210}Pb age-depth model and the soil properties, the correlation coefficients of the geochemical properties between the wetland and its surrounding ecosystem, as well as the historical impact of wind erosion on wetlands, were reconstructed in this study. Furthermore, we aim to reveal the influence of regional human activities on wind erosion in the natural ecosystem and to understand the importance of this wetland/desert transitional region on regional wind erosion in semi-arid regions.

2. Materials and methods

2.1. Site description and sampling

The western Songnen Plain is located in a series of ecological transition zones characterized by frequent changeovers between desert-like and re-established ecosystems, and it is influenced by wind erosion. The annual precipitation ranges from 350 to 450 mm per year; westerly winds are predominant, causing the dust and sand in the western Songnen Plain to be mainly derived from steppes and deserts in Inner Mongolia, which is located to the west of the western Songnen Plain (Qiu, 2007; Statistics Office of Jilin Province, 2017). These conditions have caused this semi-arid region to be listed as one of the key sandy desertification control regions in China (Wang et al., 2008). Low precipitation and low plant coverage in the summer have been connected to elevate dust generation in the spring season of the following year (Wu et al., 2016).

Detailed information about the samples collected from this region have been provided in previous studies (He et al., 2015; Wang et al., 2008). Four regions along a gradient of distance to the sand sources and wind erosion on the western Songnen Plain were selected (Fig. 1). Wetland samples were collected from one wetland core in four regions in the field (i.e., Boluopao, BLP, 44°22′49″N, 124°49′12″E; Dabusu, DBS, 44°47′56″N, 123°41′28″E; Jiandipao, JDP, 45°00′05″N, 122°20′09″E; Wulanpao, WLP, 45°09′12″N, 121°56′46″E), and each collected wetland core was sectioned at 2-cm intervals in 2005 (depth: BLP: 54 cm; DBS: 64 cm; JDP: 54 cm; WLP: 56 cm). Different depth samples in each collected wetland core were regarded as replication of wetland soils in each site. Five surface samples (surface layer, up to 2 cm) were collected from locations within vegetated areas of other ecosystems (i.e., desert, farmland, grassland) in four regions and used to reveal the physicochemical properties of soil in these ecosystems. Based on the plant coverage in the WLP desert and JDP desert, three different degrees of sandy desertification in the desert (i.e., plant coverage greater than 75%, low degree of sandy desertification; plant coverage 50–75%, middle degree of sandy desertification; plant

Table 1
Average and standard deviation of typical elements, low-frequency magnetic susceptibility (LFMS), magnetic frequency dependent susceptibility (FDMS), and soil properties in different ecosystems at four study sites. The pH, organic carbon (Corg), Al, Ca, Fe, Pb, residual-P, organic-P, inorganic-P, clay, silt, and sand values are cited from (Wang et al., 2008; He et al., 2015). N means the number of surface samples or the number of total samples in wetland core.

	grassland				farmland				wetland	
	BLP N = 5	DBS N = 5	JDP N = 5	WLP N = 5	BLP N = 5	DBS N = 5	JDP N = 5	WLP N = 5	BLP N = 27	DBS N = 32
Al mg/g	56.8 ± 15.5	58.5 ± 19.8	43.2 ± 4.1	35.3 ± 2.2	65.4 ± 16.0	56.0 ± 4.8	37.0 ± 4.3	35.1 ± 3.6	56.2 ± 7.6	37.4 ± 10.7
Ca mg/g	19.1 ± 0.8	17.7 ± 2.8	10.1 ± 0.8	5.3 ± 0.8	18.6 ± 0.4	19.2 ± 1.8	11.2 ± 0.6	15.4 ± 1.5	31.9 ± 12.9	8.58 ± 2.7
Ti mg/g	4.6 ± 0.1	4.4 ± 0.6	2.2 ± 0.3	2.0 ± 0.2	5.0 ± 0.2	4.6 ± 0.6	1.7 ± 0.1	2.2 ± 0.1	3.1 ± 0.5	1.6 ± 0.3
V mg/kg	79.6 ± 1.7	70.6 ± 17.6	28.7 ± 3.3	27.0 ± 2.3	95.9 ± 4.6	73.0 ± 7.3	23.6 ± 1.0	40.9 ± 15.1	88.7 ± 8.4	34.4 ± 5.5
Fe mg/g	22.2 ± 0.7	19.9 ± 6.9	8.1 ± 0.7	6.9 ± 0.8	34.9 ± 16.0	19.3 ± 1.7	6.7 ± 0.3	8.9 ± 0.6	28.0 ± 2.6	5.8 ± 1.6
Na mg/g	13.6 ± 2.2	14.3 ± 1.0	10.7 ± 0.5	12.0 ± 0.4	10.3 ± 0.3	14.7 ± 0.5	9.8 ± 0.5	9.8 ± 0.5	20.1 ± 1.7	23.2 ± 3.6
K mg/g	14.0 ± 0.9	15.8 ± 0.9	15.3 ± 0.7	16.0 ± 1.0	14.0 ± 0.8	16.4 ± 1.1	14.2 ± 1.0	12.9 ± 1.0	15.2 ± 2.0	18.6 ± 5.2
Mg mg/g	5.2 ± 0.4	4.2 ± 0.5	1.6 ± 0.2	1.2 ± 0.2	5.0 ± 0.2	3.0 ± 0.2	1.5 ± 0.1	3.1 ± 0.3	11.9 ± 2.0	1.9 ± 0.8
Pb mg/kg	14.9 ± 1.5	10.2 ± 1.1	18.4 ± 6.4	20.8 ± 5.8	19.0 ± 9.0	11.6 ± 1.9	16.8 ± 8.5	14.8 ± 1.6	19.3 ± 2.8	13.8 ± 1.8
Residual-P mg/kg	105 ± 6	80.8 ± 23.4	15.5 ± 2.7	24.1 ± 4.7	128 ± 15	62.8 ± 10.8	10.3 ± 1.8	30.1 ± 8.2	79.4 ± 12.8	14.1 ± 2.6
Inorganic-P mg/kg	341 ± 100	269 ± 22	96.7 ± 6.0	75.5 ± 20.1	441 ± 75	194 ± 13	79.0 ± 6.4	92.2 ± 8.0	282 ± 39	70.2 ± 21.5
Organic-P mg/kg	64.7 ± 11.3	84.1 ± 19.5	75.9 ± 11.5	40.0 ± 8.2	74.8 ± 24.4	81.6 ± 10.7	47.5 ± 4.9	42.7 ± 7.5	59.9 ± 28.0	6. 6 ± 3.0
LFMS 10^{-8} m^3/kg	577 ± 30	540 ± 79	281 ± 33	261 ± 19	675 ± 44	561 ± 91	239 ± 22	288 ± 34	417 ± 58	220 ± 31
FD MS χfd %	4.3 ± 1.0	7.5 ± 0.2	7.8 ± 0.5	6.8 ± 2.1	5.9 ± 0.9	6.9 ± 0.8	7.3 ± 0.9	3.0 ± 0.8	5.1 ± 1.8	5.6 ± 1.8
Clay %	18.7 ± 1.4	15.8 ± 4.0	7.5 ± 2.5	5.4 ± 0.8	32.0 ± 2.9	10.9 ± 0.8	5.9 ± 1.2	8.4 ± 0.3	26.7 ± 3.7	3.8 ± 1.8
Silt %	53.6 ± 2.3	51.4 ± 2.6	22.4 ± 6.1	18.9 ± 4.2	56.0 ± 3.0	45.0 ± 1.2	13.9 ± 2.3	22.5 ± 2.0	56.9 ± 4.6	21.2 ± 12.9
Sand %	27.7 ± 3.5	32.7 ± 4.8	70.1 ± 8.6	75.7 ± 4.8	12.0 ± 2.4	44.2 ± 1.9	80.3 ± 3.3	69.1 ± 2.2	16.4 ± 5.8	75.0 ± 14.3
pH	9.0 ± 0.2	9.3 ± 0.2	8.9 ± 0.2	8.8 ± 0.1	9.0 ± 0.1	9.1 ± 0.2	9.1 ± 0.0	9.1 ± 0.1	9.5 ± 0.4	10.4 ± 0.1
Corg mg/g	20.4 ± 2.0	19.1 ± 3.5	9.8 ± 1.5	11.6 ± 4.4	12.6 ± 1.1	13.0 ± 0.7	4.8 ± 0.8	10.2 ± 1.9	8.5 ± 1.9	0.6 ± 0.5

	wetland		desert						
	JDP N = 27	WLP N = 28	DBS N = 5	JDP a N = 5	JDP b N = 5	JDP c N = 5	WLP a N = 5	WLP b N = 5	WLP c N = 5
Al mg/g	50.5 ± 12.8	38.8 ± 6.3	50.6 ± 2.9	41.2 ± 7.0	34.3 ± 1.6	22.2 ± 4.4	41.0 ± 2.7	36.6 ± 1.9	32.9 ± 4.0
Ca mg/g	33.9 ± 13.9	7.2 ± 2.8	15.9 ± 2.7	4.0 ± 0.4	4.2 ± 1.9	3.0 ± 0.2	13.5 ± 2.5	7.1 ± 0.1	5.2 ± 0.4
Ti mg/g	2.3 ± 0.3	1.5 ± 0.3	4.8 ± 1.4	1.1 ± 0.1	1.4 ± 0.3	1.1 ± 0.2	2.6 ± 0.5	2.4 ± 0.2	1.9 ± 0.2
V mg/kg	61.2 ± 12.5	39.3 ± 7.1	55.5 ± 11.6	15.1 ± 0.8	16.8 ± 3.4	15.7 ± 6.3	37.6 ± 4.8	35.0 ± 2.4	26.0 ± 2.7
Fe mg/g	13.3 ± 2.5	9.1 ± 2.2	11.1 ± 2.0	4.8 ± 0.4	4.7 ± 1.0	4.0 ± 1.1	9.9 ± 1.3	9.2 ± 0.6	6.5 ± 0.5
Na mg/g	17.9 ± 2.8	17.6 ± 1.9	16.7 ± 1.3	9.6 ± 0.9	9.7 ± 0.7	7.0 ± 0.4	11.7 ± 0.3	11.6 ± 0.2	11.4 ± 0.5
K mg/g	14.8 ± 3.2	15.8 ± 3.2	16.1 ± 0.8	14.8 ± 1.3	14.5 ± 0.8	11.5 ± 0.7	15.6 ± 0.5	15.3 ± 1.1	15.7 ± 1.2
Mg mg/g	6.0 ± 1.9	2.2 ± 1.0	2.1 ± 0.3	0.6 ± 0.1	0.7 ± 0.1	0.6 ± 0.1	2.4 ± 0.6	1.6 ± 0.2	0.9 ± 0.1
Pb mg/kg	13.7 ± 3.0	12.9 ± 2.3	8.7 ± 3.2	11.4 ± 2.0	21.9 ± 3.9	23.9 ± 11.5	11.1 ± 1.4	11.9 ± 0.8	11.9 ± 1.5
Residual-P mg/kg	32.9 ± 10.7	26.3 ± 23.2	47.3 ± 30.4	18.0 ± 5.0	23.7 ± 1.4	17.2 ± 3.7	34.8 ± 6.7	36.9 ± 2.9	25.6 ± 3.1
Inorganic-P mg/kg	143 ± 55	66.4 ± 34.6	133 ± 36	72.3 ± 9.9	77.5 ± 3.9	59.8 ± 17.1	107 ± 18	86.9 ± 6.4	59.7 ± 3.8
Organic-P mg/kg	56.1 ± 58.0	25.2 ± 24.0	24.3 ± 8.9	35.6 ± 9.6	25.9 ± 1.6	20.1 ± 2.5	39.6 ± 3.6	37.8 ± 9.6	38.1 ± 4.9
LFMS 10^{-8} m^3/kg	332 ± 52	245 ± 34	561 ± 187	176 ± 8	179 ± 41	169 ± 43	340 ± 55	314 ± 22	240 ± 13
FD MS χfd %	13.9 ± 5.1	7.1 ± 2.3	4.1 ± 1.4	7.9 ± 1.9	9.8 ± 1.1	9.3 ± 0.8	5.8 ± 0.4	7.1 ± 1.1	7.6 ± 0.7
Clay %	11.3 ± 5.0	5.4 ± 1.6	6.5 ± 1.6	3.5 ± 0.8	3.4 ± 0.4	2.8 ± 0.4	9.5 ± 4.5	6.7 ± 1.6	4.6 ± 0.4
Silt %	40.4 ± 13.1	15.0 ± 7.4	42.3 ± 8.8	8.6 ± 4.0	7.2 ± 1.2	5.2 ± 1.0	21.6 ± 8.3	19.2 ± 3.2	10.6 ± 0.8
Sand %	48.3 ± 16.3	79.6 ± 8.9	51.2 ± 9.5	87.9 ± 4.7	89.3 ± 1.5	92.0 ± 1.3	69.0 ± 12.7	74.1 ± 4.6	84.8 ± 1.1
pH	8.7 ± 0.4	8.8 ± 0.3	10.0 ± 0.1	9.0 ± 0.1	9.2 ± 0.2	9.3 ± 0.2	9.0 ± 0.2	8.7 ± 0.2	8.7 ± 0.2
Corg mg/g	20.2 ± 30.2	5.9 ± 9.0	2.5 ± 1.4	4.6 ± 2.1	2.8 ± 0.4	2.2 ± 0.4	5.8 ± 1.1	4.6 ± 0.6	3.0 ± 0.7

a, b, c: indicated intensity of sandy desertification (i.e. evaluated by plant coverage), a plant coverage > 75%; b plant coverage 50-75%; c plant coverage < 50%.

coverage < 50%, high degree of sandy desertification) were selected for study. The numbers of wetlands samples in each wetland core and surface samples collected from other each ecosystem is shown in Table 1. All of the samples were stored in polyethylene plastic bags at −20 °C. Samples were loosely disaggregated to facilitate air drying at 20 °C.

2.2. Physicochemical analysis

The chronology and bulk density analyses followed the methodology of He et al. (2015). Briefly, sediment accumulation rates were calculated using a ^{210}Pb depth-age model, which applies a constant rate of supply (CRS) model to determine ages based on ^{210}Pb counts and bulk density data (Binford, 1990; Turetsky et al., 2004). The bulk density was measured by weighting the dry weights of primary soils with their known volumes; dry weights were determined by oven drying at 105 °C for 12 h. The particle size data, pH data, total organic carbon contents and contents of Al, Fe, and Ca were taken from Wang et al. (2008). Other trace elements (e.g., Ti and V) were measured using the same procedure used for the elemental analyses (i.e., total digestion with a concentrated mixture of $HNO_3/HClO_4/HF$) and were determined using atomic emission spectrometry with inductively coupled plasma (ICP-AES, ICPS-7500) (Gao et al., 2014a). Mass magnetic susceptibility (MS, $*10^{-8}$ m^3/kg) was quantified from the homogenized, dried samples using an MS2 sensor (Bartington Instruments Ltd, Oxford, UK). High-frequency magnetic susceptibility (HFMS, 4700 Hz) and low-frequency magnetic susceptibility (LFMS, 470 Hz) were used to calculate the magnetic frequency-dependent susceptibility (FDMS, X_{fd}, %). One of every ten samples was measured three times as repeat analyses to evaluate the results of the instrument, and five surface samples from each site were analyzed as repeat to assess the properties of the soils in grassland, desert, and farmland.

2.3. Data selection and statistical methods

Mantel's test is a statistical test of the correlation between data from two matrices; it is widely used to correlate soil properties between studied regions and their potential source regions (Legendre and Legendre, 2012; Oksanen et al., 2015). Instead of using average results, the data of all samples in each source were used for the source matrices, and Mantel's test was used to evaluate the differences between wetland soils and potential dust sources. In this study, with the exception of wetland soil samples, we collected soil samples from other ecosystems (i.e., farmland, grassland, desert) in four regions (WLP, JDP, DBS, and BLP) to evaluate the potential sources of wetland soils in each region. The typical elemental concentrations (i.e., Al, Ti, V, Ca, Fe, Zr, Na, K, Mg, Pb, inorganic P, organic P, residual P; mg/kg), OM (mg/g), LFMS ($*10^{-8}$ m^3/kg), FDMS (%), pH, and particle sizes (%) of each soil were regarded as the basic physicochemical properties of these soils. To assess the links between the soil properties of the wetland and those of the surrounding ecosystem, we calculated the Spearman's rank correlation coefficient between the compositional dissimilarity within wetland soils and the other types of soils using Mantel's tests.

Linear discriminant analysis is a method of linear modeling that is widely used in taxonomy and fingerprinting approaches (Legendre and Legendre, 2012). A stepwise selection algorithm, based on the minimization of Wilkes' lambda ($F < 0.05$), was used in this analysis (Carter et al., 2003). Similar to Mantel's tests, the data in all samples were used to evaluate the relationship between samples in each source in the analytical results. To identify the historical contributions of different potential source types to wetland soils over the last 150 years, the contents of conservative elements and soil properties (i.e., Al, Ti, V, Ca, Fe, Zr, residual P and LFMS) were regarded as special properties of dust sources and chosen for a fingerprinting approach. The ^{210}Pb depth-age model was used to select the samples at the bottom of the profiles that accumulated before the 1880s as the background of wetland soils because regional human activities and the degree of wind erosion were assumed to be weakest before the 1880s.

3. Results

3.1. Magnetic susceptibility

The average and standard deviation values of LFMS ($*10^{-8}$ m^3/kg) and frequency-dependent magnetic susceptibility (FDMS, %) are shown in Table 1. In grassland soils, the average value of FDMS (χfd %) in BLP grassland was 4.3 ± 1.0 $*10^{-8}$ m^3/kg and was the lowest of the four sites. For farmland soils, the FDMS (χfd %) value in WLP was 3.0% ± 0.8%, which was the lowest of all the soil samples. With the decreasing density of plant coverage in the desert, the FDMS increased in both the JDP and WLP deserts (from 7.9% ± 1.9% to 9.3% ± 0.8% and from 5.8% ± 0.4% to 7.6% ± 0.7%, respectively).

The average LFMS value in BLP farmland was 675 ± 44 $*10^{-8}$ m^3/kg, which was the highest of all soil samples. For farmland and grassland, the LFMS values in BLP and DBS were similar (from 540 ± 79 to 675 ± 44 $*10^{-8}$ m^3/kg) and nearly double those in JDP and WLP (from 239 ± 22 to 288 ± 34 $*10^{-8}$ m^3/kg). For desert soils, the LFMS in the DBS desert (561 ± 187 $*10^{-8}$ m^3/kg) was substantially higher than those in the other desert samples, and those in the JDP desert were lowest (169 ± 43–179 ± 41 $*10^{-8}$ m^3/kg). With the decreasing density of plant coverage, the LFMS value in the WLP desert decreased from 340 ± 55 $*10^{-8}$ m^3/kg to 240 ± 13 $*10^{-8}$ m^3/kg, and no obvious decreasing trend was observed in the JDP desert. For the wetland soils, the LFMS value in BLP was 417 ± 58 $*10^{-8}$ m^3/kg, which was higher than those observed in the wetland soils at the other sites. The LFMS value in the DBS wetland (220 ± 31 $*10^{-8}$ m^3/kg) was the lowest in all four regions of wetland soils. In the JDP wetland and DBS wetland, the LFMS values were obviously lower than those in the surrounding ecosystem. From eastern to western sites, the differences in the LFMS values between the wetland and its surrounding ecosystem decreased obviously. The LFMS values in the JDP wetland and WLP wetland were similar to those in the surrounding ecosystem and closer to those observed in the grassland soils.

3.2. Major and trace elements concentrations

Considering the concentrations of elements and the scale of values, the units of Al, Ca, Ti, Fe, Na, K, Mg were selected as mg/g, and the units of V and Pb were selected as mg/kg. The trace element concentrations of Al, Ca, Fe, and Pb are drawn from previous studies (He et al., 2015; Wang et al., 2008). The average and standard deviation of Ti, V, Na, K, and Mg were obtained in this study (Table 1). The concentrations of most trace elements (except Na in wetland soils, Pb in grassland soils) in the soils decreased from east (BLP) to the west (WLP). For example, the Ti and V in BLP grassland were 4.6 ± 0.1 mg/g and 79.6 ± 1.7 mg/kg, respectively, whereas, the Ti and V in WLP grassland were 2.0 ± 0.2 mg/g and 27.0 ± 2.3 mg/kg, respectively. The Ti and V in desert soils were lower than those in other ecosystem soils, and with the decreasing density of plant coverage, the Ti and V concentrations were lower in WLP desert and fluctuated in JDP desert. There was a similar trend of Na, K and Mg concentrations, which also decreased with the density of plant coverage decreasing in both WLP and JDP desert.

3.3. Correlation coefficients between wetland soils and other soils

The correlation coefficients of wetland soils in different regions and other ecosystem soils, as determined using Mantel's test, are shown in Fig. 2. High correlation coefficient indicates the properties of two kinds of soils are more similar than those which have a low correlation coefficient. The correlation coefficient of wetland soils between the JDP wetland and the WLP wetland was 0.773, which was much higher than

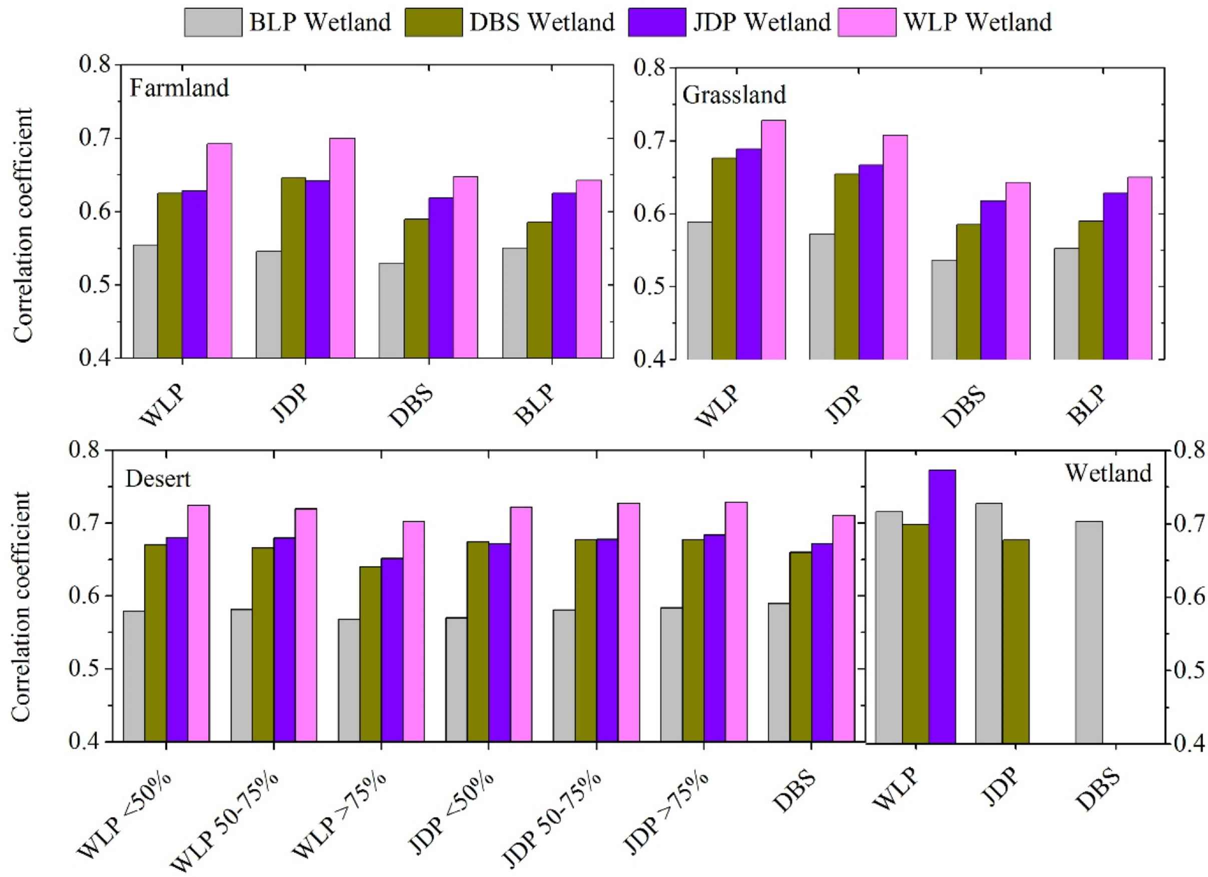

Fig. 2. Correlation coefficients of the geochemical properties between wetland soil samples at each site and soil samples from other wetlands or other types of ecosystems (i.e., desert, farmland, grassland) in four regions. Correlation coefficients were Spearman's rank correlation and calculated by Mantel's statistics. All correlations are significant at the 0.05 level. Desert soils in WLP and JDP were divided by plant coverage.

those observed between other wetlands. In contrast, the soil properties in the DBS wetland were the least correlated with those of other wetland soils. The results of Mantel's test also indicated that the correlation coefficients between wetland soils and other ecosystem soils increased from east to west. For example, the correlation coefficients between the BLP wetland soils (the easternmost site) and other ecosystem soils ranged from 0.5 to 0.6; however, most of the correlation coefficients between the WLP wetland soils (the westernmost site) and other soils were higher than 0.7.

Comparing the correlation coefficients between wetland soils and other ecosystem soils reveals that the correlation coefficients between farmland soils and wetland soils were the lowest and that the correlation coefficients between desert soils and wetland soils were the highest. At the easternmost site (BLP), the correlation coefficients between wetland soils and the other three types of ecosystem soils were similar (0.546–0.590), and the desert soils in DBS were more like BLP wetland soils than they were to others (0.590). In contrast, at the westernmost sites (JDP and WLP), the correlation coefficients between deserts and wetlands were clearly higher than those of the other two ecosystems, and the wetland soils in the western region were more similar to the surrounding desert and grassland soils.

3.4. Historical variations in particle size

Because it is difficult to evaluate historical landscapes in wetland/desert transitional regions (i.e., the DBS wetland distribution region) and the degree of influence that deserts exert on DBS wetlands, we used only the wetlands in WLP, JDP, and BLP to evaluate the historical variations in wind erosion in the western Songnen Plain. The ^{210}Pb age-depth model (He et al., 2015) and historical variations in particle size (Wang et al., 2008) (i.e., sand proportion) of these three wetlands over the last 150 years were recalculated and are shown in Fig. 3a-f. From the western to eastern sites, the sand fraction (particle size greater than 63 μm) in wetland soils decreased from 80% to 20%. The clay fraction (particle size < 4 μm) in the BLP wetland soils was approximately 25% during the last 150 years. In the western sites (WLP and JDP), more than 50% of the soils comprised sand, and particles with diameters of larger than 500 μm were only observed in the WLP wetland; in contrast, silt (particle size 4–63 μm) was the major component in the BLP wetland. The sand fraction in the WLP wetland was approximately 80% before the 1960s, while, fluctuated between 60% and 80% after the 1960s. Around 1970, the fraction of sand in the WLP wetland decreased to 70% and was obviously lower than it was during other periods before the 1980s. Since the 1990s, the fractions of sand in the WLP wetland deceased from 85% to 65% and the fractions of silt were changed from 10% to 30%. A similar trend was found in the JDP wetland, where the sand fraction decreased from 70% to 40% around 1970, and silt increased from 30% to 60% since the 1960s.

4. Discussion

4.1. Correlation in soil properties between wetlands and other ecosystems

Correlation in soil properties between wetlands and other ecosystems were calculated by Mantel's tests and the correlation coefficients of the geochemical properties between the wetland and its surrounding ecosystem are shown in Fig. 2. The correlation coefficient between the JDP and WLP wetlands was 0.773. Both of these two wetlands are

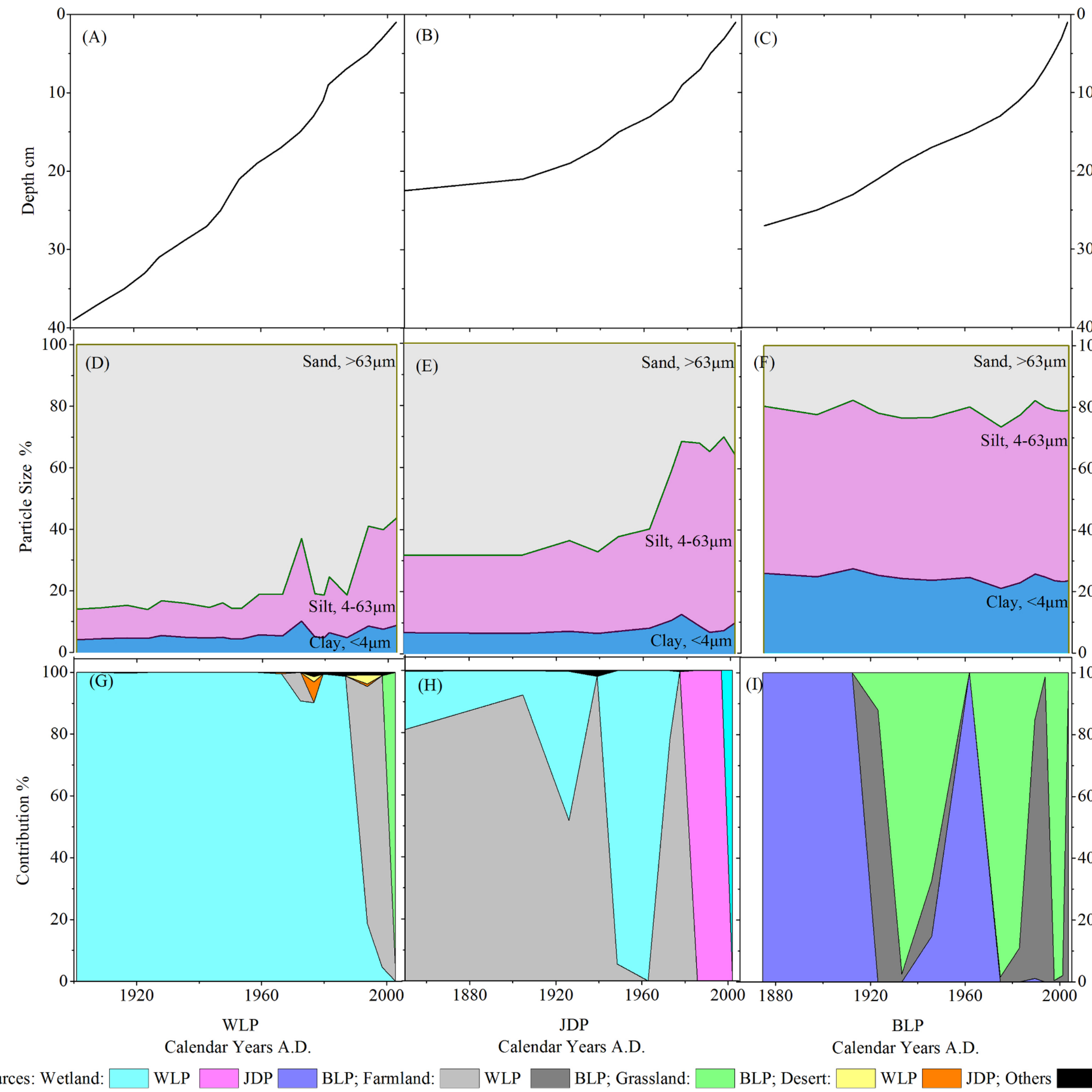

Fig. 3. ^{210}Pb age-depth model of WLP, JDP and BLP (A-C) (He et al., 2015); particle sizes (D-F) in the WLP, JDP and BLP wetlands (Wang et al., 2008); and historical sources of wetland soils identified using linear discriminant analysis (G-I) over the last 150 years. Different colors in the results of linear discriminant analysis correspond to different potential sources of wetland soils.

located in the western region of the wetland/desert transitional region; the degrees of wind erosion and potential dust sources in these two areas are similar, and the soil properties at these two sites are the most closely correlated. Because the DBS wetland is located in the middle of the wetland/desert transitional region and the influencing factors of the DBS wetland are more complex than those in other regions, the properties of the wetland soils in DBS were different from those of the other wetland soils, and they yielded lower correlation coefficients.

High correlation coefficients between wetland soils and other soils in the western sites indicate that the wetland soils in the western sites were more easily influenced by soils in surrounding ecosystems than those in the eastern sites. Precipitation in Jilin Province decreases from east to west (Statistics Office of Jilin Province, 2017); low precipitation in summer decreases the density of plant coverage, and dusty springs occur more easily in the western sites (Wu et al., 2016). The wind direction in the western Songnen Plain is mainly from west to east, and the surface soils in the western sites were eroded by wind and deposited in the eastern region. Dust from the western sites caused the soil properties of wetland soils to be closer to those of soils in the western sites, and the correlation coefficients between wetland soils and other ecosystem soils increased from east to west. The western sites are located at the margin of the wetland/desert transitional region, and the desert is the major ecosystem surrounding these sites. The low density of plant coverage in the desert caused the surface soils in the desert region to be more easily influenced by wind erosion than the soils in other ecosystems (Li et al., 2008a; Yang et al., 2007). Similar to previous studies in Central Spain, the microstructures of wetland soils in a sandy transitional zone in the Mancha Plain were also clear indicating their aeolian origin (Giménez et al., 2015). Because of the high density of plant coverage in wetlands, wetland soil surfaces can more easily capture and store sand or dust (Yu et al., 2014), and the majority of dust captured by wetland patches was removed from the surrounding desert. This explains why the correlation coefficients between desert soils and wetland soils are the highest and why the correlation coefficients between desert soils and western wetland soils (i.e., WLP, JDP, and DBS) increased with decreasing plant coverage in the desert. Desert soils, however, exerted little influence on the BLP wetland soils (i.e., low correlation coefficients), which were located in the eastern wetland/

desert transitional region. Thus, the wetlands in the western regions were more easily influenced by the dust that was transported from the surrounding desert.

Overall, the results of Mantel's test showed that the geochemical characteristics of the soil properties in wetlands located in the middle and western regions of the wetland/desert transitional region were both influenced by dust from deserts, as their correlation coefficients increased with the increasing intensity of wind erosion (from east to west). The geochemical characteristics of the wetlands located in the eastern region of the wetland/desert transitional region were more weakly influenced by the desert region, and their soil properties were more different than those in the western wetlands.

4.2. Historical degree of wind erosion in the western Songnen Plain

Unlike the wetlands in WLP and JDP, which were strongly influenced by the surrounding desert, the wetlands in BLP were protected by wetland patches in a wetland/desert transitional region (i.e., the DBS wetland distribution region) and were weakly influenced by the western desert. To compare the historical degree of the influence of wind erosion on wetland ecosystems, historical variations in the particle size (e.g., sand proportions) of these three wetlands over the last 150 years were reconstructed to evaluate variations in the degree of wind erosion (Fig. 3). Wind and water erosion are two major processes that transport and redistribute sediment in natural ecosystems. We speculate that most of the sediment transport was by wind erosion because of the low rainfall in western wetlands and the lack of gullies in the landscape. Thus, most of the dust captured by wetland patches was transported by wind. Silt (4–63 μm) could be transport by water and is an important predictor of threshold friction velocity and sediment production. And, most sand (particle size greater than 63 μm) can be transferred by severe wind erosion and used to identify the intensity of wind erosion (Belnap et al., 2014; Wang et al., 2008). Nearly 80% of the soils comprised clay and silt in the BLP wetland (Fig. 3), which indicated that wind erosion was less severe. The horizontal sediment flux out of bare patches was 20% greater than from herbaceous patches and 50% greater than from shrub-dominated patches (Field et al., 2012), thus, further downwind and the wetland patches in the wetland/desert transitional region decreased the amount of dust transported by wind were two major factors that led to a lower degree of dust being deposited in the BLP wetland.

In the western sites (WLP and JDP), more than 50% of the soils comprised sand; in contrast, silt (particle size 4–63 μm) was the major component in the BLP wetland (Fig. 3). The transport of particles with diameters greater than 500 μm only occurs through surface creep or fluvial processes from the surrounding desert (Goudie and Middleton, 2006) and was only observed in the WLP wetland, which means that the WLP wetland was directly influenced by the surrounding desert. The large particles, especially that with particle sizes greater than 250 μm, increased substantially in the 1920s and 1940s. The historical variations in the large particles in the WLP wetland indicated that the intensity of wind erosion in the WLP wetland was stronger than those observed at the other two sites and decreased around 1970. A similar trend was found in the JDP wetland, where the sand fraction decreased around 1970. The silt fraction in the JDP wetland increased from 30% (1960s) to 60% (2000s) and became the major component after 1970. Several reservoirs in the western Songnen Plain were constructed in the 1950s (Editorial Committee of Jilin chronicles, 2001). These reservoirs decreased the downstream water supply, which led to more riverbeds being exposed to wind; thus, riverbeds became an important dust source (Belnap et al., 2011; Lehner et al., 2011). Regional human activities produced more dust sources in the western Songnen Plain, and the silt fraction increased in the WLP and JDP wetlands as the sand fraction decreased after the mid-1960s.

4.3. Historical potential sources of dust captured by wetland patches

As mentioned above, the wetlands located in the western region of the wetland/desert transitional region were mainly influenced by wind erosion from the western desert. In contrast, wetlands located in the eastern wetland/desert transitional region were further downwind and were also protected by wetland patches in the wetland/desert transitional region; thus, less dust accumulated in the eastern wetlands. To quantify the influence of the surrounding ecosystems on wetland soils, the historical proportions of potential sources in the WLP, JDP, and BLP wetlands over the last 150 years were reconstructed and are shown in Fig. 3g-i.

The soil properties in the WLP wetland over the last 150 years were closer to those of deeper soils, and dust from the surrounding desert and farmland in the WLP only started to influence the WLP wetland in the 1960s. Before the 1900s, the ecosystems in the western Songnen Plain were minimally influenced by human activities, and natural factors led to the WLP wetlands being influenced by wind erosion from the surrounding desert. The soil properties in the WLP wetland that accumulated before the 1950s were similar to the background of soils in the WLP wetland (Fig. 3). Similar soil properties mean that the degree of wind erosion in the WLP was similar to that before the 1950s. In addition, the WLP wetland has been influenced by wind erosion from the surrounding desert for more than 150 years. Agriculture decreases the accumulation of larger-sized clay aggregates and increases the risk of these particles being removed by wind (Colazo and Buschiazzo, 2015). In Texas Southern High Plains (U.S.), tillage indices for the watersheds indicated increased wetland sedimentation in tilled as compared to predominately grassland watersheds (Gitz et al., 2015). The regional area of farmland and agricultural population in Jilin Province from 1949 to the present are shown in Fig. 4. The increase in agriculture led to more sand and dust from the surrounding desert and farmland being deposited into the WLP wetlands. The WLP wetland soils were more seriously affected by transported dust from soils in the surrounding desert and farmland after 1960, and a significant increase appears after 1980 (Fig. 3). With the increasing population and area of agricultural

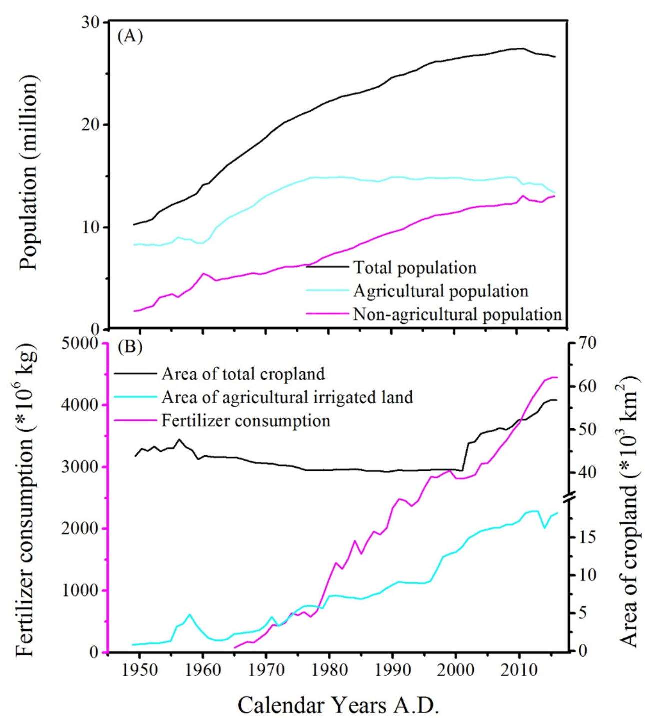

Fig. 4. Regional population, agricultural population, non-agricultural population, area of cropland, area of agricultural irrigated land, and consumption of fertilizer in Jilin Province (Statistics Office of Jilin Province, 2017).

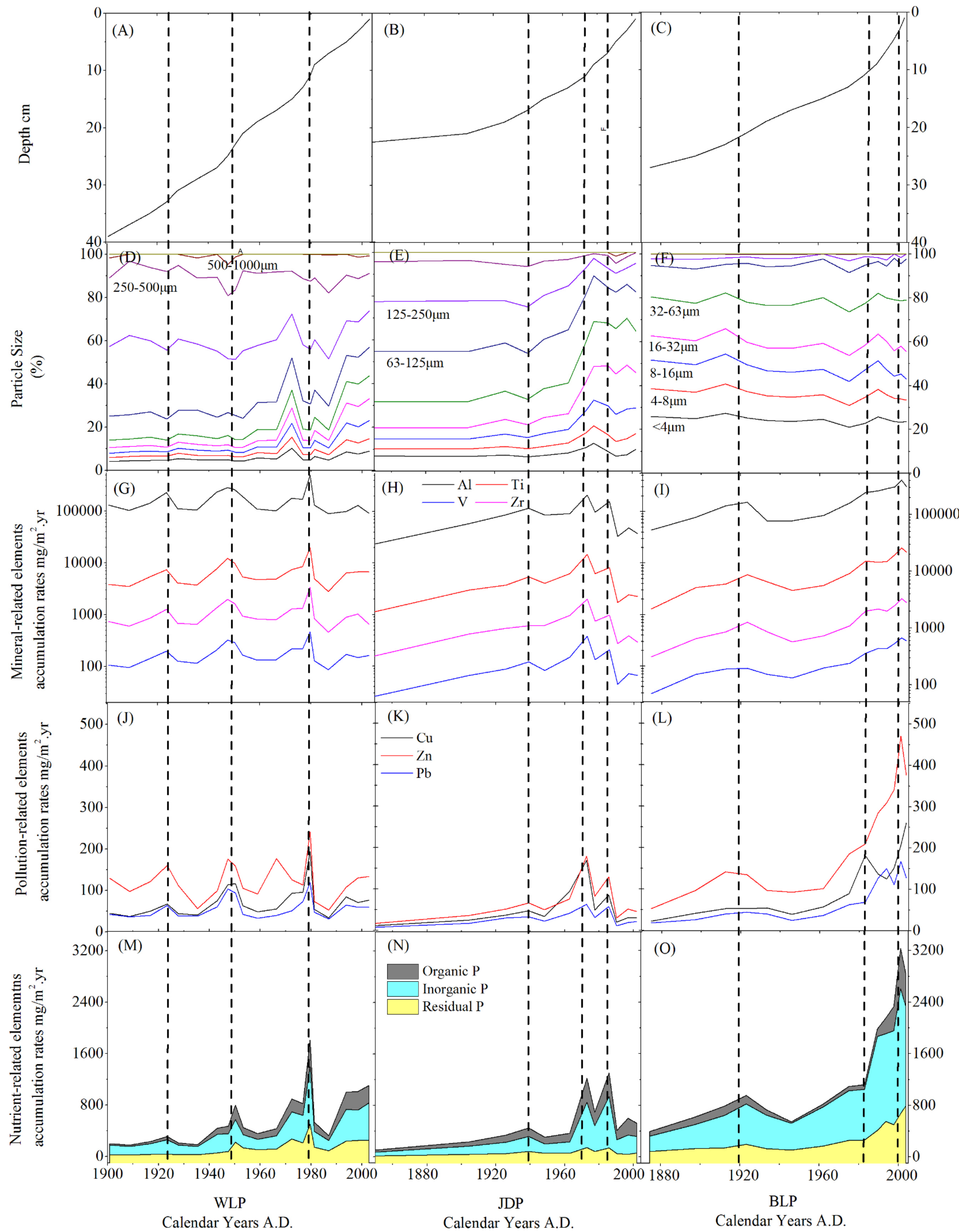

Fig. 5. Historical variations in particle sizes (A-C) and historical accumulation rates of mineral-related elements (Al, Ti, V, Zr) (D-F), pollution-related elements (Cu, Pb, Zn) (G-I), and nutrient-related elements (inorganic P, organic P, residual P) (J-L) in wetlands of the WLP, JDP and BLP over the last 150 years. Al, Pb, residual-P, organic-P, inorganic-P, clay, silt, and sand values are cited from Wang et al. (2008).

irrigated land, human activities have led to the intensification of sandy desertification in recent years (Qiu, 2007). The increasing area of sandy desertification, together with the increasing intensity of wind erosion, resulted in the WLP wetland capturing more dust from the surrounding desert and farmland; thus, the wetland soils were majorly influenced by surrounding farmland from the 1990s to the present.

The chemical composition and physical properties of the JDP wetland soils were similar to those of the soils in farmlands and wetlands in the WLP over the last 150 years (Fig. 3). Only the surface of the JDP wetland soils, which accumulated around the 2000s, was similar to the bottom soils in the JDP wetlands. The JDP wetland is located in the eastern WLP, and the degree of wind erosion in the JDP is slightly lower than that in the WLP. Similar to the WLP wetland, the JDP wetland was also influenced by wind erosion from the surrounding desert before the 1900s. Westerly winds could transport dust and silt from the western ecosystem (i.e., the WLP desert) to the JDP wetland. Farmland reclamation in the WLP led to surface soils being eroded and transported by wind; these surface soils were more easily deposited into eastern sites (i.e., the JDP wetland), and WLP farmland was one of the most important dust sources in the JDP wetland during the last 150 years. Because WLP and JDP were both influenced by serious wind erosion, similar dust sources in the WLP wetland and JDP wetland led to the soil properties in these two wetlands being similar, and the WLP wetland was identified as one of the dust sources in the JDP wetland before

1960. The similar sources of dust between the WLP and JDP wetlands indicated that the JDP wetland was also influenced by the wind erosion of surface soils in the surrounding ecosystem over time.

Unlike those of the western wetland sites, the soil properties in the BLP wetland were similar to those of the bottom of the BLP wetland before the 1920s. After the 1920s, the BLP wetland soils were gradually influenced by surrounding farmland and grassland soils, and the surface soils on BLP farmland or BLP grassland were the major sources for the BLP wetland in the 1920s-1940s and from the 1980s to the present. Similar to other regions in northeast China (Zhang et al., 2006), more people moved into the Songnen Plain after the 1900s and the area of cropland increased, which led to less water being available for natural ecosystems. The increase in cropland for residential living increased the intensity of desertification and wind erosion in the western Songnen Plain after the 1920s. Desertification is often associated with a decrease in herbaceous cover (Peters et al., 2006), and the decrease of the herbaceous cover in farmland in spring led to the wetlands and other ecosystems in the western Songnen Plain being more easily influenced by wind erosion. Soils on the surfaces of farmlands and grasslands were transported to wetlands as airborne dust after the 1920s. Unlike the dust sources in the WLP and JDP wetlands, the soil properties of the BLP wetland were only influenced by the surrounding ecosystems of the BLP. Surface soils in the western and middle parts of the wetland/desert transitional region were hardly deposited into the BLP wetland, and the wetland/desert transitional region could thus be regarded as a "natural buffer region". Dust from the western or surrounding desert was captured by and stored in these wetland patches, and few surface soils in this region were transported to other regions as airborne dust. As most of the dust was captured by the wetland/desert transitional region, the soil properties in the BLP wetland were only influenced by the soil erosion of nearby ecosystems.

Overall, wind transported surface soil components in deserts or farmlands from west to east in the western Songnen Plain. The wetland/desert transitional region in the western Songnen Plain acted as a natural buffer that captured and stored dust that was transported through this region. Because wetland patches captured the dust transported over long distances in the wetland/desert transition region and long distance from the wind erosion source, the soil properties in the wetlands and other ecosystems located in the eastern wetland/desert transitional region were weakly influenced by dust from the western desert and majorly influenced by nearby ecosystems.

4.4. Historical impact of wind erosion on the soil properties in wetlands

To evaluate the historical impact of wind erosion on the typical elements that accumulated in the wetland ecosystems in the western Songnen Plain, the historical variations in the accumulation rates of mineral-related elements (Al, Ti, V, Zr), pollution-related elements (i.e., Cu, Pb, Zn), and different forms of P in these three wetlands over the last 150 years were reconstructed (Fig. 5). There were three periods (i.e., the 1920s, 1940s, and 1970s) with high accumulation rates of mineral-related elements (e.g., Ti, V), pollution-related elements and different forms of P in the WLP wetland (Fig. 5). Similar increasing trends in trace element accumulation rates and sand proportions appeared in the JDP wetland around the 1940s (Fig. 5). Most of the soil nutrients and organic matter are more easily attached to small particles in soils and are transported together with dust; the soil fertility in dust source areas thus becomes depleted while sink areas (e.g., wetlands) are concomitantly enriched (Li et al., 2008b; Field et al., 2010). The high concentrations of these elements carried by dust from the desert and deposited into wetland soils caused accumulation rates to substantially increase. Before the 1950s, little fertilizer was consumed for agricultural production (Fig. 4), and the anthropogenic sources of P and other trace elements were weak. Increasing wind erosion was the major reason why the accumulation rates of trace elements and P increased around the 1940s. Due to the lack of protection of the wetland/desert transitional region, the pollution and nutritional elements in desert surface soils were the major sources of these elements in the WLP and JDP wetlands before the 1950s. After the 1950s, the increasing area of agricultural irrigated land and increasing numbers of residents accelerated the wind erosion processes during this period (Mao et al., 2014; Montgomery, 2007). Because few plants grow on farmland during winter and spring, the decreased grass cover in these seasons compounded this problem, as the loss of cover increases dust emissions and precludes capture (Field et al., 2012). The silt fractions in the WLP and JDP wetlands increased substantially after the 1970s, which means that more dust was deposited into these wetlands, and strong wind erosion was speculated to be the major factor. The wetlands located in the western wetland/desert transitional region were mainly influenced by the transport of dust from deserts and the degree of wind erosion. Regional farmland reclamation and increasing human activities increased the intensity of wind erosion in the western Songnen Plain. The high intensity of wind erosion led to more pollution-related elements and P being deposited in this region, and the accumulation rates of these elements in the WLP and JDP wetlands increased substantially after the 1980s.

Historical variations in the wetland soil properties of the BLP wetland, which is weakly influenced by wind erosion, were notably different from those in the other two wetland sites. Unlike the historical accumulation rates of mineral-related elements in the other two wetlands, the accumulation rates of Ti and V increased before the 1920s. After a short period of decrease around the 1920s, the accumulation rates increased steadily to the present, and no obvious peak values appeared in the BLP wetland. Unlike those of mineral-related elements, the accumulation rates of pollution-related elements (i.e., Pb, Cu, Zn) and P were stable before the 1960s, except when they increased during a short period around the 1920s. The accumulation rates of pollution-related elements (e.g., Zn) increased obviously after the 1960s and decreased slightly in the surface layers after the 2000s. Most of the P in the BLP wetlands was inorganic P, and the accumulation rates of inorganic P increased substantially after the 1940s. The residual P in the BLP wetland was stable before the 1980s and started to increase after the 1980s. At the beginning of the 1920s, drought and wars in south China led to many people from south China moving to northeast China (Fan and Zheng, 2015). Similar to the Sanjiang Plain, which is located to the north of the western Songnen Plain, people moved to the western Songnen Plain and started to increase the area of farmland (Gao et al., 2018). The increasing human activities and increasing area of farmland were the major factors that led to more pollution-related elements and P accumulating in the BLP wetland, and the accumulation rates of these elements slightly increased. After the Korean War ended in 1953, the Chinese government encouraged people to move to northeast China, and fertilizers came into use and farmland started to irrigate in Jilin Province around 1960 (Zhang et al., 2006; Statistics Office of Jilin Province, 2017). The increased area of irrigated agricultural land and the addition of more fertilizers to farmland increased the P accumulation rates in the surrounding wetlands during this period. With regional industrial development, more pollution-related elements produced by human activities may have been the major factors that caused the accumulation rates of pollution-related elements to increase after the 1960s. In summary, because the BLP wetland was protected by wetland patches in the wetland/desert transitional region, little dust from the western desert was deposited into the BLP wetland, and regional human activities were the major factors controlling the accumulation rates of pollution and nutritional elements in the BLP wetlands.

Overall, the accumulation rates of elements in the wetlands located in the western region of the wetland/desert transitional region were more easily influenced by historical dust deposition than the eastern sites. Dust captured by wetland patches is one of the important sources of pollution and nutritional elements in these wetland patches. However, wetland patches in the wetland/desert transitional region decrease the intensity of wind erosion and capture significant amounts of airborne dust. Little airborne dust from the western desert is deposited in the eastern region of the wetland/desert transitional region, and the accumulation rates of elements in the eastern region were mainly influenced by surrounding human activities. Increasing regional human activities, together with the addition of more fertilizers to farmland, caused the accumulation rates of pollution and nutritional elements in the eastern wetland to increase after the 1950s and especially after the 1980s.

5. Conclusions

In this study, the soil properties in different ecosystems of the wetland/desert transitional region in the western Songnen Plain, which is located in a semi-arid region, were investigated, and the historical sources of wetland soils were identified using discriminant analysis. The results show that the wetlands in the western wetland/desert transitional region were strongly influenced by wind erosion and that dust from surrounding ecosystems (especially deserts) was deposited and stored in these wetlands. Wetland patches acted as natural buffers to decrease the influence of wind erosion on eastern ecosystems. Due to the wetland/desert transitional region in the western Songnen Plain, the wetlands located in the eastern wetland/desert transitional region were weakly influenced by wind erosion and mainly influenced by local farmland and grassland when immigrants arrived after the 1920s. With increasing regional human activities, farmland reclamation, and residential water consumption, the areas of wetlands decreased and the severity of wind erosion increased. Strong wind erosion led to more dust being deposited into the western wetlands after the 1960s and accelerated wetland degradation. Because wetland degradation decreased the density of plant coverage, increased the potential wind erosion on the western Songnen Plain and negatively influenced food production in Jilin Province, local governments must address wetland degradation in the wetland/desert transitional region.

CRediT authorship contribution statement

Chuanyu Gao: Conceptualization, Methodology, Software, Writing - original draft. **Chunfeng Wei:** Methodology, Investigation, Writing - original draft. **Lening Zhang:** Methodology, Data curation, Writing - review & editing. **Dongxue Han:** Visualization, Writing - review & editing. **Hanxiang Liu:** Visualization, Writing - review & editing. **Xiaofei Yu:** Conceptualization, Project administration, Funding acquisition, Writing - review & editing. **Guoping Wang:** Conceptualization, Supervision, Funding acquisition, Writing - review & editing.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.aeolia.2019.03.004.

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