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REGULAR ARTICLE

Soil phosphorus fractions and tree phosphorus resorption in pine forests along an urban-to-rural gradient in Nanchang, China

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Abstract Urbanization has been rapid across the world but the responses of phosphorus (P) cycling to urbanization have not been well-investigated. This study was to understand the influences of rapid urbanization on forest P cycling in a developing country. Soil P fractions and P resportion were determined for nine slash pine (*Pinus elliottii* Engelm.) forests along a 30-km long urban-suburban-rural gradient in Nanchang City, southern China. The total P stocks in the surface soils in urban and suburban forests were 317% and 182% higher, respectively, than levels found in rural forests. The concentrations of soil available P, labile P, slow P, occluded P and total extractable P were also much higher in urban and suburban forests than in rural forests ($P<0.05$). Soil weathered P concentrations were highest in urban forests. Annual mean foliar P concentrations were enhanced in urban and suburban forests compared to rural forests. The P resorption efficiency (PRE) was higher in rural forests than in suburban and urban forests, while the P resorption proficiency (PRP) was lower in rural forests than in suburban and urban forests. Urbanization associated with high extraneous P inputs has altered soil P status and plant P uptake. Foliar P concentration, PRE and PRP were largely dependent on soil P availability in our study forests.

Keywords Nutrient resorption · Soil P fractionation · Soil P leaching · Subtropical region · Urban forests

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Introduction

About 50% of the human population now lives in urban areas, with a projected increase to 60% by 2025 (Pickett et al. 2001). Compared with non-urban ecosystems, the processes and functions of urban ecosystem are more controlled by complex interactions between society and environment (Kaye et al. 2006; Grimm et al. 2008). Recently ecological processes along urban-rural gradients have become a focus of much ground breaking research examining the effects of urbanization (McDonnell et al. 1997; Pickett et al. 2001; Fang et al. 2011).

Soil P is one of the most important elements limiting plant growth (Cramer 2010), especially in subtropical and tropical regions where primary production of many ecosystems is considered to be P rather than N limited (Walker and Syers 1976; Vitousek et al. 2010). However, soil P can also be a pollution source and a threat to water quality when P availability increases so substantially that P is transported to water bodies by surface runoff and groundwater infiltration (Heckrath et al. 1995; Zhang et al. 2001, 2005). Because soil P turns over slowly, the legacy of enhanced soil P patterns may affect freshwaters for centuries (Bennett et al. 2004). Soil total P levels as well as varied fractions have been reported to be elevated in urban regions compared to suburban and rural regions (Zhang et al. 2001; Zhang 2004; Yuan et al. 2007). The accumulated P has become a potential non-point source of pollution for surface and ground water in some cities (Zhang et al. 2001, 2005).

However, Bennett (2003) found that extractable P concentrations showed no significant differences in soils along urban-rural gradients in Dane County, Wisconsin, USA. She argued that it is sometimes difficult to quantify urban-rural gradients due to differences in the many factors playing a role in soil P accumulation and storage such as soil parent material, land use, land cover, fertilizer use, manure applications, historical land use, and management. An examination of urban-rural gradients, an emerging experimental design in urban ecology, may be more useful and effective if sampling is focused on just one particular land use (Carreiro and Tripler 2005).

In urban forests, soil P can be imported with animal droppings, vehicles, dustfall, precipitation and various anthropogenic waste deposits (Waller 1977; Zhang et al. 2001). Therefore, soil P transformation and plant P uptake (P cycling) may be altered with urbanization. China has been experiencing a dramatic and unprecedented level of urbanization associated with rapid economic growth since the initiation of economic reforms in 1978. Urban areas in most less-developed regions of China are experiencing population growth, industrialization and a rapid increase in motor vehicle transportation (Chen et al. 2010b). The urban population in China rose from 18% in 1978 to 45% in 2008 and is projected to be 65% by 2030 (Ni 2008). Increased soil P availability has been observed in some cities in southern China, such as Hangzhou (Zhang 2004) and Nanjing (Yuan et al. 2007). However, little information is available on the nature and accumulations in soil P and its cycling in forests along urban–rural gradients. We have a limited understanding of the P leaching risk caused by P accumulation in urban forests and tree nutrient uptake responses to the alteration of soil P availability.

In this study nine slash pine (*Pinus elliottii* Engelm.) forests along a short urban-suburban-rural gradient in Nanchang, southern China were selected to investigate the influences of rapid urbanization on ecosystem P cycling with measurements of soil P fractions and foliar P concentrations in different seasons. We hypothesized that (1) soil total P pools and various P fractions in the studied forests would decrease along the gradient from urban to rural, and increased soil extractable P in urban forests might become a potential risk for P leaching; and (2) foliar P concentration and P resorption proficiency (PRP) would decrease, while P resorption efficiency (PRE) would increase along the gradient from urban to rural due to leaf-level P use efficiency which mostly depends upon soil P availability (Ostertag 2010).

Materials and methods

Study area

This study was conducted in Nanchang City (115°27′–116°35′E, 28°09′–29°11′N), the capital of Jiangxi Province. The total metropolitan area is 7,402 km^2 with a population that increased from 2.4 million in 1970, to 4.0 million in 1996 and 4.8 million in 2009. The number of motor vehicles increased almost 8-fold between 1995 and 2006 (Chen et al. 2010a). The study region has a subtropical monsoon climate (wet and mild) with mean annual precipitation of about 1700 mm and mean annual relative humidity of about 77%. Mean annual air temperature is 17.5°C with an annual frost free period averaging 291 days.

In order to avoid the complicating influences of vegetation type and soil types on P cycling, in this study we only chose slash pine forests along a 30-km long gradient in Nanchang extending from urban, through suburban, and to rural areas. In 2007, nine slash pine plantations were chosen along this gradient, with three each in urban, suburban and rural areas (Chen et al. 2010a). The ages of the pine forests ranged from 16 to 20 years old, with stand density from 600 to 800 trees ha^{-1}, mean diameter at breast height (DBH) from 10 to 16 cm and canopy height from 12 to 16 m (Yu 2009). All forests are located on low hills at an elevation range of 30–80 m. All the soils on the study sites are red soil formed from arenaceous shale (Ultisols), which is a typical soil type in the subtropical region of China (Zhao et al. 1988). In the urban forests the collection of surface detritus by humans has mostly eliminated the litter layer, while litter accumulates to levels of 4.1–6.3 t ha^{-1} (approximately 4-cm depth) in the suburban and rural sites (Chen et al. 2010a).

Soil sampling and chemical analysis

In each forest, a 20×20 m plot was established and divided into four subplots (10×10 m). In each subplot, after removing the litter layer, five soil cores (2.5 cm in diameter) were randomly collected from the 0–15 cm layer in August 2007 for total P analysis. Soil total P were analyzed by a phosphomolybdic acid blue colour method after sulphuric acid digestion (320°C) using a selenium mixture as catalyst (Liu et al. 1996). In addition, soil samples were collected within each subplot using a 5.0-cm sampling cylinder for determination of soil bulk density at each of three layers: 0–5, 5–10, and 10–15 cm.

Five soil cores (4.8 cm in diameter) to a 15 cm depth were collected randomly from each subplot in April 2008 (spring), July 2008 (summer), October 2008 (autumn), and January (winter) 2009, respectively. The soils from each subplot were composited into a single sample for each sampling event and air-dried. After removal of visible plant residue, all soil samples were sieved through a 2-mm screen, mixed and stored at room temperature.

The soil P fractionation technique has been widely used to study soil P transformation processes since the method was first presented by Hedley et al. (1982) with later development by Crews et al. (1995) and Motavalli and Miles (2002). This study employed those methods to quantify soil P composition. Air-dried soil samples were ground to pass a 0.5 mm sieve and processed following the soil P fractionation sequential procedure (Chen et al., 2010b). The corresponding supernatants sequentially exacted with anion exchange resin, 0.5 M $NaHCO_3$, 0.1 M NaOH, 0.1 M NaOH with sonication, 1.0 M HCl were collected by centrifuging samples at 1.7×10^4 m s^{-2} (3,200 rpm) for 5 min in a centrifuge, followed by filtering samples through a 0.45-μm micropore filter. Resin-P, $NaHCO_3$-P, NaOH-P, sonication-P and HCl-P are defined as available P, labile P, slow P, occluded P and weathered mineral P, respectively (Motavalli and Miles 2002). Bio-available P is the sum of available P and labile P, while the extractable P includes available P, labile P, slow P, occluded P and weathered mineral P. Phosphorus concentration in each supernatant was determined by the phosphomolybdic acid blue color method (Liu et al. 1996).

Leaf and litter sampling and chemical analysis

Needles were collected monthly from September 2007 to August 2008. First, three representative trees (with DBH and heights close to the average levels for each plot) were selected for sampling in each plot. Then for each selected tree, the needles from one first order branch were collected from each of the four cardinal directions and combined them together to obtain a composite sample. We also collected fresh litter under each selected tree with six 0.5×0.5 m nylon traps, and mixed these together as a composite sample for each plot.

The needles and fresh litter samples were washed with deionized water to remove dust, oven-dried at 70°C for 48 h, ground in a mill and screened with a 0.25 mm sieve. Total P concentration was measured using the phosphomolybdic acid blue color method. Their organic C was determined by dichromate oxidation and titration with ferrous ammonium sulfate (Liu et al. 1996).

Calculation and statistics

Soil P stocks for the 0–15 cm layer was calculated based on total P concentrations and bulk density. Nutrient resorption efficiency was calculated as a percentage of the amount of nutrient present in the leaf before senescence (Aerts 1996).

$$\mathrm{PRE} = ([\mathrm{P}]\ \text{of fresh leaf} - [\mathrm{P}]\ \text{of senescent leaf}) / [\mathrm{P}]\ \text{of fresh leaf} \times 100$$

Where, [P] of fresh leaf is the observed maximum P concentration in a year; [P] of senescent leaf is the

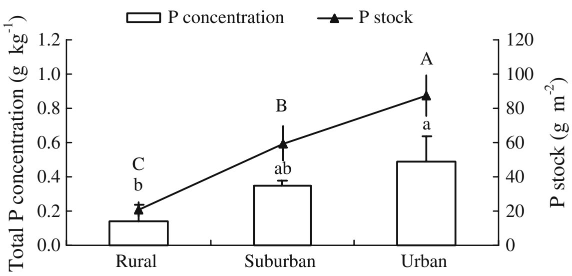

Fig. 1 Concentrations and stocks of P in top soil (0–15 cm) under the pine forests along an urban-rural gradient in Nanchang City, China. Shown are mean ± one SE (n=3). Different lowercase and uppercase letters indicate significant differences in total P concentration and P stock, respectively, among three locations at 0.1 levels

average P concentration of the litterfall (during the period from December to March in the present study). The change in leaf mass during senescence varied from 5% to 10% (Aerts 1996). In this study the effect induced by leaf mass change on P resorption was not considered. PRP was defined as the concentration of P remaining in senesced leaves (litterfall) throughout a year (Killingbeck 1996). In this study, PRP is the average P concentration of the litterfall collected from December to March.

The averages to the plot level were used for the variables measured at subplot level. One-way ANOVA with location as the fixed main factor was performed for concentrations and stocks of total P, foliar P concentration, PRE and PRP. Two-way ANOVA was used to examine the effects of location, season and their interactions on soil various P fractions, foliar C, P concentrations and foliar C:P ratio over the course of a year. Tukey's multiple comparisons method was used to identify significant differences among gradients. Pearson's tests were used for comparing the significance of correlations among soil P fractions and leaf P traits. All data were used to test for normalized distributions and transformed by $\log_{10}$ if required. All analysis was performed using SPSS software (SPSS Inc. 2001, Version 11.0). Statistically significant differences were set at P values<0.05 unless otherwise stated.

Results

Soil P stock

Total P concentrations in the surface soils were the highest in urban forests and the lowest in rural forests (P=0.097, Fig. 1). Soil total P stocks were 66.5 g m^{-2} and 38.3 g m^{-2} in urban and suburban forests, respectively, which were 317% and 182% higher than that in rural forests (21.0 g m^{-2}) (Fig. 1).

Soil P fractions

The location effects on all soil P fractions were significant, while seasonal effects were not except on soil weathered P. No interactions of location and season on any soil P fractions were found (Table 1).

The concentrations of available P, labile P, slow P, occluded P and extractable P (sum of five P fractions) were significantly higher in urban and suburban forests than in rural forests (P<0.05), but were not significantly different between urban and suburban forests. The average stocks of available P, labile P, slow P, occluded P and the extractable P were 0.67 g m^{-2}, 2.33 g m^{-2}, 11.43 g m^{-2}, 4.28 g m^{-2}, 22.02 g m^{-2}, respectively, in urban forests, 0.83 g m^{-2}, 2.28 g m^{-2}, 11.67 g m^{-2}, 4.54 g m^{-2}, 20.23 g m^{-2}, in suburban forests, and 0.20 g m^{-2}, 0.20 g m^{-2}, 2.07 g

Table 1 *ANOVA* of effects of location and season on the concentrations of various P fractions in pine forests along the urban-suburban-rural gradient in Nanchang City, China

Factor	*df*	*F* values					
		Available P	Labile P	Slow P	Occluded P	Weathered P	Extractable P
Location	2	4.86*	2.93*	4.70*	4.67*	8.30***	5.20**
Season	3	0.89^{NS}	0.30^{NS}	0.61^{NS}	1.44^{NS}	2.77*	0.15^{NS}
Location×season	6	0.04^{NS}	0.13^{NS}	0.10^{NS}	0.27^{NS}	0.71^{NS}	0.01^{NS}

^{NS} not significant, *P<0.05, **P<0.01, ***P<0.001.

m^{-2}, 0.82 g m^{-2}, 3.95 g m^{-2}, respectively in rural forests. Soil weathered P was higher in urban forests than in suburban and rural forests in all four seasons (Fig. 2), with levels of 3.31, 0.91 and 0.66 g m^{-2} in urban, suburban and rural forests, respectively (Fig. 2). Slow P was the dominant form in the extractable P in all forests, and the proportion of weathered P to the extractable P was increased in urban forests (Fig. 3).

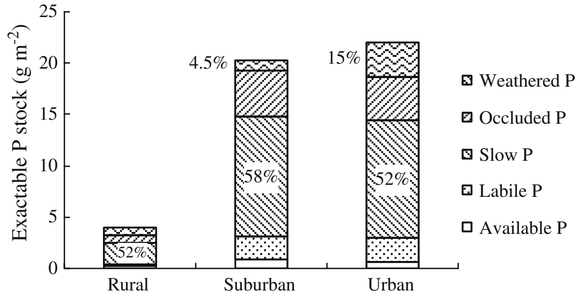

Fig. 3 The accumulative stocks of annual average extractable P and their fractions in top soil (0–15 cm) under pine forests along the urban-suburban-rural gradient in Nanchang City, China

Foliar P concentrations and P resorption

Foliar P concentrations generally displayed a seasonality ($F_{11,72}$=2.22, P<0.05), with the lowest values in later winter or early spring in the suburban and rural forests (Fig. 4). The annual mean concentrations of foliar P were higher in urban (0.94 g kg^{-1}) and suburban (1.03 g kg^{-1}) forests than in rural forests (0.78 g kg^{-1}) with no significant difference between the urban and suburban forests (Fig. 4). Foliar C concentrations ($F_{2,72}$=10.77, P<0.001) and foliar C:P values ($F_{2,72}$=10.94, P<0.001) also varied with location. The averaged foliar C:P value was significantly higher in rural forests (625) than suburban (476) and urban (505) forests with no significant differences between the suburban and urban.

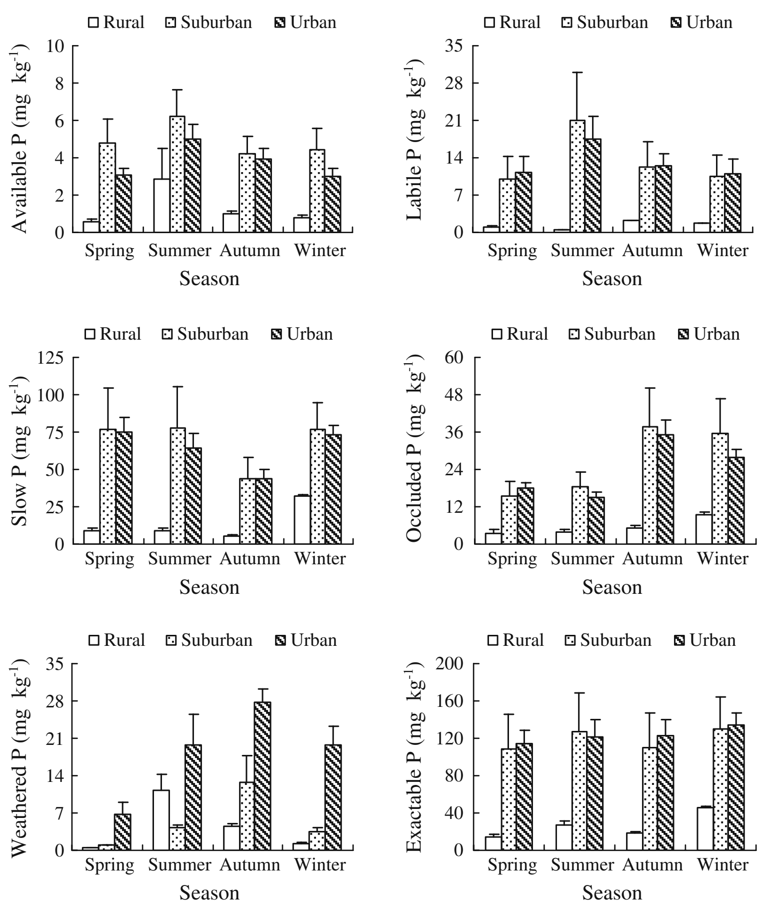

Fig. 2 Seasonal variations in soil phosphorus concentrations of the top soils in pine forests along the urban-rural gradient in Nanchang City, China. Shown are mean ± one SE (n=3)

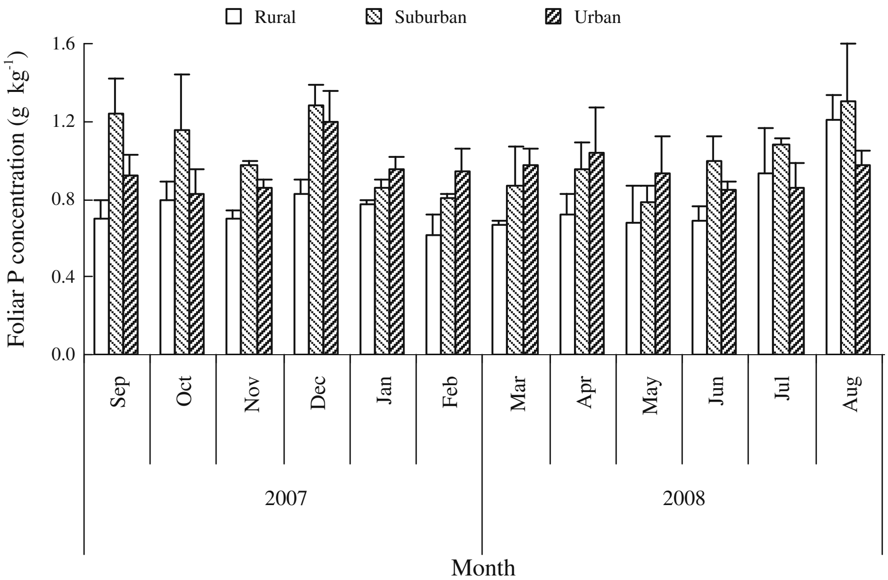

Fig. 4 The monthly variations in foliar P concentrations of *Pinus elliottii* in the pine forests along the urban-suburban-rural gradient in Nanchang City, China during 2007 and 2008. Shown are mean ± one SE (n=3)

The PRE was higher in rural forests (84%) than in suburban (75%) and urban (76%) forests, while the PRP was lower in rural forests (0.20 g kg^{-1}) than in the suburban (0.32 g kg^{-1}) and urban (0.29 g kg^{-1}). The differences in PRE and PRP between suburban and urban forests were not significant (Fig. 5).

The relationships between foliar P and soil extractable P

Foliar P concentrations and PRP were positively correlated with all soil P fractions except for weathered P and the total extractable P (P<0.05) while PRP was positively correlated with soil total P. Both foliar C:P and PRE were negatively correlated with available P, labile P, bio-available P and extractable P. Additionally, foliar C:P was negatively correlated with slow P and occluded P, and PRE was negatively correlated with soil total P. Foliar P properties did not correlate with soil weathered P (Table 2).

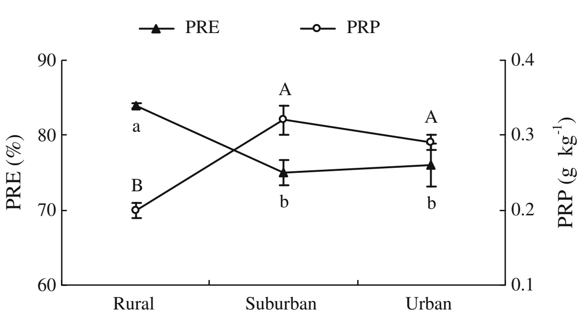

Fig. 5 Phosphorus resorption efficiency (PRE) and phosphorus resorption proficiency (PRP) of *Pinus elliottii* along the urban-suburban-rural gradient in Nanchang City, China. Shown are mean ± one SE (n=3). Different lowercase and uppercase letters mean significant difference in PRE and PRP, respectively, among three locations at 0.05 levels

Discussion

As urban ecology matures, the spatial heterogeneity of urban landscapes, soil resources, temperature and plant communities has been reported (Bennett 2003, Kaye et al. 2008; Zhu et al. 2008). We narrowed our study focus on a simple urban-suburban-rural gradient to understand what variables in P cycling along the gradient can or cannot be predicted. We found that total P stock in the topsoil was substantially enhanced in urban and suburban forests, with levels 317% and 182% higher than levels found in rural forests (Fig. 1). Correspondingly, we also observed enrichment in extractable P, including available P and labile P (Figs. 2 and 3). These results demonstrate that P status and availability were elevated during urbanization. Our results are consistent with some previous studies, which used mixed land use types as sampling

Table 2 Pearson correlations (n=9) between tree P resorption efficiency (PRE), P resorption proficiency (PRP) and top soil average annual concentrations of each P fraction in nine pine forests along the urban-suburban-rural gradient in Nanchang City, China

Soil P variables	Foliar P concentration	Foliar C:P	PRE	PRP
Available P	0.88**	−0.74*	−0.72*	0.73*
Labile P	0.84**	−0.74*	−0.73*	0.68*
Bio-available P	0.85**	−0.74*	−0.73*	0.69*
Slow P	0.87**	−0.74*	-0.66^{NS}	0.72*
Occluded P	0.87**	−0.75*	-0.63^{NS}	0.73*
Weathered P	0.43^{NS}	-0.52^{NS}	-0.66^{NS}	0.42^{NS}
Extractable P	0.87**	−0.77*	−0.71*	0.73*
Total P	0.58^{NS}	-0.66^{NS}	−0.90***	0.72*

^{NS} not significant, *P<0.05, **P<0.01 and ***P<0.001.

sites (Foy et al. 2003; Zhang 2004; Yuan et al. 2007). For example, total P concentrations in urban, suburban and rural surface soils were reported as 1.78, 1.24 and 0.51 g kg^{-1}, respectively in Hangzhou City (Zhang 2004), while levels of 2.50, 1.25 and 0.35 g kg^{-1}, respectively were reported in Nanjing City, southern China (Yuan et al. 2007). In contrast, Baxter et al. (2002) compared soil P availability (labile inorganic P determined by Bray's dilute acid extraction) in oak stands located in either an urban or a rural area, NY, USA, and found that soil P availability was lower in the urban than the rural stands. Many differences including soil type, tree species, land use history and climate condition between Baxter et al. (2002) and our study could explain the different results. However, high extraneous P inputs from various anthropogenic waste deposits (such as solid and organic waste) in our urban study sites could be a determining factor for the higher P levels we found. Nanchang is a rapidly developing city where domestic wastes increased from 800 t d^{-1} in 1997 to 1800 t d^{-1} in 2007, accompanying with the rapid increases in the urban population (Gazette of the People's Government of Jiangxi Province, 2007; http://www.jxzb.gov.cn/2007-8/20078171845568.htm). Compared with developed countries, the intensity of urbanization in developing countries is likely stronger, which needs further attention.

The component of P fractions is an important issue for urban mangers. Our results showed that soil slow P was the dominant fraction among the five extractable fractions, accounting for 52–58% of the total extractable P (Fig. 3). This is in agreement with results reported by Tiessen et al. (1984) and Beck and Sanchez (1994), who found that slow P plays an important role in plant nutrition in highly weathered ultisols. Additionally, our data indicate that soil P fractions are closely related to soil P availability; with significantly positive correlations among available P, labile P, slow P, occluded P and the extractable P (r>0.88, P<0.001, n=36 for all). Neufeldt et al. (2000) found that soil available P and labile P displayed the same trends as the slow P and suggested that slow P is, at least in part, readily plant available. This finding agreed with the results of Sharpley et al. (1987) who also reported that slow P was well correlated with the most common standard P tests in highly weathered soils.

Interestingly, the stock of weathered P and its percentage of the extractable P were significantly higher in urban forests (3.31 g m^{-2} and 15.0%) than in suburban forests (0.91 g m^{-2} and 4.5%) (Fig. 3). Soil weathered P is usually present at a very low level or nondetectable in highly weathered acidic soils (Agbenin and Tiessen 1995). In our study, the great increase in soil weathered P observed in urban soils probably results from the inputs of material with abundant Ca-phosphates (Tiessen and Moir 1993). The higher soil pH in urban forests (5.63) compared to suburban forests (4.47) (Chen et al. 2010a), and the close relationship between soil pH and weathered P (r=0.75, P=0.019, n=9) further support this speculation.

It was surprising that there were no differences in total P and all the P fractions except weathered P, between urban and suburban forests in our study. Much higher weathered P in urban forests than suburban forests indicates that urban forests may have accumulated more materials with abundant Ca-phosphates than suburban forests. Phosphorus released by aggressive extractants (e.g. HCl or H_2SO_4 solution) may be unavailable to plants over a short period; however, they can be transformed to other soil P fractions and made available on a slightly longer time frame (Tiessen and Moir 1993; Cross and Schleshinger 1995). Similarly, there were no significant differences found in foliar P concentrations, C:P, PRP, and PRE between urban and suburban forests.

In the present study, we found several indicators of plant luxury P consumption under relatively high P availability in the urban and suburban soils. First, foliar P concentrations were significantly enhanced by urbanization, with levels 20–30% higher in urban and suburban forests than in rural forests (Fig. 4). This also points to the high sensitivity of foliar nutrition to changing P availability. We suggest that the effect of increasing soil P availability on foliar P accumulations in urban and suburban forests could propagate further up the food web, affecting herbivore P and the abundance of P-rich RNA in herbivores (Schade et al. 2003). Second, our results showed that the senesced needles from the pine trees grown in urban and suburban soils accumulated more P (i.e., higher P concentration in litterfall) than those in rural soils. Third, as a consequence, PRE was much lower in urban and suburban forests than that in rural forests and PRE was negatively correlated with soil available P, labile P, bio-available P and the extractable P. This result is consistent with the expectation that nutrient resorption will decrease along the rural–urban gradient, associated with increasing soil P availability and foliar P concentration (Kobe et al. 2005).

Increased soil P availability and changes in foliar P properties in urban and suburban forests are likely a result of increased P inputs from animal droppings, vehicles, dustfall, precipitation (Pett-Ridge 2009) and various anthropogenic waste deposits (Zhang et al. 2001; Chen et al. 2010b), although they have not yet been quantified in our study area. However, this P enhancement is also likely due to increased decomposition of organic matter and accelerated weathering induced by elevated N deposition, CO_2, O_3 and temperature as separate process or in combination (Isebrands et al. 2001; de Groot et al. 2003; Campbell and Sage 2006; Ghannoum et al. 2010). For example, in examining data on foliar N concentrations (Chen et al. 2010a), we found that fresh foliar N:P ratios were higher in urban forests (13.1) than in suburban (12.2) and rural forests (12.7), while the senesced foliar N:P ratios showed the opposite tendency (16.4, 19.5 and 17.8 in urban, suburban and rural forests, respectively). These results indicate N enrichment in urban forests, which results from elevated atmospheric N deposition. However, since we are not able to distinguish the contributions of extraneous P input from other factors, this requires more detailed research.

High P accumulation in urban and suburban soil is a potential non-point pollution source for surface and ground waters (Zhang et al. 2001). Scientists have been interested in quantitatively assessing high soil P storage as an indicator of the potential for P leaching (Hesketh and Brookes 2000). Zhang et al. (2005) sampled urban soils in Nanjing (118°22′−119°14′E, 31°14′−32°37′N, ~500 km from Nanchang), southern China, to investigate the relationship between extractable P and soil P mobility, and found that 25 mg kg^{-1} Olsen-P was the threshold value for P leaching, which could be an important criteria for assessing the potential risks for P leaching from urban soils.

In this study, the average concentrations of bio-available P (available P+ labile P), equivalent to Olsen-P, were 16.8, 18.4 and 2.6 mg kg^{-1} in urban, suburban and rural forests, respectively. While these values are all lower than the threshold value of 25 mg kg^{-1} for potential P leaching proposed by Zhang et al. (2005), the concentrations of leachable bio-available P varied with season (Fig. 2) and plot (Note: see SE of mean in Fig. 2). Among the 36 samples of bio-available P averaged per plot each season, more than half, especially in summer, were much higher than this threshold value in urban and suburban forests, while no samples were above the threshold value in rural forests. Thus, our data strongly suggests that the seasonal P leaching could potentially occur in urban and suburban slash pine forests in Nanchang, China.

In conclusion, urbanization increased the stock of all soil P fractions and total P in slash pine forests in urban and suburban areas in Nanchang City, southern China. Many P enhanced forest soils in urban and suburban areas show a potential seasonal risk for P leaching. The responses of slash pine to urbanization showed higher foliar P concentrations, higher PRP, and lower PRE in urban and suburban forests than rural forests, and leaf-level P use efficiency dependent upon soil P availability.

Due to the great temporal and spatial heterogeneity of P inputs in urban sites and complicated urban environmental factors, P cycling in forests along urban-to-rural gradient needs further study. Since urban forests have been exposed to elevated atmospheric deposition, temperature, ozone and other pollutants, they may be ahead of the global change “response curve” (Carreiro and Tripler 2005). Understanding element cycling in urban forests would be very useful for improving predictions of ecosystem responses to global change.

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