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

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Abstract

Purpose Village landscapes, which integrate small-scale agriculture with housing, forestry and a host of other land use practices, cover more than 2×10^6 km^2 across China. Village lands tend to be managed at very fine spatial scales (≤30 m), with managers altering soil fertility and even terrain by terracing, irrigation, fertilizing, and other land use practices. Under these conditions, accumulation of excess phosphorous in soils has become important contributor to eutrophication of surface waters across China's densely populated village landscapes. 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.

Materials and methods First, China's village landscapes were divided into five environmentally distinct regions across China. Within each region, a single 100 km^2 research site was then selected, and 12 500×500 m square landscape sample cells were selected for fine-scale mapping. Soils were sampled within fine-scale landscape features using a regionally weighted landscape sampling design.

Results and discussion STP stock across the 0.9×10^6 km^2 area of our five village regions was approximately 0.14 Pg (1 Pg=10^{15} g), with STP densities ranging from 0.08 kg m^{-2} in Tropical Hilly Region to 0.22 kg m^{-2} in North China Plain and Yangtze Plain, with village landscape STP density varying significantly with precipitation and temperature. Outside the Tropical Hilly Region, STP densities also varied significantly with land form, 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. As a combined result of these high STP densities and the predominance of agricultural land use, most village STP stock was found in agricultural lands. A

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surprisingly large portion of village STP stock was associated with built structures and disturbed lands surrounding them (15.0% in North China Plain, 19.3% in Yangtze Plain, 5.9% in Sichuan Hilly Region, 7.8% in Subtropical Hilly Region, 2.7% in Tropical Hilly Region), which had a significant relationship with population density.

Conclusions 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 which have increased their potential contribution to P pollution. With the rapid change in land use/land cover in China's densely populated landscapes, such information is essential for rational planning of future management to reach agricultural sustainability.

Keywords China · Land cover · Land form · Land use · Pollution · Soil phosphorus · Village landscapes

1 Introduction

Phosphorus (P), derived from rock, is highly heterogeneous in spatial distribution. Besides parent material, many other factors can affect the P distribution, such as climate, biota, topography, time, and human activity. Most terrestrial ecosystems are considered nitrogen (N) and/or P limited (Aerts and Chapin 2000). However, N limitation can be progressively alleviated by inputs from anthropogenic deposition, such as N decomposition from fossil fuel and N fertilization, and the P cycle is an incomplete cycle, such that P availability in the biosphere tends to decrease over time, finally creating a situation in which the availability of P is more important than that of N in regulating carbon balance and community composition (Wollast 1993; Litaor et al. 2005). Further, P inputs are critical in determining whether eutrophication occurs (Allen et al. 2006; Franklin et al. 2007; 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, also called global change (Vitousek 1994). The village landscape is a mosaic of natural environment and human management that varies in size, shape, and arrangement (Zhou 2000; Forman and Gordorn 1986; Burgess and Sharper 1981). Densely populated villages cover approximately 8×10^6 km^2 globally or about 7% of Earth's land surface (Ellis 2004). In China alone, village landscapes cover about 2×10^6 km^2, or about 25% of the global village area, providing habitation for more than 500 million people and including more than half of China's arable land (Ellis 2004). Given their vast extent and large population, changes in land use across China's village landscapes have the potential to play a major role in the global biogeochemical cycle.

China's diverse village landscapes are found in environmental conditions ranging from the northern temperate zone to the edge of the tropics and from fertile floodplains to mountainous regions, and changes in land use and land cover within these intensively populated village landscapes are dominated by fine-scale landscape changes. Soil sampling and measurement are challenging within the highly heterogeneous mosaics of fine-scale landscape features managed by a complex assortment of land management practices that are the defining characteristic of village landscapes. Though major anthropogenic changes in soil properties have certainly occurred and are occurring in these landscapes, most of these changes occur only at very fine spatial scales, 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 mapping and measuring land use and its changes within and across densely populated landscapes (Ellis et al. 2000; Ellis et al. 2006).

The purpose of this study was to measure and compare soil total phosphorus (STP) densities under different land form, land use, and land cover conditions at fine spatial scales within each densely populated village landscapes of China. We accomplished this by sampling the top 30 cm of soils according to a regionally weighted sampling design (the layer most sensitive to modification by land use practices; Bowman et al. 1990; Batjes and Sombroek 1997; Batjes and Dijkshoorn 1999), across a regionally representative sample of fine-scale land use and land cover features in landscape from five environmentally distinct village regions across China. Then the regional significance of STP variation associated with fine-scale features is assessed and compared with the importance of regional environmental factors (precipitation and temperature).

2 Materials and methods

2.1 Study area

China's village landscapes (>150 persons per square kilometer) were first stratified into five biophysically distinct initial regions at 32 km resolution gridded dataset developed by Verburg et al. (1999) using a K-means cluster analysis of data for terrain, climate, and soil fertility as illustrated in Table 1 and Fig. 1. It is notable that the regions derived by this analysis accounted for >90% of China's agricultural population but <80% of its arable land. Data in Table 1 and Fig. 1 include all cells with population density >150 persons per square kilometer, regardless of similarity to

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

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

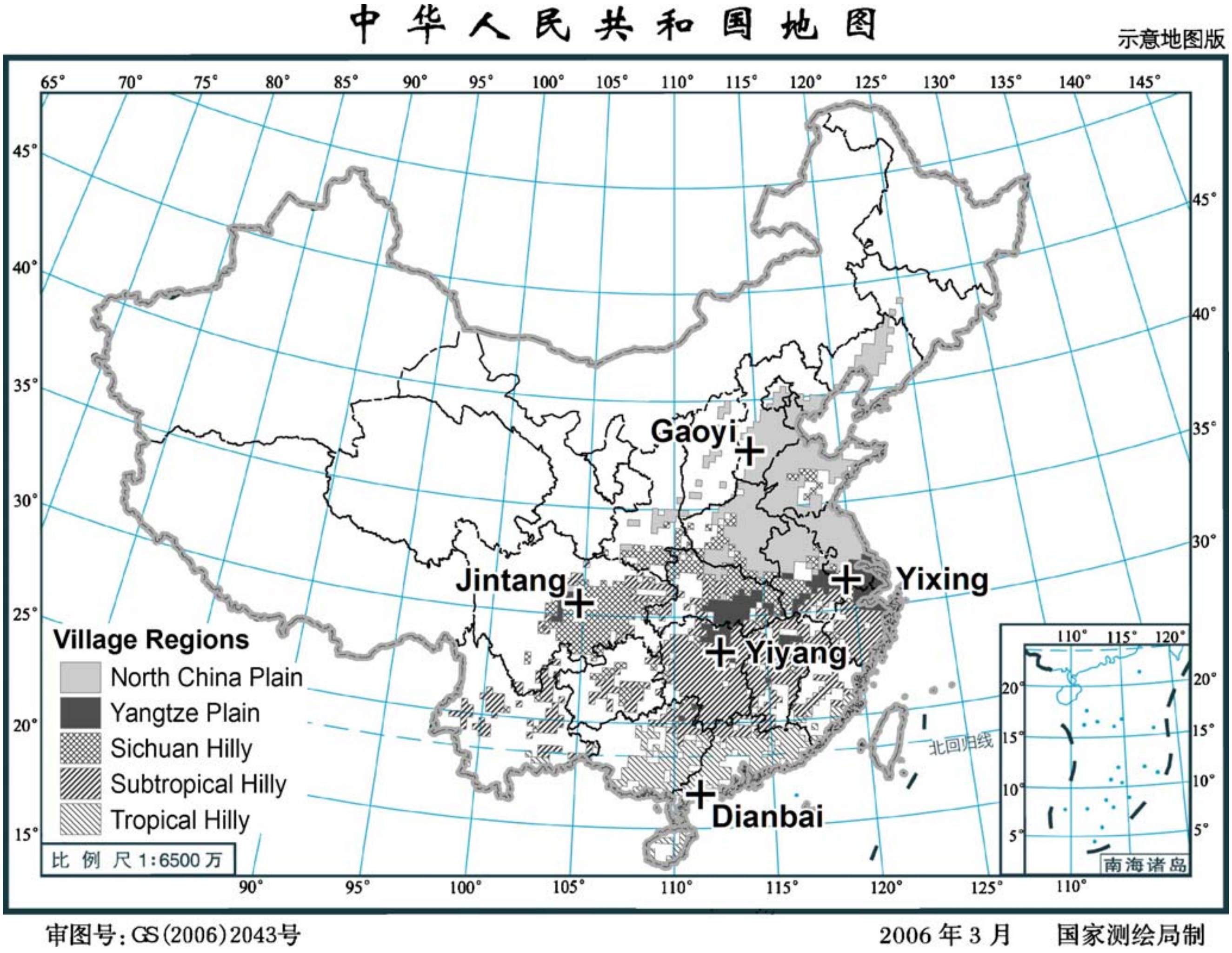

Fig. 1 Location of research sites and initial village regions across China

Table 2 The descriptions of land form, land use, and land cover (modified from Ellis et al. 2006)

Classes	Name	Code	Description
Land form	Anthropogenic	AN	Anthropogenic surfaces and structures
	Bench plateau	BP	Natural bench plateau, <15% slope between >30% slopes
	Canal margin	CM	Margin of flowing anthropogenic watercourse
	Excavated	EX	Excavations, mines, and pits >2 m deep and 30 m across
	Floodplain	FP	Alluvial floodplain, <3% slope
	Flowing marsh	FM	Slowly flowing wetland in channel, usually in floodplain
	Foot slope	FS	Level areas at bottom of hills with non-alluvial soils, <5% slope
	Large canal	CB	Flowing anthropogenic watercourse, >30 m wide
	Large pond	PB	Anthropogenic lentic water body, >30 m wide
	Marsh	MA	Lentic wetland
	Seasonal river	SR	Seasonally flowing natural watercourse, >30 m wide
	Sloping	SL	Sloping hillsides, 3–30% slope
	Small canal	CA	Flowing anthropogenic watercourse, <30 m wide
	Small pond	PA	Lentic water body, <30 m wide
	Steep slope	SS	Steep slopes, >30% slope
	Summit	SU	Hilltop plateau, <15% slope surrounded by >30% slopes
	Terraced slope	TS	Artificial terraces on >5% slope
Land use	Aquaculture	A	Aquatic livestock and crops
	Constructed	C	Artificial surfaces and structures (except livestock and horticultural production)
	Disturbed	D	Fragmented or disturbed by human activities without consistent use
	Fallow	F	Larger areas recovering from past human disturbance and without current or planned use
	Forestry	T	Managed for regular harvest of noncrop vegetation biomass
	Horticulture	H	Intensive horticulture in artificial structures
	Irrigated	I	Irrigated agriculture
	Mine and fill	M	Active mining, filling, and dumping
	Ornamental	O	Managed for esthetic, conservation, and other nonproduction uses
	Paddy	P	Rice and other flooded crops
	Rainfed	R	Rainfed agriculture
	Variable	V	Management varies in response to unpredictable environment (e.g., seasonal river channels)
Land cover	Annual	A	Herbaceous vegetation, surface >25% soil, herbaceous >25%
	Bare soil	E	Bare soil, surface >75% soil, herbaceous <25%
	Barren	X	Minerals, permanent snow and ice, surface <10% soil, herbaceous <10%
	Mixed	M	Mix of herbaceous, open woody and tree cover, herbaceous is variable
	Perennial	P	Cover by trees, shrubs, or other woody perennials, herbaceous >60%
	Sealed	S	Artificial structures and surfaces, surface >75% artificial, compacted, or imported, herbaceous <25%
	Variable	V	Too variable across years to classify (seasonal river channels, etc.)
	Water	W	Water surface, surface >90% water, herbaceous <10%

regional cluster means. When only cells with high resemblance to regional definitions were included, the total area incorporated within the five regions was reduced to ~65% of China's agricultural population and ~50% of its arable land (Ellis 2004; Ellis et al. 2006). Within each region, a single 100 km^2 rural landscape site was then selected for detailed field research after visiting at least 3 potential sites per region and excluding sites with substantial influence from neighboring cities or other atypical regional or local factors (major factories, etc.; Ellis 2004). 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 to identify the most regionally representative sample cells within each site (Ellis 2004).

2.2 Landscape classification

Ecologically distinct anthropogenic landscape features (anthropogenic ecotopes) were mapped across each sample cell based on 1 m resolution IKONOS imagery acquired and orthorectified across each site in 2002 (Ellis 2004; Ellis et al. 2006; Wang and Ellis 2005). Landscape features were classified into ecotopes using the four-level classification hierarchy: form → use → cover → group + type, combining simple land form, 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). The definitions of the land form, use, and cover were illustrated in Table 2 (Ellis et al. 2006); details of all classes available at: http://ecotope.org/aem/classification.

2.3 Sampling and analysis

Soil samples were selected using a multistage stratified sampling procedure designed to allocate a maximum of 150 soil sample points within each site among the ecotope classes having the greatest relative regional areas. In the first stage of sampling, a maximum of ten and a minimum of three samples were allocated to each ecotope class in direct proportion to their regional areas (regionally weighted estimates using Cluster Distance Weighting (CDW); Ellis 2004) by the equation: Sample number = 150×regional area of each class (in percent). When sample numbers for form + use + cover (FUC) classes and use + cover (UC) classes were fewer than their sample areas would have yielded by the equation above (e.g. limited to 10), additional samples were added to ecotope classes in proportion to their relative area within each FUC and UC class (Ellis et al. 2006; http://ecotope.org/aem/classification). Samples of $n=3$ were then allocated to all unsampled ecotope and UC classes that covered >0.5% of regional area in the order of their regional area. Next, a smaller set of ecotope feature samples were selected in each site, based on the largest regional changes in ecotope areas from the 1940s to 2002 (Ellis et al. 2006), the subject of a future study. These "change feature" samples were included here because they were chosen only within the existing ecotope classes of the sample chosen as above and resulted only in increases in sample number within ecotope classes, up to the maximum described above. When <125 samples were selected within a site using the above procedure (this occurred only in the Gaoyi and Dianbai sites), additional samples were selected in the order of regional ecotope areas: (1) three samples were added for ecotopes with area >0.25% of a region, (2) up to five samples were added to ecotope classes limited to ten samples by the equation above, and (3) ecotope samples of $n=3$ were increased to $n=5$.

After allocating samples to ecotope classes, features representing each ecotope class were selected for soil sampling at random without replacement from the set of all features mapped within each class. A spatially random point location was then chosen within each feature using GIS. At the Gaoyi site, a few very large ecotope features (irrigated staple crops) dominated landscape samples, so we added an additional ten sample points, each near the center of the ten largest of these. Areas surrounding sample points were cleared of surface debris, leaves, and grass, and a single soil core was extracted using an AMS Split Core sampler with a 5.08 cm internal diameter core tip and 30 cm sleeve (AMS, American Falls, Idaho). A slide hammer was used to introduce the probe to 30 cm depth, with care taken to avoid core compression. Still, total core lengths were usually less than 30 cm because of friction, and core length was therefore recorded. Cores were split into two at half their measured length and stored as separate top and bottom samples in separate plastic bags. The Yangtze Plain Region included substantial areas of water surface. We therefore sampled submerged sediments in the Yixing site using a coring tube system with 6.90 cm internal diameter and 80 cm length (Uwitec, Austria). A boat enabled access to sampling locations indicated by GPS; the coring tube was introduced »30 cm into sediments, a core was extracted, sediments at >30 cm depth were discarded, and the remaining sediment sample was stored in a plastic bag. Soil samples were weighed immediately after returning from the field (twice per day), to record their fresh weight and then opened to the air and kept cool and dry until transport to the lab. After delivering samples to the lab, whole samples were spread on paper to air dry. Once completely air dried, the weight of whole samples was determined. Debris was then removed (chunks of bark, wood, and stones), entire soil samples were ground and sieved to 2 mm, and the entire sample was again weighed. Subsamples of 2 mm sieved soil samples were then pulverized to pass through a 0.25-mm sieve and then used for STP analysis by method of Perchloric acid ($HClO_4$) digestion (Olsen and Sommers 1982). STP density (kg P m^{-2}) was calculated for each sample point by multiplying STP concentration (g kg^{-1}), by soil density (kg m^{-3}), and core depth (0.3 m); regional estimates of STP density were calculated by multiplying ecotope STP densities by the regional areas of each ecotope. And the STP stock is the result of multiplying STP density (kg P m^{-2}) by its area.

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 form, land use, and land cover classes on STP densities within each site because the number and extent of land cover and land use classes differed substantially between sites, making cross-site ANOVA impractical. Prior to analysis, data within each land form, land use, and land cover class was tested for normality using the Kolmogorov–Smirnov test; none differed significantly from normality.

When statistically significant differences within sites were identified by ANOVA, significant differences among specific land form, land use, and land cover classes within each site were tested using Duncan's honestly significant difference; when variance between classes was unequal, Dunnett's *C* test was used to test differences.

3 Results and discussion

3.1 STP densities and stocks

Total STP stock (0–30 cm) across the 0.908×10^6 km^2 area of the five village regions was approximately 0.144 Pg, and the average STP density was 0.53 kg m^{-3} or 0.16 kg m^{-2} (30 cm) (Table 3). For comparative purposes, our 30 cm mean STP density would yield a 50-cm depth estimate of 0.53 kg m^{-3}, if we were to assume uniform P density with depth. Though this was certainly an overestimate, as STP density tended to decline sharply with depth, this estimate (0.53 kg m^{-3}) was still lower than Smil's estimate of 0.75 kg m^{-3} and Zhang et al.'s estimate of 0.83 kg m^{-3} at the top 50 cm soil across total China (Smil 2000; Zhang et al. 2005). Underestimation may have occurred because estimations from the other studies were coarse and miss fine-scale variability, such as housings, roads, and small agricultural plots (Ellis et al. 2000), which may cause the P density differences when extrapolated to coarser regional and global scales.

The regional STP density ranged from 0.08±0.04 kg m^{-2} in Tropical Hilly Region, 0.11±0.03 kg m^{-2} in Subtropical Hilly Region, and 0.19±0.04 kg m^{-2} in Sichuan Hilly Region, 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 fourfold difference (see Table 3). The Tropical Hilly Regions had the lowest STP density because the conditions of high precipitation and temperature (see Table 1) can enhance the degree of soil weathering and P loss through surface soil erosion (Onthong et al. 1999; Neufeldt et al. 2000) and leaching through the soil profile. In contrast, the higher STP densities (0.22 kg m^{-2}) of the North China Plain and the Yangtze Plain may be attributed to the large area of arable land with high P fertilizer inputs (see Table 1) (Tang et al. 2003).

STP density appeared to be related to soil age, e.g., was higher in the younger soils of the North China Plain's Inceptisols and Yangtze Floodplain (0.23 kg m^{-2}), and lower (0.08 kg m^{-2}) in the older soils of the Tropical Hilly region's Ultisols (see Tables 1 and 3). Zhang et al. (2005) also found the similar results that total P content decreased from 0.9 to 0.49 kg m^{-2} at the top 50 cm of soil in China according to the weathering status from slight to strong. The distribution of STP density at the coarse scale was mainly affected by the conditions of precipitation and temperature (Jiao et al. 2006). 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 Region, 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).

3.2 Hierarchical scale effects on STP densities and stocks

3.2.1 Land form

Significant differences in STP density were found under land form in each region except Tropical Hilly Region (Table 4). STP densities ranged from 0.06 kg m^{-2} in steep slope of Tropical Hilly Region to 0.32 kg m^{-2} in floodplain of Yangtze Plain. The steep slope was susceptible to soil erosion and, therefore, nutrient loss via particle adhesion,

Table 3 STP density and stock across five regions

Region (site)	Area[a] (10^6km^2)	Samples	Sampled ecotope area[b] (%)	STP[c] (kgm^{-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[d]	735[d]	92.5[e]	0.16[e]	0.144[d]

[a] Areas of five regions used for regional estimates were revised after sampling and therefore differ from Ellis (2004)

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

[c] STP density determined as the ecotope area-weighted average of each region

[d] Sum

[e] Average

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

Land form	North China Plain			Yangtze Plain			Sichuan Hilly Region			Subtropical Hilly Region			Tropical Hilly Region			All Regions
	n	Stock (%)	Density (kgm^{-2})	*n*	Stock (%)	Density (kgm^{-2})	*n*	Stock (%)	Density (kgm^{-2})	*n*	Stock (%)	Density (kgm^{-2})	*n*	Stock (%)	Density (kgm^{-2})	Mean density (kgm^{-2})
Anthropogenic	44	15.0	0.22±0.06 a	41	19.3	0.26±0.27 a	14	5.9	0.18±0.05 ab	15	7.8	0.12±0.06 abc	7	2.7	0.11±0.07	0.18
Bench Plateau	–	–	–	–	–	–	46	52.8	0.21±0.08 a	–	–	–	–	–	–	0.21
Excavated	–	–	–	–	–	–	–	–	–	3	0.4	0.08±0.01 c	3	0.3	0.07±0.03	0.08
Floodplain	72	77.2	0.22±0.06 a	58	61.9	0.32±0.30 a	–	–	–	–	–	–	–	–	–	0.27
Foot Slope	–	–	–	–	–	–	35	14.2	0.19±0.04 ab	17	30.7	0.16±0.03 a		12.9	0.07±0.02	0.14
Sloping	–	–	–	–	–	–	9	2.7	0.19±0.05 ab	107	48.5	0.10±0.05 bc	134	76.3	0.08±0.07	0.12
Seasonal River	18	2.3	0.16±0.03 b	–	–	–	–	–	–	–	–	–	–	–	–	0.16
Steep Slope	–	–	–	–	–	–	39	12.9	0.15±0.04 b	–	–	–	5	1.1	0.06±0.01	0.11
Summit	–	–	–	–	–	–	4	2.5	0.23±0.03 a	–	–	–	–	–	–	0.23
Terraced Slope	–	–	–	–	–	–	–	–	–	10	4.6	0.13±0.04 ab	–	–	–	0.13
Water[a]	–	–	–	54	10.6	0.11±0.08 b	–	–	–	–	–	–	–	–	–	0.11

Different letters indicate differences between classes significant at $P \leq 0.05$

[a] The seven types of land form (small canal, large canal, canal margin, flowing marsh, marsh, small pond, and large pond) were combined as water to calculate conveniently in Yangtze Plain, and all the samples were sediments

most notably in the high precipitation region of Tropical Hilly. The floodplain form mainly consisted of farmland with high manure and fertilizer application rates. The STP density distribution was easier to interpret in the two plains than the hilly region because there were fewer landform categories. The highest STP densities were found under floodplain form in the two plains (0.22±0.06 kg m^{-2} in North China Plain and 0.32±0.30 kg m^{-2} in Yangtze Plain); In Sichuan Hilly, Subtropical Hilly, and Tropical Hilly regions, where there was no floodplain form present; the land forms that had the highest STP density were summit form (0.23±0.03 kg m^{-2}), foot slope form (0.16±0.03 kg m^{-2}), and anthropogenic form (0.11±0.07 kg m^{-2}), respectively. In each region, the anthropogenic land form had relatively high STP density, demonstrating a substantial source of P in these human-impacted areas.

In the North China Plain and Yangtze Plain, the floodplain form had the highest STP stock which was due to their relatively large areas within these regions: 77.2% and 61.9%, respectively. While in the three hilly regions, the bench plateau form or sloping form had the highest STP stock. The STP stock of anthropogenic form in five regions was positively correlated with population density (R=0.91, P=0.03).

3.2.2 Land use

STP densities varied strongly with land use in every region except Tropical Hilly Region (Table 5), demonstrating that land use was likely a significant factor controlling STP densities in village landscapes. In all regions, the land use types in the order of highest to lowest STP densities were constructed (artificial surfaces and structures), rainfed (rainfed agriculture), disturbed (fragmented or disturbed by human activities without consistent use), followed by paddy (rice and other flooded crops) and forestry (managed for regular harvest of noncrop vegetation biomass). Many factors can result in high STP density (result from high STP concentration and soil bulk density) in constructed use: runoff carrying high levels of P from human and animal waste origin; decomposing of plant and animal bones releasing high levels of P (China Agricultural University 1998); and trampling by humans, animals and vehicles making soil more compact and resulting in high soil bulk density (Jiao et al. 2006). Many studies reported that high P inputs to the aquatic environment from the agricultural land, identified as one of the main contributors of P to watercourses, resulted in eutrophication of aquatic ecosystem (Sharpley and Rekolainen 1997; Zhang et al. 2003). From the results above, we found that in addition to agriculture land, other human-influenced land uses such as constructed and disturbed use with certain area (10.8% of total five regions) and high STP densities (0.20 and

Table 5 Relative STP stocks and densities among land use classes within each region

Land use	North China Plain			Yangtze Plain			Sichuan Hilly Region			Subtropical Hilly Region			Tropical Hilly Region			All regions
	n	Stock (%)	Density (kgm^{-2})	*n*	Stock (%)	Mean density (kgm^{-2})	*n*	Stock (%)	Density (kgm^{-2})	*n*	Stock (%)	Density (kgm^{-2})	*n*	Stock (%)	Density (kgm^{-2})	Mean density (kgm^{-2})
Aquaculture	–	–	–	25	8.9	0.11±0.10 bc	–	–	–	–	–	–	–	–	–	0.11
Constructed	38	12.3	0.22±0.06 bc	25	9.4	0.35±0.31 a	11	6.4	0.19±0.05 ab	15	5.8	0.12±0.06 abc	4	0.7	0.11±0.06	0.20
Disturbed	6	1.0	0.20±0.05 bc	15	3.7	0.32±0.37 abc	15	3.8	0.16±0.04 b	13	4.3	0.12±0.03 ab	13	6.5	0.11±0.07	0.18
Fallow	5	0.3	0.13±0.01 d	23	5.1	0.10±0.02 c	–	–	–	3	0.3	0.07±0.04 abc	–	–	–	0.10
Forestry	–	–	–	3	0.6	0.11±0.01 bc	33	14.7	0.15±0.04 b	69	33.2	0.08±0.03 c	65	42.2	0.07±0.03	0.10
Horticulture	3	0.3	0.30±0.06 a	–	–	–	–	–	–	–	–	–	–	–	–	0.30
Irrigated	63	78.4	0.23±0.06 b	12	5.7	0.20±0.07 ab	–	–	–	–	–	–	–	–	–	0.22
Mine and fill	–	–	–	–	–	–	–	–	–	3	0.3	0.08±0.01 bc	3	0.1	0.07±0.03	0.08
Ornamental	3	0.8	0.17±0.03 bcd	3	0.1	0.09±0.03 bc	–	–	–	–	–	–	–	–	–	0.13
Paddy	–	–	–	12	51.2	0.20±0.23 abc	35	16.1	0.20±0.04 a	26	37.5	0.15±0.03 a	10	17.5	0.07±0.02	0.16
Rainfed	6	1.0	0.19±0.03 bcd	35	7.8	0.32±0.30 a	53	49.9	0.21±0.08 a	23	8.5	0.14±0.07 a	54	26.1	0.09±.010	0.19
Variable	10	0.3	0.15±0.03 cd	–	–	–	–	–	–	–	–	–	–	–	–	0.15

0.18 kg m^{-2}, respectively, at the top 30 cm) may also contribute to eutrophication of aquatic ecosystem.

Forestry use (0.10 kg m^{-2}) had the lowest average STP density, confirming the results of Grerup et al. (2006) that total P tended to be higher in the formerly cultivated fields than in the continuously forested land. Saikh et al. (1998) concluded that deforestation and cultivation resulted in no significant changes in total P levels within the Simlipal National Park, India; and Jiang et al. (2005) found that the woodland had the highest P density, followed by fallow and paddy in Shenyang Experimental Station of Ecology, Chinese Academy of Sciences. 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.

The land use types were different across regions, and the area of the same land use in different regions was also different. This was because the climate, geography, economic system, and government's decision were different across regions. For example, there was no paddy use in North China plain because of small annual precipitation, and there was large area of aquaculture in Yangtze Plain because of the rich rainfall and local economic system. The 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 Region (rainfed, 49.9%), Subtropical Hilly Region (paddy, 37.5%), Tropical Hilly Region (forestry, 42.4%) (see Table 5). The Subtropical Hilly Region highest STP stock was paddy (37.5%); however, the greatest area extent was forestry with a STP stock of 33.3%; the discrepancy was due to a density which was 0.08 kg m^{-2} less than paddy.

3.2.3 Land cover

In each region, the distribution of STP density under the level of land cover was presented in Table 6. The land cover type that had the highest STP density in each region was bare soil (0.27±0.05 kg m^{-2}, North China Plain and 0.23±0.06 kg m^{-2}, Sichuan Hilly Region), sealed (0.38±0.32 kg m^{-2}, Yangtze and 0.11±0.06 kg m^{-2}, Tropical Hilly Region), and mixed (0.20±0.13 kg m^{-2}, Subtropical Hilly Region). 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}) (see Table 6). 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 (China Agricultural University 1998) due

Table 6 Relative STP stocks and densities among land cover classes within each region

Land cover	North China Plain			Yangtze Plain			Sichuan Hilly Region			Subtropical Hilly Region			Tropical Hilly Region			All Regions
	n	Stock (%)	Density (kgm^{-2})	*n*	Stock (%)	Mean density (kgm^{-2})	*n*	Stock (%)	Density (kgm^{-2})	*n*	Stock (%)	Density (kgm^{-2})	*n*	Stock (%)	Density (kgm^{-2})	Mean density (kgm^{-2})
Annual	67	76.2	0.23±0.06 ab	55	56.5	0.22±0.19 c	69	61.0	0.20±0.07	49	44.0	0.14±0.05 bc	19	16.6	0.07±0.03	0.17
Bare soil	5	2.9	0.27±0.05 a	3	0.3	0.12±0.03 bc	3	1.4	0.23±0.06	6	1.9	0.09±0.02 bc	–	–	–	0.16
Mixed	5	1.5	0.15±0.03 c	6	2.5	0.25±0.19 ab	11	2.6	0.17±0.07	3	3.5	0.20±0.13 abc	47	28.4	0.08±0.09	0.17
Perennial	6	1.0	0.18±0.04 bc	22	6.2	0.38±0.41 abc	56	21.5	0.18±0.06	82	36.2	0.09±0.03 a	76	46.8	0.08±0.05	0.19
Sealed	36	11.0	0.22±0.06 ab	22	16.6	0.38±0.32 a	8	4.4	0.17±0.04	12	6.3	0.13±0.07 abc	4	1.3	0.11±0.06	0.23
Variable	15	1.8	0.14±0.02 c	–	–	–	–	–	–	–	–	–	–	–	–	0.14
Water	–	–	–	45	9.7	0.11±0.08 ab	–	–	–	–	–	–	–	–	–	0.11
Barren	–	–	–	–	–	–	–	–	–	–	–	–	3	0.3	0.07±0.03	0.07

to human and vehicle traffic along with considerable human disturbance and P pollution which together contributed to high STP densities.

The annual cover had the highest STP stock percentage in each region except Tropical Hilly Region: 76.2% in North China Plain, 56.5% in Yangtze Plain, 61.0% in Sichuan Hilly Region, and 44.0% in Subtropical Hilly Region. The perennial cover had the highest STP stock percentage (46.8%) in Tropical Hilly Region. 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 Region; however, the STP stock in perennial cover increased from 1.0% in North China Plain to 46.8% in Tropical Hilly Region (see Table 6).

3.2.4 Ecotope

Ecotope-level analysis further revealed fine-scale heterogeneity of STP density within five regions. The types and numbers of ecotope, illustrated in Table 7, were much more than that of the land use/cover in each region, and there were high values of coefficient of variation (CV) of STP density at the ecotope level (Table 8). Consequently, The STP density and stock of each ecotope within regions were much more complex than that of the coarser land form/use/cover. The ecotope with the highest STP density for each region was ANHSgh02 (detached houses with multistories) in North China Plain, FPDPdb08 (regrowth area with structures or debris and tree) in Yangtze Plain, BPRAac01 (small-scale intensive annual vegetable crops or horticulture) in Sichuan Hilly Region, SLRMmc01 (mixed annual, woody, or tree crop) in Subtropical Hilly Region, and SLDMdb07 (regrowth area with structures or debris, and woody or tree) in Tropical Hilly Region. The five largest ecotopes of STP stock were 82.7% in North China Plain, 66.9% in Yangtze Plain, 67.2% in Sichuan Hilly Region, 67.4% in Subtropical Hilly Region, and 56.1% in Tropical Hilly Region.

The Ecotope contained the greatest amount of variation (CV) compared to land form, use, and cover. The CV of STP density ranged from 81% of ecotope in Yangtze Plain to 13% of land cover in Sichuan Hilly Region with an average of 40% across the five regions. The CV of STP densities of the land form, use, cover, and ecotope levels were highest in Yangtze Plain and lowest in Sichuan Hilly Region (see Table 8) (Shen et al. 1993). There were two reasons causing the highest spatial variation of STP density in Yangtze Plain. Firstly, because of the highest population density, people must increase the amount of fertilizer to get higher food production to maintain people's lives, and the P pollution caused by people was also serious; the higher CV in disturbed (88.6%) and constructed use (115.6%) could prove it (see Table 5). Second, because of the developed

Table 7 Relative areas and STP densities of the five most P-rich ecotope classes within each region

Regions	Ecotope	Area (%)	*n*	Mean ± SD (kgm^{-2})	Description
North China Plain	ANHSgh02	0.28	3	0.30±0.06	Detached houses with multistories
	ANCEtr01	2.15	5	0.27±0.05	Unpaved roads, paths, or access, >2 m wide
	FPIAac02	2.46	3	0.26±0.01	Medium-scale (>30 m to 1 ha) intensive annual vegetable crops or horticulture plots
	FPIAac01	0.99	10	0.25±0.09	Small-scale (<30 m) intensive annual vegetable crops or horticulture plots
	FPIAac05	65.17	35	0.24±0.03	Medium-scale (>30 m to 1 ha) non-intensive annual vegetable crops
Yangtze Plain	FPDPdb08	0.40	3	0.77±0.66	Regrowth area with structures or debris, and tree
	ANCSnb06	0.49	3	0.69±0.65	Large-scale (>30 m) government, public building
	FPDMdb07	1.32	3	0.42±0.09	Regrowth area with structures or debris, and woody or tree
	FPRAac04	2.57	12	0.38±0.26	Small-scale (<30 m) non-intensive annual vegetable crops or horticulture plots
	FPRPdw39	1.08	13	0.38±0.40	Small-scale (<30 m) mature mulberry
Sichuan Hilly	BPRAac01	0.72	3	0.32±0.28	Small-scale intensive annual vegetable crops or horticulture
	ANCEtr01	1.20	3	0.23±0.06	Unpaved roads, paths, or access, >2 m wide
	SURAac04	2.14	4	0.23±0.03	Small-scale (<30 m) non-intensive annual vegetable crops or horticulture plots
	BPRMmc01	1.64	3	0.23±0.11	Mixed annual, woody or tree crop
	BPRPoe33	5.70	13	0.22±0.06	Small-scale (<30 m) mature mandarin orange orchard
Subtropical Hilly	SLRMmc01	2.06	3	0.20±0.13	Mixed annual, woody or tree crop
	FSPAri01	22.06	17	0.16±0.03	Rice paddy, not used for transplant every year
	SLRAac01	2.18	7	0.16±0.05	Small-scale (<30 m) intensive annual vegetable crops or horticulture plots
	ANCSho04	1.77	3	0.14±0.04	Shared wall or courtyard with multistories
	SLRAac02	3.55	6	0.14±0.08	Medium-scale (>30 m to 1 ha) intensive annual vegetable crops or horticulture plots
Tropical Hilly	SLDMdb07	3.03	4	0.17±0.06	Regrowth area with structures or debris, and woody or tree
	SLRMoe44	1.95	5	0.14±0.24	Large-scale mature (>1 ha) longyan orchard
	ANCSho03	0.78	3	0.13±0.06	Shared wall or courtyard with single story
	SLRPoe41	7.35	13	0.12±0.10	Large-scale mature (>1 ha) litchi orchard
	ANDMdb07	1.03	3	0.11±0.09	Regrowth area with structures or debris, and woody or tree

economy and modern agriculture, there were much more kinds of land use, such as horticulture, paddy, aquaculture, and so on, which had significant effect on the STP distribution, while in Sichuan Hilly Region, the conventional agriculture was important because of the undeveloped economy. From the results above, we can conclude that at the regional scale, the spatial variation of STP between densely populated village regions 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

Table 8 Variation in STP densities in land form, use, cover, and ecotope classes within and among regions

Within region													Among regions[a]		
Region	Land form			Land use			Land cover			Ecotope					
	Mean	SD	CV (%)	Mean	SD	CV (%)	Mean	SD	CV (%)	Mean	SD	CV (%)	Mean	SD	CV (%)
North China Plain	0.20	0.03	17	0.20	0.05	27	0.20	0.05	25	0.20	0.05	29	0.16	0.07	40
Yangtze Plain	0.23	0.11	47	0.20	0.11	53	0.24	0.12	49	0.22	0.18	81			
Sichuan Hilly	0.19	0.03	14	0.18	0.03	14	0.19	0.03	13	0.19	0.04	22			
Subtropical Hilly	0.12	0.03	26	0.11	0.03	29	0.13	0.05	35	0.11	0.04	34			
Tropical Hilly	0.08	0.02	25	0.09	0.02	23	0.08	0.02	20	0.08	0.03	40			

Use an example to describe how to calculate the mean STP density in each class. In North China Plain, there are three types of land form (Table 3), the mean STP density (0.20 kg m^{-2}) is the average of 0.22 kg m^{-2} (anthropogenic), 0.22 kg m^{-2} (floodplain), and 0.16 kg m^{-2} (seasonal river), the SD is the result of STDEV (0.22, 0.22, 0.16), and CV (coefficient of variance) is the result of SD/mean (17%=0.03/0.20×100%)

[a] The mean STP density among five regions is the average of all 735 points

activities, such as soil nutrient management, fertilizer application, and so on. In southwestern Amazon, Holmes et al. (2005) also found the same results that the land cover at the shortest scales account for the majority of the spatial variability in the biogeochemically important properties (organic carbon, N, P), while precipitation and topography lead to the variable distribution of soil properties over large areas.

Since STP density between land form, 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. For example, many of the ecologically distinct features we sampled, such as those associated with buildings and roads, were ignored by soil surveys and regional analyses. Moreover, 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 researchers neglect the small variations because of their limited resources (Lardy et al. 2002; Lu et al. 2005; Xiao et al. 2005). Nevertheless, fine scale patterns of land use and land cover were associated with the majority of local variation in STP, making this scale of observation as critical for understanding the causes and consequences of soil P variation as regional patterns caused by climate and parent material.

4 Conclusions

This study integrated high spatial resolution mapping with soil sampling to demonstrate that STP stock across the 0.9×10^6 km^2 area of our five village regions was approximately 0.14 Pg, the highest STP density was present in North China Plain and Yangtze Plain, and the lowest STP density was present in the Subtropical and Tropical Hilly regions. STP density had high spatial variability across China's densely populated village landscapes, and the land form, use, cover, and ecotope had significant effects on STP density in all the densely populated village landscapes we studied outside of the Tropics, demonstrating that local patterns of land management and human residence were associated with substantial differences in STP both within and across China's village landscapes. High STP densities generally observed near housing further demonstrate that fine scale anthropogenic pools of soil P are likely both significant globally and a potential contributor to P pollution locally.

5 Recommendations and perspectives

Human activities can affect the distribution of STP density at various landscape levels from form to use to cover to ecotope. Because of the dearth of comparable P-stock data in the literature, it is difficult to compare our fine-scale observations in densely populated landscapes with others. The 0–30 cm soil layer should be investigated in P stocks due to its importance in agro-ecosystem management. With the rapid 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.

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