Reg Environ Change (2011) 11:651–662
DOI 10.1007/s10113-010-0197-2

ORIGINAL ARTICLE

Rural settlement expansion and paddy soil loss across an ex-urbanizing watershed in eastern coastal China during market transition

Shiliang Su · Qi Zhang · Zhonghao Zhang · Junjun Zhi · Jiaping Wu

Received: 8 June 2010 / Accepted: 4 December 2010 / Published online: 25 December 2010

Abstract Historically, paddy soils are the most valuable natural resources that produce about 90% of staple food in eastern coastal China. Dispersed patterns of rapid rural settlement expansion, or "exurban", are recognized as key threats to the region's food security through paddy soil loss. Analyzing the process of ex-urbanization and its impact has profound implications for the sustainable development of rural China. Based on official statistics and data derived from satellite images, dynamics of rural settlement expansion and paddy soil loss were outlined for Tiaoxi watershed during China's market transition period (1994–2003). Particularly, rural settlements became more aggregated and total area expanded by 183% at an average rate of 12.3% per year for the whole watershed. Existing cores, open areas away from urban centers and areas near major transportation lines and river channels, observed the highest specialization in rural residential growth. Being closely associated with rural settlement in spatial distribution, open large paddy soil patches acted as another kind of center for rural settlement expansion within the landscape. Variations in rural settlement expansion were detected among different-tier counties, such as speed of rural settlement expansion, speed of build-ups growth per capita. These variations were closely related to social-economic development. The rapid rural settlement expansion led to a considerable loss of paddy soil, about 11% of the total amount for the whole watershed. Linear regression identified a significant relationship between paddy soil loss and rural settlement expansion. Given the social and ecological problems associated with paddy soil loss, we argue that innovative and effective planning policies as well as management programs that target at paddy soil protection should be developed and implemented in rural China. In particular, we suggest using watershed as an appropriate spatial unit for sustainable paddy soil management in this investigation.

Keywords Rural settlement expansion · Paddy soil · Ex-urbanization · Watershed · China

S. Su · Q. Zhang · Z. Zhang · J. Zhi · J. Wu (✉)
College of Environment and Natural Resources,
Zhejiang University, Hangzhou, China
e-mail: jw67@zju.edu.cn

Introduction

As one of the most important human activities, urban expansion exerted enormous impacts on natural resources and environment. Although urban expansion in the form of land cover (either built-up or impervious surfaces) occupies less than 2% of the earth's land surface, there is plentiful evidence that human disturbance due to urbanization has significantly altered ecological environment (Ogden et al. 2006; Schaldach and Alcamo 2007; Napton et al. 2010). The environmental effects are most profound in areas where human land use is most intense, such as cities and industrial areas, and where human habitation and wild lands meet (Radeloff et al. 2005; Gonzalez-Abraham et al. 2007). However, urban expansion is not limited to urban and suburban areas, and the environmental effects have recently extended into rural areas. Studies on urban expansion increasingly focus on ex-urbanization, defined as low-density residential growth in rural areas situated at longer commuting distances from urban and suburban centers (Compas 2007; Gonzalez-Abraham et al. 2007; Basu and Chakraborty 2008).

This is the case in large parts of eastern coastal China, and the problem is even more serious in Yangtze Delta, where the average population density is about 1,500 persons/km^2 and therefore three times the China level. This means that the expansion is not restricted to urban areas any more and occurs also vigorously in rural places. One of the many problems resulting from this rapid expansion is the cultivated land loss, in particular, land conversion of soils with high productivity to development uses (Lin and Ho 2003). Research revealed that China's total cultivated land decreased 4.73 million hectares between 1978 and 1996, and most of the loss had occurred in China's coastal and central provinces (Yang and Li 2000). More alarmingly, fertile and productive cultivated soil is mainly concentrated in eastern coastal China (Dutt and Xie 1992; Gale 2002). Paddy fields, due to rich water and climate resources and fertile soils, are the main form of cultivated land in these regions (Xie et al. 2005). Previous studies showed that urban expansion in eastern coastal China had occupied a large number of fertile paddy fields and caused a sharp decline of paddy soil (Chen 2007; Pan and Zhao 2007; Zhang et al. 2007). However, these studies were carried out in urban cities, and there exists little information or reliable official statistics available about paddy soil loss in rural China.

Urban expansion is often triggered by changing socio-economics, institutions, and policies, all of which relate tightly with paddy soil loss. The market transition that occurred in China offers a unique "natural experiment" to study broad-scale determinants. Such broad-scale factors are key for land use decisions (Müller and Sikor 2006; Kuemmerle et al. 2009) and for determining the profitability of farming (MacDonald et al. 2001). Due to the Market-transition policy since 1993, a fundamental social change from state socialism toward a market economy swept over China. And the change was superimposed on a coastal regional system that paralleled those of a number of fast developing settings, especially in eastern coastal China. In terms of land use perspective, agriculture was heavily subsidized and production was mainly targeted at socialist markets, but the situation changed drastically after 1993. Most regions in eastern coastal China carried out land reforms and took various measures such as reconstructing land market, charging cultivated land (land prices, taxes and fees), separating land usufruct rights from land property rights, and upgrading land productivity and prosperity of real estate (Ding 2003). However, drawbacks also emerge: massive transference from paddy fields to constructive land (Tan et al. 2005), degradation of soil productivity, and cultivated abandonment accompanied by large flows of young people into cities (Yang 2004). Altogether, these processes resulted in widespread cultivated land loss across eastern coastal China during market transition. The problem is that although general trends in paddy soil loss are acknowledged, little quantitative information on paddy soil loss due to ex-urbanization during the market transition is available.

The spatial process of (either urban or rural) expansion can occur at various geographic scales. The optimal spatial scale level for analyzing ecological consequences of expansion is controversially discussed and depends largely on natural preconditions as well as on the intensity of human impacts (Wrbka et al. 2004). Banko et al. (2003) suggested the use of predefined, ecologically meaningful landscape types as reference units for analysis. Watershed systems are widely recognized as fundamental geographic units for the research, assessment, management, and monitoring of natural resources and ecosystems in a landscape (United States Environmental Protection Agency 2000). We therefore suggest that analyzing paddy soil loss in response to ex-urbanization in a watershed setting can provide important references for environmental managers. However, seldom studies have characterized paddy soil loss at watershed scale.

Given that urban expansion is always applied to describe urbanization, rural settlement expansion or rural residential growth is referred to indicate ex-urbanization (Johnson and Maxwell 2001; Long et al. 2007; Mann 2009). In general, the application, performance and outputs analyzing and characterizing rural settlement expansion depend strongly on the data available for parameterization. Remote sensing (RS) and geographic information systems (GIS) have been recognized as powerful and effective tools for detecting the spatiotemporal dynamics of rural settlement expansion. Usually, spatially explicit time series of rural settlement can be interpreted based on RS, and the corresponding expansion can be discovered using GIS and statistical analysis. In addition, landscape metrics are critical in the description, analysis, and modeling of land cover and its changes (Herold et al. 2003). Researchers can use these metrics to objectively quantify the structure and patterns of rural settlement expansion.

Although there are many areas in rural China undergoing ex-urbanization, for this study, we selected the Tiaoxi watershed in Yangtze Delta, eastern coastal China. This will be done by combining multiple research approaches: RS, GIS, statistical analysis, and landscape metrics. More specifically, our objectives are to (1) identify dynamics of rural settlement expansion and analyze its drivers in Tiaoxi watershed during China's market transition; (2) characterize the patterns of paddy soil loss in response to rural settlement expansion in this area; and (3) provide a frame of reference for policy makers to promote the protection of paddy soil resources as well as to advance sustainable development at watershed scale.

Background

China's market transition

China's open-door reform since 1978 has evolved in two stages with the November 1993 decision marking a turning point. The essence of this decision is to replace the planning system with a modern market system. The first stage spanned about 15 years between 1978 and 1993 and the second stage began in 1994. Although the two stages had much continuity between them, the division is quite clear: the watershed being the historic decision of November 1993, "Decision on Issues Concerning the Establishment of a Socialist Market Economic Structure," adopted by the Chinese central government.

It is important to get a deep understanding of social and environmental processes raised by rapid ex-urbanization associated with the 1993 reforms. One of the most notable features of environmental change since 1993 is the conversion of paddy fields. Though there are no systematic data about China's paddy fields, China's agricultural economy faces a scarcity of cultivated soil, given that the country is feeding 22% of the global population on less than 9% of the world's cultivated land. Therefore, it is a critical issue for Chinese central government and the international community to have a better understanding of paddy soil conversion dynamics.

Study area

Tiaoxi watershed lies in the northern part of Zhejiang Province, eastern coastal China (Fig. 1). It borders Taihu Lake to the north, Shanghai to the northeast, and the province of Jiangsu to the northwest. As an important component of Taihu Lake basin, Tiaoxi watershed accounts for 70% of freshwater flowing into the Taihu Lake annually. Constituted by six counties (Fig. 1), it covers approximately 6,000 km^2 and has a population of 4.3 million. With a warm temperate, subtropical monsoon climate, the region enjoys four distinct seasons. Annual temperature averages 17.5°C, and rainfall averages 1,100 mm. Paddy soil is fertile and occupies a large portion of the total area. All the natural conditions are beneficial for agricultural production, and the crop yield is high. Tiaoxi watershed thus serves as an important grain production base in eastern coastal China.

With the opening-up policy started in 1978, this area has followed its own development model, dubbed the "Huzhou model". This "Huzhou model" refers to the situation that economic development of Huzhou region relies on small private business and tourism businesses. Responsive to the whims of the market, this watershed has been undergoing extensive ex-urbanization. It witnessed rapid economic development, considerable rural settlement expansion, non-agriculture population growth, and improvement of people's living standards. However, for lack of corresponding land planning and supervision mechanism, the ecological consequences of uncontrolled rural settlement expansion in this watershed are particularly serious. The environmental condition continues to worsen and has become a major impediment to regional sustainable development and social progress. In addition, water-quality issues of Taihu Lake are nationally concerned. The eco-environmental functions of paddy fields are one of the keys to tackling with water-quality issues of Taihu Lake. Considerable attention is required from the scientific and public policy communities to characterize paddy soil loss in this watershed.

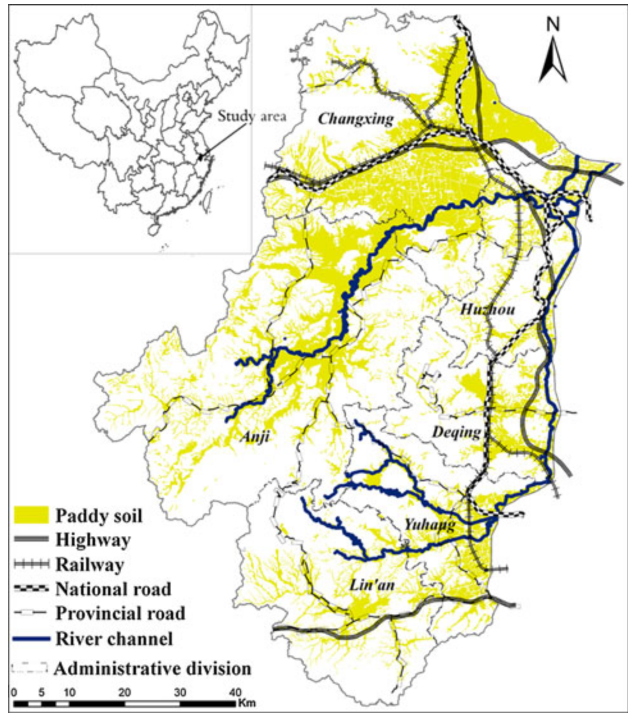

Fig. 1 Location, administrative divisions, and spatial distributions of paddy soil, major transportation lines and river channels of Tiaoxi watershed, China

Method

Rural settlement expansion detection

Rural settlement expansion was assessed using remotely sensed data. Two times Landsat Thematic Mapper (TM) images in 1994 and 2003 were interpreted to obtain information of build-ups. The ''built-up'' class depicts rural residential areas of single houses and apartment buildings, shopping centers, industrial and commercial facilities, highways and major streets, and associated properties and parking lots. The geometric registration was done using the quadratic method. The specification for image to image registration was 0.5 pixel in both directions, and this precision requirement was met for all 2 years. Spectral mixture analysis (SMA), a technique that shows promising applicability in heterogeneous environment, in particular, was used to interpret TM images in this study. More specifically, multiple endmember spectral mixture analysis (MESMA), which allows the number and type of endmembers to vary on a per pixel basis, was applied given the high degrees of spectral heterogeneity exhibited by the complex land cover patterns in the study area (For details, see Powell et al. 2007). During the interpreting process, mutil-temporal TM images, topography, and soil information were used as the ancillary data. An accuracy assessment was performed following 3 × 3 majority filtering. The overall classification accuracy was 90.6%. Then build-up maps (Fig. 2) were integrated into a GIS in order to calculate rural settlement expansion. In addition, the expansion degree (changes of build-ups) and average expansion rate are, respectively, calculated using Eq. (1) and Eq. (2)

$$C = \frac{R_2 - R_1}{R_1} \times 100\% \quad (1)$$

where C is the expansion degree; R_1 is the area of rural settlement at the date t_1; R_2 is the area of rural settlement at the date t_2.

$$R = \sqrt{[n-1]}\frac{R_2}{R_1} - 1 \quad (2)$$

where R is the rate of rural settlement expansion; R_1 is the area of rural settlement at the date t_1; R_2 is the area of rural settlement at the date t_2; and n the difference of years between the two dates (10 years between 1994 and 2003 in this case study).

Landscape metrics are effective in quantifying spatial patterns of rural settlement. For Tiaoxi watershed, we selected several landscape metrics: numbers of patches (NP), patch density (PD), largest patch index (LPI), landscape shape index (LSI), patch cohesion index (COHESION), and aggregation index (AI). All the landscape metrics were calculated at class level using FRAGSTATS 3.3 (McGarigal et al. 2002). The PD equals the number of patches of build-ups per 100 ha and is an indicator for fragmentation. The LPI quantifies the percentage of total land area comprised by the largest patch of build-ups and is a simple measure of dominance. The LSI equals the ratio of sum of edge lengths to total area of build-ups measured against a circle standard and measures shape configuration. COHESION quantifies the connectivity of a particular patch type and AI is calculated from a patch adjacency matrix. These two metrics can be applied to indicate clumpiness or aggregation.

Elasticity of rural settlement expansion to non-agriculture population growth

The elasticity of settlement expansion to urban population growth (Tan et al. 2005), firstly developed by the Chinese Academy of Urban Planning and Design (CAUPD) and denoted as E(sep) in this paper, was used to assess the relationship between rural settlement expansion and non-agriculture population growth. When calculating E(sep), the former urban population was replaced by non-agriculture population since the study area was in rural areas. It is expressed as:

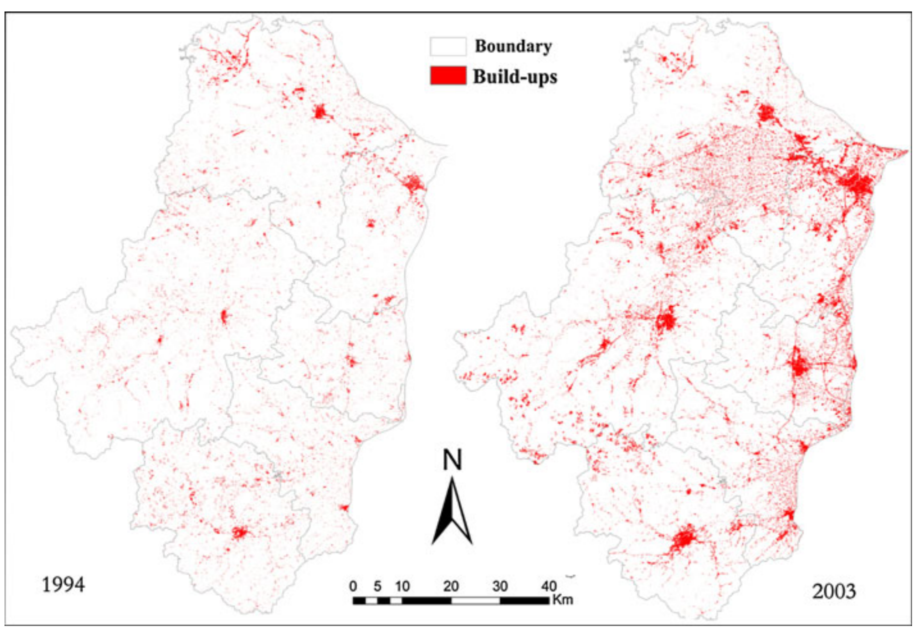

Fig. 2 Distribution of build-ups in Tiaoxi watershed in 1994 and 2003

$$\mathrm{E(sep)} = \frac{A_{(i)}}{\mathrm{Pop}_{(i)}} \quad (3)$$

where $A_{(i)}$ is the annual rate of rural settlement expansion of county i, and $\mathrm{Pop}_{(i)}$ is annual rate of non-agriculture population growth of county i.

According to the economic principle of marginal value, the growth rate of rural residential would be expected to be less than that of non-agriculture population, because the new population does not need an entirely new and independent infrastructure system but rather uses existing facilities (Shoshany and Goldshleger 2002; Tan et al. 2005). The CAUPD suggested that the desirable value of E(sep) was 1.12 for China under the assumption that developed land use can meet the need of basic construction and environment protection (Tan et al. 2005).

Paddy soil loss detection

Overlay analysis provides an alternate approach to determining the rate of paddy soil conversion to development uses. In order to get the area and the location of the paddy soil loss, interpreted build-up maps were overlaid with digital soil map (at scale of 1:50,000, Fig. 1). Then, by using the clip and other functions from the GIS system, the paddy soil occupied by rural settlement expansion could be obtained for the study period. Regression is applied to further analyze the association between rural settlement expansion and paddy soil loss. All statistics are performed using the ''Statistical Package for the Social Sciences Software-SPSS 16.0 for Windows'' (SPSS Inc., Chicago, IL).

Neighboring index

Settlements are generally situated in plain areas with rich water resources and suitable lands for agriculture. This situation determines that settlements are usually surrounded by intensive arable land, and thus their expansion is often associated with a loss of paddy soil (Tan et al. 2005). In this paper, the metrics of build-ups neighboring on paddy soil [$I(i)$], proposed by Tan et al. (2005), was applied to measure the spatial relationship between rural settlement and the paddy soil around it

$$I(i) = \left[\sum_{j=1}^{n} L_{ij}(l) \div \sum_{j=1}^{n} L_{ij}(p)\right] \times 100\% \quad (4)$$

where $L_{ij}(l)$ refers to the total length of borderlines between an build-up patch j of a county i and the paddy soil around this patch, and $L_{ij}(p)$ is the total perimeter of the patch. The value of $I(i)$ ranges between 0.0 and 100.0. If $I(i)$ is 100, county i is completely encompassed by paddy soil. Higher $I(i)$ means more opportunities for encroachment of paddy soil by rural settlement.

Results

Rural settlement expansion and landscape changes

Tiaoxi watershed experienced a rapid ex-urbanization during the market transition (1994–2003), characterized by immense spatial expansion of rural settlements. Some 28,778 new hectares had become "settlement" during this period, with build-ups rising from 1.9% of the total area of the region in 1994 to 5.4% in 2003. Total rural settlement area expanded by 183% (Table 1) at an average rate of 12.3% per year. Studying the spatial and temporal heterogeneity of the land cover changes at the

Table 1 Statistics of indicators for rural settlement expansion in Tiaoxi watershed between 1994 and 2003

County	Year	Area of build-ups (ha)	Build-up utilization per capita (m^2)	E(sep)
Anji	1994	3,198.2	72.1	2.5
	2003	10,409.8	232.8	
	C (%)	225.5	223.1	
	R (%)	14.0	13.9	
Changxing	1994	4,193.0	68.7	2.5
	2003	10,570.1	170.5	
	C (%)	152.1	148.1	
	R (%)	10.8	10.6	
Deqing	1994	1,293.8	31.6	4.0
	2003	4,875.9	115.2	
	C (%)	276.9	264.9	
	R (%)	15.9	15.5	
Huzhou	1994	2,244.2	21.7	1.3
	2003	9,469.5	87.9	
	C (%)	322.0	309.5	
	R (%)	17.3	17.0	
Lin'an	1994	3,233.8	64.1	0.7
	2003	4,740.3	92.1	
	C (%)	46.6	43.6	
	R (%)	4.3	4.1	
Yuhang	1994	1,521.5	12.8	7.6
	2003	4,396.9	36.5	
	C (%)	189.0	186.4	
	R (%)	12.5	12.4	
Total	1994	15,684.5	37.3	2.1
	2003	44,462.4	103.7	
	C (%)	183.5	178.2	
	R (%)	12.3	12.0	

E(sep) presents elasticity of rural settlement expansion to non-agriculture population growth

C represents changes of build-ups area, *R* denotes annual rate of rural settlement expansion administrative level allowed us to identify fast and slow sprawling areas that could not be detected at the watershed level. The largest increase was particularly observed in the Huzhou (322%), followed by Deqing (277%) and Anji (225%), while the lowest increase was detected in Lin'an (47%). A more detailed analysis of the new settlements between 1994 and 2003 revealed some changes in the general ex-urbanization trends and points toward a modification of the rural character of the study area: (1) new settlements tended to cluster around the existing cores; however, new developments in the open area were also common. Figure 2 revealed that most open areas away from growth centers (areas whose neighborhood saw significant increases in build-ups) in Changxing and Anji became hot-spots for rural settlements; (2) accessibility seemed to control the spatial pattern of settlements to a large extent. By virtue of buffer analysis, we found that approximately 46% of increased build-ups (13,096.5 ha) fell within the vicinity of main roads and river channels (<2 km). Flat land near major transportation lines and river channels, thus, observed the highest specialization in this settlement land use; (3) expanded lands mainly occupied lands most suitable for growing crops (being flat and historically near human settlement) (Fig. 3), since about 16,317 ha paddy fields were encroached by the increased build-ups.

Landscape metrics helped highlight trends in expansion patterns over the transition decade. Our results denoted that aggregation was the most obvious characteristics of rural settlement change with the AI increased by 22%. LSI is a

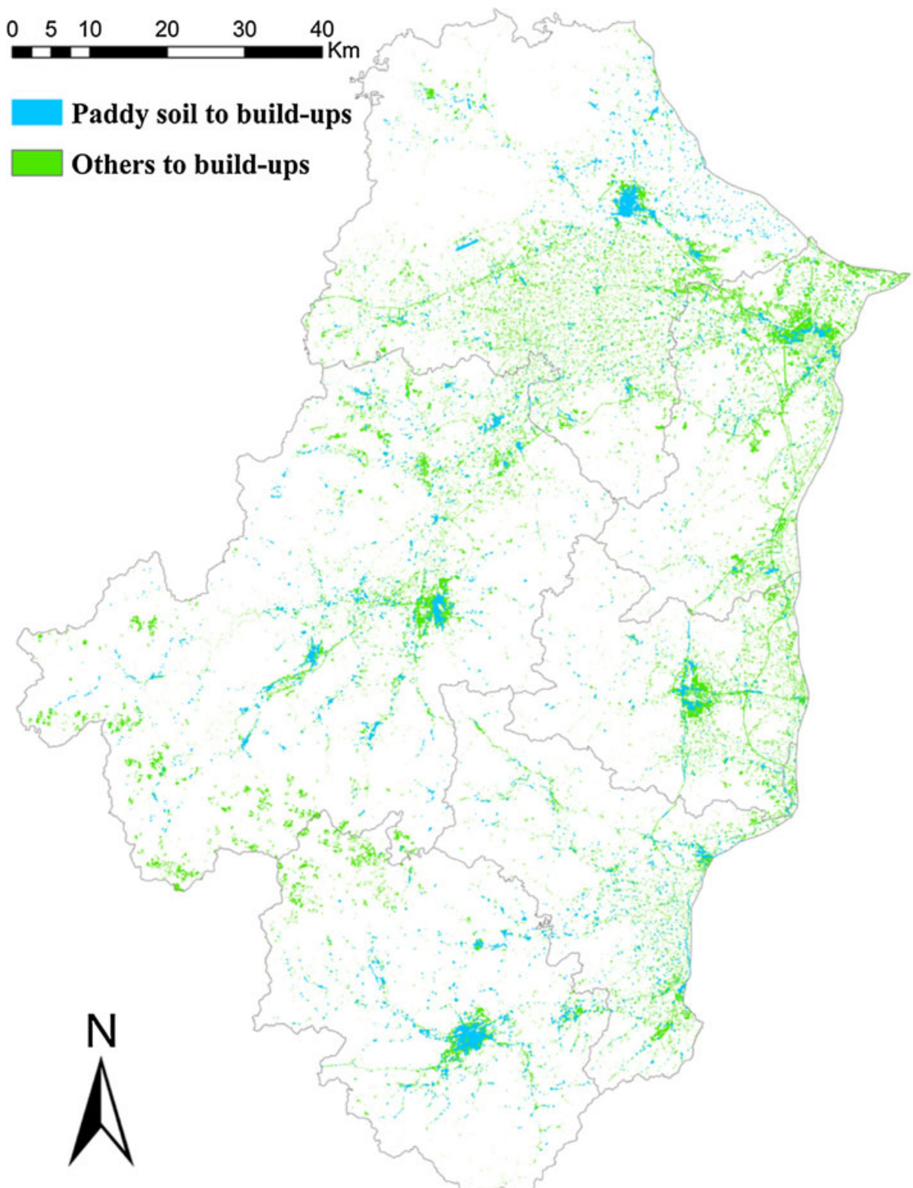

Fig. 3 Distribution of paddy soil and non-paddy soil encroached by increased build-ups in Tiaoxi watershed between 1994 and 2003

Table 2 Landscape metrics for build-ups in Tiaoxi watershed between 1994 and 2003

County	Year	NP	PD	LPI	LSI	COHESION	AI
Anji	1994	7,212	225.5	5.7	94.5	77.5	50.0
	2003	9,355	89.8	11.5	108.8	92.8	68.2
	Change (%)	29.7	−60.2	101.8	15.1	19.7	36.4
Changxing	1994	5,944	141.7	10.4	80.1	88.1	63.2
	2003	12,081	114.3	8.4	124.9	92.2	63.7
	Change (%)	103.2	−19.3	−19.2	55.9	4.7	0.8
Deqing	1994	2,610	201.7	8.1	57.3	82.2	52.7
	2003	3,826	78.4	34.4	70.2	97.0	70.1
	Change (%)	46.6	−61.1	324.7	22.5	18.0	33.0
Huzhou	1994	2,542	113.3	22.2	56.0	93.8	64.9
	2003	3,867	40.8	33.9	76.0	98.2	76.8
	Change (%)	52.1	−64.0	52.7	35.7	4.7	18.3
Lin'an	1994	5,652	179.5	13.1	84.3	86.1	55.0
	2003	3,225	68.0	28.0	64.9	95.5	72.0
	Change (%)	−42.9	−62.1	113.7	−23.0	10.9	30.9
Yuhang	1994	3,489	229.2	6.4	65.7	77.4	49.7
	2003	4,346	98.7	13.1	76.9	93.0	65.5
	Change (%)	24.6	−56.9	104.7	17.0	20.2	31.8
Total	1994	27,346	175.5	3.2	180.4	86.4	56.7
	2003	36,533	82.2	7.2	217.0	95.8	69.2
	Change (%)	33.6	−53.2	125	20.3	10.9	22.0

NP numbers of patches, *PD* patch density, *LPI* largest patch index, *LSI* landscape shape index, *COHESION* patch cohesion index, *AI* aggregation index

robust metric used to describe landscape structure across spatial scales by calculating the complexity of settlement patches according to their size. The continuous increase in LSI and decline in PD (Table 2) indicated the aggregation of rural settlements. Patch cohesion increases as the patch type becomes more clumped or aggregated in its distribution; hence, more physically connected (Long et al. 2009). From the rising trend of COHESION, it can be clearly seen that settlements pattern in 2003 turned more aggregated than those of 1994. Specifically, this phenomenon was more obvious in Yuhang, with a significant increase in COHESION (Table 2).

Change of settlement utilization per capita

Rural settlement area per capita had increased by 178.2% in the Tiaoxi watershed (Table 1). Changes of growth speed of build-ups per capita varied with the county tiers in the Tiaoxi watershed. Huzhou experienced the highest growth of build-ups per capita (309.5%), followed by Deqing (264.9%), Anji (223.1%), Yuhang (186.4%), Changxing (148.1%), and Lin'an (43.6%).

Change of E(sep)

Across Tiaoxi watershed, rural settlement expansion rate was faster than the non-agriculture population increase rate between 1994 and 2003. E(sep) averaged 3.1, much higher than the value of 1.17 for China as a whole (Shoshany and Goldshleger 2002). This signified the excess rural residential growth relative to non-agriculture population increase in Tiaoxi watershed. Among the six counties, the value of E(sep) for Yuhang ranked top (7.6), followed by Deqing (4.0), Anji (2.5), and Changxing (2.5). Lin'an had the lowest E(sep) value (0.7), indicating that rate of non-agriculture population growth was nearly equal to that of rural settlement expansion.

Considerable loss of paddy soil

As evident from the results obtained, the paddy soil area in Tiaoxi watershed had drastically decreased (Table 3). For whole watershed, paddy soil declined by 17,453.0 ha, a net change of 10.9%. Specifically, Huzhou and Deqing had seen a relatively dramatic conversion of paddy soil, compared to other counties. Net change for Huzhou and Deqing was 2,423.8 ha (17.8%) and 2,094.4 ha (17.6%), respectively. The observed trends of decreasing paddy soil areas marked the wide-spread paddy soil loss. Expressed as percentage, the impact of rural settlement expansion on paddy soil could be distinctly identified. Table 3 showed that paddy soil accounted for 56.7% of the total increased build-ups of Tiaoxi watershed. The percentage of paddy soil in increased build-ups for Huzhou was only 26.2%, much lower than other counties. These marked that rural settlement expansion occupied other types of soil rather

Table 3 Paddy soil loss of Tiaoxi watershed between 1994 and 2003 (ha)

	Anji	Changxing	Deqing	Huzhou	Lin'an	Yuhang	Total
Lost paddy soil area	4,912.2	4,702.1	2,094.4	2,423.8	1,138.7	1,669.1	17,453.0
Increased build-up area	7,211.6	6,377.1	3,582.1	9,245.1	1,506.5	2,875.4	30,797.7
Lost paddy soil in increased build-ups (%)	68.1	73.7	58.5	26.2	75.6	58.0	56.7
Lost paddy soil in total paddy soil (%)	10.3	8.2	17.6	17.8	8.4	10.3	10.9

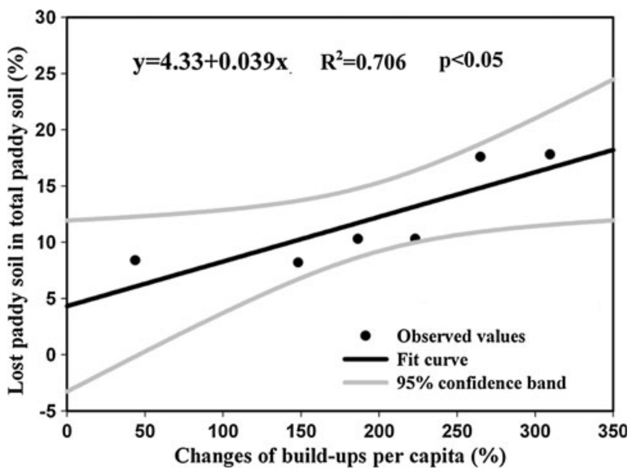

Fig. 4 Linear regression between change of build-ups per capita (%) and lost paddy soil in total paddy soil (%) between 1994 and 2003

Table 4 ANOVA statistics for linear regression analysis

Model	Parameters	Mean square	*F*	Sig.
1	Regression	69.250	9.595	0.036
	Residual	7.218		
	Total	19.624		
2	Regression	0.839	11.222	0.029
	Residual	0.075		
	Total	0.228		

Model 1 represents linear regression between change of build-ups per capita (%) and lost paddy soil in total paddy soil (%) between 1994 and 2003; Model 2 represents linear regression between change of build-up area per capita (%) and change of GDP per capita (%) between 1994 and 2003

than paddy soil in Huzhou. In contrast, rural settlement expansion in the other counties encroached mainly paddy soil (Fig. 3). Regarding the positive impact of rural settlement expansion on paddy soil loss, the result revealed strong evidence supporting close association between change of build-ups per capita (%) and lost paddy soil in total paddy soil (%) ($R^2 = 0.71$) (Fig. 4). *F*-test for ANOVA supported a significant linear correlation between paddy soil loss and rural settlement expansion (Table 4).

Discussion

Characteristic of settlement expansion

The patterns of build-ups reflect the geographic and environmental attributes that people prefer and provide information about landscape consequences of those preferences, which ultimately help manage and plan land use (Gonzalez-Abraham et al. 2007). Analyzing the factors that influence the activities they conduct in the landscape, deepens our understanding of the process of ex-urbanization and interaction between rural settlement expansion and paddy soil loss. The aggregation of build-ups along roads and rivers reflected rural residents' preferences for building sites, as few barriers exist to development across the landscape.

Our results also supported the fact that open areas were popular with people (Dwyer and Childs 2004). Open large paddy soil patches acted as another kind of center for rural settlement expansion within the landscape. Figure 3 reflected the low-density residential growth in open areas situated at longer commuting distances from urban centers. This kind of rural settlement expansion fits the ex-urbanization model. This result was consistent with the opinion that households prefer low-density areas and urban higher density areas pushed people to lower-density exurban areas (Carrión-Flores and Irwin 2004). The specific social-economic conditions may account for this result. For one thing, the housing prices in the neighboring central cities like Shanghai and Hangzhou have been keeping rising in the last 20 years, which can go as high as 30 thousand RMB Yuan per square meters. Many people working in these urban centers cannot afford such high costs and thus choose to live in exurban areas where the housing prices are relatively low. For another, as the life quality rises, many people are willing to buy extra houses in exurban areas, where the ecological environment quality is relatively high. Consequently, more and more build-ups appeared, the larger the area of build-ups the smaller the overall amount of paddy soil left. Our analysis also explained rural settlement expansion with measures of COHESION and AI of build-up patches. The increased COHESION and AI values of build-ups signified delegation-style patterns in Tiaoxi watershed.

Rural settlement expansion in Tiaoxi watershed presented similar spatial characteristics to other areas undergoing ex-urbanization. Gude et al. (2006) pointed out that agricultural suitability, transportation and services, natural amenities, and past development were the primary determinants of rural settlements across the Greater Yellowstone. Growth of rural residential development was negatively related to distance from major roads and concentrated access to farmland and waters. Patterns of build-ups across northern Wisconsin indicated that rural settlements were affected mostly by lake area, public land ownership, and the abundance of vegetation (Gonzalez-Abraham et al. 2007). In Su-Xi-Chang region of China and Lublin region of Poland, similar patterns were detected with regard to rural settlement expansion (Long et al. 2009; Bański and Wesołowska 2009).

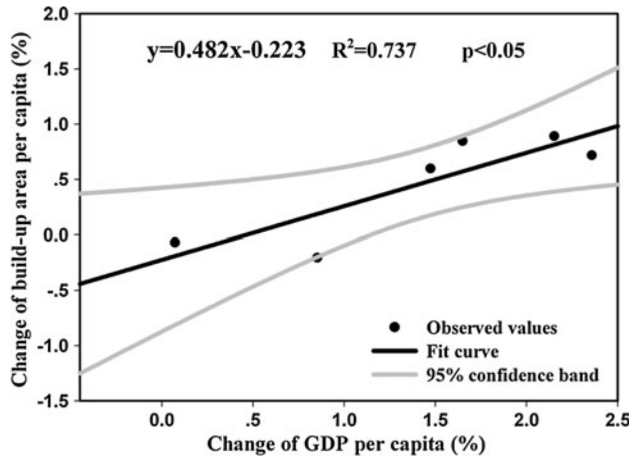

Fig. 5 Linear regression between change of build-up area per capita (%) and change of GDP per capita (%) between 1994 and 2003

Rapid social-economic development spurs rural settlement expansion

During market transition, the GDP of the Tiaoxi watershed was increased by 162%, greatly spurring the rural settlement expansion. On one hand, the economic advancement paved the way for the increase in living space per capita, transportation land per capita, common green belt per capita, and so on (Tan et al. 2005). For Tiaoxi watershed as a whole, the build-ups per capita increased by 178.2% between 1994 and 2003. For instance, the change of build-up area per capita exhibited a positive association with change of GDP per capita (Fig. 5). In the development process, the local government, focusing mostly on economy, had put more emphasis on the determination of industry and tourism as a source of income and employment. A number of industrial areas were built, surrounded by rural settlements providing employees to these districts. In addition, infrastructures and service facilities were largely constructed in pace with the development of industry and tourism. Besides, economic development was the major criterion to assess political performance of local government. Officials had paid less attention to those large-scale construction activities in order to gain political achievements. While doing so, the government had lost track of ex-urbanization management. All these contributed to the considerable rural settlement expansion.

On the other hand, the high rate of economic growth led to the increase in non-agriculture population percentage in Tiaoxi watershed. The increase in non-agriculture population percentage led to more demand for buildings to work and live. However, the point worth noticing was that the E(sep) value for Tiaoxi watershed was quite high, marking the excess rural residential growth relative to non-agriculture population increase. Being symbolic of wealth and life quality, residents had been keen on house construction in the study area. Innumerable tall buildings had been built in their large courtyards during 1994–2003. However, the non-agriculture population did not rise accordingly. Consequently, there was more and more idle rural housing land, vacant rural housing, with unoccupied land in villages. This can also stimulate the expansion of rural settlements in Tiaoxi watershed. Based on the above analysis, it could be reached that in Tiaoxi watershed, the basic purpose of massive new residential construction was for raising living standards, rather than for accommodating population increase.

Impact of settlement expansion on paddy soil

The watershed lost 10.9% of the paddy soil just within 1994–2003. The built-ups amounted to 5.4% of the total area in 2003. Many parts of China also experienced the high rates of settlement expansion and paddy soil loss. During 1988–1993, Pearl River Delta lost 13.1% of the agricultural land and the built-up land amounts to 11.3% of its total area in 1997 (Li and Yeh 2004). Of the total land area, 11.3% of Nanjing city was in urban use (2003) and the loss of soil ranged from 4.8% in 1984 to 11.8% in 2003 (Zhang et al. 2007). In Yangtze River Delta and Jing-Jin-Tang region, the same results were also found associated the loss of paddy soil or agricultural land to development uses (Tan et al. 2005; Pan and Zhao 2007; Long et al. 2009). Outside China, build-ups now occupy 13% of the total land area and 47% of the best agricultural land in Vallès county, Spain (Olarieta et al. 2008). It is estimated that 52% of the Germany soil in built-up areas has been occupied and 3% of agricultural land along Mediterranean coast had been encroached in the 1990s (European Environment Agency 2006). Besides, the richest agricultural soils along the Henares River have been converted into build-ups (García Rodríguez and Pérez González 2007). In the USA, 4.5% of soils are in danger of substantial loss (Amundson et al. 2003). All these cases denote that this alarming issue has become worldwide.

Rural settlement expansion is fancy for sprawling around paddy soil. According to the spatial association between paddy soil and build-up patches, we found that converted paddy soil largely fell within the 5 km buffer of build-up patches. Given that paddy soil is most suitable for growing crops also tends to be most suitable for "growing houses" (being flat and historically near human settlements) (Ewing 1994), a disproportionate amount of paddy soil was lost to rural settlement expansion across Tiaoxi watershed (Table 3). After examining $I(i)$s of the six counties, we found that most of them were over 75%, and some of them even reach 95%. Moreover, the change of $I(i)$s had similar characteristics to the change tendency of paddy soil loss rate. Thus, counties in Tiaoxi watershed had to expand at the expense of paddy soil around them, resulting in high rates of paddy soil loss. When expressed as percentage, the association between paddy soil loss and rural settlement expansion is displayed as Fig. 4. Three possible explanations can be proposed for this relationship: (1) "Spillover effects" that make nearby farming operations less profitable and cause farmers to disinvest. In Tiaoxi watershed, for instance, farmers turned former paddy fields into bamboo workshops, hotels and other facilities, contributing to the considerable loss of paddy soil; (2) The "seek of well-off life" that causes farmers to abandon farmland prematurely in anticipation of urban development. Large amounts of abandoned paddy soils were thus converted to development use; (3) Underestimation of the ecological or environmental values of paddy soil. Settlers and many officials always take for granted that consumption of paddy soil was inevitable for realization of urbanization.

Management implications

The rapid ex-urbanization in rural areas has led to a lot of land use conflicts and related environmental issues. The loss of the paddy soil resources would result in more possible decline of food production, posing great threat to food security. In addition, paddy soils perform a number of crucial functions and the soil being covered will no longer be able to perform the range of environmental functions associated with it as it will be separated from the other environmental compartments (Scalenghe and Marsan 2009). Consequently, the challenges that planners and policy makers face of managing rural settlement expansion and protecting paddy soil in rural China are daunting. The Chinese government recognized the situation at the beginning of the fast growing period, and adopted the ''basic farmland protection areas regulation'' policy to protect paddy soil from being converted to developed land (Pan and Zhao 2007). However, due to the lack of planning in rural China, the insufficient utilization and management of land resource led to notable loss and waste of paddy soil. China's rural area had to pay the bill for these costs due to lacking early planning. Therefore, innovative and effective planning policies and management programs will be required to stem the tide of paddy soil-consumptive development in rural China.

The promotion of register system and compact development is an important way to protect paddy soils. Once the idle and vacant rural houses or cases where one household owns two or more houses according to local conditions are registered, the actual potential of existing construction land could be estimated. Then, the local governments could set down and implement rational land use plans according to the general land use planning and local developing strategy, in order to enhance the intensity of land use and save soil resources for further needs (Long et al. 2007). Compact development model, putting together the dispersed rural housing to establish new residential areas and new industrial areas with unified planning and infrastructure, can help to reduce the consumption of paddy soil during the ex-urbanization process.

Given the environmental problems associated with paddy soil loss, specific management system targeting at soil protection should be established in China. Specifically, general agreement about the principle of soil protection, the manner in which national rules and regulations are to be defined, and the spatial scale based on which paddy soil loss is monitored and managed, should be taken seriously. A watershed is considered an appropriate spatial unit for sustainable soil management in this investigation (Van-Camp et al. 2004; Bouma and Droogers 2007). A Thematic Strategy for Soil Protection, providing effective operational references for watershed unit in a given region, should be proposed as quickly as possible, using available soil expertise and advanced techniques. Otherwise, severe environmental consequences may occur in this ex-urbanizing watershed with the depletion of its limited paddy soils. The study is useful for providing detailed spatial information for local planners to tackle paddy soil loss problems.

Conclusions

This paper reported a case study of a critical regional environmental issue for long developed human ecological systems. Rural settlement expansion and paddy soil loss of Tiaoxi watershed during the market transition was identified and featured. The results of this study lead us to the conclusion that rapid social-economic development is the causative factor of rural settlement expansion. The spatial association between build-ups and paddy soil further facilitates paddy soil loss. This conclusion permits to ascertain that scientific land use planning and efficient measures such as register, compact development, and soil-oriented management system have to be proposed. Though the data used in this paper covers a relatively small watershed and a limited longitudinal dimension, the knowledge gained through the case study gives a new vision on ex-urbanization in rural China. We also suggest that analyzing paddy soil loss in response to ex-urbanization in a watershed setting can provide important references for environmental managers. The approach to comprehensive application of remote sensing, spatial analysis, landscape metrics and other indices can help develop regional models of paddy soil protection under human influences.

Acknowledgments We thank Editor-in-Chief Wolfgang Cramer, Editor Jintao Xu and two reviewers for their constructive comments and suggestions that greatly improved this paper. This work was in part supported by the National Key Project Grant (No.2008ZX07101-006-01), National Natural Science Foundation (No. 41001202) and Emerging Talent Project of Zhejiang Province (No. 2010R401140).

References

Amundson R, Guo Y, Gong P (2003) Soil diversity and land use in the United States. Ecosystems 6:470–482

Banko G, Wrbka T, Schmitzberger I, Zethner G (2003) Landscape types as the optimal spatial domain for developing landscape indicators. Organization for Economic Co-operation and Development (OECD), Paris

Bański J, Wesołowska M (2009) Transformations in housing construction in rural areas of Poland's Lublin region—influence on the spatial settlement structure and landscape aesthetics. Landsc Urban Plan 94:116–126

Basu P, Chakraborty J (2008) The other side of sprawl: a county-level analysis of farm loss in Florida. Southeast Geogr 48:219–248

Bouma J, Droogers P (2007) Translating soil science into environmental policy: a case study on implementing the EU soil protection strategy in The Netherlands. Environ Sci Policy 10:454–463

Carrión-Flores C, Irwin EG (2004) Determinants of residential land-use conversion and sprawl at the rural-urban fringe. Am J Agr Econ 86:889–904

Chen J (2007) Rapid urbanization in China: a real challenge to soil protection and food security. Catena 69:1–15

Compas E (2007) Measuring exurban change in the American West: a case study in Gallatin County, Montana, 1973–2004. Landsc Urban Plan 82:56–65

Ding S (2003) Land policy reform in China: assessment and prospects. Land Use Policy 20:109–120

Dutt A, Xie Y (1992) Changing face of agricultural development strategies in socialist China. In: Raza M (ed) Development and ecology: essays in honor of professor Mohammad Shafi. Rawat Publications, New Delhi, pp 121–138

Dwyer JF, Childs GM (2004) Movement of people across the landscape: a blurring of distinctions between areas, interests, and issues affecting natural resource management. Landsc Urban Plan 69:153–164

European Environment Agency (2006) Urban sprawl in Europe. The ignored challenge. European Environment Agency, København, EU

Ewing RH (1994) Characteristics, causes, and effects of sprawl: a literature review. Environ Urban Stud 21:1–15

Gale F (2002) China's food and agriculture: issues for the 21st century. Agriculture Information Bulletin No. 775. Market and Trade Economics Division, Economic Research Service, US Department of Agriculture, Washington, DC

García Rodríguez P, Pérez González ME (2007) Changes in soil sealing in Guadalajara (Spain): cartography with Landsat images. Sci Tot Environ 378:209–213

Gonzalez-Abraham CE, Radeloff VC, Hammer RB, Hawbaker TG, Stewart SI, Clayton MK (2007) Building patterns and landscape fragmentation in northern Wisconsin, USA. Landsc Ecol 22:217–230

Gude PH, Hansen AJ, Rasker R, Maxwell B (2006) Rates and drivers of rural residential development in the Greater Yellowstone. Landsc Urban Plan 77:131–151

Herold M, Goldstein NC, Clarke KC (2003) The spatiotemporal form of urban growth: measurement, analysis and modeling. Remote Sens Environ 86:286–302

Johnson J, Maxwell B (2001) The role of the conservation reserve program in controlling rural residential development. J Rural Stud 17:323–332

Kuemmerle T, Müller D, Griffiths P, Rusu M (2009) Land use change in Southern Romania after the collapse of socialism. Reg Environ Change 9:1–12

Li X, Yeh AR (2004) Analyzing spatial restructuring of land use patterns in a fast growing region using remote sensing and GIS. Landsc Urban Plan 69:335–354

Lin CS, Ho PS (2003) China's land resources and land-use change: insights from the 1996 land survey. Land Use Policy 20:87–107

Long H, Heilig GK, Li X, Zhang M (2007) Socio-economic development and land use change: analysis of rural housing land transition in the Transect of the Yangtse River, China. Land Use Policy 24:141–153

Long H, Liu Y, Wu X, Dong G (2009) Spatio-temporal dynamic patterns of farmland and rural settlements in Su-Xi-Chang region: implications for building a new countryside in coastal China. Land Use Policy 26:322–333

MacDonald D, Crabtree JR, Wiesinger G, Dax T, Stamou N, Fleury P, Lazpita JG, Gibon A (2001) Agricultural abandonment in mountain areas of Europe: environmental consequences and policy response. J Environ Manage 59:47–69

Mann S (2009) Institutional causes of urban and rural sprawl in Switzerland. Land Use Policy 26:919–924

McGarigal K, Cushman SA, Neel MC, Ene E (2002) FRAGSTATS: spatial pattern analysis program for categorical maps, computer software program produced by the authors at the University of Massachusetts, Amherst. Available at: http://www.umass.edu/landeco/research/fragstats/fragstats.html

Müller D, Sikor T (2006) Effects of postsocialist reforms on land cover and land use in South-Eastern Albania. Appl Geogr 26:175–191

Napton DE, Auch RF, Headle R, Taylor JL (2010) Land changes and their driving forces in the Southeastern United States. Reg Environ Change 10:37–53

Ogden J, Deng Y, Horrocks M, Nichol S, Anderson S (2006) Sequential impacts of Polynesian and European settlement on vegetation and environmental processes recorded in sediments at Whangapoua Estuary, Great Barrier Island, New Zealand. Reg Environ Change 6:25–40

Olarieta JR, Rodríguez-Valle FL, Tello E (2008) Preserving and destroying soils, transforming landscapes: soils and land-use changes in the Vallès County (Catalunya, Spain) 1853–2004. Land Use Policy 25:474–484

Pan X, Zhao Q (2007) Measurement of urbanization process and the paddy soil loss in Yixing city, China between 1949 and 2000. Catena 69:65–73

Powell R, Roberts D, Dennison P, Hess L (2007) Sub-pixel mapping of urban land cover using multiple endmember spectral mixture analysis: Manaus, Brazil. Remote Sens Environ 106:253–267

Radeloff VC, Hammer RB, Stewart SI, Fried JS, Holcomb SS, McKeefry JF (2005) The wildland urban interface in the United States. Ecol Appl 15:799–805

Scalenghe R, Marsan FA (2009) The anthropogenic sealing of soils in urban areas. Landsc Urban Plan 90:1–10

Schaldach R, Alcamo J (2007) Simulating the effects of urbanization, afforestation and cropland abandonment on a regional carbon balance: a case study for Central Germany. Reg Environ Change 7:137–148

Shoshany M, Goldshleger N (2002) Land-use and population density changes in Israel—1950 to 1990: analysis of regional and local trends. Land Use Policy 19:123–133

Tan M, Li X, Xie H, Lu C (2005) Urban land expansion and arable land loss in China-a case study of Beijing-Tianjin-Hebei region. Land Use Policy 22:187–196

United States Environmental Protection Agency (2000) Principles for the ecological restoration of aquatic resources. EPA841-F-00-003. Office of Water (4501F). United States Environmental Protection Agency, Washington, DC, 4 pp

Van-Camp L, Bujarrabal B, Gentile AR, Jones RJA, Montanarella L, Olazabal C, Selvaradjou SK (2004) Reports of the technical working groups established under the thematic strategy for soil protection. EUR 21319 EN/6. Office for Official Publications of the European Communities, Lxembourg

Wrbka T, Erb K, Schulz NB, Peterseil J, Hahn C, Haberl H (2004) Linking pattern and process in cultural landscapes. An empirical study based on spatially explicit indicators. Land Use Policy 21:289–306

Xie Y, Mei Y, Tian G, Xing X (2005) Socio-economic driving forces of arable land conversion: a case study of Wuxian City, China. Global Environ Change 15:238–252

Yang H (2004) Land conservation campaign in China: integrated management, local participation and food supply option. Geoforum 35:507–518

Yang H, Li X (2000) Cultivated land and food supply in China. Land Use Policy 17:73–88

Zhang X, Chen J, Tan M, Sun Y (2007) Assessing the impact of urban sprawl on soil resources of Nanjing city using satellite images and digital soil databases. Catena 69:16–30