Available online at www.sciencedirect.com
ScienceDirect
ELSEVIER
Catena 69 (2007) 16 – 30
CATENA
www.elsevier.com/locate/catena

Assessing the impact of urban sprawl on soil resources of Nanjing city using satellite images and digital soil databases

Xuelei Zhang *, Jie Chen, Manzhi Tan, Yanci Sun

State Key Laboratory of Soil and Sustainable Agriculture (Institute of Soil Science, Chinese Academy of Sciences), Nanjing 210008, China

Abstract

The Yangtse delta area is one of the most rapidly developing areas in China. There are mega-cities like Shanghai and Nanjing and the surrounding urban areas of different sizes including those along the lower reach of the Yangtse river from Shanghai to Nanjing. In combination with their satellite counties and towns, they form one of the most densely distributed urban areas in China. This is a case study conducted in Nanjing city to evaluate the impact of urban sprawl on soil resources using satellite images and digital soil database maps. The extent of the developed land in the study area and the impact of development on soil resources at a scale of 1:200,000 are estimated. The soil types occupied by the urbanization process are determined by overlaying the soil map on the satellite images (Landsat TM) of the study area at different times (1984, 1995, 2000 and 2003). This study uses a geographic information system (GIS) to combine urban land use maps of different times derived from satellite images with data on soil characteristics contained in soil databases. The results document the rapid expansion of urbanization in Nanjing city, as well as the soil types occupied by the urbanization process, and their quality. The urban area has increased 43,544 ha, 2 times more than in 1984. The urban area expanded at an annual rate of 6.9%. Thirty of the total 32 soil types (soil families) within the city were utilized by the urbanization process among which *Loamy typic-Fe-leachic-stagnic anthrosol* ranked the highest (12,007 ha). The loss of surface land to urban use in Nanjing city has ranged from 4.8% in 1984 to 11.8% in 2003. Soils of the first class (5349 ha) and second class (20,781 ha) were 61.5% of the total occupied soil area. Results for Nanjing show that residential, commercial, and industrial development, known as "urban sprawl," appear to follow soil resources, with the better agricultural soils being the most affected. Several soil types appear to be on the verge of being replaced by urban sprawl. Growing urbanization may threaten food security, soil diversity and sustainability. The extent and geographic distribution of soil quality and the pedodiversity for land presently under urbanization in the study area may be determined through modeling.

Keywords: Urban sprawl; Yangtse delta; Nanjing city; Satellite images; Soil databases; Soil quality

1. Introduction

The conversion of natural systems to agricultural production has been the primary basis for the successful growth of human populations for the last 9000 years (Kates et al., 1990). The conflict between urban and agricultural land use, however, is now becoming a subject of controversy. The transformation of productive agricultural land to urban use under burgeoning populations has become a contentious element in debates over sustainable development and food security (Ehrlich, 1989; Daily and Ehrlich, 1992; Ehrlich and Ehrlich, 1992). As more land is converted to urban uses, the question arises as to whether this trend represents a systematic reduction in our ability to produce food by placing our infrastructure on the most productive soil resources. A disturbing consequence of this urbanization process is a growing dependence on ever greater yields per unit area on soils that remain or a reliance on more distant soil resources and agricultural production. Central to much of the debate is the difficulty in acquiring accurate measurements of the area of urban land use, monitoring changes in urban land use, and assessing the impact of these changes on agricultural land area or production in a way that

* Corresponding author. Tel.: +86 25 86881275; fax: +86 25 86881000.
E-mail address: xlzhang@issas.ac.cn (X. Zhang).

0341-8162/$ - see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.catena.2006.04.020

can be used in rational, cost-benefit analyses (Parsons, 1977; Meyers and Simon, 1994). Surprisingly, measuring the extent of urbanization using conventional methods has been difficult, even in the United States where modern census procedures are used. In 1977 for example, the U.S. Department of Agriculture (USDA) announced figures concerning the loss of agricultural land in the United States due to urban sprawl. The figures, which were derived by using census data, sparked a controversy that resulted in two significant revisions between 1977 and 1987 before finally being set at a total area of 116.4 million hectares of land converted to urban use (Meyers and Simon, 1994). Thus, census data are a valuable resource but their interpretation is controversial, i.e., they are not a substitute for direct observations of the land surface.

Urban areas represent environments that are physically distinguishable from the underlying/surrounding natural environment. The use of satellite data is an obvious choice for detecting and monitoring global change and for classifying land use transformation. Satellite sensors such as the Advanced Very High Resolution Radiometer (AVHRR), the Landsat Thematic Mapper (TM), and the French SPOT system have been used successfully for measuring deforestation, biomass burning, and other land cover changes including the expansion and contraction of deserts (Tucker et al., 1991; Skole and Tucker, 1993; Sellers et al., 1995). However, remote sensing techniques are just beginning to be used to monitor the conversion of agricultural land to infrastructure (i.e., the process of urbanization). Land conversion to urban, suburban, or commercial and industrial use is very disruptive to vegetation. "City lights" by the nighttime satellite images of the Earth overlaid on soil maps examined whether or not the most productive soils were being lost to urban sprawl. (Imhoff et al., 1997a,b, 2003). The more limiting factors a soil has, the more difficult or expensive it is to farm; consequently a soil fertility classification system based on physical factors that limit agricultural production can be used to rank soils. Results for the United States show that residential, commercial, and industrial development, known as "urban sprawl," appear to use the better agricultural soils, and some unique soil types appear to be on the verge of being entirely covered by urban sprawl.

Urbanization is a global process and China is no exception. Urbanization is considered to be one of the most important human activities in the recent history of China (Shi et al., 2000). In the late 1980s China began a period of rapid urbanization while undergoing rapid economic expansion. The urban population of China at mid-century was less than 10% (1949), but now it has increased to about 40%. The Yangtse delta region is one of the fastest urbanizing areas in the country with it's current urban population of about 45% which is about the same as the world average of 47% (Li, 1996; Ge et al., 2000; Tian et al., 2003). Rapid urbanization has caused many social and environmental problems including a clear loss of natural soils.

This study examines the quantitative and qualitative changes in the past 20 years related to urban sprawl and its impact on soils in the Yangtse delta region. Some interesting information is now available about which soil types have been occupied, the quality of these soils, and some possible long-term impacts including food security and soil diversity conservation.

2. Study site and method

2.1. Study site

Nanjing, located in the Yangtse delta (Jiangsu province, east China, Fig. 1), is known as a famous historic city. The fossils of Homo sapiens, those of ape-men's skull caps discovered at Tangshan in the east suburbs of Nanjing

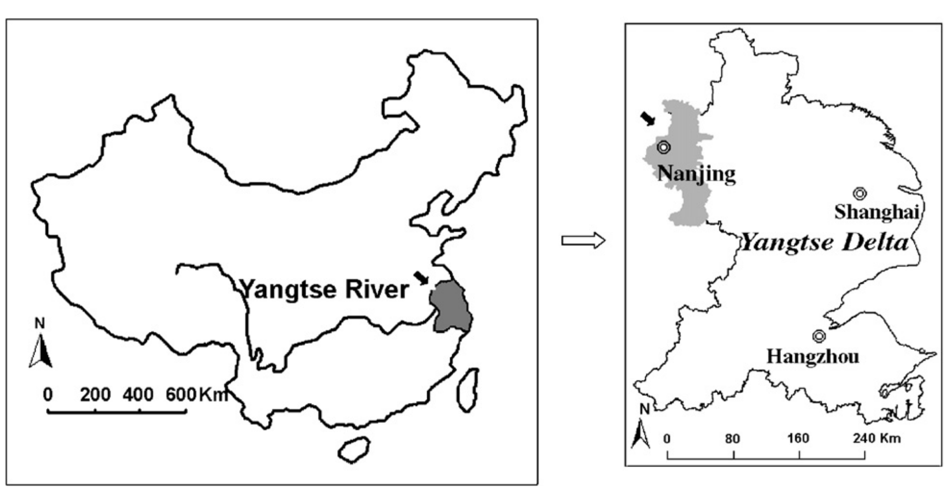

Fig. 1. Location of the study area.

indicate that Nanjing was home to a large community of human beings in the late period of the mid-Pleistocene epoch 350,000 years ago. Nanjing was made capital of the Three Kingdoms Period Eastern (A.D. 229), Jin (317–420) and of Song, Qi, Liang and Chen in the Southern Dynasties Period (420–589), thereby earning for the city its fame as the "ancient capital of six dynasties" (http://www.nanjing.gov.cn/cps/site/nanjing/052004/english/index2-mb_a2004052423904.htm). Nanjing in those periods boasted a brilliant culture, a thriving commerce, and a large population.

Nanjing has experienced extensive development in the past 2–3 decades with 9 new economic development zones established around the city. Currently it is growing faster than at any time in its history. A lot of foreign investment and joint ventures are coming to the city and this encourages

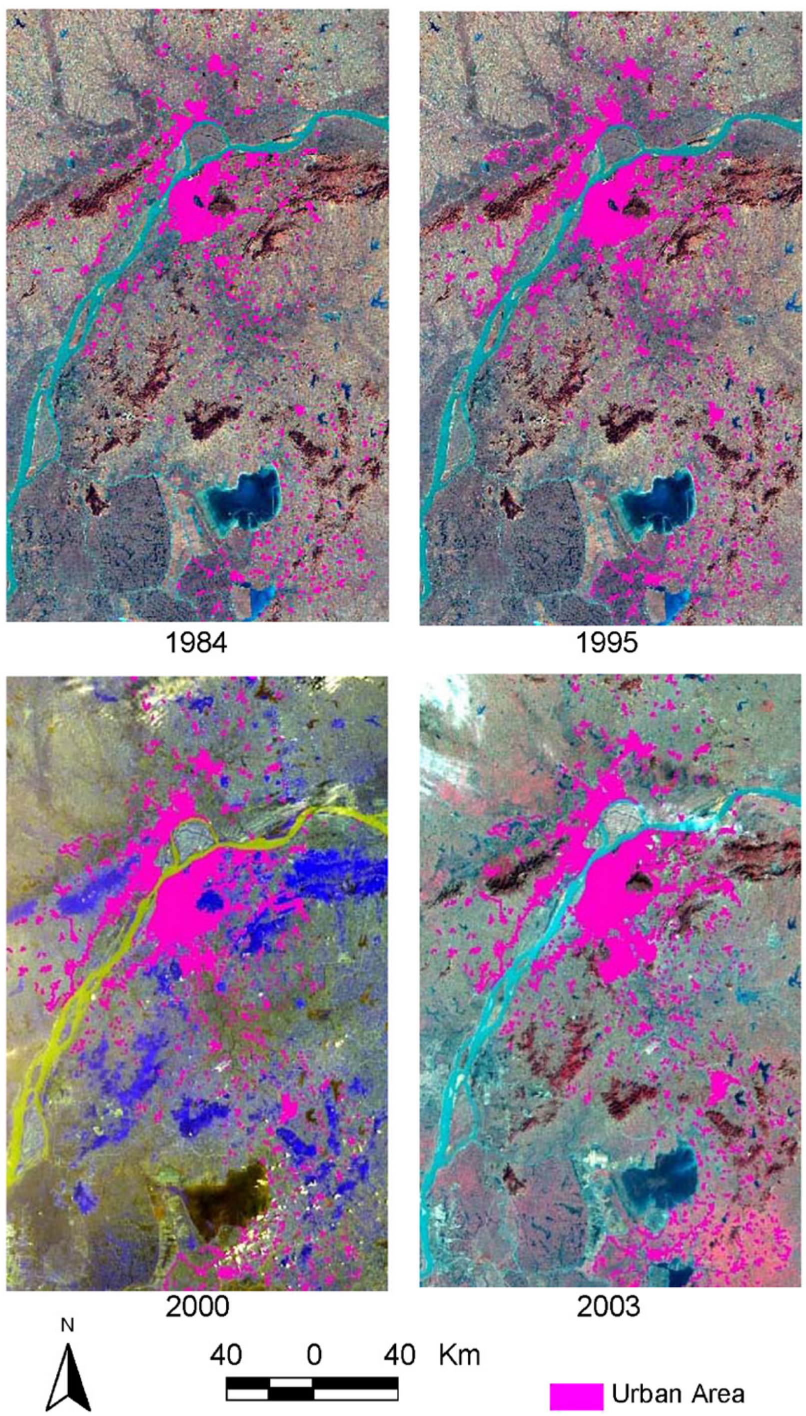

Fig. 2. Patterns of urban growth from TM satellite images.

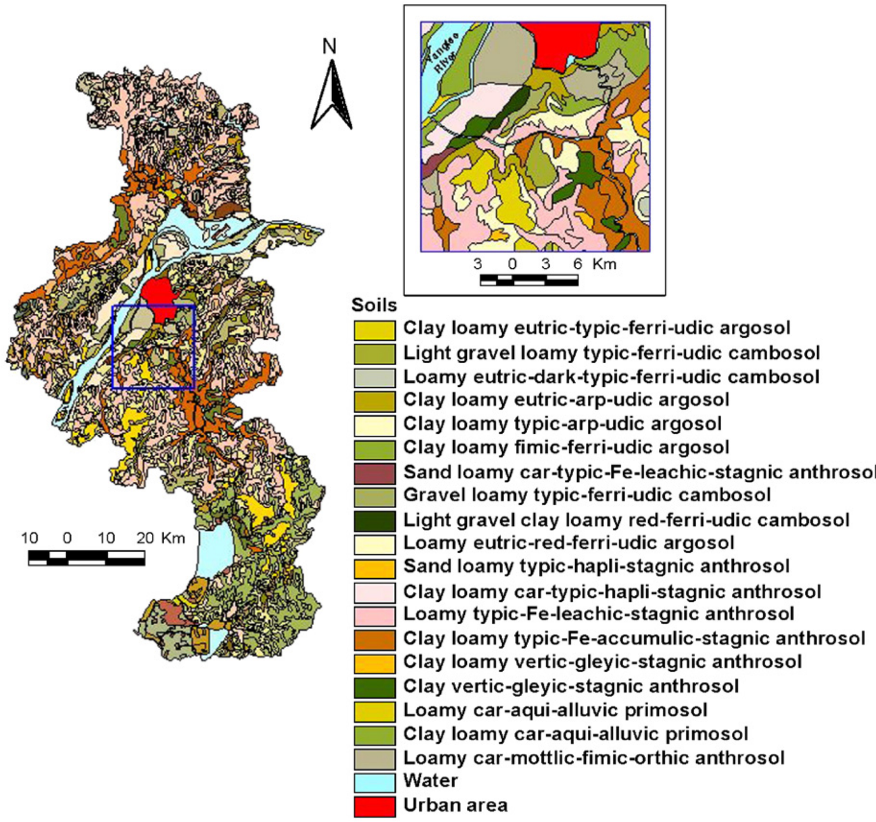

Fig. 3. Digital soil database map.

occupation of more and more soils used for agriculture. Nanjing city is becoming more international, however, environmental problems have appeared including an increasing loss of valuable land with good quality agricultural soils. More attention is now being given by both the government and the public.

Table 1
Soils in the studied area *

Soil order		Suborder					
Name	Soil process	Name	Description	Area (km^2) 1984	Area (km^2) 2003	Lost (%)	Soil units (total)
Anthrosols	Properties induced in soil subsequent to long-term management of soil for agricultural or other uses	Stagnic	Anthrosols that have an anthrostagnic moisture regime, and that have an anthrostagnic epipendon and a hydragric horizon	3504	3267	6.76	9, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25 (12)
		Orthic	Other anthrosols	49	19	61.2	29 (1)
Argosols	Illuvial accumulation of clays in soils with medium active clays	Udic	Argosols that have an udic soil moisture regime	1350	1231	8.81	1, 5, 6, 7, 8, 14 (6)
Cambosols	Low grade soil development, with formation of horizon of alteration or weak expression of other diagnostic horizons	Aqui	Cambosols that have an aquic soil moisture regime, and that have redoxic features at least in one soil horizon 10 cm or more thick within 50 cm of the mineral soil surface	48	45	6.25	28, 31 (2)
		Udic	Cambosols that have an udic soil moisture regime	4790	4517	5.70	2, 3, 4, 10, 12, 13 (6)
Gleyosols	Development of redoximorphic conditions under a permanent fluctuating water table	Stagnic	Gleyosols that have a stagnic moisture regime	87	86	1.15	30, 32 (2)
Primosols	Recent soils with no diagnostic horizons or only an ochric epipedon	Alluvic	Primosols that have lithologic character of alluvial deposits	192	185	3.65	26, 27 (2)
		Orthic	Other primosols	23	23		11 (1)

* Cooperative research group, 2001.

Table 2
The extended urban area of Nanjing city from 1984 to 2003 (ha)

Time	1984–1995	1995–2000	2000–2003
Starting area	31634.61	48410.93	60764.49
Extended area	16776.32	12353.56	14414.48
Increased area per year	1525.12	2470.71	4804.83
Yearly increase rate (%)	4.82	5.10	7.91

2.2. Data

The data used in the study is a set of Landsat satellite TM images (resolution at 30 m, Fig. 2) overlaid with the digital soil database map (at scale 1:200,000, Fig. 3) in which 19 soil mapping unit delineations forming 869 polygons (Table 1), (excluding 16 non-soil polygons) were linked with their attribute databases of natural conditions and different soil properties to examine what soil types and their quality were being lost to urban sprawl.

2.3. Method

The methodology consists of analyzing data with a geographic information system (GIS) to combine urban land use maps of different times derived from satellite images with data on soil characteristics contained in the established soil databases. The integration of satellite remote sensing and GIS technology proved to be an efficient method for mapping and analysis of urban land use change (Zhou et al., 2001; Zhao et al., 2002; Chen et al., 2003). Some ideas from SOTER methodology (van Engelen and Wen, 1995) were borrowed to build a database for spatial analysis and evaluation. In this database, two types of data can be distinguished: 1) geometric data from soil map and urban sprawl by satellite image interpretation, i.e. the location and extent of an object represented by a point, line or surface, and topology (shapes, neighbours and hierarchy of delineations), and 2) attribute data, i.e. characteristics of the object. The two types of data are present in the established database consisting of a geometric component, which indicates the location and topology of the mapping units, and of an attribute part that describes the non-spatial mapping unit characteristics. The geometry is stored in that part of the database that is handled by GIS software, while the attribute data is stored in a separate set of attribute files in tables of natural conditions and different soil properties manipulated by a Relational Database Management System (RDBMS). A unique label attached to both the geometric and attribute database connects those two types of information for each mapping unit. The overall system (GIS plus RDBMS) stores and handles both the geometric and attribute database.

This study required the combined knowledge from different fields of soil science, geography, remote sensing

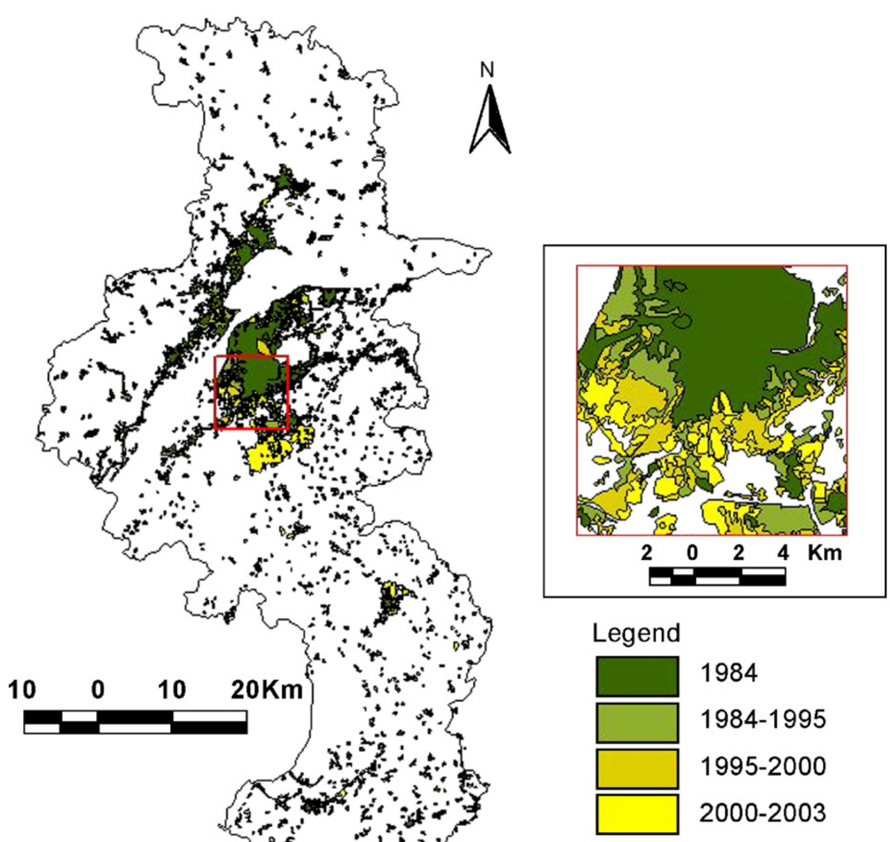

Fig. 4. The extended urban areas during the three periods 1984–1995, 1995–2000 and 2000–2003 in Nanjing city.

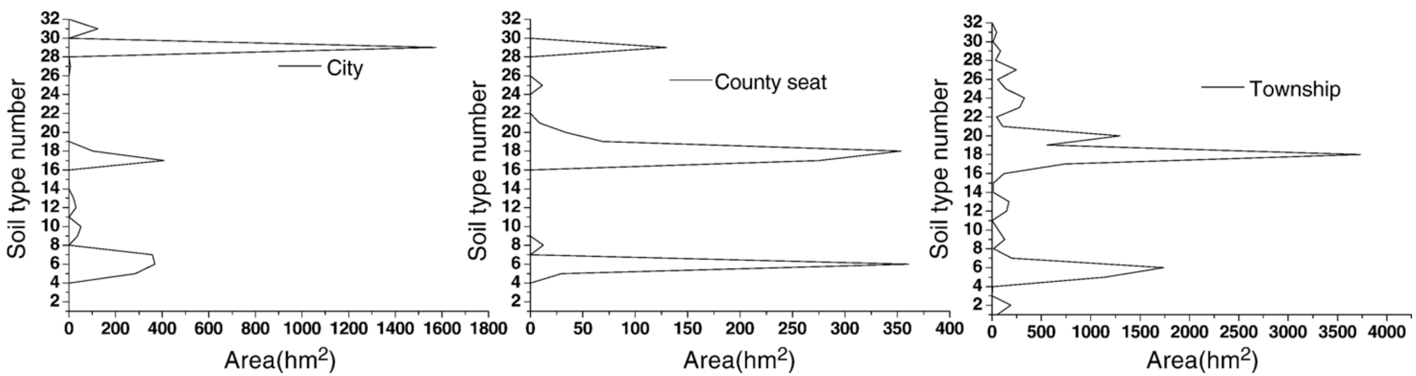

Fig. 5. Areas of soil types urbanized by different level administrative regions from 1984 to 1995.

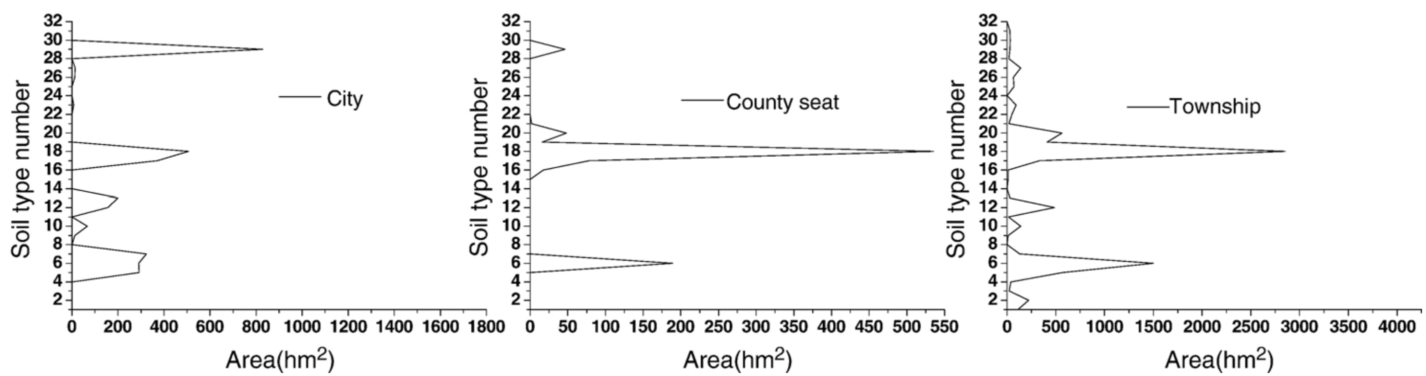

Fig. 6. Areas of soil types urbanized by different level administrative regions from 1995 to 2000.

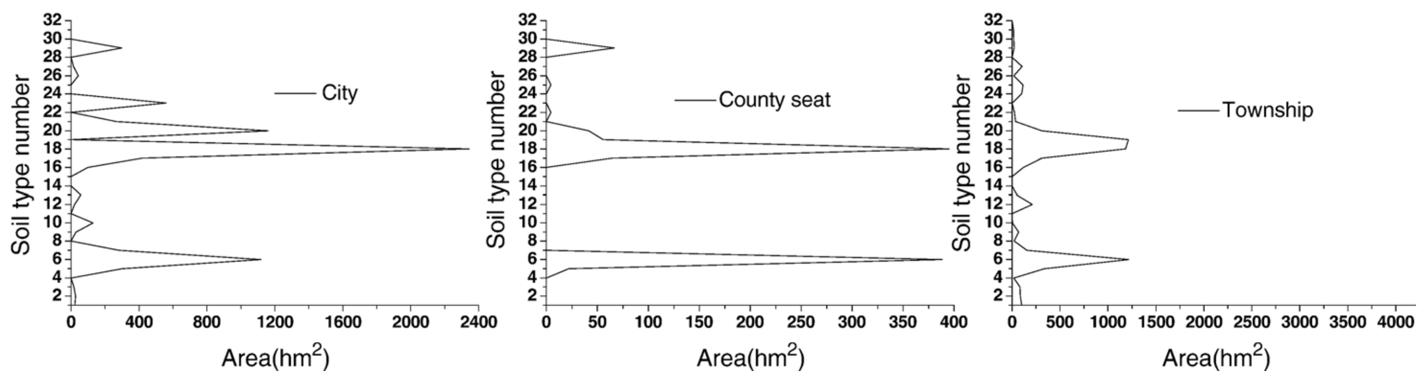

Fig. 7. Areas of soil types urbanized by different level administrative regions from 2000 to 2003.

and geographic information system techniques. Software tools that were used in the study are ERDAS IMAGINE 8.5 for satellite image preparation; ArcGIS 8.1 for satellite image interpretation and overlay; and Arcview 3.2 for spatial analysis and evaluation (Shi and Zhou, 2001).

3. Results and discussion

3.1. Urban sprawl in the past 20 years

The urban sprawl from 1984 to 2003 was obtained by interpretation of Landsat TM satellite images from different dates (1984, 1995, 2000 and 2003). The images show Nanjing undergoing rapid urbanization in the past 20 years. Table 2 shows the extended urban area of Nanjing city from 1984 to 2003. The city urban area increased 16,776 ha from its starting area 31,634 ha in 1984 to 48,410 ha in 1995 with a 1525 ha yearly increase (4.8%). During the next two periods, 1995–2000 and 2000–2003, all values were clearly higher than the previous annual increase: 2470 ha y^{-1} or 5.1% during 1995–2000 and an annual increase of 4804 ha y^{-1} or 7.9% during 2000–2003.

In the past 20 years, there has been an absolute urban area increase of 43,544 ha in Nanjing city, which is now 2 times larger than before. More urban areas including the city, attached county seat and township areas expanded each year at an annual rate of 6.9%. To further examine trends in urbanization of the city, Fig. 4 shows that the city is more urbanized southward than other directions since the city economy was naturally stopped in its growth by the Yangtse river to the northwest. It is considered to be the geographic line dividing north and south China and the mountainous area east of the city. People in this area traditionally prefered to live or do business on the south side of the Yangtse river that played an important role in shaping the city structure in its recent history. The newly established Jiangning economic development zone (Jiangning District) south of the original Nanjing city is another reason for the current city urban/suburban growth pattern.

Satellite-based calculation shows that 11.3% of the total land area of Nanjing city is now in urban use (2003) compared with only 4.8% in 1984. It is clear that the best soils are being developed first even though the percentage of the urbanized area relative to the city total land surface is not very high. There is evidence, however, that some preservation of the very best soils has been taking place.

3.2. Soil types and areas occupied by the extended urbanization

Figs. 5–7 show which soil types (Cooperative research group, 2001) have been occupied in the past 20 years through an overlay of the above mentioned urban sprawl from the TM satellite images on digital soil database maps. Thirty of the 32 soil types were utilized by the urban growth during the period 1984–1995 with *Loamy typic-Fe-leachic-stagnic anthrosols* the largest one occupied (4190 ha) while *Loamy cho-typic-ferri-udic cambosols* and *Loamy mollic-car-udic-orthic primosols* were not occupied. Thirty soil types were utilized during the period 1995–2000 with *Loamy typic-Fe-leachic-stagnic anthrosols* again the largest one (3893 ha) while *Loamy eutric-red-ferri-udic argosols* and *Clay loamy car-hapli-stagnic gleyosols* were not occupied. Twenty-eight soil types were utilized during the period 2000–2003 with *Loamy typic-Fe-leachic-stagnic anthrosols* was the largest one (3922 ha) while *Loamy mollic-car-udic-orthic primosols*, *Loamy eutric-red-ferri-udic argososl*, *Clay loamy typic-dark-aqui-cambosols* and *Clay loamy car-hapli-stagnic gleyosols* were not occupied.

The pressure of urban sprawl is not equally distributed over all of the soil types: several soil types have been strongly affected. The *Loamy typic-Fe-leachic-stagnic anthrosols*, evaluated as second class soils (Table 5), have the largest area (12,007 ha) occupied in the past 20 years by the urbanizing process.

3.3. Assessing quality of soils being occupied

Limitation factors for soil quality include climate, topography, soil properties and management measures. Without considering climate conditions like precipitation or atmospheric radiation, management measures like technique or input conditions, the natural soil quality is normally limited by factors

Table 3
Assessing factors and their weights

Factors	0		1		2		3		4		Weights
	Criteria	Rating	Criteria	Rating	Criteria	Rating	Criteria	Rating	Criteria	Rating	
Surface soil depth (cm)	> 17	5	15–17	4	13–15	3	10–13	2	<10	1	2.94
pH	6–7	5	7–7.5 5.5–6.0	4	7.5–8 5.5–5.0	3	8–8.5 4.5–5.0	2	>8.5 <4.5	1	2.72
Bulk density (g/cm^3)	1–1.1	5	1.1–1.2	4	1.2–1.3	3	>1.3	2	<1	1	6.31
Gradient (%)	0–2	5	2–4	4	4–6	3	6–8	2	>8	1	2.63
Organic matter (g/kg)	2.5–3.5	5	2.5–2	4	1.5–2	3	1–1.5	2	<1 >3.5	1	31.07
Total N (g/kg)	>0.2	5	0.15–0.2	4	0.125–0.15	3	0.1–0.125	2	<0.1	1	4.72
Total K (g/kg)	>2.5	5	2–2.5	4	1.5–2	3	1.0–1.5	2	<1	1	23.84
Depth of underground water (cm)	>100	5	80–100	4	60–80	3	40–60	2	<40	1	4.06
CEC (cmol/kg)	>25	5	20–25	4	15–20	3	10–15	2	<10	1	21.71

associated with topographic conditions and soil properties in this region (Dai, 1995; Shi and Zhou, 2001). Nine limitation factors selected by a SPSS tool for evaluating soil quality include surface soil depth, pH, bulk density, gradient, organic matter (OM), total nitrogen (TN), total potassium (TK), depth of underground water, and cation exchange capacity (CEC).

A multi-regression method was used to define how much these factors influence soil quality. Y is set as a food yield, and a multiple-regression function is developed. The final result was the following:

$$Y = 5536.637 + 1.821X_1 + 1.686X_2 + 13.453X_3 - 2.928X_4 + 19.25X_5 + 14.77X_6 + 3.909X_7 - 2.514X_8 + 1.627X_9.$$

Here, $X_{1..9}$ represent surface soil depth, pH, CEC, TN, OM, TK, bulk density, depth of underground water, and gradient, respectively.

How much a factor X_i affects the soil quality depends on the absolute value of Ai. The bigger the Ai, the more the factor affects the soil quality. So the percent of each Ai refers to the weight of the factor (Table 3), that is:

$$W_i = \mathrm{Ai}/\sum \mathrm{Ai} \times 100$$

where W_i is the weight of the factor X_i and Ai is the calculated effect of X_i on the yield Y.

Based on our analysis (Tables 4 and 5, Figs. 8–11), 61.5% of extended soil areas of cities, county seats and townships are first class (5349 ha) or second class (20,780 ha) soils. Fourth class soils (3676 ha) and fifth class (9421 ha) soils are 30.8% of the expanded urban areas. While preservation of some of the best soils does take place, it often occurs at the expense of the next best soils located nearby. It is clear that the better soils are always being occupied regardless of the level of administration, indicating that the best soils are commonly the first victims of urban sprawl. It is not unusual that the best soils should fall to urban development. Most major cities of the world are located on or near river flood plains or deltas, which are also highly productive farming areas. Unfortunately, poorly rated soils are often unsuitable not only for agriculture but also for construction because of steep slopes or other limiting factors. The economics of urbanization, however, make it easier to overcome some soil-related problems (Imhoff et al., 1997a,b, 2003).

Meanwhile, it is good to see that the first class soils occupied in the past 20 years have decreased from 2789 ha (1984–1995) to 1222 ha (2000–2003) while the fifth class soils increased from 3120 ha (1984–1995) to 3214 ha (2000–2003). This may be a result of the stricter cropland protection policy carried out by the local people supervised by the government.

The soils occupied by city level administrative regions increased from 3364 ha (1984–1995) to 7201 ha (2000–2003) while the soils occupied by township level administrative regions decreased from 11,699 ha (1984–1995) to 5931 ha (2000–2003), indicating that the urbanization process of Nanjing is characterized by growth of the main city area.

Table 4
Quality of soils urbanized in the three periods by different administrative regions (ha)

Class	City			County seat				Township				Total				Total
Year	1984–1995	1995–2000	2000–2003	Total	1984–1995	1995–2000	2000–2003	Total	1984–1955	1995–2000	2000–2003	Total	1984–1995	1995–2000	2000–2003	
1	1934.07	1112.68	844.55	3891.3	138.54	47.99	66.46	252.99	716.10	177.23	311.41	1204.74	2788.71	1337.9	1222.42	5349.03
2	553.48	908.75	4526.31	5988.54	674.09	662.30	510.79	1847.18	6652.45	4163.90	2128.65	12,945.00	7880.02	5734.95	7165.75	20,780.72
3	0.00	12.75	164.25	177	69.23	33.56	55.58	158.37	806.08	643.65	1467.21	2916.94	875.31	689.96	1687.04	3252.31
4	302.98	490.94	372.54	1166.46	42.01	0.07	21.79	63.87	1339.08	615.82	491.70	2446.60	1684.07	1106.83	886.03	3676.93
5	573.83	511.18	1293.02	2378.03	360.85	189.10	388.74	938.69	2184.91	2388.08	1532.05	6105.04	3119.59	3088.36	3213.81	9421.76
Total	3364.36	3036.3	7200.67	13,601.33	1284.72	933.02	1043.36	3261.1	11,698.62	7988.68	5931.02	25,618.32	16,347.7	11,958	14,175.05	42,480.75

Table 5
Soils by different quality class available in extended area

Quality class	Soil classification	No	Area (ha)			Lost (%)
			Original	Converted	Remains	
1	*Clay car-vertic-gleyic-stagnic anthrosol*	24	9855	428	9427	4.3
	Loamy car-mottlic-fimic-orthic anthrosol	29	4936	3080	1856	62.4*
	Clay loamy vertic-gleyic-stagnic anthrosol	21	4054	435	3619	10.7
	Clay loamy fimic-ferri-udic argosol	7	3490	1446	2044	41.4*
2	*Loamy typic-Fe-leachic-stagnic anthrosol*	18	175,152	12,007	163,145	6.9
	Clay loamy typic-Fe-accumulic-stagnic anthrosol	20	52,084	3455	48,629	6.6
	Clay loamy car-typic-hapli-stagnic anthrosol	17	22,292	2996	19,296	13.4
	Clay vertic-gleyic-stagnic anthrosol	23	12,908	938	11,970	7.3
	Clay loamy car-aqui-alluvic primosol	27	12,824	521	12,303	4.1
	Clay typic-hapli-stagnic gleyosol	30	7795	59	7736	0.8
	Clay typic-gleyic-stagnic anthrosol	25	5203	341	4862	6.6
	Clay loamy Fe-leachic-gleyic-stagnic anthrosol	22	5062	127	4935	2.5
	Sand loamy car-typic-Fe-leachic-stagnic anthrosol	9	3891	284	3607	7.3
	Clay loamy typic-dark-aqui-cambosol	28	2852	52	2800	1.8
3	*Loamy albic-Fe-leachic-stagnic anthrosol*	19	54,961	2322	52,639	4.2
	Clay loamy eutric-typic-ferri-udic argosol	1	25,575	278	25,297	1.1
	Loamy eutric-dark-typic-ferri-udic cambosol	4	6431	64	6367	1.0
	Loamy car-aqui-alluvic primosol	26	6381	199	6182	3.1
	Sand loamy typic-hapli-stagnic anthrosol	16	3088	366	2722	11.9
	Light gravel loamy typic-Fe-leachic-stagnic anthrosol	15	1887	25	1862	1.3
4	*Clay loamy eutric-arp-udic argosol*	5	26,458	2970	23,488	11.2
	Light gravel clay loamy red-ferri-udic cambosol	13	3899	522	3377	13.4
	Clay cho-typic-ferri-udic argosol	8	1848	50	1798	2.7
	Loamy cho-typic-ferri-udic cambosol	3	1538	121	1417	7.9
	Loamy eutric-red-ferri-udic argosol	14	852	14	838	1.6
5	*Clay loamy typic-arp-udic argosol*	6	76,770	7169	69,601	9.3
	Light gravel loamy typic-ferri-udic cambosol	2	22,370	520	21,850	2.3
	Clay loamy red-ferri-udic cambosol	12	8616	1047	7569	12.2
	Gravel loamy typic-ferri-udic cambosol	10	5043	456	4587	9.0
	Loamy mollic-car-udic-orthic primosol	11	2331	12	2319	0.5
	Clay typic-hapli-aqui-cambosol	31	1942	216	1726	11.1
	Clay loamy car-hapli-stagnic gleyosol	32	898	1	897	0.1

* Endangered because of rapid loss to urbanization.

3.4. Concern about pedodiversity conservation

Another concern brought out by this study is the potential loss of certain soil types or unique soil units to urbanization. Our results indicate that 2 soil types, *Clay loamy fimic-ferri-udic argosol* and *Loamy car-mottlic-fimic-orthic anthrosol* as classified in the Chinese Soil Taxonomy (Cooperative research group, 2001), may be in danger of disappearing under urban/suburban structures because they have been decreased by 41.4% and 62.4%, respectively in the past 20 years. Seven soils decreased by more than 10%, and 8 others decreased by more than 5% (Table 5, Fig. 12). All of these soil types can be considered endangered since the physical alteration of the soil profile is substantial. The potential loss of entire soil mapping units, with their unique history of formation and biology, gives rise to the issue of the loss of biological diversity inherent in those soils (Imhoff et al., 1997a,b, 2003). Is the loss of “soil diversity” meaningful in a biological or economic sense? The study of soil biodiversity is a relatively new field, yet recent studies indicate that great diversity may exist in soils (Zhang et al., 2003, 2004), with their unique physical structure, environment, and history of formation (Huston, 1993). Land use changes, especially resulting from the rapid urbanization process, have often had a great impact on pedodiversity (Amundson et al., 2003) The loss of soil types may therefore represent loss of whole biological communities unique to that soil type. The conservation of pedodiversity also brings into question the wisdom of converting to agriculture those soils that have not previously been cultivated. Agriculture seriously disrupts the soil by changing its chemistry, structure, and ecological dynamics. Many of the soils that have already undergone agricultural transformation are in locations that (for the most part) limit soil loss to erosion and other adverse impacts. As stable soils become unavailable to agriculture through conversion to urban/suburban infrastructure, soils less suited for cultivation may be used for farming. Farming such marginal soils may increase erosion resulting in the destruction of many soils, right down to the bedrock or parent material (Ehrlich, 1997).

4. Conclusions

In Nanjing city alone during the past 20 years, there has been an urban area increase of 43,544 ha at an annual rate of 6.9%. Thirty of 32 soil types (soil families) within the city

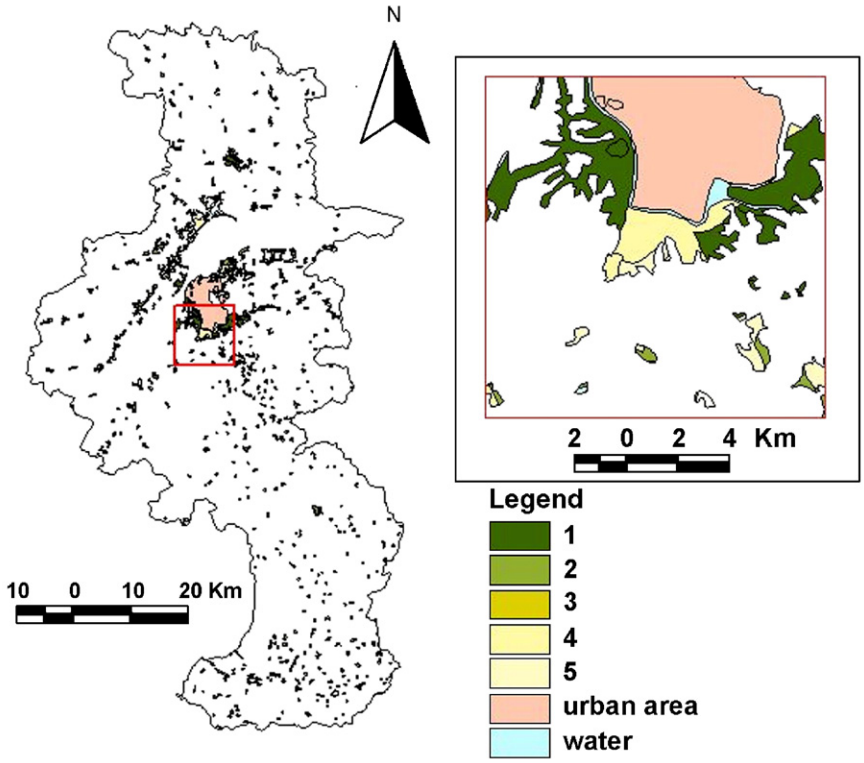

Fig. 8. Quality of soils urbanized by the urban originally in 1984.

were more or less occupied by the urbanization process among which *Loamy typic-Fe-leachic-stagnic anthrosol* ranked the highest (12,007 ha). Areas occupied by the extended city, county seat and township areas consist of first class soils (5349 ha) and second class soils (20780 ha) that total 61.5% of the occupied soil area (42480 ha, excluding

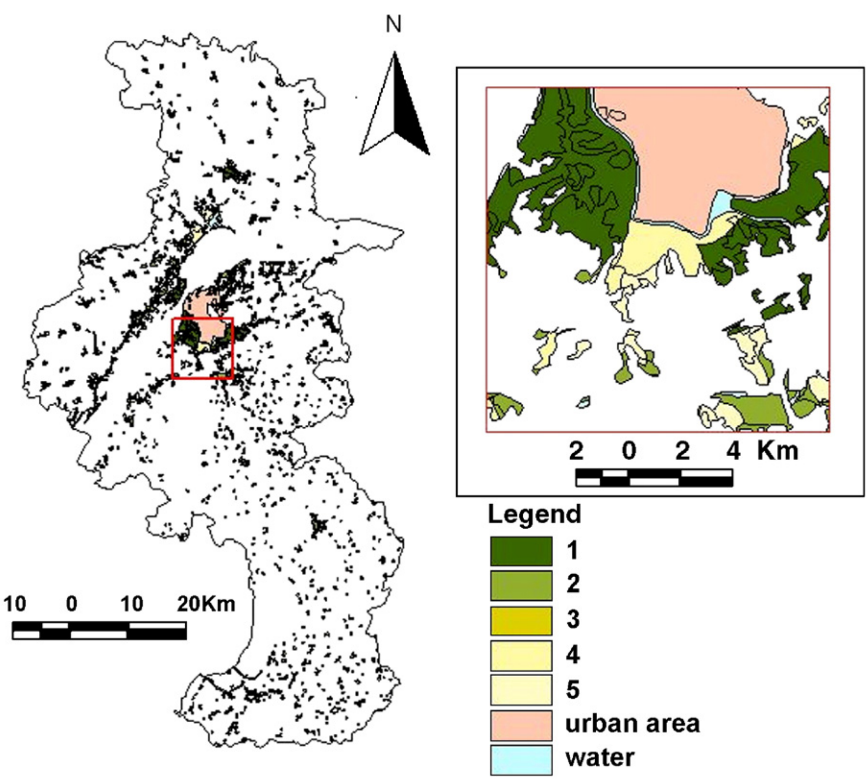

Fig. 9. Quality of soils in extended urban areas during the period of 1984–1995.

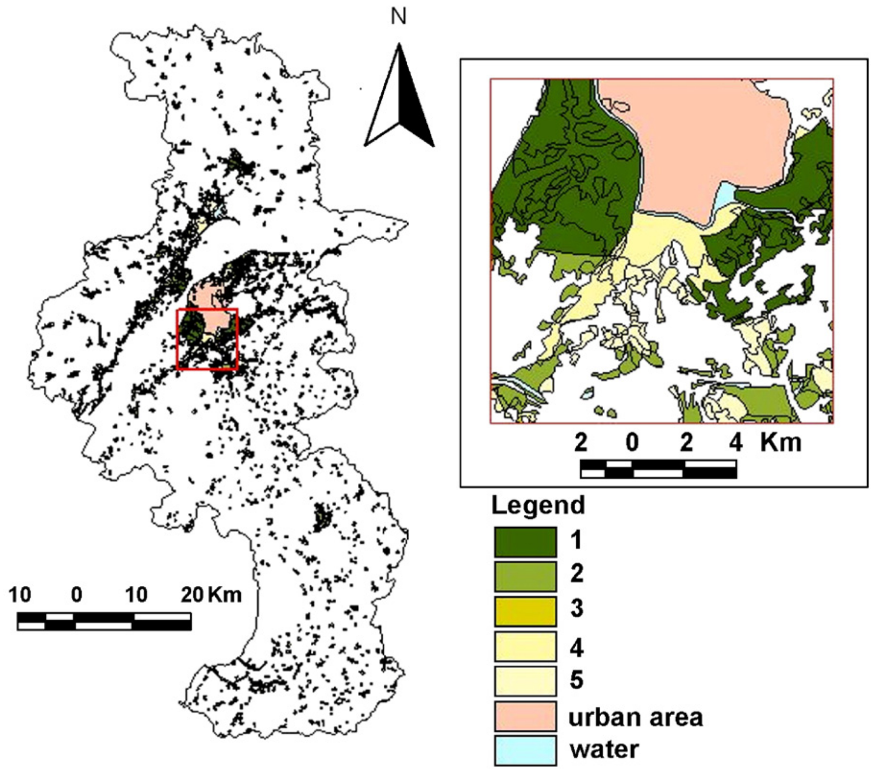

Fig. 10. Quality of soils in extended urban areas during the period of 1995–2000.

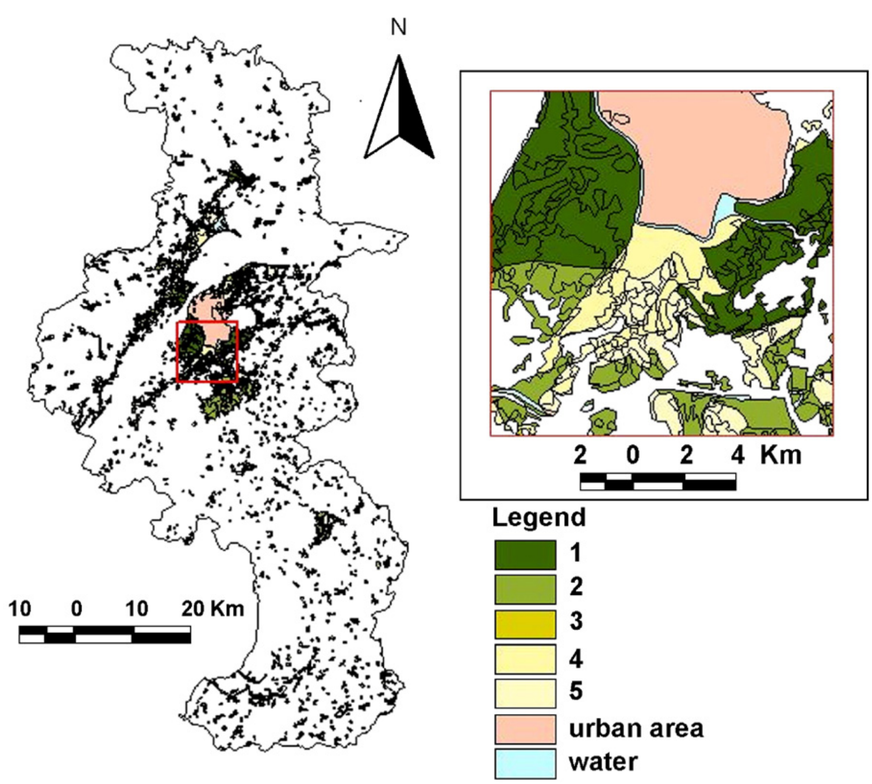

Fig. 11. Quality of soils in extended urban areas during the period of 2000–2003.

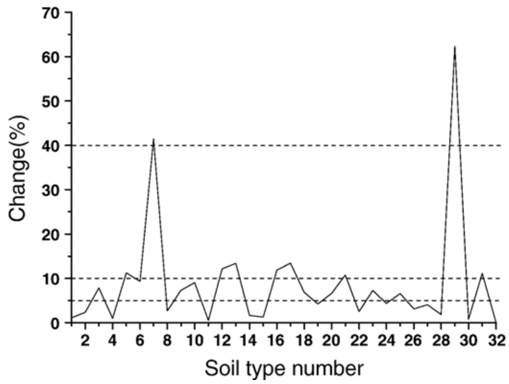

Fig. 12. Percentage change of soil areas from 1984 to 2003.

non-soil area) while the fourth (3676 ha) and fifth class soils (9421 ha) comprised 30.8%. Similar to a study done in the United States (Imhoff et al., 2003), the results of this study show that the extended urban area known as "urban sprawl," appears to be following soil resources, with the better agricultural soils being the most affected.

Rapid expansion of urbanization in the Yangtse delta area is still progressing. There has been an absolute increase of 6124 km^2 of urban area in the whole Yangtse delta (from 4873 km^2 in 1984 to 10,997 km^2 in 2003) in the past 20 years. Urban area expansion of 322 km^2 each year was at an annual rate of 6.6%. Nanjing city has lost from 4.8% in 1984 to 11.3% in 2003 of it surface land to urban use. In the Yangtse delta area, there are other very fast growing cities like Suzhou where it is now 4 times as big as it was previously (Zhang et al., 2005, 2006). In addition, some distinct soil types, with their unique physical structure and history of formation, may be in danger of elimination, likely resulting in a substantial loss of below ground and above ground biodiversity.

It is a pressing situation at the moment in the Yangtse delta area because the rapid urban sprawl has been occupying good quality soils that will never come back to agriculture use again. It is considered prudent to maintain valuable soils to help ease food security and soil diversity conservation in the future.

Acknowledgments

This work was supported by the Chinese Academy of Sciences (CAS Knowledge Innovation Project No. KZCX3-SW-427) and the National Natural Science Foundation of China (NSFC Grant No.40541003, 40235054). We gratefully acknowledge Richard W. Arnold and V.W.P. van Engelen for their comments on the manuscript.

References

Amundson, Ronald, Guo, Y., Gong, P., 2003. Soil Diversity and Land Use in the United States. Ecosystems. Online publication: 30 May http://rizzo.springer-ny.com/onlinefirst/10021/contents/02/0160/paper.

Chen, S.Q., Liu, J.Y., Zhuang, D.F., Xiao, X.M., 2003. Characterization of land cover types in the Xilin River Basin using multi-temporal Landsat images. Journal of Geographical Sciences 13 (2), 130–138.

Cooperative research group, 2001. Chinese Soil Taxonomy. Science Press, Beijing, pp. 1–196.

Dai, X., 1995. Theory and method for land evaluation Beijing. Science Press, pp. 20–58 (in Chinese).

Daily, G.C., Ehrlich, P.R., 1992. Population, sustainability, and Earth's carrying capacity. BioScience 42, 761–771.

Ehrlich, P.R., 1989. The limits to substitution: meta-resource depletion and a new economic-ecological paradigm. Ecological Economics 1, 9–16.

Ehrlich, P.R., 1997. A world of wounds: ecologists and the human dilemma. Ecology Institute, Ohlendorf/Luhe, Germany. 210 pp.

Ehrlich, P.R., Ehrlich, A.H., 1992. The value of biodiversity. Ambio 21 (3), 219–226.

Ge, Q.S., Zhao, M.C., Zheng, J.Y., 2000. Land use change of China during the 20th century. Acta Geographica Sinica 55 (6), 689–706 (in Chinese, with English Abstr.).

Huston, M., 1993. Biological diversity, soils, and economics. Science 262, 1676–1680.

Imhoff, M.L., Lawrence, W.T., Elvidge, C.D., Paul, T., Levine, E., Prevalsky, M., Brown, V., 1997a. Using nighttime DMSP/OLS images of city lights to estimate the impact of urban land use on soil resources in the U.S. Remote Sensing of Environment 59, 105–117.

Imhoff, M.L., Lawrence, W.T., Stutzer, D.C., Elvidge, C.D., 1997b. A technique for using composite DMSP/OLS "city lights" satellite data to accurately map urban areas. Remote Sensing of Environment 61, 361–370.

Imhoff, M.L., W.T. Lawrence, D Stutzer, C Elvidge. 2003. Assessing the Impact of Urban Sprawl on Soil Resources in the United States Using Nighttime "City Lights" Satellite Images and Digital Soils Maps. http://biology.usgs.gov/luhna/chap3.html, 20-Nov-2003.

Kates, R.W., Turner II, B.L., Clark, W.C., 1990. In: Turner, B.L. (Ed.), The Earth Transformed by Human Action. Cambridge University Press, Cambridge, U.K, pp. 1–17.

Li, X.B., 1996. A review of the international researches on land use/land cover change[J]. Acta Geographica Sinica 51 (6), 553–558 (in Chinese, with English Abstr.).

Meyers, N., Simon, J., 1994. Scarcity or Abundance: A Debate on the Environment. Norton, New York, N.Y. 254 pp.

Parsons, J., 1977. Population Fallacies. Elek/Pemberton, London, U.K. 286 pp.

Sellers, P.J., Meeson, B.W., Hall, F.G., Asrar, G., Murphy, R.E., Schiffer, R. A., Bretherton, F.P., Dickinson, R.E., Ellingson, R.G., Field, C.B., Huemmrich, K.F., Justice, C.O., Melack, J.M., Roulet, N.T., Schimel, D. S., Try, P.D., 1995. Remote sensing of the land surface for studies of global change: models–algorithms–experiments. Remote Sensing of Environment 51, 3–26.

Shi, C.Y., Zhou, H.Z., 2001. Evaluation of Land Quality Based on GIS — a case study on paddy field in Suzhou. Acta Pedologica Sinica 38 (3), 248–255 (in Chinese, with English Abstr.).

Shi, P.J., Chen, J., Pan, Y.Z., 2000. Land use change mechanism in Shenzheng city. Acta Geographica Sinica 55, 151–160 (in Chinese, with English Abstr.).

Skole, D., Tucker, C.J., 1993. Tropical deforestation and habitat fragmentation in the Amazon: satellite data from 1978 to 1988. Science 1905–1909.

Tian, G.J., Zhuang, D.F., Liu, M.L., 2003. The spatial–temporal dynamic change of cultivated land in China in 1990s. Advance in Earth Science 18 (1), 30–36 (in Chinese, with English Abstr.).

Tucker, C.J., Dregne, H., Newcomb, W., 1991. Expansion and contraction of the Sahara Desert from 1980 to 1990. Science 253 (5017), 299–301.

van Engelen, V.W.P., T.T. Wen, 1995. Global and national soils and terrain digital database (SOTER). Procedures manual (revised edition). ISSS-UNEP-FAO-ISRIC, Wageningen, Netherlands.

Zhang, X.L., Chen, J., Zhang, G.L., Tan, M.Z., Ibáñez, J.J., 2003. Pedodiversity analysis in Hainan Island, China. Journal of Geographical Sciences 13 (2), 181–186.

Zhang, X.L., Chen, J., Gong, Z.T., 2004. What to do in China after a review of research practices on pedodiversity in Europe and America. Acta Ecologica Sinica 24 (5), 1063–1072 (in Chinese, with English Abstr.).

Zhang, X.L., Tan, M.Z., Chen, J., Sun, Y.C., 2005. Impact of Land Use Change on Soil Resources in the Peri-urban Area of Suzhou City. The Journal of Geographical Sciences 15 (1), 71–79.

Zhang, X., Sun, Y., Tan, M., Chen, J., 2006. Regional Pedodiversity Dynamic Change and Its implication to the Evolvement of Soil Spatial Patterns under the Intensive Urbanization Process. 18th World Congess of Soil Sciences (WCSS), Philadelphia, Pennyslvania, USA, July 9–15.

Zhao, M.D., Tang, G.A., Shi, W.Z., Liu, Y.M., 2002. A GIS-based research on the distribution of rural settlements in Yulin of northern Shaanxi. Journal of Geographical Sciences 12 (2), 171–175.

Zhou, H.M., Zhou, C.H., Ge, W.Q., Ding, J.C., 2001. Spatial distribution characteristics of urban thermal conditions: application of GIS and remote sensing. Journal of Geographical Sciences 11 (3), 261–270.