Distributions of soil phosphorus in China's densely populated village landscapes

Linzhang Yang

Institute of Soil Science, Chinese Academy of Sciences, Nanjing, 210008, China

Abstract
Village landscapes, which integrate small-scale agriculture with housing, forestry and other land use practices, cover more than 2×106 km2 across China. And accumulation of excess phosphorous in soils has become an important contributor to eutrophication across China. The aim of this study was to investigate relationships between fine-scale patterns of agricultural management and soil total phosphorus (STP) within China's village landscapes. The results showed that STP stock across five village regions (0.9×106 km2) was approximately 0.14 Pg (1 Pg=1015 g), with village landscape STP density varying significantly with precipitation and temperature. Outside the Tropical Hilly Region, STP densities also varied significantly with land use, and cover. As expected, the highest STP densities were found in agricultural lands and in areas near buildings, while the lowest were in nonproductive lands and forestry lands. A surprisingly large portion of village STP stock was associated with built structures and disturbed lands surrounding them, which had a significant relationship with population density. Our results demonstrated that local patterns of land management and human residence were associated with substantial differences in STP both within and across China's village landscapes.

Key Words
Phosphorus density, village landscape, China.

Introduction
Phosphorus (P) is highly heterogeneous in spatial distribution, and P inputs are critical in determining whether eutrophication occurs (Vadas *et al.* 2007). It is therefore critical to understand how P varies in response to climate, land use, and other factors when evaluating the role of terrestrial ecosystem processes in altering the global P cycle. Landscape change is an important part of environmental earth dynamics (Vitousek 1994). Densely populated villages cover approximately 8×106 km2 globally, and in China alone, village landscapes was about 25% of the global village area (Ellis 2004). Changes in land use and land cover within China's intensively populated village landscapes are dominated by fine-scale landscape changes, preventing the precise measurement of these changes using conventional, coarse-resolution (≥30 m), land-use mapping systems (Ellis *et al.* 2006). For this reason, fine-scale (<1 m) feature-based mapping is an especially useful system for these small changes (Ellis *et al.* 2000; Ellis *et al.* 2006).

Methods
Study area and landscape classfication
China's village landscapes (>150 persons per square kilometer) were first stratified into five biophysically distinct initial regions using a K-means cluster analysis of data for terrain, climate, and soil fertility as illustrated in Table 1(Verburg *et al.* 1999). Within each region, a single 100 km2 rural landscape site was then selected for detailed field research. Within each site, 12 500×500 m square landscape sample cells (25 ha) were then selected for fine-scale mapping, soil sampling, and other field measurements using a regional cluster analysis of land cover patterns (Ellis 2004).

Ecologically-distinct anthropogenic landscape features were mapped across each sample cell based on 1 m resolution IKONOS imagery and orthorectified across each site in 2002 (Ellis et. al., 2006). Landscape features were classified into ecotopes using the four level classification hierarchy: FORM→USE→COVER→GROUP+TYPE, combining simple land use and cover classes (FORM, USE, COVER) with a set of more detailed feature management and vegetation classes (GROUPs) stratified into TYPEs (Ellis *et al.* 2006; http://ecotope.org/aem/classification).

Sampling and Analysis
Soil samples were selected using a multi-stage stratified sampling procedure designed to allocate a maximum of about 150 soil sample points within each site among the ecotope classes. First, a maximum of 10 and a minimum of 3 samples were allocated to each ecotope class in direct proportion to their regional areas. A

spatially random point location was then chosen within each feature using GIS. Soil core was extracted using an AMS Split Core sampler (AMS, American Falls, Idaho), and the submerged sediments in Yangtze Plain Region were sampled using a coring tube system (Uwitec, Austria). All statistical tests were conducted using SPSS 11.5 (SPSS, Chicago, Illinois, USA). P values < 0.05 were used to test statistical significance in all analyses. One-way analysis of variance (ANOVA) was used to examine the effect of land use, and land cover classes on STP densities.

Table 1. Sampled regions and sites (modified from Ellis 2004)

Region	Site (County, Province)	Main soil types (US Soil Taxonomy, suborder level)	Agricultural Population density (pers km^2)	Area (10^3 km^2)	Arable Land (%)	Flat land (%)	Poor soils (%)	Annual Precipitation (mm)	Annual Mean Temperature (°C)
North China Plain	Gaoyi, Hebei	Ochrepts, Umbrepts	321	486	51	61	6	645	9
Yangtze Plain	Yixing, Jiangsu	Fluvents	464	75	44	70	17	1312	16
Sichuan Hilly	Jintang, Sichuan	Orthents, Psamments	248	198	30	4	5	950	11
Subtropical Hilly	Yiyang, Hunan	Aqualfs	188	172	18	5	85	1426	14
Tropical Hilly	Dianbai, Guangdong	Aquults	233	71	20	16	78	1651	20

Results

STP densities and stocks

Total STP stock (0–30 cm) across the 0.908×106 km2 area of the five regions was approximately 0.144 Pg, and the average STP density was 0.16 kg m–2 (30 cm) (Table 2). The regionally STP density ranged from 0.08±0.04 kg/m^2 in Tropical Hilly to 0.22 kg m–2 both in North China Plain (0.22±0.04 kg/m^2) and in Yangtze Floodplain (0.22±0.19 kg /m^2), which was almost a four fold difference (Table 2).
The Tropical Hilly Regions had the lowest STP density because the hydrothermal conditions of high precipitation and temperature can enhance the degree of soil weathering and P loss through surface soil erosion (Neufeldt *et al.* 2000). In contrast, the higher STP densities of the North China Plain and the Yangtze Plain may be attributed to the large area of arable land with high P fertilizer inputs (Tang *et al.* 2003). In our study, the annual precipitation (R=0.99, P=0.02) and mean annual temperature (R=0.95, P=0.05) were highly related to STP densities. In the natural land ecosystem, the STP density was highest in the North China Plain, and lowest in the Tropical Hilly, and the distribution and cycle of STP at the regional scale related to climatic, geography (China Agriculture University, 1998), the same rule in our study (except the Yangtze Plain).

Table 2. STP density and stock across five regions

Region (site)	Area (10^6 km^2)	Samples	Sampled ecotope area‡ (%)	STP (kg /m^2)	STP stock (Pg)
North China Plain (Gaoyi)	0.276	134	94.4	0.22±0.04	0.062±0.011
Yangtze Floodplain (Yixing)	0.086	153	91.8	0.22±0.19	0.019±0.016
Sichuan Hilly (Jintang)	0.084	147	91.0	0.19±0.04	0.016±0.003
Subtropical Hilly (Yiyang)	0.284	152	92.0	0.11±0.03	0.032±0.009
Tropical Hilly (Dianbai)	0.178	149	93.3	0.08±0.04	0.014±0.007
All regions	0.908	735	92.5	0.16	0.144

‡ Total sampled ecotope area was less than 100%, because ecotope classes with areas ≤ 0.25% of each site were omitted from the sample.

Hierarchical scale-effects on STP densities and stocks

STP densities varied strongly with land use in every region except Tropical Hilly (Table 3), demonstrating that land use was likely a significant factor controlling STP densities in village landscapes. In all regions, the Constructed (Artificial surfaces and structures) had the highest STP density, because of runoff carrying high levels of P from human and animal waste origin; and decomposing of plant and animal bones releasing high levels of P (China Agricultural University 1998). While, the Forestry USE (0.10 kg m–2) had the lowest average STP density, confirming Grerup *et al.*'s (2006) results that total P tended to be higher in the formerly cultivated fields than in the continuously forested land. Variations in STP distribution results could be affected by differences in parent material, soil weathering, human effects, and the relative importance of these factors among regions.

STP stock was calculated using STP density and its area. It was therefore not surprising that the largest STP for a given region was related to the extent of the land USE. Each region had a unique dominant land Use and STP stock: North China plain (Irrigated, 78.4%), Yangtze Plain (Paddy, 51.2%), Sichuan Hilly (Rainfed, 49.9%), Subtropical Hilly (Paddy, 37.5%), Tropical Hilly (Forestry, 42.4%) (Table 3).

In each region, the distribution of STP density under the level of land COVER was presented in Table 4. Across the five regions, the highest average STP density presented was Sealed COVER (0.23 kg m–2), followed by perennial (0.19 kg m–2) and annual COVER (0.17 kg /m^2), and the lowest STP density was found in Barren COVER (0.07 kg /m^2) (Table 4). But in our results, the Sealed COVER with low vegetation cover had the highest STP density. This is because the sealed COVER (roads, housings) had high soil bulk densities due to human and vehicle's traffic along with considerable human disturbance and P pollution which coupled contributed to high STP densities.

The Annual COVER had the highest STP stock percentage in each region except Tropical Hilly (Perennial COVER had the highest STP stock percentage). There was an obvious STP stock gradient from north to south due to climate and geography: the STP stock in Annual decreased from 76.2% in North China Plain to 16.6% in Tropical Hilly, however, the STP stock in Perennial COVER increased from 1.0% in North China Plain to 46.8% in Tropical Hilly (Table 4).

Table 3. Relative STP stocks and densities among land USE classes within each region.

Land USE	North China Plain		Yangtze Plain		Sichuan Hilly		Subtropical Hilly		Tropical Hilly		All Regions
	stock (%)	density (kg /m^2)	stock (%)	density (kg /m^2)	stock (%)	Mean density (kg /m^2)	stock (%)	density (kg /m^2)	stock (%)	density (kg /m^2)	Mean density (kg /m^2)
Aquaculture	–	–	8.9	0.11±0.10 bc	–	–	–	–	–	–	0.11
Constructed	12.3	0.22±0.06 bc	9.4	0.35±0.31 a	6.4	0.19±0.05 ab	5.8	0.12±0.06 abc	0.7	0.11±0.06	0.20
Disturbed	1.0	0.20±0.05 bc	3.7	0.32±0.37 abc	3.8	0.16±0.04 b	4.3	0.12±0.03 ab	6.5	0.11±0.07	0.18
Fallow	0.3	0.13±0.01 d	5.1	0.10±0.02 c	–	–	0.3	0.07±0.04 abc	–	–	0.10
Forestry	–	–	0.6	0.11±0.01 bc	14.7	0.15±0.04 b	33.2	0.08±0.03 c	42.2	0.07±0.03	0.10
Horticulture	0.3	0.30±0.06 a	–	–	–	–	–	–	–	–	0.30
Irrigated	78.4	0.23±0.06 b	5.7	0.20±0.07 ab	–	–	–	–	–	–	0.22
Mine & Fill	–	–	–	–	–	–	0.3	0.08±0.01 bc	0.1	0.07±0.03	0.08
Ornamental	0.8	0.17±0.03 bcd	0.1	0.09±0.03 bc	–	–	–	–	–	–	0.13
Paddy	–	–	51.2	0.20±0.23 abc	16.1	0.20±0.04 a	37.5	0.15±0.03 a	17.5	0.07±0.02	0.16
Rainfed	1.0	0.19±0.03 bcd	7.8	0.32±0.30 a	49.9	0.21±0.08 a	8.5	0.14±0.07 a	26.1	0.09±.010	0.19
Variable	0.3	0.15±0.03 cd	–	–	–	–	–	–	–	–	0.15

Table 4. Relative STP stocks and densities among land COVER classes within each region.

Land COVER	North China Plain		Yangtze Plain		Sichuan Hilly		Subtropical Hilly		Tropical Hilly		All Regions
	stock (%)	density (kg /m^2)	stock (%)	density (kg /m^2)	stock (%)	Mean density (kg /m^2)	stock (%)	density (kg /m^2)	stock (%)	density (kg /m^2)	Mean density (kg /m^2)
Annual	76.2	0.23±0.06 ab	56.5	0.22±0.19 c	61.0	0.20±0.07	44.0	0.14±0.05 bc	16.6	0.07±0.03	0.17
Bare soil	2.9	0.27±0.05 a	0.3	0.12±0.03 bc	1.4	0.23±0.06	1.9	0.09±0.02 bc	–	–	0.16
Mixed	1.5	0.15±0.03 c	2.5	0.25±0.19 ab	2.6	0.17±0.07	3.5	0.20±0.13 abc	28.4	0.08±0.09	0.17
Perennial	1.0	0.18±0.04 bc	6.2	0.38±0.41 abc	21.5	0.18±0.06	36.2	0.09±0.03 a	46.8	0.08±0.05	0.19
Sealed	11.0	0.22±0.06 ab	16.6	0.38±0.32 a	4.4	0.17±0.04	6.3	0.13±0.07 abc	1.3	0.11±0.06	0.23
Variable	1.8	0.14±0.02 c	–	–	–	–	–	–	–	–	0.14
Water	–	–	9.7	0.11±0.08 ab	–	–	–	–	–	–	0.11
Barren	–	–	–	–	–	–	–	–	0.3	0.07±0.03	0.07

Ecotope-level analysis further revealed fine-scale heterogeneity of STP density within five regions. The types and numbers of ecotope were much more than that of the land USE/COVER in each regions (the data was too large, so it was not presented), and there were high values of coefficient of variation (CV) of STP density at the ecotope level (Table 5). Consequently, The STP density and stock of each ecotope within regions were much more complex than that of the coarser land USE/COVER. The CV of STP density ranged from 81% of ecotope in Yangtze Plain to 13% of land COVER in Sichuan Hilly with an average of 40% across the five regions. The CV of STP densities of the land USE, COVER and ecotope levels were highest in Yangtze Plain and lowest in Sichuan Hilly (Table 5). From the results above, we can conclude that at the regional scale, the spatial variation of STP between densely populated village landscapes was related to the climatic factors (precipitation and temperature) and geography; while within village landscape, the spatial variation of STP was mainly attributable to human activities, such as soil nutrient management, fertilizer application, and so on.

Since STP density between land USE, COVER, and ecotope was highly heterogeneous, estimations and comparisons of STP density at local or regional scales may contain errors if fine variations were ignored. In regional and especially in global analyses, most of the landscapes we sampled were characterized as consisting entirely of croplands- this was undoubtedly a source of substantial error in regional STP estimates.

However, many researches usually neglect the small variations because of their limited resources (Lardy *et al.* 2002). Meanwhile, the large variation in the STP density across regions suggested that further study was needed to determine the macroscopical climate and geography. Generally, the variations of STP density within and across regions both need to be considered.

Table 5. Variation in STP densities in land use, cover and ecotope classes within and among regions.

With regions										Among regions†		
Region	Land use			Land cover			Ecotope					
	Mean	SD	CV	Mean	SD	CV	Mean	SD	CV	Mean	SD	CV
North China Plain	0.20	0.05	27%	0.20	0.05	25%	0.20	0.05	29%			
Yangtze Plain	0.20	0.11	53%	0.24	0.12	49%	0.22	0.18	81%			
Sichuan Hilly	0.18	0.03	14%	0.19	0.03	13%	0.19	0.04	22%	0.16	0.07	40%
Subtropical Hilly	0.11	0.03	29%	0.13	0.05	35%	0.11	0.04	34%			
Tropical Hilly	0.09	0.02	23%	0.08	0.02	20%	0.08	0.03	40%			

Conclusions

This study integrated high spatial resolution mapping with soil sampling to demonstrate that local patterns of land management and human residence were associated with substantial differences in STP both within and across China's village landscapes. The high STP density around the housings demonstrated soil P must be considered to be a significant global pool of P and also a potential contribution to P pollution. With the rapidly change in land use/land cover in Chinese densely populated landscapes, such information is essential for rational planning of future management to make agricultural development sustainable.

References

China Agricultural University (1998) Agricultural chemistry. Beijing: Agricultural press, pp 115–123

Ellis EC (2004) Long-term ecological changes in the densely populated rural landscapes of China. In 'Ecosystems and Land Use Change. American Geophysical' (Eds RS DeFries, GP Asner, RA Houghton) pp 303–320. (Union, Washington, DC.).

Ellis EC, Li RG, Yang LZ, Cheng X (2000) Long-term change in village-scale ecosystems in China using landscape and statistical methods. *Ecol. Appl*. **10**, 1057–1073.

Ellis EC, Wang H, Xiao HS, Peng K, Liu XP, Li SC, Ouyang H, Cheng X, Yang LZ (2006) Measuring long-term ecological changes in densely populated landscapes using current and historical high resolution imagery. *Remote Sens. Environ*. **100**, 457–473.

Grerup UF, Brink DJT, Brunet J (2006) Land use effects on soil N, P, C and pH persist over 40–80 years of forest growth on agricultural soils. *Forest Ecol. Manag.* **225**, 74–81.

Lardy LC, Brossard M, Assad MLL, Laurent JY (2002) Carbon and phosphorus stocks of clayey Ferralsols in Cerrado native and agroecosystems, Brazil. *Agr. Ecosyst. Environ.* **92**, 147–158.

Neufeldt H, Silva JED, Ayarza MA, Zech W (2000) Land-use effects on phosphorus fractions in Cerrado oxisols. *Biol Fertil Soils* **31**, 30–37.

Tang JD, Ye XY, Rao GL, Lin BS (2003) Effect of human activities on quality of cultivated land in Guangdong province. *Soil* **1**, 8–12. (in Chinese)

Vadas PA, Gburek WJ, Sharpley AN, Kleinman PJA, Moore PA, Cabrera ML, Harmel RD (2007) A model for phosphorus transformation and runoff loss for surface-applied manures. *J. Environ. Qual.* **36**(1), 324–332.

Verburg PH, Veldkamp A, Fresco LO (1999) Simulation of changes in the spatial pattern of land use in China. *Applied Geography* **19**(3), 211–233.

Vitousek PM (1994) Beyond global warming: Ecology and global change. *Ecology* **75,** 1861–1876.