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RESEARCH PAPER

Topsoil phosphorus signature in five forest types along an urban-suburban-rural gradient in Nanchang, southern China

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Abstract: Conversions from rural to urban land uses have the potential to greatly modify soil phosphorus (P) levels. Soils in shrubs, Masson pine forest, conifer and broadleaf mixed forest, evergreen broadleaved forest and bamboo forest in the mid-subtropical region along an urban-rural gradient in Nanchang City, southern China, were analyzed for total P and P fractions using the modified Hedley P sequential fractionation method. Results show that the topsoil total P and total exactable P concentrations were significantly higher in the urban area (0.71 $g\cdot kg^{-1}$ and 378.50 $mg\cdot kg^{-1}$, respectively) than in the suburban (0.30 $g\cdot kg^{-1}$ and 150.74 $mg\cdot kg^{-1}$, respectively) and rural areas (0.31 $g\cdot kg^{-1}$ and 147.38 $mg\cdot kg^{-1}$, respectively) ($p<0.05$). Among the five P fractions of resin-P, $NaHCO_3$-P, NaOH-P, Sonication-P and HCl-P, the relative abundance of HCl-P in urban forest soils (36%) was the highest and also significantly higher than in suburban (8%) and rural soils (6%), while NaOH-P was the dominant form in suburban (41%) and rural soils (50%). Phosphorus accumulation in the urban soils could affect the cycle of P in urban forest systems, particularly the HCl-P fraction that might rapidly enrich aquatic systems in urban areas.

Keywords: hilly red soil; phosphorus accumulation; soil phosphorus fractionation; urbanization; urban forest

Introduction

Over 50% of the world's population lives in urban areas (World Resources Institute 1996). The expansion of urban areas worldwide impels a need for a deeper understanding of the effects of urbanization on forest soils. During the last century, rapid urban growth has exerted heavy pressure on land and resources, in growing urban and nearby rural areas (Hoogstra et al. 2004). Rapid urbanization can result in problems such as deterioration in air quality, higher air temperatures, increasing noise levels, greater psychological stress and a decreased sense of community, especially in the cities of many developing countries. Urban forests provide a variety of services (Zhu & Zhang 2008) and are very helpful to deal with the physical, social, and environmental problems in the cities (Atmis et al. 2007).

Since urban forests play a vital role in the environmental and aesthetic ‘‘health’’ of cities (Iverson & Cook 2000), questions about how to achieve sustainable management of urban forests are increasingly important. Soil nutrients e.g. nitrogen (N) and phosphorus (P) are important factors for forest growth and ecosystem health (Chen et al. 2007; Zhan et al. 2009). Recently, effect of urbanization on soil N transformation has been reported (Zhu & Carreiro 2004; Yu et al. 2009). However, the effect of urbanization on P accumulation and fractions in forest soils has not been addressed in detail in the forest ecology literature.

Soil P is one of the most important elements limiting plant growth, especially in subtropical and tropical region (Walker & Syers 1976; Vitousek & Farrington 1997). However, soil P can be a pollution source and a threat to water quality when leaching of P increases substantially and P is transported to water bodies by surface runoff and groundwater infiltration (Heckrath et al. 1995; Zhang et al. 2001; 2005). Soil P accumulation and changes in forms of P in the soil can be used to estimate population size, duration, and intensity of settlements (Leonardi et al. 1999; Zhang 2004) and are a very good indicator of past human occupation and activities (Schlezinger & Howes 2000). In urban forest ecosystems, soil P can be imported with food, and various anthropogenic waste deposits (Zhang et al. 2001). The urban development process, including population density and levels of urban infrastructure, can influence soil P accumulation and the distribution of P in urban environments (Yuan et al. 2007). Cumulative effects of continued annual or seasonal P cycling processes, including chemical and biological processes controlling

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the balance between P immobilization and mineralization, result in changes in the concentrations and chemical nature of P (Turrion et al. 2000).

Urban and suburban areas in China have been expanding rapidly since the 1950s and there is some urgency to evaluating how urban areas can affect P accumulation and forms. Nanchang City in south China provides an excellent location for studying the effects of new urban environments on P accumulation, since it has 33.8% vegetation coverage, a long habitation history and the land use gradients from urban to rural under various forest types (Yu et al. 2009).

This study investigated soil P forms in forest types, comprising four typical succession stages including shrubs, Masson pine (*Pinus massoniana*) forest, conifer and broadleaf forest, and evergreen broadleaved forest, and a disturbance climax stage bamboo forest in China's hilly red soil region along an urban–rural gradient to determine whether urbanization affects the fractions and accumulation of P in the forest soils within and near a metropolitan area. Biological processes regulate the movement and distribution of P (Schlesinger 1997), although the importance of human impacts on the P cycle has been well documented (Zhang et al. 2001; Yuan et al. 2007). We examined the following hypotheses that: (1) topsoil P pool and various P fractions increase along a gradient of rural < suburban < urban area due to an increase in extraneous P sources with human activity (Zhang 2004); (2) there are differences in the components of P fractions along the urban-suburban-rural gradient due to inputs of various materials by humans in urban ecosystems (Zhang et al. 2004; Yuan et al. 2007), while biological and chemical processes have a comparatively larger contribution to soil P in rural ecosystems (Walker & Syers 1976; Vitousek & Farrington 1997); (3) soil P availability cannot be rapidly improved with natural forest succession because P is tightly cycled within a forested ecosystem (Wood et al. 1984) .

Material and methods

Study area

This study was conducted in the mid-subtropical zone in Nanchang City (115°27′−116°35′ E, 28°09′−29°11′ N). The total area is 740 thousand ha with a population of 4.8 million. Nanchang is the capital of Jiangxi Province, China, and a typical rapidly urbanizing city. The subtropical monsoon climate is wet and mild, with abundant precipitation and changing seasons. The average altitude is 25 m. Mean annual precipitation is about 1 600−1 800 mm, with mean annual relative humidity about 77%. Mean annual temperature is 17.5^{o}C. The average annual sunlight time is 1 900 h. The frost free period is 291 days.

Nanchang urban forest has rapidly expanded in recent years. The total vegetation coverage and per capita greenbelt increased from 33.8% and 5.0 m^2 in 2000 to 38.2% and 7.5 m^2 in 2008, respectively (unpublished data Nanchang Forestry Bureau).

Plot selection

The sites were studied in August of 2008. All forests (total 30 plots) selected for the study were located along a 35 km by 7 km belt transect extending from central urban Nanchang, through suburban, and rural areas (Yu et al. 2009). All sites are located on low hills with a relative elevation of 30–80 m in the hilly red soil region. These plant communities and succession stages are representative of those found in the mid-tropical region of China (Table 1). They involve five typical forest types including four typical succession stages from shrubs, Masson pine forest, conifer and broadleaf forest to evergreen broadleaved forest, and a disturbance climax stage bamboo forest in each area. Each forest type has two replicate plots in urban, suburban and rural areas, respectively. These three areas included five forest types with two replicate plots for a total of 30 plots in this study. Plots (400 m^2 for each) selected for the study were on well-drained upland sites, with no evidence of disturbances such as fire or logging in the last decade. All sites are underlain by Ultisols (local name is red soil), a typical soil type in the mid-tropical region of China.

Table 1. Stand characteristics of 30 plots along an urban-suburban-rural gradient in Nanchang, southern China

Site symbol*	VC, DBH and H**	Representative species
US1	1.0, 5 cm, 1.2 m	*Euonymus japonicas, Buxus sinica*
US2	1.0, 8 cm, 1.0 m	*E. japonicas, Mahonia fortunei*
UM1	0.8, 20 cm, 18 m	*Pinus massoniana*
UM2	0.7, 15 cm, 13 m	*P. massoniana*
UC1	0.9, 18 cm, 16 m	*P. massoniana, Cinnamomum camphora*
UC2	0.9, 19 cm, 17 m	*P. massoniana, C. camphora*
UE1	0.8, 25 cm, 20 m	*C. camphora, Ilex chinensis, Camellia oleifera*
UE2	0.8, 32 cm, 25 m	*C. camphora, Ligustrum lucidum*
UB1	1.0, 3 cm, 6 m	*Phllostachys sp.*
UB2	0.9, 8 cm, 10 m	*Ph. pubescens*
SS1	0.8, 3 cm, 0.8 m	*Symplocos paniculata, Philadelphus sp.*
SS2	0.9, 4 cm, 1.2 m	*Quercus serrata var. brevipetiolata, Miscanthus floridulus*
SM1	0.7, 15 cm, 20 m	*P. massoniana*
SM2	0.7, 25 cm, 18 m	*P. massoniana*
SC1	0.8, 18 cm, 16 m	*P. massoniana, C. camphora, Liquidambar formosana*
SC2	0.9, 19 cm, 18 m	*P. massoniana, Schima superba, Castanopsis sclerophylla*
SE1	0.9, 30 cm, 22 m	*C. camphora, S. superba, C. sclerophylla*
SE2	0.8, 15 cm, 20 m	*C. sclerophylla, C. Camphora, S. superba*
SB1	0.7, 12 cm, 14 m	*Ph. pubescens*
SB2	0.8, 15 cm, 18 m	*Ph. pubescens*
RS1	1.0, 7 cm, 1.6 m	*Q. serrata var. brevipetiolata, Loropetalum chinense*
RS2	1.0, 7 cm, 1.8 m	*Adinandra millettii, , Loropetalum chinense*
RM1	0.8, 20 cm, 15 m	*P. massoniana*
RM2	0.8, 15 cm, 16 m	*P. massoniana*
RC1	0.8, 15 cm, 15 m	*P. massoniana, S. superba, C. Sclerophylla, L. formosana*
RC2	0.9, 18 cm, 16 m	*P. massoniana, C. Camphora, Cunninghamia lanceolata*
RE1	0.8, 30 cm, 18 m	*C. Camphora, Camellia oleifera*
RE2	0.8, 28 cm, 23 m	*C. sclerophylla*, *C. Camphora*, *S. superba*
RB1	0.9, 10 cm, 15 m	*Ph. pubescens*
RB2	0.8, 12 cm, 17 m	*Ph. pubescens*

Note:* U, S and R indicate urban, suburban and rural zone, respectively; S, M, C, E and B indicate shrubs, Masson pine forest, conifer and broadleaf mixed forest, evergreen broadleaved forest and bamboo forest, respectively. ** VC, DBH and H indicate vegetation coverage ratio, Diameter at breast height (cm) and average height (m), respectively.

Soil sampling and soil P fractionation

Nine random topsoil (0−15 cm) samples were collected and mixed as a composite sample from each plot. A total of 270 soil samples were taken using a soil core sampler with 4.8 cm diameter. All soil samples were air-dried. After removal of visible plant residue, the soil samples were sieved through a 2-mm screen, mixed and stored at room temperature prior to chemical analyses. Subsamples of the air-dried soils were further ground to pass a 0.15-mm sieve and analyzed for total P. Total P was analyzed using the molybdate blue method after digestion in sulfuric acid and perchloric acid (Liu et al. 1996).

Soil samples were air-dried and ground to pass a 0.5-mm sieve and processed following the soil P fractionation procedure (Crews et al. 1995; Motavalli & Miles 2002) based on the method provided by Hedley et al. (1982). Corresponding supernatants 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. After filtration, the corresponding supernatants were used to measure resin-P, $NaHCO_3$-P, NaOH-P, Sonication-P and HCl-P using the phosphomolybdic acid blue color method (Liu et al. 1996). Total extracted P is the sum of resin-P, $NaHCO_3$-P, NaOH-P, sonication-P and HCl-P. Residue-P was calculated by subtracting total extracted P from the total P concentration in the samples.

Statistical analysis

The Tukey's multiple comparisons method was used to identify significant differences in soil total P concentration and P sequential fractions along the rural-suburban-urban gradient or among the succession stages after ANOVA tests for significance. SPSS software (SPSS Inc. 2001 Version 11.0) was used in order to perform these analyses as well as to examine correlations among different fractions and coefficients of variation (CV) of each variable in each gradient. For all these data, differences were considered significant at $\alpha = 0.05$.

Results

Mean values of topsoil total P and all P fractions except sonication-P under five forest types were higher in urban than in suburban and rural areas (Table 2). Moreover, all these including sonication-P, in each forest type, except Masson pine forest, were also higher in urban than in suburban and rural areas (Fig. 1).

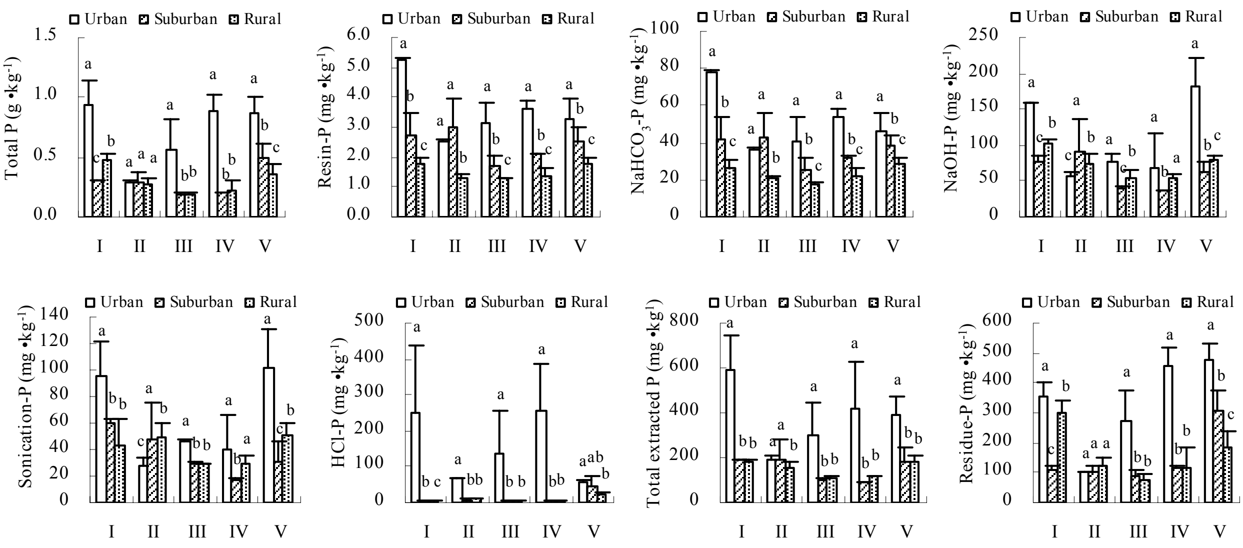


Fig. 1 Topsoil total P, resin-P, $NaHCO_3$-P, NaOH-P, Sonication-P, HCl-P, total extracted P and residue-P in different forest types (I: shrubs; II: Masson pine forest; III: conifer and broadleaf mixed forest; IV: evergreen broadleaved forest; V: bamboo forest) along an urban-suburban-rural gradient in Nanchang City and vicinity. Different letters indicate significant differences of mean values ($p<0.05$) among three areas.

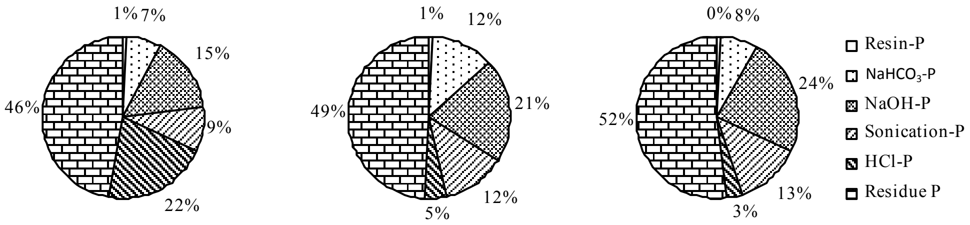
The components of topsoil P fractions showed that HCl-P, the dominant form, among all extractable P in urban areas shifted to NaOH-P in suburban and rural forests (Fig. 2). The coefficients of variation (CVs) of all extractable P were higher in urban and suburban than in rural areas, while the residue-P showed an opposite trend (Table 2). In addition, the ratios of residue-P to total P among urban, suburban and rural areas were not significantly different (Fig. 2).

Our data analyzed by ANOVA showed that topsoil total P ($F_{4,25}$=0.95, p=0.454), resin-P ($F_{4,25}$=1.31, p=0.295), $NaHCO_3$-P ($F_{4,25}$=2.29, p=0.088), sonication-P ($F_{4,25}$=0.35, p=0.844), HCl-P ($F_{4,25}$=0.82, p=0.525), total extractable P ($F_{4,25}$=2.62, p=0.059) and residue-P ($F_{4,25}$=1.51, p=0.230) showed no significance differences among five forest types, except soil NaOH-P ($F_{4,25}$=2.95, p=0.040) in shrubs and bamboo forest was higher than in Masson pine and conifer and broadleaf mixed and evergreen broad leaved forests.

Table 2. Mean ±SE and coefficient of variation (CV) of total P and P fractions in topsoil under forest ecosystems along urban-suburban-rural gradient in Nanchang City and vicinity.

Gradient		Total P (g·kg^{-1})	Resin-P (mg·kg^{-1})	NaHCO$_3$-P (mg·kg^{-1})	NaOH-P (mg·kg^{-1})	Sonication-P (mg·kg^{-1})	HCl-P (mg·kg^{-1})	Total extractable P (mg·kg^{-1})	Residue-P (mg·kg^{-1})
Urban	Mean ±SE	0.71±0.10a	3.57±0.34a	51.07±5.53a	107.73±19.68a	62.54±12.31a	153.60±47.75a	378.50±64.20a	333.50±50.17a
	CV	0.44	0.30	0.34	0.58	0.62	0.98	0.54	0.48
Suburban	Mean ±SE	0.30±0.04b	2.42±0.25b	36.19±3.66b	61.47±10.15b	36.90±6.94a	13.78±6.73b	150.74±22.19b	145.26±29.69b
	CV	0.45	0.33	0.32	0.52	0.59	1.55	0.47	0.65
Rural	Mean ±SE	0.31±0.04b	1.49±0.10c	23.18±1.68b	72.89±6.82b	40.20±4.92a	9.64±2.57b	147.38±12.51b	158.62±30.30b
	CV	0.42	0.21	0.23	0.30	0.39	0.84	0.27	0.60

Note: The same characters in each variable mean value indicate no significant difference among urban, suburban and rural soils, and different ones indicate significant difference.



Urban (a) Suburban (b) Rural (c)

Fig. 2 The components of topsoil P fractions in five forest types under urban (a), suburban (b) and rural (c) areas in Nanchang City and vicinity

Discussion and conclusions

Minimal information is available on soil P and its accumulation along urban–suburban-rural gradients. Our result indicated that soil total P content in urban areas increased by 2.3 times compared to the level found in rural areas. Various soil P fractions in urban areas were 1.5−15.9 times higher than those found in rural areas (Table 2).

Previous studies have shown that urban soils are generally enriched in P by direct human inputs and physical disturbances such as fire (Foy et al. 2003; Zhang et al. 2001; Zhang 2004; Yuan et al. 2007). Given these other reported results, it was surprising that there were no differences found in total P and P fractions, except resin-P, between suburban and rural areas in our study. Compared with two adjacent capitals, Nanjing (118°22′–119°14′E, 31°14′–32°37′N) of Jiangsu Province and Hangzhou (118°21′–120°30′E、29°11′–30°33′N) of Zhejiang Province, P enrichment in urban Nanchang soils were lower than those found in the other two cities. For example, total P in urban, suburban and rural surface soils are about 2.50, 1.25 and 0.35 g·kg^{-1}, respectively in Nanjing City (Zhang 2004), while about 1.78, 1.24 and 0.51 g·kg^{-1}, in Hangzhou City, China (Yuan et al. 2007). There are three possible explanations that: (1) the urbanization level is lower in Nanchang City than in Nanjing and Hongzhou Cities (Zhang 2004; Yuan et al. 2007; Yu et al. 2009); (2) the effect of urbanization on P in natural forest ecosystems lags behind impacts found in other ecosystems, such as crop lands due to stronger resilience to disturbance in forests; (3) phosphorus is more tightly cycled within a forest ecosystem in general (Wood et al. 1984).

The relative abundance of P fractions in the Nanchang urban area showed a decrease in this order: residue-P > HCl-P > NaOH-P > sonication-P > NaHCO$_3$-P > resin-P; while the suburban and rural areas showed residue-P > NaOH-P > sonication-P > NaHCO$_3$-P > HCl-P> resin-P (Fig. 2). Our results showing NaOH-P as the dominant fraction (50% and 41%, respectively) among the five extractable fractions in rural and suburban soils are in agreement with results reported by Tiessen et al. (1984) and Beck and Sanchez (1994), who found that NaOH-P played an important role in plant nutrition in highly weathered ultisols. However, among the five fractions extracted, the percentages of HCl-P to total extractable P increased from 6% and 8% in rural and suburban soils to 36% in urban soils (Table 2). Soil HCl-P, as weathered mineral P (Motavalli & Miles 2002) is usually present at very low levels or absent in highly weathered acidic soils (Agbenin & Tiessen 1995) since weathering affects mainly Ca-phosphates. In our study, urban soil showed a high increase in soil HCl-P, probably from inputs of material with abundant Ca-phosphates. According to results reported by Tiessen & Moir (1993), the HCl-P fraction may also contain both very recalcitrant Fe-associated P and easily available organic P associated with plant organic matter (POM). Thus, soil soluble P from Ca bound P will be further increased due to soil acidification accelerated with N and acid deposition in urban ecosystems.

Soil P can be transported into water bodies by both surface runoff and infiltration into groundwater (Heckrath et al. 1995; Zhang et al. 2001). Moreover, soil P may affect water quality over long periods due to slow soil P transformations among various fractions and movement from soil to water (Bennett et al. 2004). Thus, P accumulating in the urban soils may be a potential source of aquatic pollution (Bennett 2003; Zhang et al. 2005).

Previous studies have shown that urbanization may change the balance of P inputs and outputs. Urban areas are acknowledged sources of waste P with the forms and dynamics of soil P varying along urban-suburban-rural gradients (Bennett 2003; Zhang et al. 2001; Zhang 2004; Yuan et al. 2007). The cumulative effects of continued annual or seasonal P cycling processes, including chemical and biological processes that control the balance between P immobilization and mineralization, results in changes in the concentration and chemical nature of P (Turrion et al. 2000).

Soil P forms and cycling have been found to generally change with forest succession (Crews et al. 1995). However, significant positive correlations among topsoil total P and varied P fractions for all treatments were observed in our study (Fig. 3). Contrary to our expectations, our study showed that the close positive correlations among total P, bioavailable P, extractable P and residue-P did not change with urbanization and forest succession. This can generally be explained by the fact that P is tightly cycled and slowly transformed within the forest ecosystems (Wood et al. 1984). Similar P components in urban waste and soils are another possible explanation for a lack of changes in P fractions. Thus, bioavailable P, extractable P and residue-P would increase with the addition of total P in urban soils.

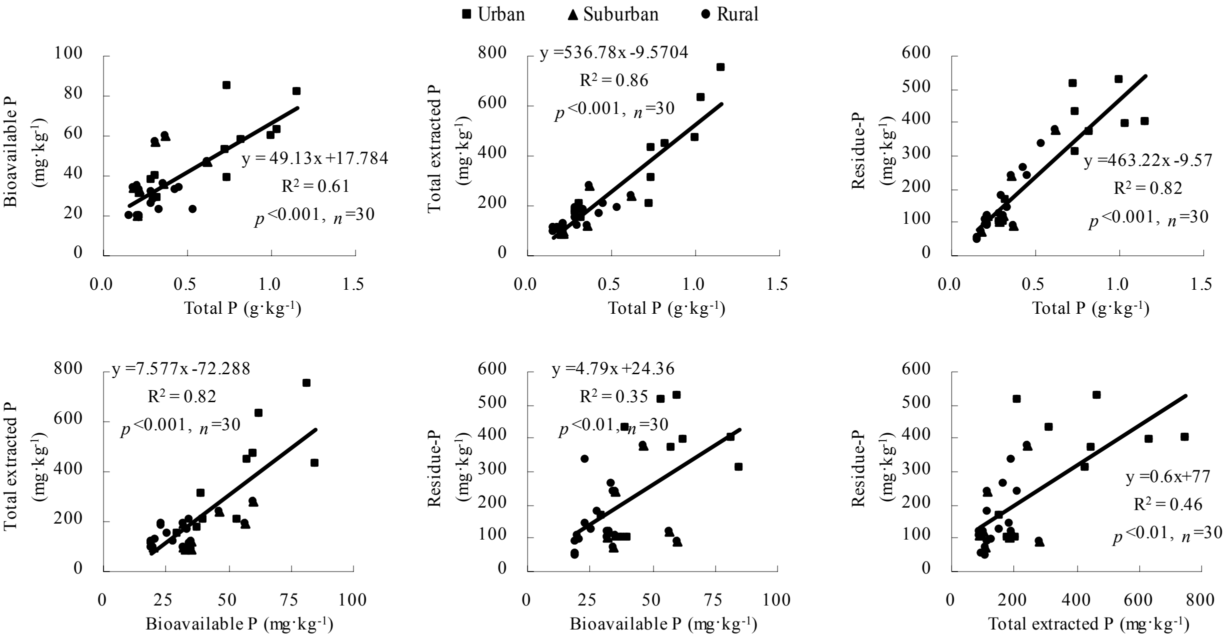


Fig. 3 Correlations among topsoil total P and P fractions along urban-suburban-urban gradient in Nanchang City and vicinity. Forests types were pooled for this analysis.

Potential problems with increased P levels are that: (1) plants in urban soils can not take up all bioavailable P, with some of the excess exported to surface waters (Zhang et al., 2005); (2) levels of extractable P can be increased for export with increases in urban N and acid deposition because soil HCl-P was the dominant fraction in urban soils; (3) residue-P can be continuously released to other fractions including extractable P and bioavailable P (Bennett et al. 2004); (4) compared with rural soils, there were significant higher spatial variability of total P and P fractions, for example soil HCl-P ranged from 12.71 to 437.27 mg·kg^{-1} among ten plots in urban forests (Table 2 and Fig. 1), with higher levels increasing the possibility of P loss from soil. Therefore, elevated P concentrations in P-rich urban soil could have long term impacts on aquatic quality. More detailed assessments are required if potential secondary eutrophication caused by excess P release from anthropogenic high-P soils is to be avoided (Yuan et al. 2007).

In general, increases in soil P pool and its availability in our study region were not significantly increased by the biological process of forest succession (Fig. 1) due to slow P transformations and tightly cycled P within our study ecosystems. Surprising results were that topsoil total P and P fractions were generally higher in shrubs and bamboo forest than in Masson pine and conifer and broadleaf mixed forest across the urbanization gradient, while the differences between evergreen broadleaved forest and other forest types depended on P fractions and position on the urbanization gradient. Shrubs are considered the primary stage of forest succession in our subtropical region; although shrubs can be a disturbance climax stage maintained by continuous cutting since shrubs are an important cooking fuel in rural areas in southern China. Shrubs in urban areas are also intensively managed for amenity values in the landscape and maintained in climax state. Bamboo forest is intensively managed in China with rapid rotations as an economic investment. In contrast to these continued disturbances in shrubs and bamboo, Masson pine forest, conifer and broadleaf mixed and evergreen broadleaved forest have less human disturbance due to Chinese forest protection policies and our data indicated that P pool and P fractions do not appear to increase substantially with forest succession in our study area.

In conclusion, topsoil phosphorus signatures in our study showed that urbanization and human activity were important factors influencing P nature and accumulation in forest ecosystems with the minimal effect of forest succession on improving soil P. Phosphorus enrichment, especially from the HCl-P fraction accumulated in the urban soils may be a source of aquatic pollution with potential long-term impacts on human health.

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