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Land Use and Soil Organic Carbon in China's Village Landscapes*[1]

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ABSTRACT

Village landscapes, which integrate small-scale agriculture with housing, forestry, and a host of other land use practices, cover more than 2 million square kilometers across China. Village lands tend to be managed at very fine spatial scales ($\leq$ 30 m), with managers both adapting their practices to existing variation in soils and terrain (*e.g.*, fertile plains *vs.* infertile slopes) and also altering soil fertility and even terrain by terracing, irrigation, fertilizing, and other land use practices. Relationships between fine-scale land management patterns and soil organic carbon (SOC) in the top 30 cm of village soils were studied by sampling soils within fine-scale landscape features using a regionally weighted landscape sampling design across five environmentally distinct sites in China. SOC stocks across China's village regions (5 Pg C in the top 30 cm of 2×10^6 km^2) represent roughly 4% of the total SOC stocks in global croplands. Although macroclimate varied from temperate to tropical in this study, SOC density did not vary significantly with climate, though it was negatively correlated with regional mean elevation. The highest SOC densities within landscapes were found in agricultural lands, especially paddy, the lowest SOC densities were found in nonproductive lands, and forest lands tended toward moderate SOC densities. Due to the high SOC densities of agricultural lands and their predominance in village landscapes, most village SOC was found in agricultural land, except in the tropical hilly region, where forestry accounted for about 45% of the SOC stocks. A surprisingly large portion of village SOC was associated with built structures and with the disturbed lands surrounding these structures, ranging from > 18% in the North China Plain to about 9% in the tropical hilly region. These results confirmed that local land use practices, combined with local and regional variation in terrain, were associated with most of the SOC variation within and across China's village landscapes and may be an important cause of regional variation in SOC.

Key Words: agriculture, land cover change, land use change, soil carbon sequestration, spatial heterogeneity

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INTRODUCTION

Soil organic carbon (SOC) is the largest carbon reservoir in terrestrial ecosystems and can act as both a sink and a source in response to changes in climate, land use, and atmospheric CO_2 (Murty *et al.*, 2002; Lal, 2004; Houghton, 2005). Annual soil carbon sequestration is 0.4 to 1.2 Pg C year^{-1} globally, equivalent to 6% to 20% of the annual CO_2 release from fossil fuel combustion (Lal, 2004; Houghton, 2005). This makes control of SOC a potentially important factor in mitigating atmospheric carbon accumulation and global warming. It is, therefore, critical to understand how SOC varies in response to climate, land use, and other factors when evaluating the role of terrestrial ecosystem processes in altering the global carbon cycle and carbon accumulation in the atmosphere (Houghton, 2005).

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Densely populated agricultural villages cover about 8×10^6 km^2 globally or about 7% of earth's ice-free land surface (Ellis and Ramankutty, 2008). In Asia, most arable crops are produced within village landscapes, which are also the dwelling space for approximately 1.4 billion people or nearly a quarter of global population (Ellis, 2004). In China alone, village landscapes cover about 2×10^6 km^2, about 25% of the global village area, incorporate more than half of China's arable land and provide residence for more than 500 million people (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 carbon cycle. However, the role of land use practices in controlling soil carbon sequestration across these ancient agricultural landscapes is a challenge to study because these practices are mediated at fine spatial scales by millions of land managers under environmental conditions ranging from temperate to tropical and from fertile floodplains to steep mountain slopes.

Few studies have analyzed soil variability within densely populated village landscapes (Buerkert and Hiernaux, 1998; Ellis *et al.*, 2000; Manlay *et al.*, 2004a, b). This is likely the result of the complexities of soil sampling and measurement within village landscapes, which are highly heterogeneous mosaics of fine-scale landscape features ($\leq$ 30 m) managed by a diverse assortment of land management practices (Ellis *et al.*, 2006). Although major anthropogenic changes in soil properties have certainly occurred and are occurring in these landscapes, most of these changes take place at very fine spatial scales, challenging measurements based on conventional coarser resolution ($\geq$ 30 m) land use and land cover mapping systems.

This study measured and compared SOC densities under different land use and land cover conditions at fine spatial scales within and across the densely populated village landscapes of China in order to determine whether fine-scale variation caused by land use is significant at regional scales. This was achieved by sampling the top 30 cm of soils (the layer most sensitive to modification by land use practices; Batjes, 1996), across a regionally representative sample of fine-scale land use and land cover features in landscape samples from five environmentally distinct village regions across China. The regional and local significance of SOC variation associated with fine-scale land use features was then assessed and compared with the importance of regional environmental factors (climate and terrain).

MATERIALS AND METHODS

Regions, sites, and samples

China's village landscapes were first stratified into five biophysically distinct initial regions at 32 km resolution using a K-means cluster analysis of data for terrain, climate, and soil fertility (Verburg *et al.*, 1999; Ellis, 2004; Ellis *et al.*, 2009). Within each region (Table I, Fig. 1), a single 100 km^2 research site was chosen, and a sample of twelve 500 m $\times$ 500 m square landscape sample cells (25 ha) were then selected for fine-scale mapping, soil sampling, and other field measurements within each site using a K-means cluster analysis of sub-regional land cover patterns in 500 m grid cells across two Landsat scenes in each region, as detailed in Ellis (2004) and outlined below. Replicate sample cells were selected for each regional land cover cluster ($n \geq 3$) in proportion to the regional abundance of each cluster, with priority given to cells with the greatest resemblance to regional cluster means. The "regional representativeness" of the sample cells within each site was then quantified by weighting each cell by the regional abundance of its land cover cluster and its relative cluster distance using cluster distance weighting (CDW), yielding "regional cluster distance weights" for each sample cell (Ellis, 2004; Ellis *et al.*, 2009). Initial estimates of regional land use and other classified areas were then calculated by multiplying the area measurements within sample cells by the CDW for each sample cell.

Landscape mapping and 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

TABLE I

Regions, sites, and samples

Region	Site (county, province)	Area[a)]	Population density	Precipi-tation	Tempera-ture	Eleva-tion	Slope	Main soil types (USA)	Number of land classes			No. of samples	Sampled ecotope area[b)]	SOC density[c)]	Total SOC[c)]
									Use	Cover	Ecotope				
		$\times 10^6$ km^2	persons km^{-2}	mm year^{-1}	°C	m	%						%	kg C m^{-2}	Pg C
North China Plain	Gaoyi, Hebei	0.276	598	670	14.0	45.6	0.83	Inceptisols	8	6	17	134	94.4	2.76	0.76
Yangtze Plain	Yixing, Jiangsu	0.086	573	1 146	16.0	8.2	0.76	Fluvents	8	6	27	153	91.8	3.45	0.30
Sichuan hilly	Jintang, Sichuan	0.084	539	1 069	17.1	386	12.3	Orthents, Psamments	5	5	25	147	91.0	2.12	0.18
Subtropical hilly	Yiyang, Hunan	0.284	279	1 535	16.7	171	15.2	Alfisols	7	5	21	152	92.0	2.74	0.78
Tropical hilly	Dianbai, Guangdong	0.178	308	1 622	21.0	170	14.4	Ultisols	6	5	26	149	93.3	2.68	0.48
Total across sampling regions		0.908	434	1 209	16.7	86.7	9.0		12	8	95	735	92.5	2.74	2.50

[a)] Regional areas, population densities, and environmental data (precipitation, temperature, elevation and slope) are from Table I of Ellis *et al.* (2009).

[b)] Total sampled ecotope area was less than 100% because only ecotope classes with areas $\geq 0.25\%$ of each site were sampled.

[c)] SOC (soil organic carbon) densities were calculated as ecotope area-weighted averages (areas adjusted to regional estimates by multivariate regional optimization; Ellis *et al.* 2009); Total SOC is the product of SOC density and region area.

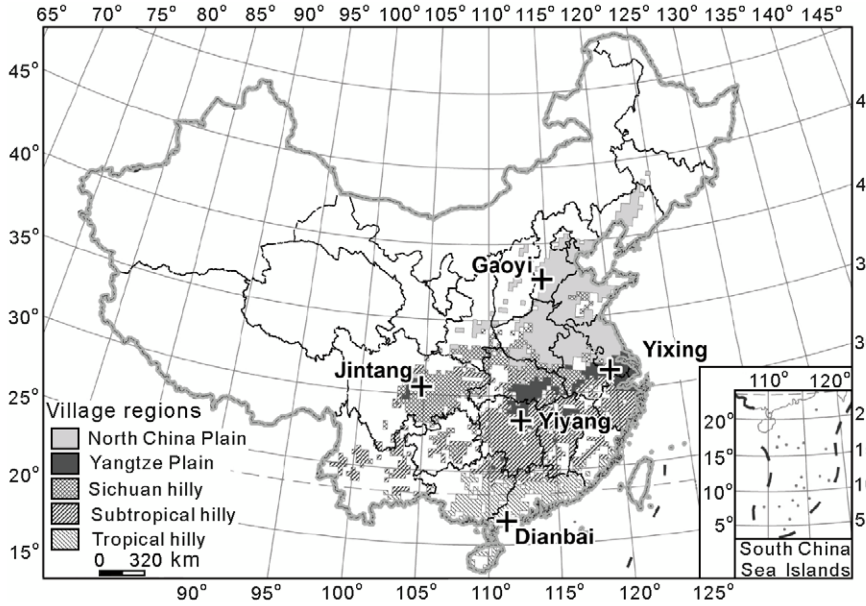

Fig. 1 Location of research sites and initial village regions across China.

2002 (Ellis, 2004; Wang and Ellis, 2005; Ellis *et al.*, 2006). Ecotope features were mapped and classified using anthropogenic ecotope mapping (AEM; Ellis *et al.*, 2006), a standardized high-resolution ecological feature mapping procedure combining the direct interpretation of ecotope features from high-resolution imagery ($\leq$ 1 m) in a geographic information system (GIS; ArcInfo 9.0; Environmental Systems Research Institute, Redlands, California), with the validation and correction of all features in the field by the interpreter assisted by local land managers. 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; details for all classes at http://ecotope.org/aem/classification). Ecotope classes are created by combining all four classification levels within each feature, however, only land USE and land COVER classes were used for analysis in this study.

Selection of soil samples

Sampling points were selected using a multistage stratified sampling procedure designed to allocate a maximum of 150 soil sample points to ecotope features within each site based on the relative regional areas of each ecotope class. In the first stage of sampling, a maximum of 10 and a minimum of three samples were allocated to each ecotope class in direct proportion to their regional areas (CDW-weighted estimates) by the equation, sample number = 150 $\times$ regional area of each class (in percent). When sample numbers within FORM + USE + COVER (FUC) classes and USE + COVER (UC) classes were smaller than their regional areas would yield by the above-mentioned equation, additional samples were added to ecotope classes within these FUC and UC classes in proportion to their relative regional area. Samples of $n = 3$ were then allocated to all unsampled ecotope and UC classes that covered > 0.5% of regional area in order of their regional area. Next, a smaller set of ecotope feature samples were selected from 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 in this study 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 in the Gaoyi and Dianbai sites only), additional samples were selected in order of regional ecotope areas as follows: 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 10 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 10 sample points, each near the center of the 10 largest of these.

Soil sampling and laboratory analysis

After sample points were selected, soil cores were obtained for each point in April 2004 in Jintang and Gaoyi, in November 2004 in Dianbai and Yiyang, and in May 2005 in Yixing. First, the soil sample points were located in the field using a hand-held global positioning system (GPS) assisted by printed maps of sample points and ecotope features overlaid on IKONOS imagery, allowing sample locations to be confirmed in relation to feature boundaries observable in the field, helping to overcome limitations to the accuracy of real-time GPS. For ecotope features with impervious cover (buildings, roads, and other sealed surfaces), samples were selected in exposed soils as close to the selected sample points as possible and a new GPS location was acquired for the sample location. Areas surrounding the 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. Therefore, submerged sediments in the Yixing site were sampled using a coring tube system with 6.90 cm internal diameter and 80 cm length (Uwitec, Mondsee, 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 > 30 cm depth were discarded, and the remaining sediment sample was stored in a plastic bag.

Soil samples were weighed immediately upon returning from the field (twice per day) to record their fresh weight. The samples were then exposed to air and allowed to cool and dry until transported to the laboratory. In laboratory, whole samples were spread on paper and air dried. Once completely dried, the dry weight of whole samples was determined. Then, debris was removed (chunks of bark, wood, and stones), and 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 used for SOC analysis by modified Tyurin's wet oxidation method (Tyurin, 1931), with a correction factor of 1.08. The SOC density, in kg C m^{-2}, was calculated for each sample point by multiplying the SOC concentrations, in g kg^{-1}, by soil density in kg m^{-3} (estimated from the volume and air dry mass of each sample core) and core depth (0.3 m). The SOC densities were calculated using SOC concentrations and core density measurements from the same sample cores, thereby linking measurements of soil bulk density and SOC concentration and allowing a high degree of replication in soil bulk density measurements. Data from the top 15 cm and bottom 15 to 30 cm cores were combined in each sample for all the calculations of this study. In this study, multiple soil cores were not bulked together so that the variance of individual soil sample locations would include within-field variation.

Statistical methods

All statistical tests were carried out using SPSS 11.5 (SPSS, Chicago, Illinois, USA). P values < 0.05

were used to test the 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 SOC densities within each site because the number and the extent of land cover and land use classes differed substantially between sites, making cross-site ANOVA impractical. Before analysis, data within each land use and land cover class were tested for normality using the Kolmogorov-Smirnov test; none of the data differed significantly from normality. When statistically significant differences within sites were identified by ANOVA, significant differences among specific land use and land cover classes within each site were tested using Tukey's honestly significant difference (assuming equal variance; variance was not statistically distinguishable for all but land use in the Yangtze Plain and land cover in the North China Plain); when variance between classes was unequal, Dunnett's C test was used to test the differences. Regression analyses were then conducted to test for the linear relationships between SOC density, environmental factors, and population density.

Regional estimates of SOC were calculated by multiplying ecotope SOC densities by the regional areas of each ecotope. Regional ecotope areas were estimated from sampled ecotope areas using a regional weighting procedure that minimized the difference between sample means and regional means across a set of independently measured regional variables (land cover, terrain, and population; multivariate regional optimization; Ellis *et al.* 2009). Regional mean estimates presented in this study are best estimates, but do not include the substantial uncertainties inherent in the regional weighting analysis (Ellis *et al.*, 2009); they should be used only as indicators of regional SOC amounts and differences.

RESULTS AND DISCUSSION

Regional SOC stocks and densities

Total SOC stocks and SOC densities (kg C m^{-2}) are presented in Table I. Total SOC across the total extent of these five sampling regions (0.9×10^6 km^2) was approximately 2.5 Pg C. As these five regions are a good proxy for the entire 2×10^6 km^2 extent of village regions in China (Ellis *et al.*, 2009), 5 Pg C is a reasonable estimate of total SOC stock across China's village landscapes at 30 cm depth. This is equivalent to about 3% to 4% of global SOC stocks in croplands (128 to 165 Pg; Houghton, 2005).

Village landscape SOC density ranged from 3.45 kg C m^{-2} in the Yangtze Plain to 2.1 kg C m^{-2} in the Sichuan hilly region, with the other three regions hovering around 2.7 kg C m^{-2}. High SOC density was expected in the Yangtze Plain because the region has long been famous for its fertile and productive paddy soils (Ellis and Wang, 1997). But, surprisingly, the Sichuan hilly region had the lowest SOC density overall, especially when compared with the soils of the subtropical and tropical hilly regions, given their highly weathered soils. Regional trends in village SOC densities resembled those observed at 20 cm depth by Xie *et al.* (2004b), following the same sequence across regions, except for the North China Plain, which had a low SOC density in another study of Xie *et al.* (2004b), but a moderate SOC density in our study. Wang *et al.* (2003) also reported lower SOC densities in China's "east" and "north" regions, but these regions are not truly comparable with those of this study, as they included large areas without dense populations that were excluded from this study.

For comparative purposes, the 30 cm mean SOC density estimated across village regions in this study (2.74 kg C m^{-2}) would yield a 1 m depth estimate of 9.13 kg C m^{-2}, if we were to assume uniform C density with depth. Though this is certainly an overestimate, as SOC density tends to decline sharply with depth, this is substantially lower than Wang *et al.*'s (2003) estimate of 10.53 kg C m^{-2} across China at 1 m depth, though it is surprisingly similar to Xie *et al.*'s (2004b) estimate of 9.13 kg C m^{-2} and higher than Xie *et al.*'s (2004a) estimate of 7.31 kg C m^{-2}. Given that all three 1 m estimates were derived from the same raw data, the second national soil survey across China, and that these vary from 7.3 to 10.5 kg C m^{-2}, this study's SOC density estimate for China's village regions may be considered to be within the range of, or perhaps a bit lower than, typical estimates across China as a whole. Village mean SOC density was also quite similar to estimates for densely populated agricultural village regions in Kenya and the Indo-Gangetic plains of India (about 3 kg C m^{-2} in the top 30 cm; Bhattacharyya *et al.*, 2007; Kamoni *et al.*, 2007).

We expected that SOC density would be substantially higher in China's village regions than in China as a whole, based on the hypothesis that agricultural populations are densest on the most productive agricultural lands (Ellis and Ramankutty, 2008) and that the intensive management practices of these regions, such as manuring, fertilizing, and recycling of crop residues, would tend to increase the soil fertility and SOC in these regions. However, the observation that SOC densities across China's most densely settled agricultural regions tended to be lower than for China as a whole can be explained in two ways. First, China's peat lands, cool grasslands, and forests all have high SOC densities and low population densities (Xie *et al.*, 2004a) and were excluded from this village analysis. Second, village regions had lower soil bulk densities (1.2 g cm^{-3} in the North China Plain and tropical hilly regions, and about 1 g cm^{-3} in the other three regions) than those estimated for China as a whole at 1 m depth (1.3 to 1.4 kg cm^{-3}; National Soil Survey Office, 1998); as would be expected for the fertile agricultural lands and for the top layer of soils.

Climate and terrain effects on regional SOC

In contrast with previous studies (*e.g.*, Jobággy and Jackson, 2000; Wang *et al.*, 2004), regional climate was not a strong predictor of landscape SOC density in this study (Table I). When regional SOC densities were regressed linearly against the environmental variables in Table I (including population density), none of these regressions showed a statistically significant relationship (all had $P > 0.2$), except for a strong inverse relation between regional mean elevation and SOC density (adjusted $R^2 = 0.80$, $P = 0.02$). In undisturbed ecosystems, SOC variation with climate is explained by the climatic control of vegetation type and productivity and therefore carbon supply to soils and its influence on microbial processes that regulate SOC accumulation and loss (Davidson *et al.*, 2000; Jobággy and Jackson, 2000). The observation that SOC density was not significantly influenced by macroclimate across village regions may indicate that human alteration of soils and vegetation by intensive long-term cultivation, irrigation, fertilization, and other land use practices may have stronger influences on SOC density than does climate in these regions (Guo and Gifford, 2002). The correlation of SOC density with elevation across village regions also makes sense in this light because terrain tends to constrain both local and regional land use practices and is also a strong predictor of soil parent materials, which are more slowly influenced by land management than SOC.

Effect of land use on SOC

A single soil type tended to predominate within each 100 km^2 site, and this soil type was among those most common within each region (Table I). As a result, major differences in soil type were not a significant factor in controlling the SOC variation within these sites. But soil bulk density did vary significantly within sites, forming an important cause of variation in SOC density to 30 cm depth. For this reason, our analysis, which relates differences in SOC density (kg C m^{-2}) and total SOC stocks to differences in land use and land cover are in fact describing the combined effects of these (or any other) factors on both SOC concentration (kg C kg^{-3}) and soil bulk density (kg m^{-3}) to 0.3 m depth.

Land use and SOC density. SOC density varied strongly with land use in each region and among regions, indicating that the land use is likely a significant factor in controlling SOC density in village landscapes (Table II; Guo and Gifford, 2002). SOC density ranged from 4.85 kg C m^{-2} under ornamental use in the North China Plain (mostly ornamental gardens in schoolyards and along a section of highway) to 0.52 kg C m^{-2} in lands with mine & fill use in the subtropical hilly region ($P < 0.01$; Table II).

The highest SOC densities were found in paddy land in each region where this land use occurred (all except North China Plain), with rainfed and irrigated agriculture usually following behind this. Observation of higher SOC densities in flooded paddy soils agrees well with previous studies and is

TABLE II

Soil organic carbon (SOC) densities (mean±standard deviation) in different land use classes within each region

Land use	North China Plain		Yangtze Plain		Sichuan hilly		Subtropical hilly		Tropical hilly		Across regions
	n	SOC	n	SOC	n	SOC	n	SOC	n	SOC	
		kg C m^{-2}		kg C m^{-2}		kg C m^{-2}		kg C m^{-2}		kg C m^{-2}	kg C m^{-2}
Fallow	5	0.79±0.17 c[a)]	23	2.32±0.34 cd	-	-	3	1.20±0.49 cd	-	-	1.44±0.33
Variable	10	1.28±0.70 c	-	-	-	-	-	-	-	-	1.28±0.70
Forestry	-	-	3	2.63±0.61 abcd	33	2.38±0.82 ab	69	2.21±0.68 b	65	2.77±0.80 a	2.50±0.73
Rainfed	6	2.27±0.68 b	35	3.62±0.85 a	53	1.94±0.61 b	23	2.44±0.64 b	54	2.41±0.87 a	2.54±0.74
Irrigated	63	2.84±0.70 b	12	3.33±0.99 abcd	-	-	-	-	-	-	3.09±0.85
Paddy	-	-	12	3.67±0.77 a	35	2.86±0.63 a	26	4.13±0.88 a	10	2.85±0.96 a	3.38±0.81
Aquaculture	-	-	25	2.66±0.55 bc	-	-	-	-	-	-	2.66±0.55
Ornamental	3	4.85±0.63 a	3	1.86±0.33 d	-	-	-	-	-	-	3.36±0.48
Disturbed	6	2.38±0.99 b	15	3.49±0.60 a	15	2.37±1.06 b	13	2.32±0.86 b	13	2.18±1.07 a	2.55±0.92
Mine & fill	-	-	-	-	-	-	3	0.52±0.29 d	3	1.02±1.16 b	0.77±0.72
Horticulture	3	2.73±0.73 b	-	-	-	-	-	-	-	-	2.73±0.73
Constructed	38	2.52±0.93 b	25	3.12±0.85 ab	11	2.16±0.47 ab	15	1.93±0.93 bc	4	2.09±0.61 a	2.36±0.76

[a)] Values followed by the same letter(s) are not significantly different between classes at $P \leq 0.05$, as determined by Tukey's honestly significant difference test.

explained by natural fertility of wetlands and other lowlands and by the long-term use of organic fertilizers and flooding, which provide a strong supply of organic carbon and lower decomposition rates, respectively (Fu *et al.*, 2001; Wang *et al.*, 2003). The generally higher SOC of other agricultural lands also agrees with previous studies (Xie *et al.*, 2007) and may be explained by farmer selection of the most fertile lands for agriculture (Ellis and Ramankutty, 2008), long-term applications of carbon-rich organic fertilizers, and increased supply of plant carbon resulting from crop fertilization and irrigation (Lal, 2004).

In comparison with croplands, village forestry lands tend to be less disturbed, supporting mature and productive woody vegetation, explaining a moderate trend toward higher SOC densities in this land use and underlining the global importance of forestry land in soil carbon sequestration (Scholes and Noble, 2001). The lower SOC densities of village forests (SOC density 2.50 kg C m^{-2}) compared with croplands, such as paddy (3.38 kg C m^{-2}) and irrigated lands (3.09 kg C m^{-2}), might imply that transforming village forests into paddy or irrigated croplands could increase their SOC density. Yet this is certainly not the case. Village forestry is almost always practiced on steeper slopes and in other areas where low SOC densities, and therefore low soil fertility, make agriculture less productive. Moreover, the lower SOC densities of these lands are generally the result of previous unsustainable agricultural use. Indeed, most studies show that transforming forests into cropland reduces SOC densities substantially (Houghton, 1983; Detwiler, 1986; Wang and Medley, 2004). The observation that paddy and irrigated lands tend to have higher SOC levels than forestry land is, therefore, best explained by farmer selection of the most "naturally fertile" lands, especially floodplains, for intensive agriculture, and the use of carbon-rich organic fertilizers.

SOC densities were at their lowest in lands without agricultural, forestry, or other productive use, such as fallow land, mined areas, and in areas where variability from natural disturbance precluded regular cultivation (seasonal riverbeds; "Variable" land use and land cover classes). Lower SOC densities in these areas may be explained both by anthropogenic and natural removal of topsoil (artificial and natural erosion) and by the tendency of these areas to have lower vegetation cover. In many cases, the only difference between fallow and forestry lands was the absence of trees or other plantings, indicating that forestry practices may be increasing SOC densities over the low levels typical of most fallow lands in villages.

Remarkably, soils in the most disturbed village land uses of all, constructed (mostly housing and roads) and disturbed (mostly unused land around buildings and roads) tended to have moderate SOC densities, in the range of 2 to 3 kg C m^{-2}. SOC levels in ornamental lands, found mostly around larger roads and schools, were very high in one site and very low in the other site where this was observed, and with the rarity of this class making it difficult to draw conclusions.

Land use and SOC stock. The relative distribution of total SOC stocks among different land use classes is shown for each region in Fig. 2a. In the North China Plain, irrigated land dominated SOC stocks because of the relatively large extent of this use within the region (73.6%) and its high SOC density (Table II). This land use alone accounted for more than three quarters of the region's SOC stocks, making it by far the largest across China's village regions in terms of SOC storage, totaling about 1.2 Pg C if considered proportionally across China's entire village extent. The next largest regional SOC pools were in paddy and forestry lands within the subtropical hilly region (0.64 and 0.58 Pg C, respectively).

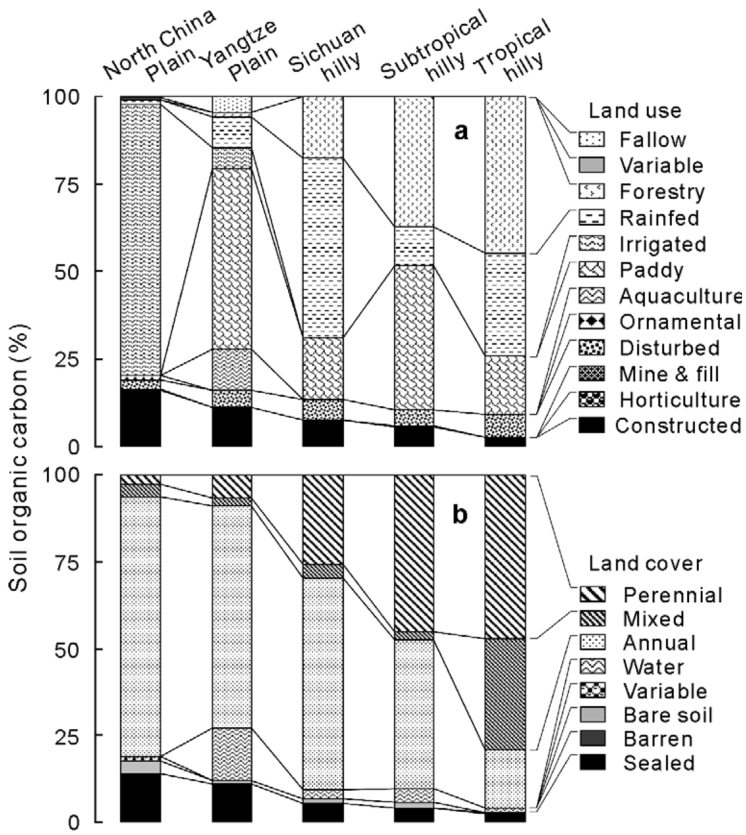

Fig. 2 Percent of total soil organic carbon stocks within different land use (a) and land cover (b) classes in five village regions across China.

Most SOC was found within agricultural land in all regions except the tropical hilly region, where nearly 45% of the SOC was found in the forestry land. Forestry also accounted for a significant portion of the SOC in the subtropical and Sichuan hilly regions but was insignificant in the plain regions where forestry was rare. Interestingly, SOC associated with constructed features (mostly building and roads) and with the disturbed vegetation usually found around them was a very significant component of regional SOC in all regions, accounting for more than 18% of SOC in the North China Plain and 16% in the Yangtze Plain to a low of 9% in the tropical hilly region, roughly paralleling population density.

Effect of land cover on SOC

Land cover and SOC density. SOC densities differed significantly ($P < 0.01$) among the different land cover classes in each region except for in the Sichuan hilly region ($P > 0.5$; Table III). In each region, the SOC density under herbaceous vegetation cover (annual class) tended to be the highest, an effect best explained by the observation that most herbaceous cover was found in agricultural lands and these tended to have the highest SOC densities in village landscapes (Table II). SOC density also tended to be higher under closed canopy trees and woody vegetation (perennial class), but this effect was not consistent, mostly because of the high variability in the SOC densities within each land cover class across regions (Tables III and IV). For example, SOC density under perennial cover was significantly lower than that under annual cover in the subtropical hilly region, but it was significantly higher under annual cover in the Yangtze Plain and in the tropical hilly region. In general, areas without vegetation (sealed, barren rock and minerals, bare soil, and variable) tended to have the lowest SOC densities, but again these trends were not always consistent.

TABLE III

Soil organic carbon (SOC) densities (mean±standard deviation) in different land cover classes within each region

Land cover	North China Plain		Yangtze Plain		Sichuan hilly		Subtropical hilly		Tropical hilly		All regions
	n	SOC	n	SOC	n	SOC	n	SOC	n	SOC	SOC
		kg C m^{-2}		kg C m^{-2}		kg C m^{-2}		kg C m^{-2}		kg C m^{-2}	
Perennial	6	3.37±1.70 ab[a)]	22	3.77±1.08 a	56	2.36±0.76	82	2.25±0.71 b	76	2.66±0.81 a	2.88±1.01
Mixed	5	2.45±0.43 a	6	2.56±0.83 ab	11	2.11±1.06	3	2.46±1.15 ab	47	2.64±0.92 a	2.44±0.88
Annual	67	2.82±0.74 a	55	3.36±0.73 a	69	2.34±0.81	49	3.21±1.27 a	19	2.19±1.02 a	2.79±0.91
Water	-	-	45	2.52±0.49 b	-	-	-	-	-	-	2.52±0.49
Bare soil	5	3.10±1.15 ab	3	2.84±0.23 ab	3	2.46±0.59	6	1.76±1.40 ab	-	-	2.54±0.84
Variable	15	1.12±0.62 b	-	-	-	-	-	-	-	-	1.12±0.62
Barren	-	-	-	-	-	-	-	-	3	1.02±1.16 b	1.02±1.16
Sealed	36	2.46±0.87 a	22	3.16±0.89 a	8	2.05±0.41	12	1.67±0.82 b	4	2.09±0.61 a	2.29±0.72

[a)]Values followed by the same letter(s) are not significantly different between classes at $P \leq 0.05$, as determined by Tukey's honestly significant difference test.

TABLE IV

Coefficient of variation (CV) of soil organic carbon density among land use and land cover classes within each region and among regions

Region	Within regions						Among regions		
	land use			land cover			Mean	SD	CV
	Mean	SD[a)]	CV	Mean	SD	CV			
	kg C m^{-2}		%	kg C m^{-2}		%	kg C m^{-2}		%
North China Plain	2.46	1.20	49	2.55	0.79	31	2.75	0.47	17
Yangtze Plain	2.97	0.63	21	3.04	0.51	17			
Sichuan hilly	2.34	0.34	15	2.26	0.18	8			
Subtropical hilly	2.11	1.13	54	2.27	0.62	27			
Tropical hilly	2.22	0.66	30	2.12	0.67	31			
Across regions	2.39	0.82	34	2.20	0.72	33			

[a)]Standard deviation.

In theory, areas with the densest, least disturbed vegetation would be expected to accumulate the most SOC over time while soils under continuous tillage would be expected to have lower SOC accumulation (Su and Zhao, 2003). The observation that closed canopy perennial vegetation cover was not associated with the highest SOC densities in this study is, therefore, best explained by the preferential selection of the most naturally fertile village lands for intensive agriculture, leaving only marginal lands for forestry or tree and woody crops. This was readily apparent in the field, as ecotope features with tree and woody cover tended to be forestry or orchard lands in the first stages of recovery from previous agricultural use, which had resulted in major degradation of soil fertility. Submerged soils (sediments) also had relatively low SOC densities, even though their SOC concentrations were quite high because of their exceptionally low bulk density.

Land cover and SOC stocks. SOC stocks under different land cover classes are shown in Fig. 2b. The main trends apparent in this figure are the dominance of SOC under annual cover in the plain regions and Sichuan, and the greater importance of closed canopy (perennial) and open canopy (mixed) woody vegetation in the subtropical and tropical hilly regions. These patterns are readily explained by the relatively large areas occupied by annual crops in the plains and in Sichuan and the importance of forestry and orchards in the less densely populated hilly regions. The SOC stocks associated with impervious structures (sealed) ranged from a high of 14% in the North China Plain to a low of about 2.5% in the tropical hilly region again paralleling the trend in built structures that was observed in land use data and that followed trends in population density.

The importance of measuring fine-scale variation in SOC

Global and regional estimates of the SOC stocks are notoriously variable (Houghton, 2003). For example, Pan (1999) estimated China's total SOC stock at 50 Pg, Wang *et al.* (2002) estimated this at 92 Pg (1980s), and Xie *et al.* (2004a) estimated this at 69 Pg. The need for improved reliability and precision in these and other regional and global estimates of terrestrial carbon sequestration is clear.

The principal reason for imprecision in regional estimates of the SOC stocks is the high variability of SOC density within regions (Houghton, 2003). In this study, SOC density varied significantly with land use and land cover within each region (Tables II and III; except for land cover in the Sichuan hilly region) and also among regions (SOC density is significantly higher in the Yangtze Plain than in other regions). The degree to which SOC density varied with local land use and land cover is captured by the coefficients of variation (CVs) for SOC density in Table IV. CVs for SOC density were always larger among land use classes than among land cover classes within each region, and both land use and land cover CVs were higher within each region than among the regions as a whole (except for land cover in the Sichuan hilly region). These results showed that local differences in land use and land cover were associated with most of the regional variation in SOC density across densely populated village regions. By better understanding this source of SOC variation and incorporating it into global and regional estimates of SOC stocks, it is likely that these can be improved significantly (Houghton, 2003).

The observation that substantial variation in SOC is associated with local land use and land cover adds to the growing consensus that regional and global SOC estimates tend to be inconsistent because they are based on coarser-resolution land use and land cover measurements that cannot adequately sample local variation in SOC (Houghton, 2003). Use of a regionally stratified sampling design enabled us to make field measurements of SOC density and stocks both within and across the highly heterogeneous and intensively managed village landscapes of China. Many of the ecologically distinct features sampled in this study, such as those associated with buildings and roads, are ignored by soil surveys and regional analyses of SOC, even though these can occupy as much as 20% of village landscapes in some regions (Ellis *et al.*, 2009). In many regional and global analyses, village regions are characterized as consisting entirely of croplands, or at best, of croplands and forests. This in itself is undoubtedly a substantial source of error in regional SOC estimates. In general, global and regional change studies would be considerably improved by the ability to observe and quantify local variation in land use, SOC, and other ecological variables that tend to vary at fine spatial scales in intensively managed landscapes.

Why does SOC vary at fine spatial scales in village landscapes?

Understanding why SOC varies so much at fine spatial scales in densely populated agricultural regions is critical to modeling and estimating past and future changes in terrestrial carbon balance (Dupouey *et al.*, 2002). Although this study has shown that SOC variation in China's village regions is highly associated with fine-scale variation in land use, land cover and terrain, and not with climate, the observations in this study are insufficient to establish the cause of this variation or its association with land use or other variables. The association between land use and SOC, for example, could have three different causes. First, landscapes vary naturally in SOC and land managers may merely apply different land use practices to parts of the landscape with different SOC levels. Second, differences in land management might produce the observed differences in SOC, and third, a combination of the above two causes may cause the effect. We hypothesize that the third cause is most likely.

It has been widely observed that the most fertile, and therefore, the most SOC-rich, parts of landscapes tend to be preferentially settled by humans and used for intensive agriculture (Ellis and Ramankutty, 2008). It is also well known that some agricultural practices, such as the intensive use of organic fertilizers and flooded paddy, tend to increase SOC (Fu *et al.*, 2001; Wang *et al.*, 2003; Lal, 2004), whereas the sustained tillage and the removal of perennial vegetation cover tend to decrease SOC (Houghton, 1983; Detwiler, 1986; Su and Zhao, 2003; Wang and Medley, 2004). The most likely explanation for the fine-scale SOC variation observed in village landscapes is thus a combination of the natural SOC variation caused by differences in terrain and other variables with the anthropogenic variation caused by differential land use. That terrain was the only environmental factor that was statistically associated with SOC variation across village regions, agrees well with this finding. Given that land use can both enhance natural SOC variation by increasing SOC in the already SOC-rich parts of landscapes and by decreasing it in SOC-poor parts, and that land use can also decrease SOC variation by the opposite process, the degree to which anthropogenic alteration of SOC enhances or decreases SOC variability in landscapes remains in question and would be an excellent subject for further study.

CONCLUSIONS

This study integrated high-spatial resolution mapping with soil sampling to show that both SOC density and stocks varied significantly with local land use and land cover at fine spatial scales within China's agricultural village landscapes. In general, the highest SOC densities were associated with the most productive agricultural lands, especially paddy, and also with the least disturbed land uses, such as forestry. SOC density did not show a significant relationship with climate, highlighting the degree to which human activities may have altered SOC density in these regions, though much of the variation in SOC associated with different land use types appears to have resulted from farmer selection of the most naturally fertile lands for intensive agriculture and not from changes in SOC caused by land management practices in themselves.

Though SOC densities associated with built structures were not especially high, SOC stocks in and around built structures formed a substantial component of regional SOC stocks across all village regions because of their significant area, indicating that human residence, not just agricultural practice, is a regionally important control on total SOC stocks across village landscapes. By linking soil sampling with high-resolution ecological mapping, local variation in soil carbon sequestration associated with intensive land management practices can be quantified and understood within and across densely populated anthropogenic landscapes, including not only the villages of Asia but also potentially urban and suburban landscapes.

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