Seasonal variations in phosphorus fractions in semiarid sandy soils under different vegetation types

Qiong Zhao [a], De-Hui Zeng [a,*], Zhi-Ping Fan [a], Zhan-Yuan Yu [a], Ya-Lin Hu [a], Jianwei Zhang [b]

[a] Daqinggou Ecological Station, Institute of Applied Ecology, Chinese Academy of Sciences, 72 Wenhua Road, Shenyang, Liaoning 110016, China
[b] USDA Forest Service, Pacific Southwest Research Station, 3644 Avtech Parkway, Redding, CA 96002, USA

ARTICLE INFO

ABSTRACT

We investigated the seasonal patterns of soil phosphorus (P) fractions under five vegetation types – *Ulmus macrocarpa* savanna, grassland, *Pinus sylvestris* var. *mongolica* plantation, *Pinus tabulaeformis* plantation, and *Populus simonii* plantation – in the southeastern Keerqin Sandy Lands of China. The measured P fractions (0–20 cm depth) included: soil total P (TP), total organic and inorganic P (TPo and TPi), bicarbonate extractable organic and inorganic P (BPo and BPi), microbial biomass P (MBP), and *in situ* resin-adsorbed P (resin-P). Soil TP and TPo concentrations in the savanna and grassland were significantly lower in summer than in spring and autumn. However, they were relatively stable in three forest plantations. Soil labile P fractions showed a significant seasonal pattern under all vegetation types with the peak in summer, except soil MBP that was constant in the savanna and grassland and BPo that decreased over time in the savanna. This pattern of labile P fractions was attributed to a combination of seasonal climatic changes, low P availability, as well as the biological controls of soil P transformation in the study area. Litter decomposition played a key role in soil P availability. The monthly resin-P released from litter decomposition in summer was 2.6–7.4 times greater than in other seasons, and was 1.7–3.4 times of that in the 10 cm depth soil. Concentrations of soil P fractions were obviously affected by vegetation type. The savanna had the highest total P and MBP concentrations and the *P. tabulaeformis* plantation had the highest BPi and resin-P among all vegetation types. Among forest plantations, *P. simonii* plantation had the highest total P and MBP. These results suggest that *U. macrocarpa* savanna is the best system conserving soil nutrient (particularly P) stocks and microbial activity, followed by the grassland and *P. simonii* plantation, while the pine plantations are the worst.

© 2009 Elsevier B.V. All rights reserved.

1. Introduction

Biogeochemical transformation of different forms of organic and inorganic phosphorus (P) controls soil P availability (Frossard et al., 2000; Chen et al., 2003). Soil P transformation processes, particularly mineralization – immobilization of organic P, are strongly influenced by seasonal variations in temperature, moisture, plant growth and root activity, and by organic matter accumulation from litterfall and rhizodeposition (Perrott et al., 1990; McGrath et al., 2000). Therefore, better information on seasonal variations in soil P fractions is needed to improve our understanding on soil P transformation processes and the underlying mechanisms (Magid and Nielsen, 1992). Since the 1950s, people started to study the seasonal variations in soil P availability and fractions on cropland and pasture (Perrott et al., 1990; Magid and Nielsen, 1992; Oberson et al., 1999). Recently, a few studies on

grassland, savanna, and forest were also reported (Fabre et al., 1996; Chen et al., 2003; Styles and Coxon, 2007). However, the conflicting seasonal patterns were observed for soil P fractions, especially for labile P and microbial biomass P due to the varied climates, soils, and vegetation types (Oberson et al., 1999; Picone et al., 2003; Styles and Coxon, 2007). Moreover, most of these studies were conducted in tropical or humid temperate regions where water may not be a limiting factor. Little is known about soil P dynamics in arid and semiarid regions, where soil P transformation differs greatly from that in humid regions (Cross and Schlesinger, 2001; Zhao et al., 2007).

Land cover change also affects soil properties and biogeochemical processes (Ross et al., 1999; Zeng et al., 2009). The topic has attracted much attention worldwide due to a significant land cover change caused by increase of human population and climate change in recent decades. Land cover change may alter soil P transformation by modifying the amount of plant P demand, litter quality and quantity, and soil physical, chemical, and biological properties (e.g. Ross et al., 1999; Chen et al., 2003, 2008). Afforestation is one of the major forms of land cover change in

semiarid regions. Its effects on soil P status and availability depend on environmental conditions, tree species, pre-afforestation vegetation type, and the time scale of afforestation (Jaiyeoba, 1998; Chen et al., 2003; Farley and Kelly, 2004). Although soil P transformation with afforestation has been studied at a single time within a growing season, knowledge on the effects of afforestation on seasonal dynamics of soil P is limited (Chen et al., 2008).

In this study, we investigated seasonal variations in P fractions and *in situ* resin-adsorbed P in the topsoil of five vegetation types (elm savanna, grassland, two coniferous plantations and one broadleaf plantation) in the southeastern Keerqin Sandy Lands of China. This region was severely affected by desertification with 22.1% of the total land areas (5.17 million ha) by the late 1950s (Jiang et al., 2002). Since the 1950s, extensive afforestation has been carried out in the area, primarily for soil erosion control and for timber production (Zeng and Jiang, 2006). By studying the impacts of afforestation with Mongolian pine (*Pinus sylvestris* var. *mongolica*) on soil carbon (C) and nitrogen (N) transformations in the southeastern Keerqin Sandy Lands, we found the significant seasonal variations in soil C and N mineralization rate, and that land cover change significantly influenced soil chemical and biological properties associated with C and N transformations (Chen et al., 2006; Zeng et al., 2009). Another study on soil P properties in the same area revealed that total P and available P were at the very low level and organic P accounting for 40–80% of total P was the main source of plant available P (Zhao et al., 2007). The main objective of this study was to determine the seasonal patterns of soil P fractions under a semiarid climate and how these patterns vary among different land covers.

2. Methods

2.1. Site description

The study was conducted at the Daqinggou National Nature Reserve in the southeastern Keerqin Sandy Lands, Inner Mongolia, China (42°45′–42°48′N, 122°13′–122°15′E, elevation 240 m asl). This semiarid region under the temperate climatic zone is characterized by a cold and dry winter and a relatively hot and moist summer. The mean annual precipitation is around 450 mm, with more than 60% of rainfall occurring during June–August. The annual potential evaporation is 1300–1800 mm. The annual mean temperature is 6.4 °C, with the maximum monthly mean temperature in July (23.8 °C) and the minimum in January (−12.5 °C). The monthly mean temperature and precipitation in 2006 are shown in Fig. 1. The soil is an aeolian sandy soil (Typic Ustipsamment, sand: 90.9%, silt: 5.0%, clay: 4.1%), and is deficient
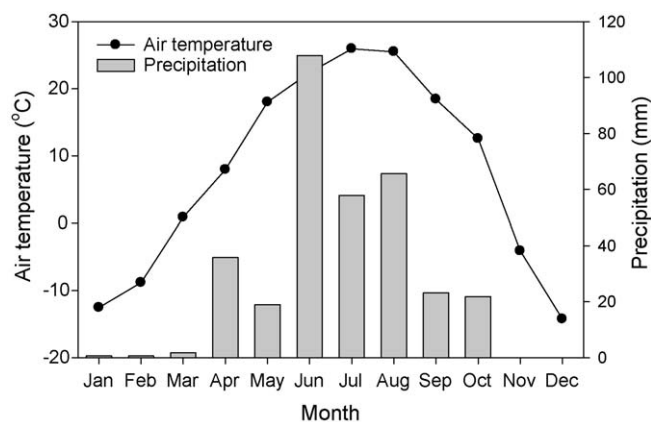
in N and P. Soil water holding capacity is between 10% and 12% (by weight).

The Daqinggou National Nature Reserve, covering an area of 8183 ha, was established in 1980 from a forest farm to conserve the remnant broadleaf deciduous forest. A ravine along which the remnant forest is distributed is 24 km long and 200–300 m wide. The landscape surrounding the ravine is characterized by flat stable sand dunes, where a large area of Mongolian pine plantation is interspersed by small patches of savanna, grassland, Chinese pine (*Pinus tabulaeformis*) and poplar (*Populus simonii*) plantations.

Five vegetation types typical of the region were selected within the reserve for this study: (1) elm (*Ulmus macrocarpa*) savanna (SA), which primarily consists of dense grasses (dominantly *Artemisia scoparia*, *Erodium stephanianum* and *Phragmites communis*), sparse elm trees and shrubs of *Lespedeza bicolor*, *Prunus armeniaca* and *Crataegus pinnatifida*; (2) grassland (GS), which is dominated by *Polygonum divaricatum*, *Setaria viridis*, *L. bicolor* and *Cleistogenes squarrosa*; (3) 22-year-old Mongolian pine plantation (MP); (4) 22-year-old Chinese pine plantation (CP); (5) 15-year-old poplar plantation (PO). The elm savanna and grassland are natural vegetations, and monospecific Mongolian pine, Chinese pine and poplar plantations are the most widespread forest plantations in the southeastern Keerqin Sandy Lands. All forest plantations were established on the degraded grassland in April by planting nursery-raised seedlings in pits of 40 cm × 40 cm × 40 cm size at a spacing of 3 m × 1 m or 2 m × 2 m. After the seedlings were planted, no management practice and disturbance was applied such as fertilization, competing vegetation control, and grazing, except that about 25% of the crown was pruned after plantations were 15–17 years old for the pines and 5–6 years old for the poplars.

2.2. Soil sampling and laboratory analyses

We established five 20 m × 20 m plots for each vegetation type for soil sampling. We randomly selected these plots from different vegetation types in a flat topography located within an about 100 ha area to ensure similar soil type and climatic condition. We collected soil samples four times during the growing season in 2006: May 1 (late spring), July 1 (middle summer), August 8 (late summer), and October15 (late autumn). In each plot, we randomly collected 10 soil cores from 0 to 20 cm mineral soil with a 6 cm diameter auger and combined them into one sample. Soil samples were placed in ziplock plastic bags and brought to the laboratory. In the laboratory, each field moist soil sample was sieved to pass a 2 mm mesh to remove roots and plant debris, and then was thoroughly mixed and divided into two subsamples. One was stored at 4 °C for measuring microbial biomass P (MBP), bicarbonate extractable organic and inorganic P (BPo and BPi) and another was air-dried and further ground to pass a 0.25 mm mesh for the analyses of total P and total inorganic P. Besides, soil pH, organic C and total N were determined for air-dried samples collected at the first time.

Soil pH was measured using a soil/water ratio of 1:2.5 (w/v). We measured gravimetric soil water content from mass loss after drying for 12 h at 105 °C. Soil organic C (SOC) was determined by the H_2SO_4–$K_2Cr_2O_7$ oxidation method (Nelson and Sommers, 1982). Total N was determined by steam distillation after Kjeldahl digestion at 370 °C. Soil total P (TP) and inorganic P (TPi) was determined as orthophosphate in extracts (0.5 mol L^{-1} H_2SO_4) of ignited and unignited soil, respectively (Saunders and Williams, 1955). Total organic P (TPo) was calculated as the difference between TP and TPi (Saunders and Williams, 1955). Soil MBP was determined by the chloroform fumigation method assuming that K_p is 0.40 (Brookes et al., 1982). The NaHCO₃-extractable inorganic and organic P fractions (BPi and BPo) were determined by the method described by Bowman and Cole (1978). The phosphate

Fig. 1. Monthly precipitation and mean air temperature at the Daqinggou National Nature Reserve in 2006.

concentration in all extracts was analyzed colorimetrically using the molybdate blue method on a continuous-flow autoanalyzer (AutoAnalyzer III, Bran + Luebbe GmbH, Germany).

2.3. In situ resin-adsorbed P

As the useful methods to determine in situ P availability, resin-filled bags and impregnated membranes have been widely used to examine the temporal and spatial variations in soil P availability under field conditions (Huang and Schoenau, 1996; McGrath et al., 2000). In contrast to soil tests that can only test soil P availability on a particular date, resin bag technique can monitor soil P availability during a period. In the present study, we monitored soil P availability using anion-exchange resin bags buried in the field at the same time as the seasonal soil tests, aiming to assess the applicability of seasonal soil tests in examining temporal variation in soil P availability. A 7.0 g anion-exchange resin (Amberjet 4200 Cl) was sewn into a rectangular bag (7 cm × 7 cm) made of fine nylon mesh. The resin bag was shaken for three washes of 30 min each in 0.5 mol L^{-1} NaHCO$_3$ solution, aiming to convert the resin from Cl$^-$ form to HCO$_3^-$ form. Before the placement, each bag was shaken to remove excess water (Richards et al., 1997). Bags were placed horizontally in two layers: beneath the litter layer and in the mineral soil at 10 cm depth. For the resin bag placed beneath the litter layer, a plastic film was adhered to the underside to avoid the adsorption of P from the mineral soil. Thus, P adsorbed onto the resin bags beneath the litter layer can be considered as the P released from litter decomposition. In this study, we randomly placed five bags at each layer per plot within savanna, Mongolian pine plantation, and Chinese pine plantation. The placement and harvest of resin bags were synchronous with soil sampling dates except for on July 1. The first time of the placement of resin bags was on October 15, 2005.

We brought resin bags removed from the soil back to the laboratory and washed with distilled water to remove soil and root material. Orthophosphate adsorbed onto the resin was desorbed by shaking each resin bag with 50 mL 0.5 mol L^{-1} HCl solution for 30 min (Richards et al., 1997). Monthly resin-adsorbed P (resin-P) and annual resin-P were calculated.

2.4. Statistical analyses

Repeated measures analysis of variance (ANOVA) was used to test the effects of vegetation types on various soil properties across the growing season. When there were significant interactions between the vegetation types and sampling time, one-way ANOVA was used to test the effects of vegetation type on soil properties at each sampling time separately, and the effects of sampling time on soil properties for each vegetation type separately. The least square difference (LSD) test was used to compare the means. Data were tested for normality and homogeneity of error variances to determine whether the transformations were needed. All statistical analyses were performed using SPSS 11.5.

3. Results

3.1. Soil pH, C, N and water content

There were no differences in soil pH, SOC and total N concentrations among different vegetation types except the elm savanna, in which three variables were significantly higher (Table 1). Soil water content had a significant seasonal variation in all vegetation types ($P < 0.01$) (Fig. 2), which is coincided with the seasonal variation in rainfall, higher in summer and lower in autumn and winter (Fig. 1). In addition, soil water content significantly differed among vegetation types. It was significantly

Table 1
Some basic soil characteristics (0–20 cm) in different vegetation types at the Daqinggou National Nature Reserve, Inner Mongolia, China.

Vegetation type	pH (H$_2$O)	SOC (g kg^{-1})	Total N (g kg^{-1})
SA	7.3(0.1)[a]	8.9 (0.8)[a]	0.80(0.06)[a]
GS	6.5(0.1)[b]	3.6 (0.3)[b]	0.35(0.02)[b]
MP	6.7(0.1)[b]	4.0 (0.8)[b]	0.38(0.03)[b]
CP	6.7(0.2)[b]	3.5 (0.9)[b]	0.29(0.02)[b]
PO	6.7(0.1)[b]	4.3 (0.9)[b]	0.35(0.04)[b]

Data are presented as the means with standard errors given in parentheses (n = 5). Values within columns with different superscript letters were significantly different at $P < 0.05$. SA: elm savanna; GS: grassland; MP: Mongolian pine plantation; CP: Chinese pine plantation; PO: poplar plantation; SOC: soil organic carbon.

($P < 0.05$) higher in the elm savanna than that in the grassland and forest plantations (Fig. 2). There was also significant interaction between vegetation type and sampling time for soil water content ($P < 0.05$).

3.2. Soil TP, TPo and TPi

Sampling time, vegetation type, and their interactions had significant effect on soil TP, TPo and TPi concentrations ($P < 0.05$). Seasonal variations in soil TP and TPo were significant in the elm savanna and grassland, but were not significant in all forest plantations. Specifically, in the elm savanna, TP and TPo concentrations were higher in spring (May 1) and autumn (October 15) than those in summer (July 1 and August 8), and the largest difference was 40.7 and 18.4 mg kg^{-1} for TP and TPo, respectively. In the grassland, TP and TPo were significantly higher in spring than in other seasons, and the largest difference was 18.1 and 18.3 mg kg^{-1}, respectively (Fig. 3a and b). Seasonal variation in soil TPi was only significant in the elm savanna (Fig. 3c).

Soil TPo accounted for 54–73% of the TP across the vegetation types and seasons. The TP and TPo concentrations were always highest in the elm savanna, intermediate in the grassland and poplar plantation, and lowest in the Mongolian pine and Chinese pine plantations throughout the study period (Table 2, Fig. 3). The TPi concentration was significantly higher in the elm savanna than in other vegetation types (Fig. 3).

3.3. Soil BPi, BPo and MBP

In the study area, labile P fractions were at very low level and the concentrations of BPi, BPo, and MBP were less than 3.1, 1.0, and
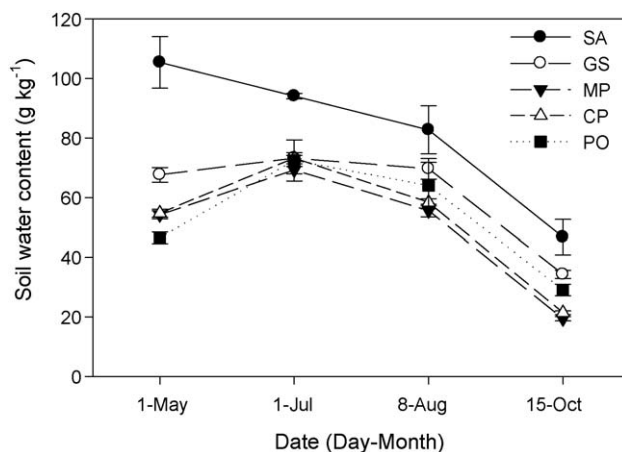
Fig. 2. Seasonal variations (mean ± SE, n = 5) in soil water content in different vegetation types at the Daqinggou National Nature Reserve, Inner Mongolia, China from May to October of 2006.
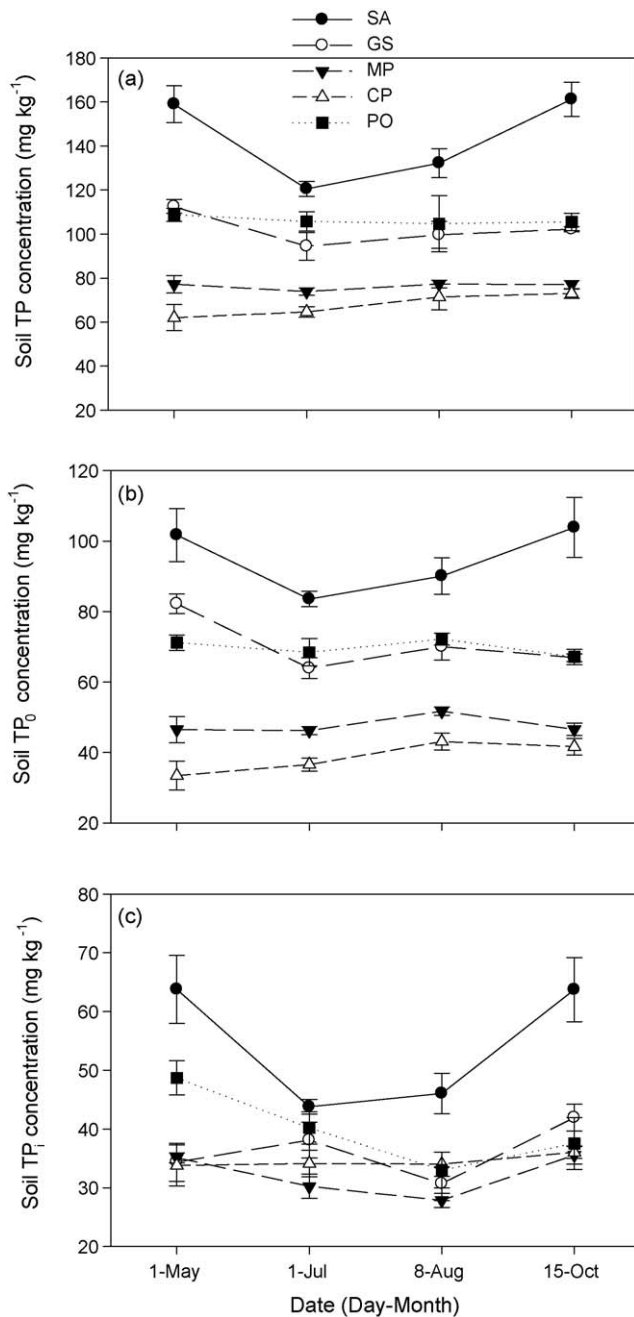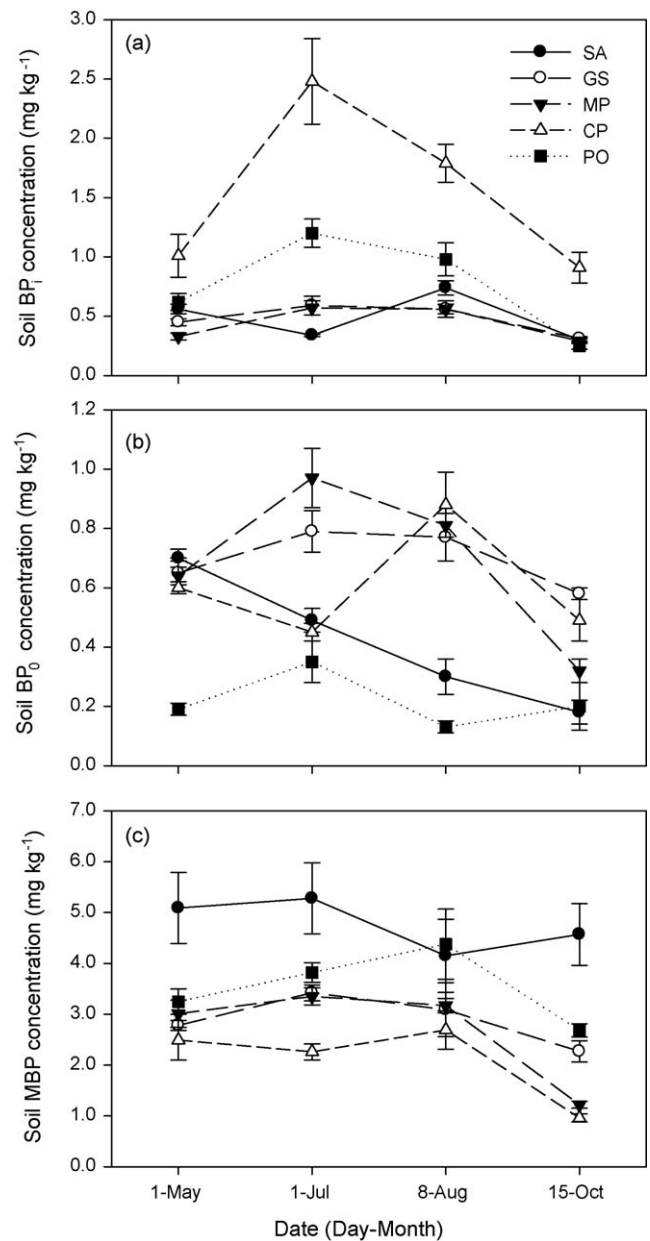
Fig. 3. Seasonal variations (mean ± SE, $n = 5$) in soil total P (TP), total organic P (TPo) and total inorganic P (TPi) in different vegetation types at the Daqinggou National Nature Reserve, Inner Mongolia, China.

Fig. 4. Seasonal variations (mean ± SE, $n = 5$) in soil NaHCO$_3$-extractable inorganic and organic P (BPi and BPo) and microbial biomass P (MBP) in different vegetation types at the Daqinggou National Nature Reserve, Inner Mongolia, China.

6.2 mg kg^{-1}, respectively. There were significant seasonal variations in soil BPi and BPo in all vegetation types ($P < 0.05$). Soil BPi concentration increased during summer and declined during spring and autumn in all vegetation types. The seasonal variation in BPi was more obvious in the Chinese pine plantation and poplar

Table 2
The average values ($n = 20$) of soil water content (SWC, g kg^{-1}) and P fractions (mg kg^{-1}) in different vegetation types across seasons.

Vegetation type	SWC	TP	TPo	TPi	BPi	BPo	MBP
SA	82.2	149.0	94.8	54.3	0.49	0.42	4.78
GS	61.2	107.0	70.7	36.3	0.48	0.70	2.89
MP	49.6	79.9	47.7	32.2	0.44	0.69	2.69
CP	51.9	73.1	38.6	34.5	1.55	0.61	2.10
PO	53.0	109.5	69.7	39.9	0.76	0.22	3.53

plantation than in others, and the biggest seasonal difference was 1.6 and 1.0 mg kg^{-1} in the two plantations, respectively (Fig. 4a). Seasonal pattern of soil BPo concentration differed significantly among vegetation types. In the elm savanna, BPo decreased by 74% from spring to autumn. In other vegetation types BPo reached its peak in summer (Fig. 4b). Concentration of MBP showed the similar seasonal pattern as BPi did in all forest plantations (0.6–1.8 times higher in summer than in spring and autumn), while it was relatively stable throughout the study period in the elm savanna and grassland (Fig. 4c).

Effects of vegetation type on soil BPi, BPo and MBP concentrations were significant at each sampling time. Specifically, BPi concentration was significantly higher in the Chinese pine plantation than in other vegetation types at each time, among which the differences in BPi were not significant in May and October (Fig. 4). The highest average concentration of BPi over seasons occurred in the Chinese pine plantation, intermediate in

Table 3
Monthly and total resin-adsorbed P (resin-P) in different vegetation types in 2006.

Layer	Vegetation type	Monthly resin-P (μg P 30 days^{-1} bag^{-1})			Annual resin-P (g P ha^{-1} year^{-1})
		October 15–May 1	May 1–August 8	August 8–October 15	
Beneath the litter layer	SA	21.83(3.74)[b]	91.71(8.90)[b]	27.42(2.48)[b]	965.7(68.0)
	MP	12.64(2.48)[b]	93.18(10.91)[b]	35.55(6.69)[b]	854.3(44.7)
	CP	45.72(4.67)[a]	136.33(7.29)[a]	51.66(5.36)[a]	1672.5(115.2)
In the mineral soil	SA	1.73(0.21)[a]	82.82(9.20)[a]	11.50(2.53)[a]	556.4(40.9)
	MP	1.76(0.07)[a]	29.69(4.17)[b]	8.09(1.15)[a]	264.5(32.7)
	CP	1.88(0.11)[a]	72.90(2.19)[a]	7.85(0.95)[a]	488.6(36.3)

Data are presented as the means with standard errors given in parentheses ($n = 5$). Within the same layer, values in columns with different superscript letters denote significant differences among vegetation types ($P < 0.05$).

the poplar plantation, and the lowest in other vegetation types (Table 2). The difference in BPo among vegetation types was strongly dependent on season. The BPo concentration was generally the lowest in the poplar plantation, intermediate in the elm savanna, and the highest in the pine plantations and grassland (Fig. 4b). MBP concentration was the highest in the elm savanna, intermediate in the poplar plantation, the lower in the grassland and Mongolian pine plantation, and the lowest in the Chinese pine plantation (Table 2, Fig. 4c).

3.4. Resin-P

Amount of monthly resin-P was significantly affected by sampling time, buried layer and vegetation type (Table 3). Monthly resin-P showed a similar seasonal pattern to that of soil BPi concentration in both layers in all three vegetation types. Yet, we found a dramatically greater resin-P (2.6–7.4 times beneath the litter layer, 3.7–47.9 times in the mineral soil) in summer than in other seasons. In addition, monthly resin-P beneath the litter layer was much higher (1.7–3.4 times) than that in the mineral soil. Beneath the litter layer, monthly resin-P was greatly higher in the Chinese pine plantation than in the elm savanna and Mongolian pine plantation throughout the study year; while in the mineral soil, it was similar among vegetation types throughout the year except in summer when it was significantly lower in the Mongolian pine plantation than in the other two systems (Table 3). The trend of total annual resin-P in both layers was Chinese pine plantation (2161 g P ha^{-1} year^{-1}) > elm savanna (1522 g P ha^{-1} year^{-1}) > Mongolian pine plantation (1119 g P ha^{-1} year^{-1}).

4. Discussion

4.1. Seasonal patterns of soil P fractions

The results of this study revealed seasonal patterns of P fractions in semiarid sandy soils. In the elm savanna and grassland, TP and TPo decreased considerably during summer, while in forest plantations, TP, TPo and TPi were relatively stable over time (Fig. 3). These results were consistent with previous studies in grassland and forest in temperate regions (Perrott et al., 1990; Fabre et al., 1996; Chen et al., 2003). After an extensive literature review, Chen et al. (2008) concluded that P recycling was mainly driven by plant P demand and sustained by root litter inputs in the grassland and leaf litter inputs in the forest. In the savanna and the grassland in our study, increased organic inputs from root litter in autumn and winter were recognized as a major contribution to the increased total P, whereas in the forest plantations, limited direct organic inputs from root litter in autumn and winter was the reason for relatively constant total P (Fig. 3), which are consistent with the previous findings (Tate et al., 1991; Chen et al., 2003, 2008). In addition, similar seasonal trends of TP and TPo, and

relatively constant TPi (Fig. 3) confirmed that organic P was the primary source of plant available P in this semiarid area, while recalcitrant inorganic P was less actively involved in soil P transformation (Zhao et al., 2007).

Seasonal patterns of soil labile P fractions (BPi, BPo and MBP) and in situ resin-P differed from the seasonal patterns of soil total P. The resin-P and soil BPi shared the same seasonal patterns (Table 3, Fig. 4), suggesting that seasonal soil tests are useful to monitor temporal variation in soil P availability. With few exceptions, soil labile P fractions greatly increased in summer and decreased in spring and autumn in all vegetation types (Fig. 4). Different or even conflicting seasonal patterns of soil labile P have been reported elsewhere. Most studies in grassland and forest in the humid temperate regions revealed that labile P fractions (BPi, BPo and MBP) accumulated during autumn and winter and declined in spring and summer. This seasonal pattern was ascribed to the greatest plant uptake and increased mineralization rate of organic P during spring and summer (Perrott et al., 1990; Fabre et al., 1996; Hooper and Vitousek, 1998; Chen et al., 2003; Styles and Coxon, 2007).

The seasonal pattern of soil labile P fractions in the present study differed from that in above-mentioned studies in the humid temperate regions. This difference was perhaps largely due to the differences in seasonal climate pattern, soil fertility and controlling mechanisms of soil P transformation. First, all those studies were conducted in the humid temperate regions (i.e. New Zealand, Southwest of France, Western Ireland) with a relatively dry summer and a wet winter and spring. However, our study area is in the semiarid region with over 60% of the annual precipitation falls during summer (June–August). Second, soil P stocks and availability in the current study area were significantly lower than that in the above-mentioned studies. Finally, mineralization of organic P and decomposition of litter were the main sources of available P, and associated biological processes controlled soil P transformation in the study area (Zhao et al., 2007). Therefore, a combination of increased temperature, moisture and plant root activity during summer promoted the biological transformation of soil P (litter decomposition, mineralization of organic P and turnover of MBP), and then increased the availability of both organic and inorganic P. Greatly increased resin-P and MBP during summer further confirmed this (Table 3, Fig. 4c). The relatively constant MBP concentration in the elm savanna and grassland may be related to the adaptation of soil microbial community to the seasonal environmental variation, as the elm savanna and grassland are natural vegetations in the study area. Magid and Nielsen (1992) also observed that soil labile inorganic P (resin-P, BPi) decreased in autumn and winter and increased in spring and summer in the Northeastern Zealand area of Denmark. They ascribed their results to physicochemical solubility of soil organic matter rather than to biological transformation of organic matter.

As with many studies (Fabre et al., 1996; Comerford et al., 2002; Chen et al., 2003), litter decomposition played an important role in

soil P availability. In the study area, monthly resin-P released from litter decomposition was much greater than that in the mineral soil, and was dramatically greater in summer than in other seasons (Table 3). In semiarid ecosystems, seasonality of plant litter inputs and decomposition was found to be especially important because of the relatively short period of the rainy season (Hooker and Stark, 2008).

In the present study, with few exceptions, soil labile P fractions in different ecosystems shared the similar seasonal pattern. The similar seasonal pattern of soil labile P between adjacent ecosystems was founded by Chen et al. (2003) and Styles and Coxon (2007) in adjacent grassland and forests, by Magid and Nielsen (1992) in adjacent arable land, grassland and pasture. This suggested that climatic and soil conditions rather than vegetation type are probably the major factors influencing the seasonal pattern of soil labile P fractions.

4.2. Soil P fractions under different vegetation types

Although study plots are located on the same soil type in a same area, all measured soil properties were significantly affected by vegetation type. Levels of soil water content, SOC, total N, TP, TPo, TPi and MBP were consistently and significantly higher in the elm savanna than in other vegetation types, suggesting the advantage of elm savanna in conserving soil fertility. The high soil fertility in the elm savanna may be also related to its high P use efficiency and its high adaptability to local environments. Elm savanna is one of the climax communities on the Keerqin Sandy Lands and has strong adaptability and anti-disturbance ability in this area (Li et al., 2004).

Variation in soil moisture among vegetation types may be responsible for the variation in MBP, as soil water content and MBP concentration were highly correlated in each season ($0.4 \leq r \leq 0.8$, $P < 0.01$). The elm savanna had higher water content compared with other ecosystems, partly resulting from higher SOC content (Table 1). For a wide range of soil types and soil textures, at low SOC contents, the sensitivity of the water retention to changes in organic matter content was highest in sandy soils (Rawls et al., 2003). Increase in organic matter content led to increase of water retention in sandy soils by increasing soil aggregate stability (Kay et al., 1997; Rawls et al., 2003). High soil water content in the savanna and grassland soils during growing seasons may also be due to lower ecosystem transpiration in these native systems than in the introduced forest plantations (Licata et al., 2008). Soil P availability is particularly sensitive to soil moisture regimes, not only because of the indirect impacts through microbial activity, but also because of the movement of phosphate ions in soils by diffusion through pores filled with water (He et al., 2002; Smith, 2002). Thus, the improved soil moisture condition in the elm savanna will ameliorate the impacts of aridity, particularly in the dry spring. Similarly, Eviner et al. (2006) reported that under field conditions, species effects on soil microclimate influenced soil N and P transformations, with species effects on soil moisture being important in the dry spring.

Mongolian pine, Chinese pine and poplar are the most used species for monocultural forest plantations in the southeastern Keerqin Sandy Lands. However, their comparative studies on soil nutrient cycling are scarce. The results from the current study showed that impacts of afforestation on soil P stocks and availability differed considerably among tree species. The Chinese pine plantation had the highest soil BPi concentration and resin-P, while the poplar plantation had higher soil total P and MBP than other forest plantations. Litter decomposition may be largely responsible for the highest soil BPi concentration in the Chinese pine plantation, because resin-P released from litter decomposition in the Chinese pine plantation was dramatically greater than

that in other ecosystems, while resin-P in the mineral soil was at an intermediate level (Table 3). Relatively high soil MBP and total P in the poplar plantation suggested that poplar plantation is better to conserve soil P stocks and microbial activity than pine plantations in the study area.

Variations in soil P fractions among vegetation types can be attributed to changes in biomass production and nutrient cycling processes associated with vegetation conversion (Hooper and Vitousek, 1998). Thus, the clarification of mechanisms underlying the variations in soil P fractions needs further quantification of P allocation and cycling processes in different ecosystems.

4.3. Implications for regional ecosystem restoration and management

van Noordwijk and Ong (1999) hypothesized that land use systems would be most likely to achieve long-term sustainability by mimicking patterns of resource use in the natural systems. Lodhiyal and Lodhiyal (2003) found that in the Bhabar belt of central Himalaya, India, Bhabar Shisham forests had shown better nutrient conservation efficiency than exotic poplar and oak forests. Goberna et al. (2007) reported that in semiarid Mediterranean area soils under natural maquis (a dense evergreen shrub) hold larger microbial respiration and C and P catalytic abilities than soils under pine plantations. Results from the current study still confirm that native vegetations were better to conserve soil fertility than forest plantations. Therefore, native tree species or introduced tree species that can improve soil structure and fertility are recommended in regional ecosystem restoration.

Because water, N and P are the three main limiting factors for plant growth in the study area (Jiao, 1989), regional ecosystem management must consider the budget and balance of these resources. Under Mongolian pine plantations in our study area, the seasonal patterns of soil inorganic N and net N mineralization rates were consistent with those of soil labile P and water content (Chen et al., 2006), suggesting the coupling of soil N and P transformations, and the great dependence of soil N and P availability on soil water availability. With regard to annual growth phenology, the fast growing of pine trees usually begins around late April and lasts about 20 days, the fast growing of broadleaved trees begins later than pine trees but lasts longer (from middle May to middle July), and grasses usually begin in early June and ends in late August (Jiao, 1989). Therefore, the limitation of soil water, N and P to tree growth is most likely to occur in spring (Chen et al., 2006), though the nutrient demand of trees in the spring can be partially met by internal resorption (Chapin, 1980). Protection of the litter layer is strongly recommended to ameliorate soil degradation and nutrient limitation in the study area, since litter layer was not only the main source of soil organic matter and available nutrients, but also the regulator of soil microbial activity (Comerford et al., 2002; Chen et al., 2003).

References

Bowman, R.A., Cole, C.V., 1978. An exploratory method for fractionation of organic phosphorus from grassland soils. Soil Science 25, 95–101.

Brookes, P.C., Powlson, D.S., Jenkinson, D.S., 1982. Measurement of microbial biomass phosphorus in soil. Soil Biology & Biochemistry 14, 319–329.

Chapin, F.S., 1980. The mineral nutrition of wild plants. Annual Review of Ecology and Systematics 11, 233–260.

Chen, C.R., Condron, L.M., Davis, M.R., Sherlock, R.R., 2003. Seasonal changes in soil phosphorus and associated microbial properties under adjacent grassland and forest in New Zealand. Forest Ecology and Management 177, 539–557.

Chen, C.R., Condron, L.M., Xu, Z.H., 2008. Impacts of grassland afforestation with coniferous trees on soil phosphorus dynamics and associated microbial processes: a review. Forest Ecology and Management 255, 396–409.

Chen, F.S., Zeng, D.H., Zhou, B., Singh, A.N., Fan, Z.P., 2006. Seasonal variation in soil nitrogen availability under Mongolian pine plantations at the Keerqin Sand Lands, China. Journal of Arid Environments 67, 226–239.

Comerford, N.B., McLeod, M., Skinner, M., 2002. Phosphorus form and bioavailability in the pine rotation following fertilization: P fertilization influences P form and potential bioavailability to pine in the subsequent rotation. Forest Ecology and Management 169, 203–211.

Cross, A.F., Schlesinger, W.H., 2001. Biological and geochemical controls on phosphorus fractions in semiarid soils. Biogeochemistry 52, 155–172.

Eviner, V.T., Chapin, F.S., Vaughn, C.E., 2006. Seasonal variations in plant species effects on soil N and P dynamics. Ecology 87, 974–986.

Fabre, A., Pinay, G., Ruffinoni, C., 1996. Seasonal changes in inorganic and organic phosphorus in the soil of a riparian forest. Biogeochemistry 35, 419–432.

Farley, K.A., Kelly, E.F., 2004. Effects of afforestation of a páramo grassland on soil nutrient status. Forest Ecology and Management 195, 281–290.

Frossard, E., Condron, L.M., Oberson, A., Sinaj, S., Faedeau, J.C., 2000. Processes governing phosphorus availability in temperate soils. Journal of Environmental Quality 29, 15–23.

Goberna, M., Sánchez, J., Pascual, J.A., García, C., 2007. Pinus halepensis Mill. plantations did not restore organic carbon, microbial biomass and activity levels in a semi-arid Mediterranean soil. Applied Soil Ecology 36, 107–115.

He, Y.Q., Zhu, Y.G., Smith, S.E., Smith, F.A., 2002. Interactions between soil moisture content and phosphorus supply in spring wheat plants grown in pot culture. Journal of Plant Nutrition 25, 913–925.

Hooker, T.D., Stark, J.M., 2008. Soil C and N cycling in three semiarid vegetation types: response to an in situ pulse of plant detritus. Soil Biology & Biochemistry 40, 2678–2685.

Hooper, D.U., Vitousek, P.M., 1998. Effects of plant composition and diversity on nutrient cycling. Ecological Monographs 68, 121–149.

Huang, W.Z., Schoenau, J.J., 1996. Microsite assessment of forest soil nitrogen, phosphorus, and potassium supply rates in-field using ion exchange membranes. Communications in Soil Science and Plant Analysis 27, 2895–2908.

Jaiyeoba, I.A., 1998. Changes in soil properties related to conversion of savannah woodland into pine and eucalyptus plantations, northern Nigeria. Land Degradation and Development 9, 207–215.

Jiang, F.Q., Cao, C.Y., Zeng, D.H., Guan, W.B., Wu, X.Y., Zheng, Y.R., 2002. Degradation and Restoration of Ecosystems on Keerqin Sandy Land. China Forestry Press, Beijing (in Chinese).

Jiao, S.R., 1989. The Structure and Function of Sand-fixation Forest Ecosystems in Zhanggutai. Liaoning Science & Technology Press, Shenyang (in Chinese).

Kay, B.D., da Silva, A.P., Baldock, J.A., 1997. Sensitivity of soil structure to changes in organic carbon content: prediction using pedotransfer functions. Canadian Journal of Soil Science 77, 655–667.

Li, G.T., Yao, Y.F., Zou, S.Y., Liu, L.C., Wei, Y.X., Jiang, P., 2004. Studies on regeneration of grassland with sparsed elm in Keerqin sandy land. Journal of Arid Resources and Environment 18, 152–157 (in Chinese).

Licata, J.A., Gyenge, J.E., Fernandez, M.E., Schlichter, T.M., Bond, B.J., 2008. Increased water use by ponderosa pine plantations in northwestern Patagonia, Argentina compared with native forest vegetation. Forest Ecology and Management 255, 753–764.

Lodhiyal, N., Lodhiyal, L.S., 2003. Aspects of nutrient cycling and nutrient use pattern of Bhabar Shisham forests in central Himalaya, India. Forest Ecology and Management 176, 237–252.

Magid, J., Nielsen, N.E., 1992. Seasonal variation in organic and inorganic phosphorus fractions of temperate-climate sandy soils. Plant and Soil 144, 155–165.

McGrath, D.A., Comerford, N.B., Duryea, M.L., 2000. Litter dynamics and monthly fluctuations in soil phosphorus availability in an Amazonian agroforest. Forest Ecology and Management 131, 167–181.

Nelson, D.W., Sommers, L.E., 1982. Total carbon, organic carbon, and organic matter. In: Page, A.L., Miller, R.H., Keeney, D.R. (Eds.), Methods of Soil Analysis. Part 2. Chemical and Microbiological Properties. 2nd ed. American Society of Agronomy, Madison, WI, pp. 539–579.

Oberson, A., Friesen, D.K., Tiessen, H., Morel, C., Stahel, W., 1999. Phosphorus status and cycling in native savanna and improved pastures on an acid low-P Colombian Oxisol. Nutrient Cycling in Agroecosystems 55, 77–88.

Perrott, K.W., Sarathchandra, S.U., Waller, J.E., 1990. Seasonal storage and release of phosphorus and potassium by organic matter and the microbial biomass in a high-producing pastoral soil. Australian Journal of Soil Research 28, 593–608.

Picone, L.I., Zamuner, E.C., Beradra, A., Marina, M.A., 2003. Phosphorus transformations as affected by sampling date, fertilizer rate and phosphorus uptake in a soil under pasture. Nutrient Cycling in Agroecosystems 67, 225–232.

Rawls, W.J., Pachepsky, Y.A., Ritchie, J.C., Sobecki, T.M., Bloodworth, H., 2003. Effect of soil organic carbon on soil water retention. Geoderma 116, 61–76.

Richards, M.B., Stock, W.D., Cowling, R.M., 1997. Soil nutrient dynamics and community boundaries in the Fynbos vegetation of South Africa. Plant Ecology 130, 143–153.

Ross, D.J., Tate, K.R., Scott, N.A., Felthman, C.W., 1999. Land-use change: effects on soil carbon, nitrogen and phosphorus pools and fluxes in three adjacent ecosystems. Soil Biology & Biochemistry 31, 803–813.

Saunders, W.M.H., Williams, E.G., 1955. Observations on the determinations of total organic phosphorus in soils. Journal of Soil Science 6, 254–267.

Smith, F.W., 2002. The phosphate uptake mechanism. Plant and Soil 245, 105–114.

Styles, D., Coxon, C., 2007. Meteorological and management influences on seasonal variation in phosphorus fractions extracted from soils in western Ireland. Geoderma 142, 152–164.

Tate, K.R., Speir, T.W., Ross, D.J., Parfitt, R.L., Whale, K.N., Cowling, J.C., 1991. Temporal variations in some plant and soil P pools in two pasture soils of widely different P fertility status. Plant and Soil 132, 219–232.

van Noordwijk, M., Ong, C.K., 1999. Can the ecosystem mimic hypotheses be applied to farms in African savannahs? Agroforestry Systems 45, 131–158.

Zeng, D.H., Hu, Y.L., Chang, S.X., Fan, Z.P., 2009. Land cover change effects on soil chemical and biological properties after planting Mongolian pine (Pinus sylvestris var. mongolica) in sandy lands in Keerqin, northeastern China. Plant and Soil 317, 121–133.

Zeng, D.H., Jiang, F.Q., 2006. Deterring "three excesses" (over-cultivation, overgrazing, deforestation) is the only way from the source to control the desertification in ecologically frangible regions in China: taking Keerqin sandy land as an example. Chinese Journal of Ecology 25, 1540–1543 (in Chinese).

Zhao, Q., Zeng, D.H., Lee, D.K., He, X.Y., Fan, Z.P., Jin, Y.H., 2007. Effects of Pinus sylvestris var. mongolica afforestation on soil phosphorus status of the Keerqin Sandy Lands in China. Journal of Arid Environments 69, 569–582.