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Distribution of phosphorus forms in surface soils of typical peatlands in northern Great Khingan Mountains and its potential to reconstruct paleo-vegetations

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ABSTRACT

Phosphorus was one of the nutrient limitations to vegetations in wetland ecosystem. In peatland, organic phosphorus is accumulated as vegetation residues in anaerobic conditions, affecting the contents of phosphorus pools for long time. It is unclear that different vegetations affect the contents of phosphorus and whether successions of vegetations could reflected by sedimentation of phosphorus forms. Phosphorus forms from six surface soils plots and four dominant vegetations in the north of the Great Khingan mountains were detected to investigate the differences of phosphorus forms of soil between different vegetations. Phosphorus forms and macrofossil were also detected in a 77-cm peat core (1-cm intervals) in TQ. A fingerprinting historical vegetations were reconstructed by phosphors forms to reflect successions of vegetations during 2200 cal yr BP in TQ area. The results showed that the main phosphorus forms in peatland were NaOH-P_o and conc. HCl-P_o. The percentages of inorganic phosphorus forms of trees were generally higher than other vegetations. Moss was more conducive for accumulation of organic phosphorus. $NaHCO_3$-P_i, NaOH-P_i, conc. HCl-P_o and P_i were selected into linear discrimination analysis. The vegetations reconstructed by phosphorus forms were strongly correlated with the pollen records of moss, herbs and shrubs, as well as with macrofossils in herbs. The fingerprinting of vegetations by phosphorus has potential geochemical reference to reflect the successions of vegetation in peatland.

1. Introduction

Phosphorus is one of the most limiting nutrients for terrestrial ecosystems that constrains the magnitude of carbon uptake and primary productivity (Du et al., 2020; Yue et al., 2018). P addition accelerate the succession of vegetation even in extreme climates (Darcy et al., 2018). In peatland, especially in oligotrophic peatland which lack of phosphorus input, the availability of phosphorus become increasingly restricted and controlled to maintain ecosystem (Elser et al., 2007; Zhu et al., 2020). Thus, phosphorus supply for vegetations may be one of the most essential factors of ecosystem development and successions (Lang et al., 2016). Distribution of P in organic and inorganic forms is one of the major physicochemical properties of the soil, closely related to the type of vegetation and actual structure and function of ecosystem (Magid et al., 1996; Turrion et al., 2007). The total organic phosphorus increased combined with increased precipitation and high plant P uptake (Brucker and Spohn, 2019). And the phosphorus forms were used as quality indicators of soil under different vegetation covers due to the tight relationship between phosphorus, soils and vegetations (Turrion et al., 2007). Therefore, it is essential to understand the connection between P forms and types of vegetations in peatland, and to knowing if it can be used as an indicator to distinguish vegetations.

The co-evolution of soils and ecosystem across the chronosequence can found in vegetation composition with geochemical changes (Damian et al., 2020). The biomass and diversity increasing at initial successional phases then may be followed by ecosystem retrogression and biomass decrease (Eger et al., 2011). Phosphorus is gradually preserved in residues of vegetations or accumulated in stable forms during the development of peatlands. And the organic phosphorus forms gradually combine with complex organic compounds, which gradually reduces the

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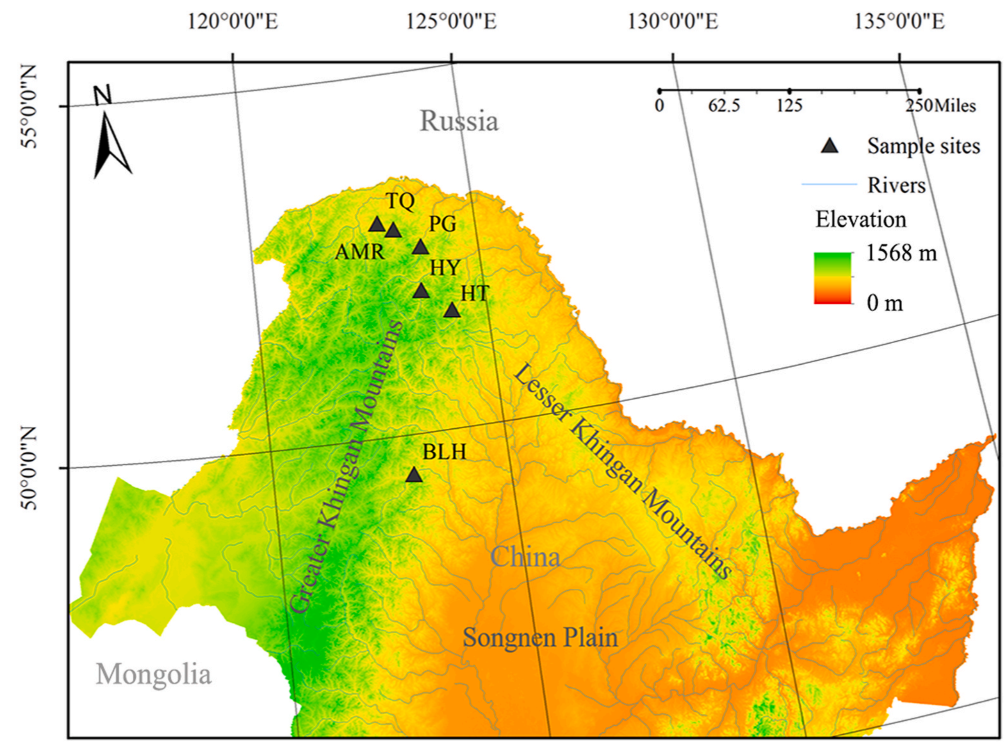

Fig. 1. Locations of sample sites in the Great Khingan Mountains.

bioavailability of phosphorus in soil. Therefore, a thick litter layer formed in this stage which contains a large amount of SOM and P_o and the vegetation community replaced to plants which are more tolerant of low nutrition (Zhou et al., 2013). In general, during successions of vegetations in peatland, most phosphorus was depleted gradually, especially in the early stages of pedogenesis, which resulted in the decreased accumulation of P along the successions, and increased limitation of vegetation (Coomes et al., 2013). Nevertheless, the speed of depletion and accumulation of P was not constant. From geological and environmental perspective, different developmental (successional) histories could result in different accumulations of P (Wang et al., 2012), and quantities and qualities of different P pools transform and varied among the change of parent materials ecosystems and other physico-chemical characteristics (Pupin and Nahas, 2015). Active phosphorus rarely changes between different plants communities, but quantity of different P forms has differences in different vegetations. It has been searched that soil phosphorus forms differed significantly among the vegetation communities during the early, middle and the late successional stages. The phosphorus forms are comprehensively affected by the vegetation communities, microorganism, soil conditions and climate conditions, and represent different content and percentage characteristics in different successional stages (Zhang et al., 2015).

In the peatland, the organic P and residual-P in depressional wetland were higher than riparian wetland (Wang et al., 2008). In profile of soil, excepted resin-P were enriched in the topsoil and decreased rapidly within the profiles, other forms have no uniform trend (Schlichting et al., 2002). Implied that the information on change of phosphorus forms with peatland succession may still retained after leaching process and sedimentation, which is recorded in the sedimentation. However, phosphorus forms was widely used to analyze assess the trends of climate-driven or anthropogenic changes in lake or river sediment record (Tõnno et al., 2013), but rarely used as environment indicator in peatland system for reflecting the history of peatland vegetations succession.

In the north of the Great Khingan Mountains, monsoon activity is the mainly reason that affected the succession of the peatland. The soil layer could be frozen for 8–9 months, which not only develop seasonal frozen layers but distribution of permafrost. Low mean temperature could limit the mineralization of organic matter, as well as that of organic phosphorus (Cassagne et al., 2000). The peatlands in north of the Great Khingan Mountain are less affected by human interference of drainage or agriculture. Avoided the anthropogenic disturbance could to be responsible for bigger differences than vegetations composition and geochemical environment (Han et al., 2020a; Linquist et al., 2010; Saltali et al., 2007). It is suitable as a research place to explore the regular and history of vegetation succession of peatland. The information of P pools changes was more likely maintain in the peat core and changed along with plant community successions.

In this paper, the phosphorus forms in surface soils of different vegetations and in peat core were respectively determined according to the Hedley sequence extraction method, and the phosphorus forms was applied to paleo-environment. The vegetation succession was reflected according to plant-phosphorus forms of surface soils and linear discriminant analysis. Our objectives were to: (1) investigate the distribution of phosphorus forms in soils under different vegetations, (2) select appropriate phosphorus forms as parameter to distinguish different vegetations, and (3) clarify whether the succession of vegetations could reconstructed through phosphorus forms.

2. Materials and methods

2.1. Site description and sampling

The Great Khingan Mountains (E 121.2000–127.0000, N 50.1667–53.5500) are 1000 m above sea level on average. There is a temperate continental monsoon climate, which the winters are cold and dry and summers are hot and wet. The winters and the summers are last from Nov. to Apr. and from Jul. to Aug, respectively. The ice-free period basically last approximately 90–100 days. Study sites was Bilahe (BLH), Hongtu (HT), Huyuan (HY), Amuer (AMR), Tuqiang (TQ), Pangu (PG) (Fig. 1), which are located in the northern of the Great Khingan Mountains. The mean annual temperature and the annual precipitation

Table 1
The site location and vegetations of surface soils.

Sampling sites	Vegetations	Site location (E longitude, N latitude)
BLH	*Carex* spp., *Calamagrostis angustifolia, Betula fruticosa, Salix viminalis* E. L. Wolf	122.9691, 49.4628
HT	*Ledum palustre* L., *Vaccinium uliginosum* Linn., *Carex* spp., *Larix gmelinii*	124.2410, 51.6187
HY	*Betula fruticosa, Ledum palustre* L., *Vaccinium uliginosum* Linn., *Carex* spp., *Larix gmelinii*	123.6318, 51.9438
AMR	*Ledum palustre* L., *Vaccinium uliginosum* Linn., *Carex* spp., *Larix gmelinii*	123.1899, 52.8297
TQ	*Betula fruticose, Vaccinium uliginosum* Linn., *Ledum palustre* L., *Chamaedaphne calyculata, Carex* spp., *Larix gmelinii*	122.8550, 52.943
PG	*Vaccinium uliginosum* Linn., *Ledum palustre* L., *Carex* spp., *Larix gmelinii*	123.7390, 52.5453

ranges from −5 °C to −1.1 °C and 450–550 mm, respectively. The coordinate and vegetation of sites were shown in Table 1.

Surface soils samples (0–3 cm) collected in July 2018 from BLH, HT, HY, AMR, TQ and PG, respectively. Four surface soil samples were collected from each site according to the dominant vegetation, including moss, herbs, shrubs and trees. Except BLH which did not contain moss. In each soil sample under the specified vegetation, the vegetation coverage was higher than 80%. In each site, three soil samples for each dominant vegetations and were collected and mixed together, stored in polyethylene plastic bags and then air dried for laboratory analysis. A 77 cm profile samples were collected in TQ, and the details about the profile, lithology, samples' slicing and storage were showed in Han et al. (2019) (Han et al., 2019).

2.2. Physicochemical analysis

The soil pH value was determined in a 1:2.5 soil/distilled water suspension using pH meter. The C_{org} content was measured using H_2SO_4–$K_2Cr_2O_7$ oxidation followed by titration with $FeSO_4$. Total N was digested with 1:10:100 Se/$CuSO_4$/K_2SO_4 and H_2SO_4, and total phosphorus was digested by using H_2SO_4–$HClO_4$. A SAN++ Continue Flow Analyzer was then used to detect the total P and N of the solution. The Al, K, Ca, Fe, Ti and Mn were digested by using ICP-AES (ICPS7500).

A sequential extraction method was used to analyze the phosphorus fractions from all surface soils samples and profile samples (Tiessen and Moir, 1993). Other details of the extraction were depicted in Li et al. (2020) (Li et al., 2020). Average recovery ranged from 80 to 120%, which calculated from the sum of phosphorus forms and total phosphorus of the soil.

2.3. Plant macrofossil analysis

The changes in species composition from profile samples were determined by the Quadrat and Leaf Count Macrofossil Analysis (Barber et al., 1994). The sub-samples with 1 cm^3 taken from each profile sample were treated, and then the plant macrofossils were identified under a low power (× 10– × 40) stereoscopic microscope and a light microscope (× 100– × 400). Summed up the absolute numbers after several times observation of the same plant macrofossil, and calculated the percentage of the macrofossil species of each plant.

2.4. ^{14}C dating

Carbon-14 radiocarbon dating was used to date peat profile samples. The calibrated ages of four samples (22, 36, 57, 77 cm) were 1065 ± 30, 1645 ± 30, 2020 ± 30 and 3045 ± 35 ^{14}C yr BP, respectively. The details of calibration, age-depth model construction and other details were showed in Han et al. (2019) (Han et al., 2019). The soil under 67 cm were silt and clay, which significantly affected on percentage of phosphorus forms. Therefore, all of the analyzations of data were contained before 67 cm (2200 cal yr BP).

2.5. Statistical methods

In this study, we collected four types of vegetations (moss, sedge shrub and trees) from six site (BLH, HT, HY, AMR, TQ, PG) to evaluate change of potential vegetation types in TQ peatland since about 2200 years ago. The average of phosphorus forms of were used Duncan ($F < 0.05$) to compare the differences between different vegetations. The composite fingerprinting procedure involved three stages. (1) use of phosphorus forms combination to identify the connection of surfaces soils under different dominant vegetation and peat core accumulated during the succession. (2) use of individual phosphorus forms to identify and select properties capable of discriminating different dominant vegetation. (3) use of linear discriminant analysis to provide quantitative estimates of the relative contribution of different dominant vegetation during 2200 cal yr BP. In the first stage, correlation coefficients were Pearson's rank correlation and calculated by Mantel's statistics. The phosphorus forms, organic phosphorus (P_o), inorganic phosphorus (P_i) and ratio of P_i/P_o regarded as the data to assess the links between phosphorus and vegetation types. In the second stage, Kruskal-Wallis H test was used to selected property phosphorus forms that can discriminant different vegetations. In the third stage, linear discriminant

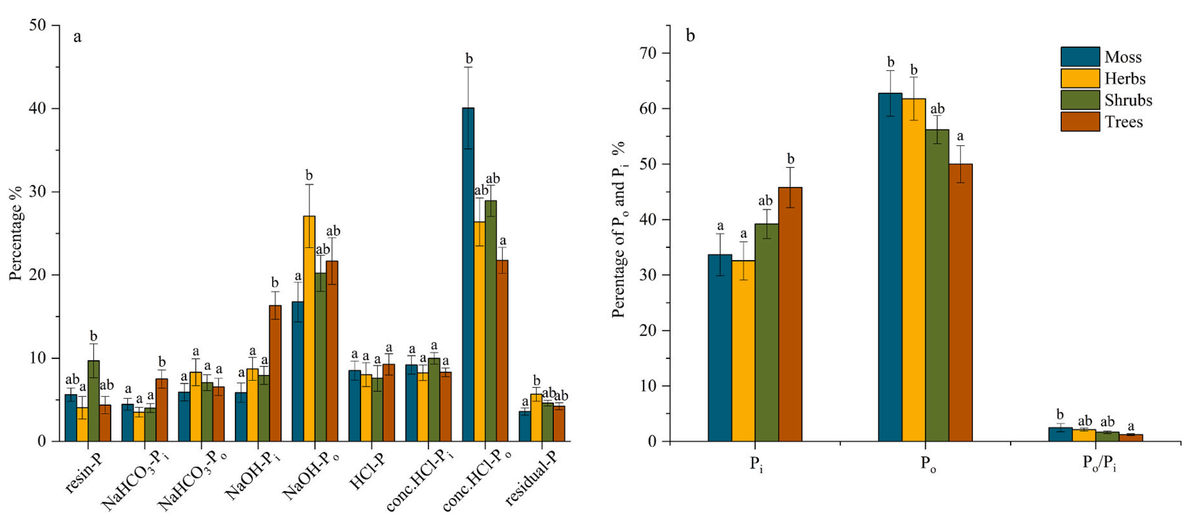

Fig. 2. Percentage of soil phosphorus forms between different vegetation communities.

analysis is a method of linear modelling that is widely used in taxonomy and fingerprinting approaches. A stepwise selection algorithm based on the minimization of Wilkes' lambda ($F < 0.05$) was used in this analysis. Instead of using average results, the data of all samples in each site and each vegetation types were used for linear discriminant analysis (Gao et al., 2019). The Mantel's test and the trees diagram of plant macrofossil cluster analysis was analysed by RStudio 3.4.3. The linear discriminant analysis was analysed by SPSS 23.0. The software Origin 9.0 and Tilia Version 1.7.16 were used to draw the figures. The RDA analysis was analysed and drew by Canoco 5.

3. Results

3.1. General characteristics of surface soils

Table s1 gives an overview on average general chemical properties of surface soils samples. The pH ranged from 3.9 to 6.2. The C_{org} ranged from 7.1% to 75.3%. The content of TN and K ranged from 4.2 to 18 g/kg and 1.3–26 g/kg, respectively. The content of Al, Ca, Fe and Mn, closely connect with inorganic phosphorus, range from 5.2 to 26 g/kg, 3.1–14 g/kg, 2.9–20 g/kg and 0.07–1.9 g/kg. And the content of Ti raged from 0.086 to 2.9 g/kg. The most of the organic carbon of trees were lesser than other vegetations. There was no obvious regular between types of vegetations in pH, TN or other general characteristics.

3.2. Distribution of phosphorus forms between different types of vegetations

In order to reduce the impact of differences in phosphorus content between different regions, the paper uses the percentage of phosphorus forms for calculation and comparison. Among all phosphorus form of vegetation types in the surface soils, the percentage of inorganic P forms with resin-P, $NaHCO_3$-P_i, NaOH-P_i, HCl–P, conc. HCl-P_i, were 4.00–9.08%, 3.24–7.99%, 8.16–18.06%, 7.21–10.56%, 8.28–9.56%, respectively. The percentage of organic P forms with $NaHCO_3$-P_o, NaOH-P_o, conc. HCl-P_o, were 5.26–9.14%, 17.84–27.08%, 21.17–31.83%, respectively. The average percentage content of residual-P was 3.84–5.48% (Fig. 2). The main phosphorus forms of different vegetation was organic phosphorus, especially NaOH-P_o and conc. HCl-P_o. Comparing the difference analysis between different types vegetations, moss has significant different between other vegetations on NaOH-P_o, conc. HCl-P_o, and P_o/P_i. Trees has significant different between other vegetations on $NaHCO_3$-P_i, NaOH-P_i, NaOH-P_o, conc. HCl-P_o, P_i and P_o.

3.3. Correlation coefficients of phosphors forms between surface soils and peat core

The correlation coefficients of phosphorus forms in different vegetations and that in different profile are shown in Fig. s1. The phosphorus forms of herbs showed significant correlation with those of all depth in peat core, which range from 0.54 to 0.63. The moss also had lower significant correlation coefficients than herbs, but slightly increased along with the depth reduced. The correlation of shrubs was the lowest at 25–32 cm without significant correlation from 25 to 40 cm. The correlation of shrubs gradually increased along with depth and strongly correlated on the surface soils. In contrast, the phosphorus forms of trees were the least correlated with all depth of the core, and the correlation coefficient was ranged from 0.29 to 0.45, which had no significant relationship with phosphorus forms of all depth.

3.4. Plant macrofossils in the peat core

The types of macrofossils identified by the core sediment analysis are relatively single, only a few species can be identified, such like *Cyperaceae* (herb), *Ericaceae* (shrub) and *Sphagnum* (moss). Others are non-identifiable monocotyledons. Four main zones were identified based on the cluster analysis of the plant macrofossil assemblages (Fig. s2). Zone A (2200-1500 cal yr BP, 60–37 cm), Zone B (1500-550 cal yr BP, 37–14 cm), Zone C (550-120 cal yr BP, 14–6 cm), and Zone D (120 cal yr BP to now, 6-0 cm), respectively. The percentage of unidentifiable materials were more than 50% before 900 cal yr BP. The *Sphagnum* occurred and sharply increased at beginning of zone C and became the dominant species. Zone B marked a rapid expansion of *Cyperaceae* that reached a maximum at about 800 cal yr BP. The macrofossils were dominated by *Ericaceae* in zone A, and decreased of *Ericaceae* occurred at the beginning of zone C and increased during 900 to 550 cal yr BP. The charcoal slightly increased before 1000 cal yr BP, and reach the highest at about 550 cal yr BP. The percentage of charcoal showed an opposite trend with that of *Cyperaceae*.

4. Discussion

4.1. Distribution of phosphorus forms from differences vegetation communities

The percentages of NaOH-P_o and conc. HCl-P_o were the major organic phosphorus forms in peat, each accounting for approximately 20%–30% of total phosphorus (Fig. 2), which was similar to other organic soil or forest (Makarov et al., 1997, 2004; Solomon et al., 2002; Wang et al., 2011). The co-evolution of soils and ecosystem across the chronosequence was found in vegetation composition with geochemical changes (Damian et al., 2020; Zhou et al., 2016). Different vegetations generally exerted a different rhizosphere effect through geochemical and biological processes then influence P cycling (Fu et al., 2020). When comparing the distinctions between vegetation types, moss showed significant differences from other vegetations on NaOH-P_o, conc. HCl-P_o, and P_o/P_i, especially stable forms such as conc. HCl-P_o. The C/P_o of the moss was the highest among vegetations, and the C/P_o of the trees was the lowest, showing the same conclusion. The conc. HCl-P_o was positively related with C_{org} and was the main organic forms in peat soils. Moss lived in wet and cold environment conditions which decelerate the transformation of organic forms into inorganic forms, and mount of organic phosphorus accumulated into peat.

In contract, there were significant differences between trees and other vegetations on $NaHCO_3$-P_i, NaOH-P_i, conc. HCl-P_o, P_i and P_o. And the percentage of P_i was gradually increased from moss to trees (Fig. 2). In the succession of forest, the intermediately available inorganic phosphorus and organic phosphorus were highest in the late successional stage (Zhang et al., 2015). In peatland, the succession of vegetation communities was distributed along the water conditions. The habitats of herbs and moss were wet and cold, shrubs lived in dry and warm conditions, and the trees lived drier condition than shrubs (Han et al., 2020b). It showed that an appropriate drier condition with more oxygen is beneficial for enhancing organic phosphorus hydrolysis, especially into high active forms such as $NaHCO_3$-P_i and NaOH-P_i in peatland, which was similar with the results when vegetation changed in coast (Huang et al., 2015). Since the microbes lives better in relatively dry and aerobic conditions in humid peatlands which benefit for microbes mineralize process (Liu et al., 2021; Zhang et al., 2015). In generally, dry climate condition always combined with low water-levels, aerobic conditions, these conditions limited the coverage of hygrophilous plants and accelerate the mineralization of organic phosphorus (Bragazza et al., 2005; Brucker and Spohn, 2019; Graham et al., 2005). The vegetation community of five surface soils sites were Ass. Larix gmelinii-Ledum palustre-Sphagnum spp. and Ass. Larix gemelinii-Vaccinium uliginosum-Carex spp. The herbs and shrubs usually associated existed in the northeast of the Great Khingan Mountains, and hardly distinguished based on single phosphorus forms. The only phosphorus form of herbs and shrubs that distinguish with other vegetations were resin-P and NaOH-P_o.

Table 2
Kruskal-Wallis H test.

Tracer property	Chi-square	P-value
Resin-P	4.598	0.204
$NaHCO_3$-P_i	9.512	0.023*
$NaHCO_3$-P_o	1.036	0.793
NaOH-P_i	17.459	0.001*
NaOH-P_o	4.477	0.214
HCl–P	3.728	0.292
conc.HCl-P_i	3.452	0.327
conc.HCl-P_o	14.309	0.003*
Residual-P	3.45	0.327
P_i	8.538	0.036*
P_o	7.842	0.049*
P_o/P_i	7.937	0.047*

* Significant at P = 0.05.

4.2. Fingerprinting paleo-vegetations by selected phosphorus forms

Correlation in all the phosphorus forms between different vegetations and depths of profile in the peat core were quite discrepant (Fig s2). The Metal test with high correlation usually indicate possible potential source of studied area (Legendre and Legendre, 2012). The phosphorus forms of trees were the least correlated with all depth of the core. The pattern of phosphorus corresponded to that of water content (Kim and Rejmánková, 2001). The samples of trees were collected from the edges of the peatland and the soil under *Larix*, which the drier condition was huge different with environment condition of undisturbed peatlands. Therefore, the phosphorus forms from surface soils were related to the peat core, and the accumulation of phosphorus in peat may originate from the phosphorus forms of moss, herbs and shrubs, but not litter of trees (Gao et al., 2019). In addition, the coefficient of moss, herbs and shrubs showed different trend along the depth of profile and significantly correlated with peat core. The gradual increase of moss and shrubs correlation coefficient indicated that moss and shrubs gradually increased in the peat core, which were consistent with the general peatland development process (Han et al., 2019). Therefore, the surface soil left evidences into core in the aspect of phosphorus forms, and correlation of phosphorus in surface and in peat core preliminarily showed vegetation succession.

The Kruskal-Wallis H test was used in order to select the forms of phosphorus that can discriminate between different vegetations (Table 2). Six parameters (resin-P, $NaHCO_3$-P_o, NaOH-P_o, HCl–P, conc. HCl-P_i and residual-P) exhibit P-values higher than the significant value of 0.05, and were therefore removed to establish the linear discriminant analysis at next stage. $NaHCO_3$-P_i, NaOH-P_i, conc. HCl-P_o, P_i, P_o and P_o/P_i were found to be significant in making the discrimination (Carter et al., 2003; Walling, 2013). Four phosphorus forms were selected ($NaHCO_3$-P_i, NaOH-P_i, conc. HCl-P_o and P_i) as tracer phosphorus forms by linear discriminant analysis for reconstructing historical succession of vegetations. The relationship between chemical characteristics and phosphorus forms was analysed by RDA (Fig. 3). $NaHCO_3$-P_i, conc. HCl-P_i and HCl–P were correlated with Ca and Mn. NaOH-P_i was generally referred as Fe and Al-combined phosphorus, and the dilute HCl–P was clearly defined as Ca-associated P (Oliveira et al., 2015; Tiessen and Moir, 1993). The results of the test showed that the most distinctions between phosphorus forms of vegetations were inorganic phosphorus and stable organic phosphorus. Implied that the inorganic phosphorus was more sensitive than organic ones to the changes lead by vegetations or environment (Turrion et al., 2007). In addition, acidic peatland, anoxic conditions and high concentration of carbon with Ca, Fe and Al ensure that most phosphorus can be adsorbed or precipitated into relatively unavailable forms which increase the stable of phosphorus (Eger et al., 2011; Rentch et al., 2008). The organic phosphorus was stable under submergence condition in the wetland sediment (Hedley et al., 1982; Peng et al., 2019). In peatland, the same pattern was showed in the organic phosphorus, especially conc. HCl, caused by its stable chemical properties.

4.3. Paleo-vegetations reconstructed by phosphorus forms and other paleo-records

The changes of vegetations during about 2200 cal yr BP were

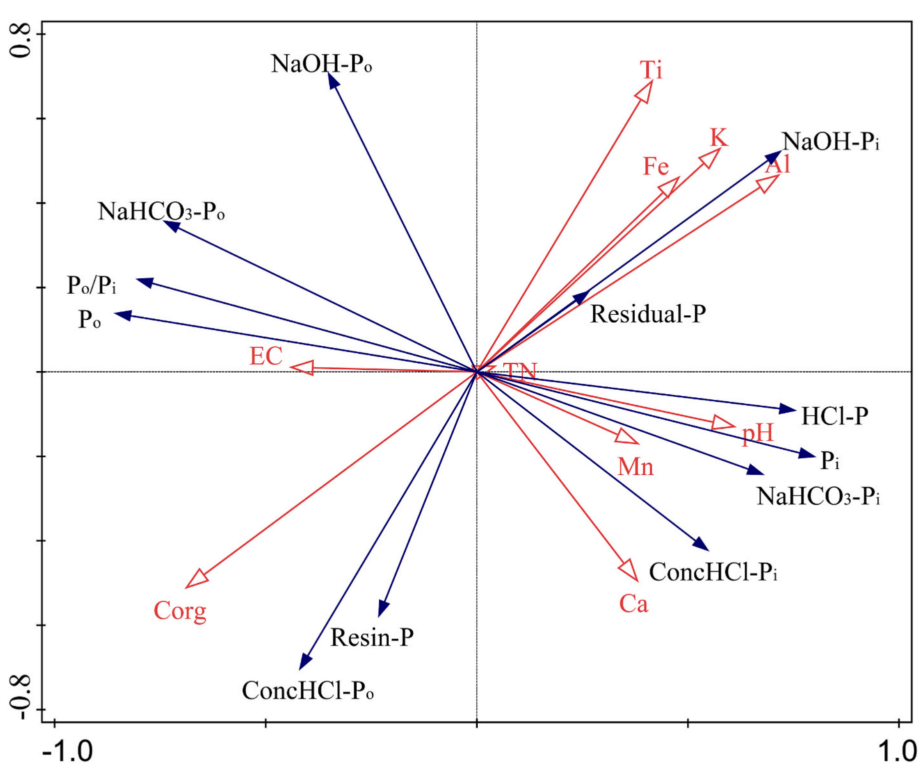

Fig. 3. RDA ordination for correlation of phosphorus forms and general characteristics.

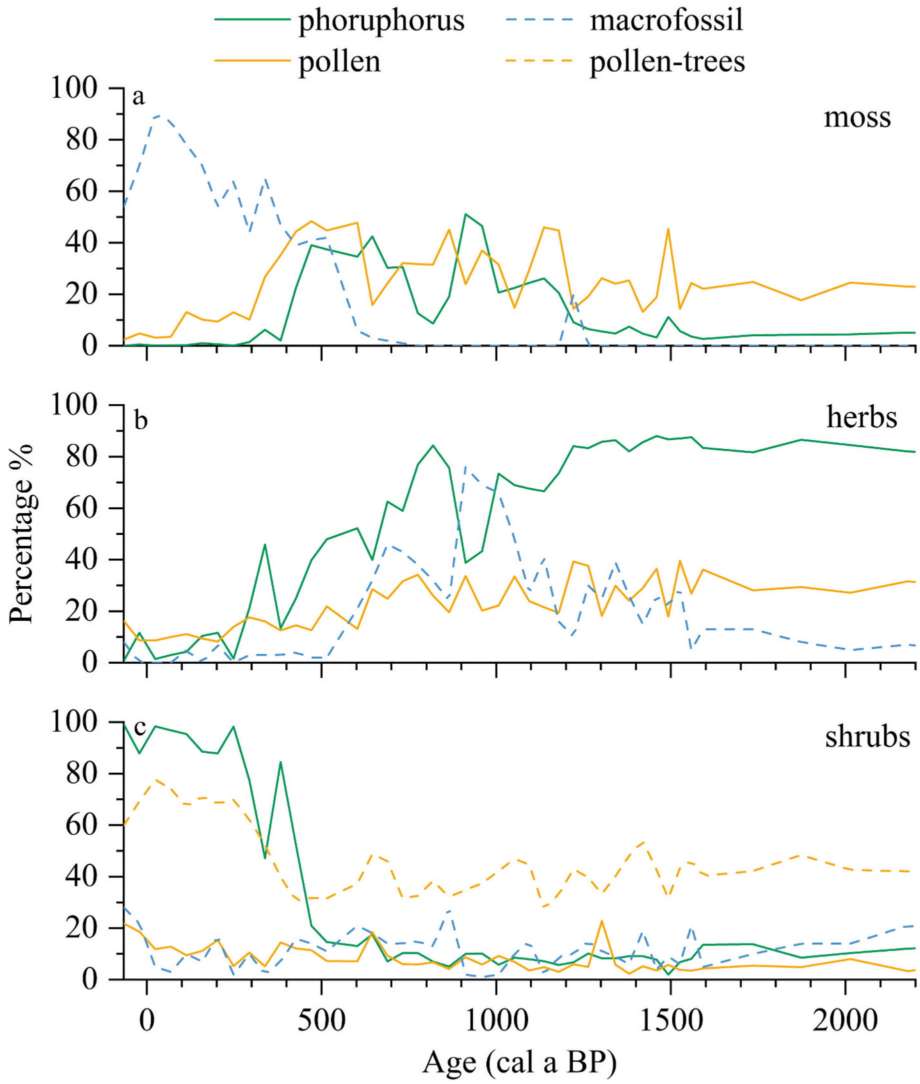

Fig. 4. Historical variations of moss, herbs and shrubs reconstructed using phosphorus forms and pollen records (Han et al., 2019) and macrofossil.

Table 3
Pearson correlation of the vegetations reconstructed by phosphorus forms with pollen and macrofossil records (n = 43).

	Pollen				Macrofossil		
	Moss	Herbs	Shrubs	Trees	Moss	Herbs	Shrubs
Moss-P	0.532[b]	0.178	−0.088	−0.512[b]	−0.286	0.471[b]	−0.24
Herbs-P	0.349[a]	0.786[b]	−0.576[b]	−0.665[b]	−0.863[b]	0.568[b]	0.502[b]
Shrubs-P	−0.532[b]	−0.776[b]	0.552[b]	0.805[b]	0.889[b]	−0.700[b]	−0.353[a]
Trees-P	0.048	0.299[b]	−0.350[a]	−0.148	0.345[a]	−0.021	−0.541[b]

[a] Correlation is significant at the 0.05 level (1-tailed).
[b] Correlation is significant at the 0.01 level (1-tailed).

calculated by Linear discriminant analysis. The changes of different vegetations reconstructed by phosphorus showed a variety of trends (Fig. 4). However, the macrofossil revealed different trends. Considering that the percentage of UOM was higher than 50% before 900 cal yr BP, which may introduced errors in the results, the pollen research results from TQ peatland were introduced to assist the verification of the results (Fig. 4) (Han et al., 2019). The herbs contained *Chenopodiaceae*, *Artemisia*, *Aster*, *Cyperaceae*, *Poaceae* and *Thalictrum*. The shrubs contained *Salix*, *Ericaceae* and *Sanguisorba*, and the trees contained *Betula*. Pearson correlation was applied to examine the relationship between vegetations reconstructed by phosphorus and macrofossil and pollen records (Table 3). The vegetations reconstructed by phosphorus forms were strongly correlated with pollen records of moss, herbs and shrubs, as well as with macrofossils in herbs. In addition, there was a close relationship between the shrubs reconstructed by phosphorus forms and pollen records of trees. It was related to the *Betula* were contain the *Betula fruticosa*, *Betula ovalifolia* and *Betula platyphylla*, which the *Betula fruticosa* and *Betula ovalifolia* were shrubs of peatlands in the northeast of the great Khingan mountains (Han et al., 2019).

The similar trends of vegetations reconstructed by phosphorus and pollen recorded showed that the percentage of moss and herbs always showed opposite trends during about 1500 to 350 cal yr BP. At about 500 to 400 cal yr BP, three evidence also recorded a dramatic change of vegetations. Herbs and moss reconstructed by phosphorus were sharply decreased, which were similar to the pollen records and herbs of macrofossil. And shrubs were rapidly expanded, which corresponded to the increased of shrubs and *Betula* of pollen records. Herbs and moss lives better than shrub in wet conditions. On the other hand, the moss and shrub are more cold-tolerant than herbs (Li et al., 2011). Therefore, the changes of vegetations reconstructed by phosphorus were close to pollen records and also accord with vegetations succession forcing by regional climate, which moderately cold and humid climate conditions before 700 cal yr BP, colder and drier climate in Little Ice Age during 700 to 300 cal yr BP and warm and dry climate after the Little Ice Age (Han et al., 2020b; Wen et al., 2010; Yu et al., 2017). The results of vegetations reconstructed by phosphorus forms were more similar with pollen results. Indicated that different indicator should be interconnected and used (Kim and Rejmánková, 2001). In addition, the fingerprint by phosphorus forms also has potential application ability.

5. Conclusions

Organic phosphorus forms were the main phosphorus forms of different vegetations in peatland, especially the NaOH-P_o and conc. HCl-P_o. The most distinctions between phosphorus forms of vegetations were inorganic phosphorus and stable organic phosphorus. $NaHCO_3$-P_i, NaOH-P_i, conc. HCl-P_o, P_i, P_o and P_o/P_i were found to be significant in discriminating between different vegetations. The proportion of inorganic phosphorus forms of trees were generally higher than other vegetations. Moss was more conducive for accumulation of organic phosphorus, especially into stable forms such as conc. HCl-P_o.

$NaHCO_3$-P_i, NaOH-P_i, conc. HCl-P_o and P_i were selected into linear discrimination analysis to reconstructed changes of vegetations during 2200 years. The vegetations reconstructed by phosphorus forms were strongly correlated with pollen records of moss, herbs and shrubs, as well as with macrofossils in herbs. The fingerprinting of vegetations by phosphorus has potential geochemical reference to reflect the successions of vegetation in peatland. Different indicator should to be interconnected and used. In future, it is necessary to add more region for confirm the universality and limitations of reconstructing the peatlands succession by P.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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Credit author statement

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