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Impact of vegetation zones on soil phosphorus distribution in Northwest China

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Abstract: Soil phosphorus (P) fraction distribution and correlation at different soil depths along vegetation succession in wetland next to a lake in the Hongjiannao National Nature Reserve, China were studied using the Hedley fraction method. The overall trend for soil P content was calcium-bound P (Ca-P) > organic P (O-P) > aluminum/iron-bound P (Al/Fe-P) > labile-P (L-P). Ca-P and O-P were the predominant P forms in all the soil layers, representing on average 53.8–84.9% and 12.9–45.2% of the total P, respectively, whereas L-P (ranging from 0.5 to 1.5 mg/kg) was less than 1%. The soil in the *Bassia dasyphylla* and *Carex duriuscula* vegetation zones had the largest P contents. In these two vegetation zones, soil L-P was greatest in the surface soil layer; Al/Fe-P was most abundant in the deep layer; O-P was highest in the middle layer. Ca-P levels were generally similar across all soil layers. Regression analysis showed that distribution of P was highly correlated with organic carbon, total nitrogen and plant biomass. Results showed that the soils under *Bassia dasyphylla* and *Carex duriuscula* have considerable carbon input potentials, which would facilitate P mineralization as compared to other plants.

Keywords: arid area; land cover; soil profile; phosphorus speciation; management practice

Phosphorus (P) is one of the indicators of wetland nutrient levels and reaches a steady biogeochemical state under natural conditions (Grunwald et al. 2006). Soil P fraction can be used to assess the availability, solubility, and dynamics of soil P under different land-use management systems (Sheklabadi et al. 2014). Hedley Continuous Extraction method divides P in wetland soils into labile-P (L-P), aluminum/iron-bound P (Al/Fe-P), calcium-bound P (Ca-P) and organic P (O-P) (Hedley et al. 1982, Cassagne et al. 2000, Cross and Schlesinger 2001, Dossa et al. 2010). Total P (T-P) in soils is commonly reported between 200 and 800 mg/kg (White and Hammond 2008). O-P fractions can operate as a source of soluble P for the soil solution (Richardson et al. 2005). L-P is an accurate indicator of the availability of soil P, which is the final product of plant residues decomposition, and is easily absorbed by plants (Castillo and Wright 2008, Sheklabadi et al. 2014).

Hongjiannao Lake is the largest desert freshwater lake in China and an important habitat for endangered birds. However, the lake area has shrunk by 25.5 km^2 due to human factors and the reduction of natural precipitation, which seriously threatens wetland biodiversity (PRCNBS 2016). Solving the problem of P nutrition to maintain plant growth and protect wetland soil biological community has become a research hotspot. Previous studies on P grading focused on farmland and forest ecosystems, there was limited research on P fractions in arid or semi-arid wetlands. Therefore, a proper

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understanding of nutrient cycles in arid lands is very important (Dieter et al. 2010).

P fractions and their profiles in wetland soil are controlled by soil factors (Samadi and Gilkes 1998, Cassagne et al. 2000). In addition, visible biomass differences among plant species are inevitably linked to different P utilization efficiencies. Information about the distribution of the P forms in wetland soils along vegetation succession would improve the assessment of P availability and how it develops along vegetation gradients (Huang et al. 2015). The objectives of this study were to determine the effects of different vegetation succession on soil P distributions and identify the key factors influencing soil P and distributions of P fractions in the desert area.

MATERIAL AND METHODS

Study area. The Hongjiannao National Nature Reserve (HNNR, ~10 768 ha) is located in the northwest of Shaanxi province in China (38°13'N, 109°42'E to 39°27'N, 110°54'E) (Figure 1). The site has average annual precipitation of 400 mm and the average annual temperature was 8.9°C (PRCNBS 2016). The HNNR has a typical plant species landward succession around Hongjiannao Lake. This can be summarized as: (1) *Bassia dasyphylla* dominates the salt swamp area; (2) *Carex duriuscula* dominates the meadow zone; (3) *Stipa bungeana* is the dominant species in grassland; (4) *Phragmites australis* dominates the sandy grassland zone; and (5) *Artemisia arenaria* is the dominant species in sand area (Figure 2). HNNR provides an ideal region to study P geochemistry behavior in desert soils.

Soil sampling and analysis. Sampling was conducted in the Zhashak River sub-basin. Five sampling sites were selected along the vegetation succession, zones A, P, S, C and B (Figure 2), and at each zone, triplicate sample plots were set up through the GPS system. In each sample plot, plant species, plant coverage and plant biomass were investigated. Soil samples were collected from a depth of 0–10, 10–20 and 20–30 cm layer with T-handle probe. Soil properties were analyzed by standard agricultural chemical analyses (Bao 2000). Soil pH was measured using a multi-parameter analytical meter. Soil moisture content was determined by the oven drying method. Soil organic carbon (OC) was determined following the method of thermal oxidation by potassium dichromate dilution (Bao 2000). Besides, total nitrogen (TN) was measured using the VarioEL III element analyzer (Elementar, Hanau, Germany). In this study, correlation analysis was calculated from the SPSS software (Model 19.0, IBM-SPSS, Armonk, USA).

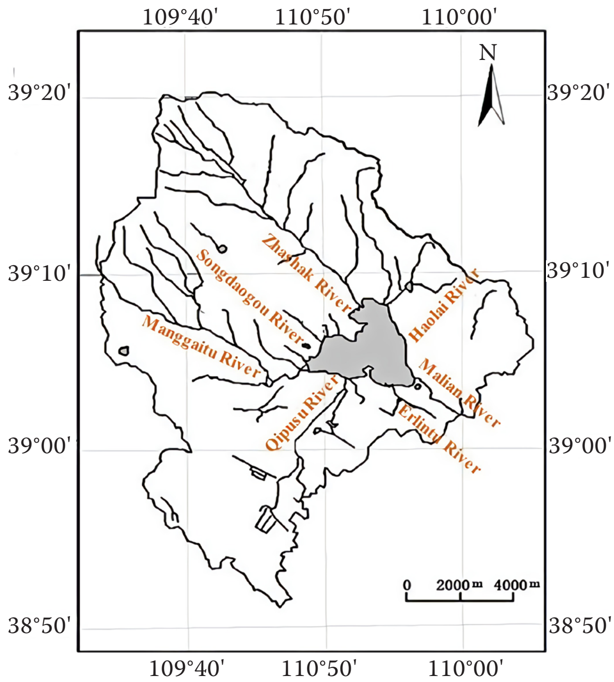

Figure 1. Location of the sampling site

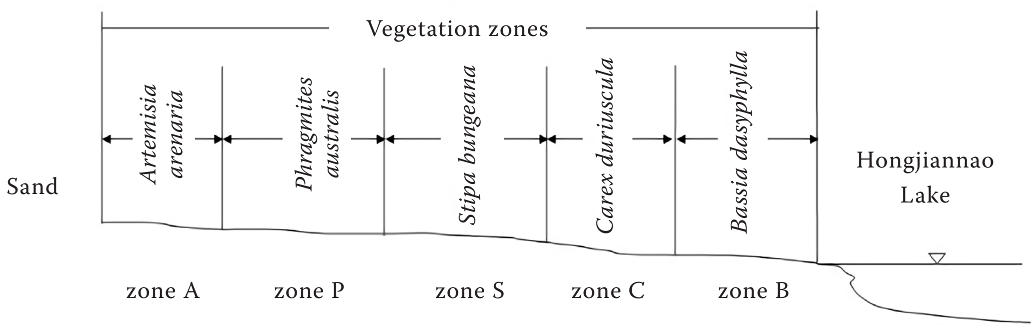

Figure 2. Schematic diagram of zonal structure in the study area

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Soil P fraction. All soil samples were air-dried at room temperature and were ground through a 2-mm sieve (100 mesh). A modified Hedley sequential extraction was used to measure P fraction. Briefly, step 1 was to determine L-P. 0.5 g soil samples was placed in 50-mL polypropylene centrifuge tube, added with 25-mL 0.01 mol/L KCl, shaken for 2 h, and then centrifuged at 6000 rpm (23 797 g) for 10 min. P contained in the supernatant of the centrifuge tube was considered as L-P (Bowman and Cole 1978). The sediments of the centrifuge tube were resuspended with deionized water (conductivity = 0.55 mS/m), filtered through filter paper (Jinteng PES, 0.45 μm). The residue retained by the filter paper was kept under 4°C. Step 2 was to extract Al/Fe-P component. The aforementioned residue was added with 25 mL 0.1 mol/L NaOH, shaken for 17 h and centrifuged for 10 min and then set aside (Syers et al. 1969). Step 3 was to analyze Ca-P. The remaining aforementioned residue was extracted with 25 mL 0.5 mol/L HCl, shaken for 24 h, and centrifuged for 10 min (Syers et al. 1969). Besides, step 4 was to measure soil T-P by the acid-soluble spectrophotometric method (Bao 2000). O-P considered as residual P was calculated indirectly by the differences of T-P minus sum of three P fractions (Noll et al. 2009). All of the P was determined using the Extraction-Phosphomolybdate Blue spectrophotometry method (model Cintra 101, GBC Scientific Equipment, Braeside, Australia) at 710 nm with 10-mm path length cuvette (Xu et al. 2006).

RESULTS AND DISCUSSION

General properties of the test soils. Table 1 showed that the soil moisture content decreased rapidly from zone B to zone A. The soil pH in the study area varied from 8.8–9.2 with comparatively small variations between the different zones (Figure 2). As soil moisture content was higher in soils with *Bassia dasyphylla* (zone B) and *Carex duriuscula* (zone C), the OC and TN contents have the same patterns. The proportion of sand, silt, and clay ranged from 13.8–96.5, 3.4–79.4, and 0.1–7.3%, respectively. The vegetation cover significantly modified the soil quality in the study area. Both *Bassia dasyphylla* and *Carex duriuscula* had much greater biomass capacity. This led to the largest OC levels in the soil with *Bassia dasyphylla* since it depends on biomass through root exudates and plant residue input (Gul et al. 2014).

Soil P distribution. Figure 3 showed that the T-P content ranged from 88.3 to 277.4 mg/kg, and L-P was between 0.5 and 1.5 mg/kg. The Ca-P and O-P represented the largest P fractions and ranged from 62.8 to 177.8 mg/kg and 22.9 to 96.4 mg/kg, respectively. The overall trend in P content was Ca-P > O-P > Al/Fe-P > L-P. T-P, Ca-P and O-P varied considerably between different plant covers. All the P fraction contents were highest in the soils collected from the *Bassia dasyphylla* and *Carex duriuscula* zones. In these two soils, the L-P content was highest in the surface layer; Al/Fe-P was most abundant in the deep layer; and O-P was abundant in the middle soil layer. Ca-P did not vary greatly between soil layers, but was slightly higher in surface and deep layers. The vegetation succession of *Bassia dasyphylla – Carex duriuscula – Stipa bungeana – Phragmites australis – Artemisia arenaria* led to a downward trend in T-P and the P fractions. The Ca-P and O-P fractions and the T-P content had a similar change pattern since the P content in the study area was low and mainly present as Ca-P and O-P.

The L-P content was lower than other P forms, and varied slightly. Deposition in the 0–10 cm soil layer was slightly higher than the other layers

Table 1. The average value of soil properties in the Hongjiannao National Nature Reserve under each vegetation cover

Zone and vegetation	Biomass (g/m^2)	Soil moisture (%)	pH	OC (mg/kg)	TN (mg/kg)	Mechanical composition		
						sand (%)	silt (%)	clay (%)
Bassia dasyphylla	425.5	50.7 ± 12.5	9.0 ± 0.2	12.6 ± 1.8	965.9 ± 260.3	13.8 ± 2.5	79.4 ± 1.9	6.9 ± 0.8
Carex duriuscula	43.7	29.7 ± 3.7	9.0 ± 0.1	10.9 ± 0.9	1069.2 ± 160.6	16.0 ± 12.1	76.7 ± 9.6	7.3 ± 2.5
Stipa bungeana	33.1	10.6 ± 9.9	9.2 ± 0.5	3.3 ± 2.0	296.20 ± 350.4	61.6 ± 11.0	35.1 ± 10.0	3.4 ± 0.9
Phragmites australis	31.8	1.9 ± 0.6	8.9 ± 0.2	1.1 ± 0.4	66.0 ± 19.0	95.7 ± 1.1	4.1 ± 1.0	0.2 ± 0.1
Artemisia arenaria	51.3	1.2 ± 1.1	8.8 ± 0.0	1.1 ± 0.2	33.9 ± 8.4	96.5 ± 0.6	3.4 ± 0.5	0.1 ± 0.1

TN – total nitrogen; OC – organic carbon

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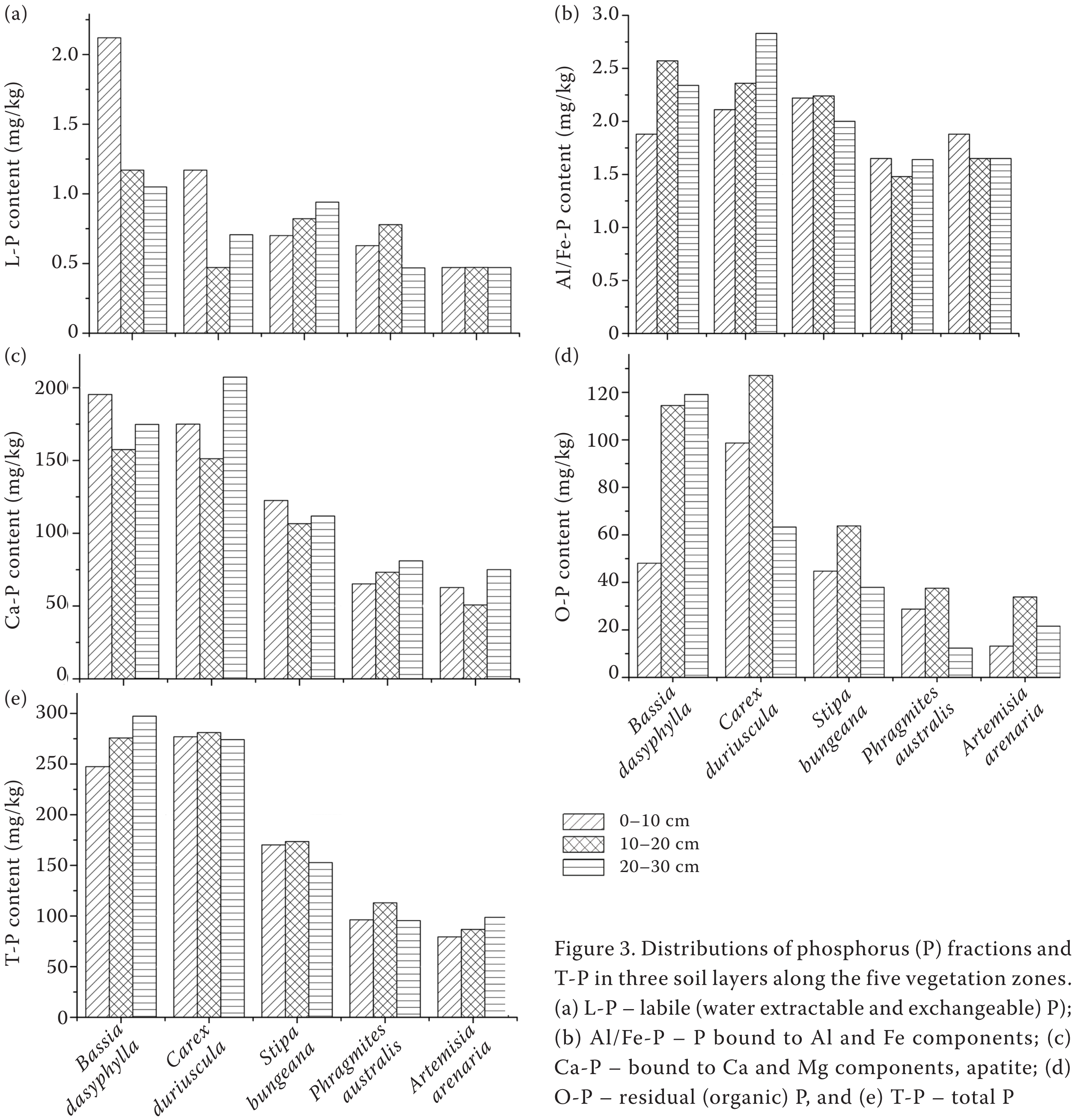

Figure 3. Distributions of phosphorus (P) fractions and T-P in three soil layers along the five vegetation zones. (a) L-P – labile (water extractable and exchangeable) P); (b) Al/Fe-P – P bound to Al and Fe components; (c) Ca-P – bound to Ca and Mg components, apatite; (d) O-P – residual (organic) P, and (e) T-P – total P

under *Bassia dasyphylla*. The water solubility of soil P was poor, and that soil P availability was low (Shariatmadari et al. 2006). The accumulation of L-P in the surface soil layer of zone B may be a result of vegetation decay and the OC decomposition. Furthermore, during vegetation growth, root exudation, such as the release of H^+ ions, increases the solubility of P forms in soils (Hedley et al. 1982) (Figure 3a).

The Al/Fe-P fraction has a strong release activity and plays an important role in the exchange of P at the soil-water interface. A higher value was observed in the deeper *Carex duriuscula* soil layer (Figure 3b). This was due to leaching and the translocation of secondary minerals in the soil profile through preferential paths in the root system (Owens et al. 2008, Sheklabadi et al. 2014). The average Al/Fe-P content was high in zones B and C (Figure 3b), as the soils were located close to the lake, partial saturation of the soil profile led to an increase of Al/Fe-P levels in this layer. It is equally possible that there was vertical translocation of P by leaching or associated colloids in the soil (Dieter et al. 2010).

Ca-P accounted for most of the P content (about 53.8–84.9%). The largest amount of inorganic P

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in semiarid wetland was stored in the form of HCl-extractable P (Ca-P) (Wang et al. 2008). Ca-P content was relatively consistent at different soil depths and among vegetation zones (Figure 3c). Ca-P is an inert form of P, and its levels are mainly determined by the local soil texture (Yang et al. 2015). Studies have shown that the main sources of Ca-P in sediments are authigenic P and calcium phosphate minerals, such as hydroxyapatite.

O-P mainly refers to the P in the organic carbon from various animal and plant residues found in the soil. The change in vegetation zones caused a decrease in vegetation coverage, which led to a reduction in soil O-P content. Soil OC is an important source of O-P. The higher O-P levels in the 10–20 cm soil layer for all the vegetation zones due to the increased soil OC content. The lowest O-P levels were found in *Phragmites australis* soil (12.3 mg P/kg) and *Artemisia arenaria* soil (13.2 mg P/kg) (Figure 3d). In these two zones, soil degradation was serious, and the land is no longer suitable for mass vegetation growth.

The T-P content did not vary much between the three soil layers, except for the *Bassia dasyphylla*

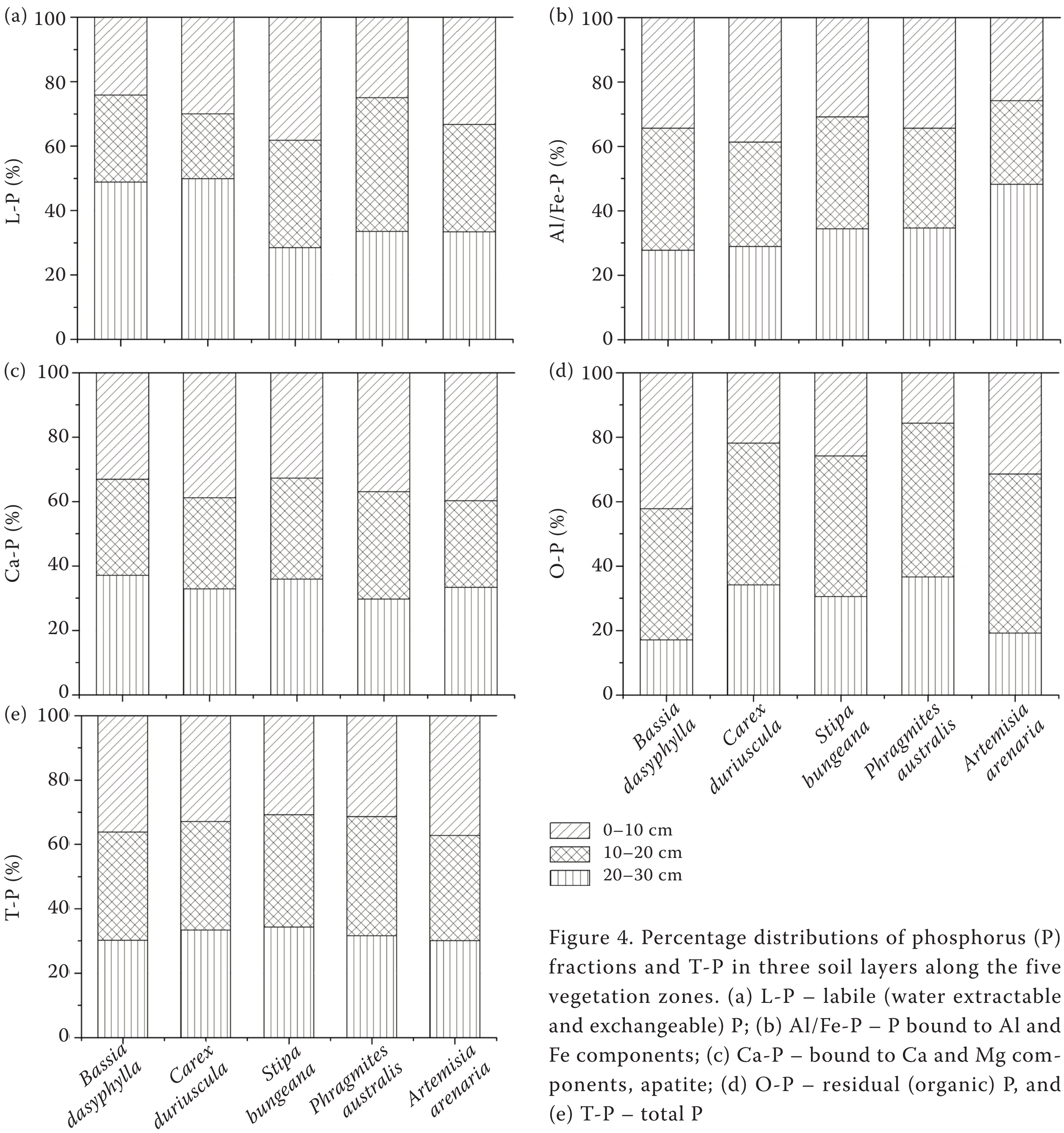

Figure 4. Percentage distributions of phosphorus (P) fractions and T-P in three soil layers along the five vegetation zones. (a) L-P – labile (water extractable and exchangeable) P; (b) Al/Fe-P – P bound to Al and Fe components; (c) Ca-P – bound to Ca and Mg components, apatite; (d) O-P – residual (organic) P, and (e) T-P – total P

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vegetation zone, where the uneven distribution of O-P content affected T-P levels (Figure 3e). As the vegetation zone changed from *Bassia dasyphylla* to *Artemisia arenaria*, the soil water content, the vegetation coverage and the soil clay particle content decreased, whereas the soil texture coarsened, which all led to a decrease in the T-P content. Notably, the change in vegetation zones significantly affected O-P and Ca-P content, which indicated a decline in soil fertility. In particular, the soil P content represented by O-P declined by 26% as the vegetation zones changed (in the 20–30 cm soil layer, O-P accounted for 42% and 16% of the P in the *Bassia dasyphylla* and *Phragmites australis* soil, respectively) (Figure 3).

Figure 4 shows the distribution of each P fraction in soil layers of the different vegetation zones. L-P was most affected by the change in vegetation zones. The L-P proportion in the surface soil layer under *Bassia dasyphylla* and *Carex duriuscula* was 48.9% and 49.8%, respectively, and was 33.3% in the surface layer of the *Artemisia arenaria* soil. The change in vegetation zones led to a 16% L-P decrease in the surface soil layer (Figure 4a). The Al/Fe-P and Ca-P proportions in the three soil layers slightly varied between the different vegetation zones, which improves the distribution model for T-P (Figures 4b,c). The Al/Fe-P percentage content showed an upward trend as the land cover changed from *Bassia dasyphylla* soil (0.8%) to *Artemisia arenaria* soil (3.9%). The O-P was highly concentrated in the 10–20 cm soil layer of all the vegetation zones, which was due to higher soil OC input (Figure 4d). The parent material, with its high P content, was eroded by weathering, which then enriched the soil and fixed O-P (Hedley et al. 1982).

In general, as the plant species landward succession changed from *Bassia dasyphylla* to *Artemisia arenaria*, both P fraction and the T-P content decreased (Figure 4). L-P, Al/Fe-P were easily absorbed and utilized by plants. Furthermore, Ca-P and O-P served as a reserve for nutrition. These results suggest a decline in soil fertility (Wang et al. 2008). The above results showed that *Bassia dasyphylla* soil and *Carex duriuscula* soil can better protect the P fraction contents, thereby maintaining soil fertility and reducing soil desertification.

Correlation analysis. Correlation analysis can be used to determine the relationship between each P component and their correlation with various environmental factors. P forms were negatively correlated with sand content and positively associated with silt and clay levels. This is confirmed by the results obtained in this study (Table 2). Often, clay content correlates with soil organic C and P because a high sand content allows a higher rate of P leaching as water percolates through the soil. No significant correlations were observed between T-P, L-P, Al/Fe-P, Ca-P, O-P and soil pH.

Table 2. Physicochemical properties correlation matrix ($r > 0.9$) for the soil phosphorus (P) fractions

	T-P	Biomass	L-P	Al/Fe-P	Ca-P	O-P	Moisture	Organic	TN	pH	Sand	Silt	Clay
T-P	1	0.84	0.90	0.73	0.958*	0.96	0.99	0.93	0.90	0.44	–0.97	0.97	0.96
Biomass		1	0.97	0.44	0.65	0.67	0.87	0.65	0.54	–0.04	–0.69	0.70	0.64
L-P			1	0.48	0.75	0.75	0.91	0.70	0.63	0.20	–0.78	0.78	0.74
Al/Fe-P				1	0.77	0.78	0.73	0.78	0.81	0.37	–0.80	0.80	0.81
Ca-P					1	1.00	0.94	0.98	0.99	0.60	–1.00	1.00	1.00
O-P						1	0.95	0.99	0.99	0.54	–1.00	1.00	0.99
Moisture							1	0.933*	0.88	0.33	–0.96	0.96	0.93
Organic								1	0.98	0.46	–0.98	0.98	0.97
TN									1	0.60	–0.98	0.98	0.99
pH										1	–0.55	0.55	0.60
Sand											1	–1.00	–1.00
Silt												1	1.00
Clay													1

T-P – total P; L-P – labile (water extractable and exchangeable) P); Al/Fe-P – P bound to Al and Fe components; Ca-P – bound to Ca and Mg components, apatite; O-P – residual (organic) P; TN – total nitrogen; + – positive correlation; – – negative correlation; *$P < 0.05$

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There was a strong correlation between soil T-P and Ca-P. T-P content in the soil is affected by soil texture, especially soil mechanical composition, all forms of P are adsorbed on the finer and clay particle fractions (due to their high specific surface energy). The L-P was highly correlated with biomass and moisture (Table 2). During vegetation growth, the root system releases L-P from the soil. The Al/Fe-P was not strongly correlated with other P forms, except for a small positive correlation between clay and finer particles (Reddy et al. 1995). The strong correlation between O-P and OC, clay and silt contents indicated that O-P was associated with OC complexes (Shenoy and Kalagudi 2005). There was a positive correlation between soil O-P and Ca-P ($P < 0.05$), both of which are inert P forms. Their relative contents were stable and hardly affected by soil properties.

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