Ecological consequences of rapid urban expansion: Shanghai, China

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Since China's economic reform in the late 1970s, Shanghai, the country's largest and most modern city, has experienced rapid expansion and urbanization. Here, we explore its land-use and land-cover changes, focusing on the impacts of the urbanization process on air and water quality, local climate, and biodiversity. Over the past 30 years, Shanghai's urban area and green land (eg urban parks, street trees, lawns) have increased dramatically, at the expense of cropland. Concentrations of major air pollutants (eg SO_2, NO_x, and total suspended particles) were higher in urban areas than in suburban and rural areas. Overall, however, concentrations have decreased (with the exception of NO_x), due primarily to a decline in coal consumption by industry and in private households. Increased NO_x pollution was mainly attributed to the huge increase in the number of vehicles on the roads. Water quality changes showed a pattern similar to that of air quality, with the most severe pollution occurring in urban areas. Differences in mean air temperatures between urban and rural areas also increased, in line with the rapid pace of urban expansion, indicating an accelerating "urban heat island" effect. Urban expansion also led to a decrease in native plant species. Despite its severe environmental problems, Shanghai has also seen major economic development. Managing the tradeoffs between urbanization and environmental protection will be a major challenge for Chinese policy makers.

摘 要：自 1970 年代末改革开放以来，中国经历了快速的城市化。作为中国最大和最现代化的城市，上海市在过去 30 年里经历了极其快速的城市化。本文利用遥感数据分析了 1975－2005 年上海市土地利用/覆盖的变化，探讨了上海的城市化过程以及对上海及周边地区大气和水质、区域小气候以及生物多样性的影响。在过去 30 年里，上海市的城镇用地和城市绿地迅速增加，农业用地急剧减少。城区大气中的主要污染物含量高于郊区和乡村，但总体上主要大气污染物的含量(氮氧化物除外)呈下降趋势，这主要源于工业和生活用煤的减少。大气中氮氧化物含量增加的原因主要源于机动车辆的迅速增加。水质的变化趋势与大气质量类似，水质退化主要发生在城区。过去 30 年，城区与郊区的气温差异明显增加，表明上海的城市热岛效应在增加。城市化导致本地的植物物种减少，同时引进了许多外来物种。尽管上海的快速城市化带来了严重的生态负面影响，但它确实促进了上海经济的繁荣发展。如何协调城市化和环境保护的关系是中国的决策者们所面临的巨大挑战。

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China has been undergoing a period of economic reform and expansion since the late 1970s, accompanied by rapid and widespread urbanization. During the early 1980s, 18% of China's population lived in cities, but this rose to 39% by 2003, while the number of cities increased from 190 to 660 (including about 170 cities with a population greater than 1 million) over the same time period. From 1980 to 2003, the contribution of Chinese cities to gross national product (GNP) increased from 69.9% to 85.9% (Chinese Statistical Bureau 2004). However, urbanization has also led to serious environmental and ecological problems, both in urban and surrounding areas, including increased air and water pollution (Briant and Guo 2000; Liu and Diamond 2005; Shao *et al.* 2006), local climate alteration (Zhou *et al.* 2004), and a major reduction in natural vegetation cover and production (Fang *et al.* 2003). Urban residents have experienced an increase in levels of cholesterol-related diseases (Lee 2004) and an overall decline in quality of life.

As the largest and most modern city, Shanghai has experienced extensive urban expansion over the past three decades (Figure 1a). Between 1975 and 2003, the city's population increased from 10.8 million to 13.4 million (Shanghai Statistic Bureau 2004). The resulting ecological consequences of urban sprawl have caused considerable concern among scientists and policy makers. Several studies have documented some environmental impacts of Shanghai's increasing urbanization; for example, an analysis of meteorological data from both the city's

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中國的環境

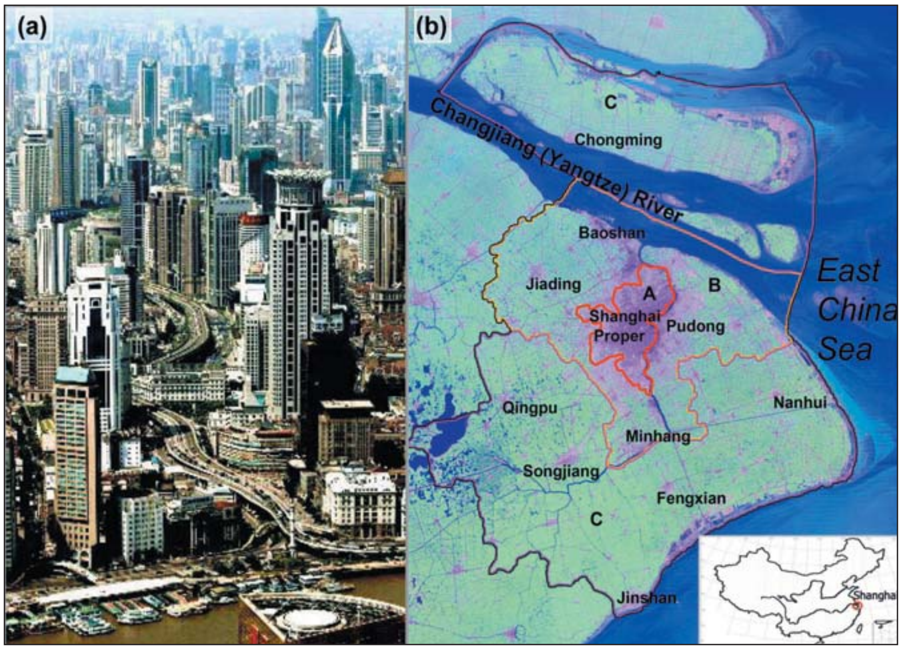

Figure 1. *The city of Shanghai. (a) An aerial view of the downtown area. (b and inset) Map showing the location of Shanghai, at the estuary of the Yangtze River, on the coast of the East China Sea. For the purposes of the current study, Shanghai was divided into three areas: (A) urban; (B) suburban; and (C) rural.*

urban and adjacent rural areas has revealed the presence of a "heat island" effect (higher air temperatures in urban areas than in the surrounding areas; Chow 1992; Chen *et al.* 2003). Water quality in the city's central business district has been seriously degraded (Ren *et al.* 2003), and soil in the Baoshan District is often contaminated with lead, zinc, and cadmium (Hu *et al.* 2004). Ye *et al.* (2000) have suggested that the huge increase in the number of motor vehicles associated with the urbanization process has led to serious human health risks in the city.

To date, however, long-term (spanning both pre- and post-urbanization periods) and spatially explicit monitoring of the urbanization of the entire Shanghai area, together with comprehensive studies of the ecological consequences, have not been conducted. Here, we document the processes of urbanization in Shanghai between 1975 and 2005, through the analyses of satellite-derived data regarding land-use and land-cover changes. We explore the changes in air and water quality, the urban heat island effect, and the biodiversity loss, and examine their possible associations with urban expansion.

Data and methods

Site description

Shanghai is located on the coast of the East China Sea, at the estuary of the Yangtze River. The climate is subtropical, with an annual precipitation of 1200 mm and a mean annual temperature of 16°C. The total area covered by the city is 8010 km^2 (latitude: 30°40' to 31°55' N; longitude: 120°50' to 121°55' E). In order to examine the ecological consequences of urbanization, we divided Shanghai into three parts, according to the level of urbanization: urban, suburban, and rural (Figure 1b).

Remote sensing data and data processing

Between 1975 and 2005, data on land use and land cover in Shanghai was obtained using cloud-free Landsat Multispectral Scanner (MSS) and Thematic Mapper (TM) remote sensing images. The data, which spanned three decades, covered seven periods: 1975, 1981, 1987, 1990, 1995, 2000, and 2005 (mostly from April to June). The first two sets of satellite images (1975 and 1981) were obtained from the MSS; for all other years, the TM was used. Landsat data were interpreted using ERDAS 8.4 image-processing software. Land-cover data were divided into four types: urban land (urbanized area), green land (ie urban parks, street trees, lawns, etc), cropland, and water body. For details on the data processing, see Fang *et al.* (2005).

Air and water quality data

Systematic monitoring data on air and water pollution in Shanghai are available from 1983 onwards (Shanghai Environmental Protection Bureau 1983–2004). To measure air quality, data were collected on sulfur dioxide (SO_2), acid rain frequency, total suspended particles (TSP), and nitrous oxides (NO_x); for water quality, the data covered dissolved oxygen (DO), chemical oxygen demand (COD), biochemical oxygen demand (BOD), Kjeldahl nitrogen (KN), total phosphorus (TP), oils, volatile phenol (VP), and total mercury (THg). We analyzed variations in the concentrations of these components in urban, suburban, and rural areas between 1983 and 2004. With the exception of DO, all these measures of air and water quality are inverse indices; that is, the higher the values, the worse the air or water quality.

Climatic data

Urbanization leads to alterations of the local climate, and in particular creates a significant heat island effect (Kalnay and Cai 2003; Zhou *et al.* 2004). We collected monthly mean air temperatures at 10 meteorological stations for the period between January 1975 and December 2004. Four of these stations were located in urban areas (Xujiahui [Shanghai proper], Minhang, Jiading, and Baoshan), with the remainder in rural areas (Nanhui, Fengxian, Jinshan, Qingpu, Chongming, and Songjiang;

Figure 1b). We analyzed the differences in mean annual temperature (MAT), monthly mean maximum temperature (MT_{max}), and monthly mean minimum temperature (MT_{min}) between the urban and rural areas. In order to study the urban heat island effect, we correlated the area of urban land with the differences in mean temperatures between the urban and rural areas from 1975 to 2005.

Biodiversity data

Urbanization exerts a substantial effect on biodiversity, resulting in the loss of native species and the introduction of non-native species (Blair 1999; McKinney 2000). To explore the impact of urbanization on biodiversity, we collected species richness data for flora and fauna from various literature sources (Xu *et al.* 1999; Yang *et al.* 2002; Shanghai Agriculture and Forestry Bureau 2004). We also carried out fieldwork to investigate the numbers of native and non-native woody plant species in different green areas (Da *et al.* 2005).

Results and discussion

Land-use and land-cover change

Land use and land cover in Shanghai have been greatly altered over the past three decades, as a result of the rapid expansion of urban areas (Figure 2). The area of urban land increased from 159.1 km^2 in 1975 to 1179.3 km^2 in 2005 (Figure 2i). There were distinct phases in the urbanization process. The slowest rate of urbanization, 17.7 km^2 yr^{-1}, occurred between 1975 and 1981 (Figures 2a and 2b), increasing to 52.4 km^2 yr^{-1} between 1990 and 1995 and 54.9 km^2 yr^{-1} from 2000 to 2005 (Figures 2d to 2g). This is consistent with China's economic policies, since the country began its economic reform in 1978, and accelerated the process in 1992 (Lin 1999).

Urbanization is generally associated with an increase in managed green areas, such as street trees, lawns, and parks for urban recreation; these improve both the visual appeal of a city and environmental quality (Attwell 2000). In parallel with its urban expansion, Shanghai's green areas have continued to increase in size, from 8.7 km^2 in 1975 to 252.9 km^2 in 2005. In contrast, agricultural land area has fallen rapidly, from 6030.7 km^2 in 1975 to 4743.1 km^2 in 2005. In addition, the area covered by water has shown small fluctuations over the past three decades (Figure 2i).

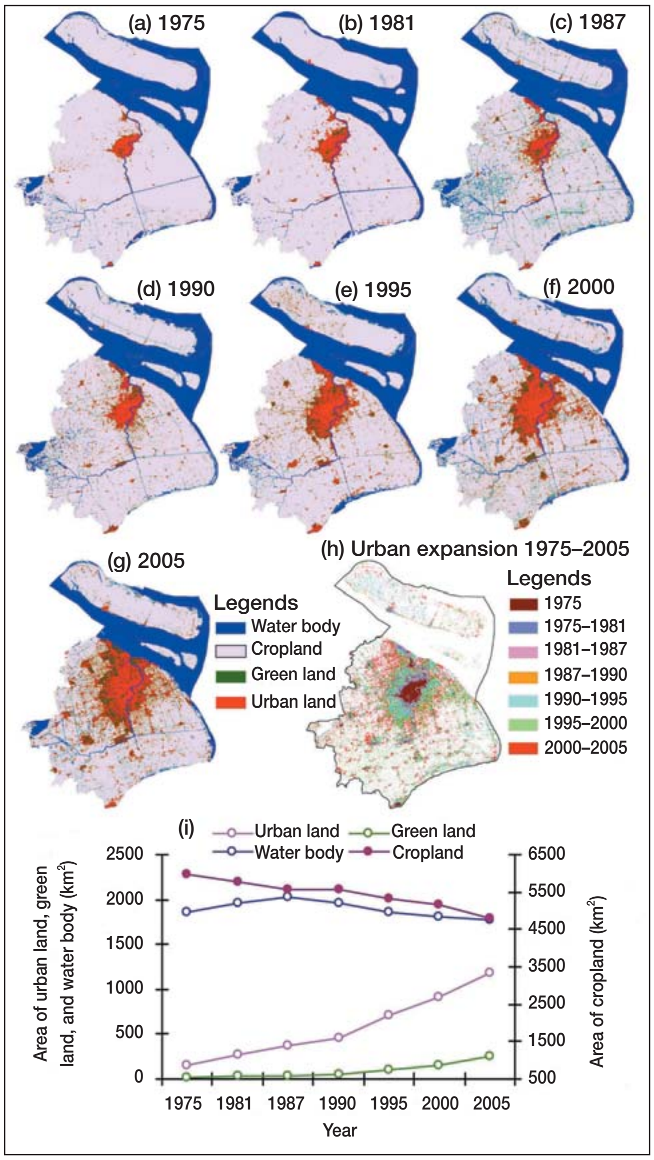

Figure 2. Changes in land-cover types in Shanghai. (a–g) Spatial distribution of land-cover types for seven time periods: 1975, 1981, 1987, 1990, 1995, 2000, and 2005. (h) Overlap of urban lands from 1975–2005. (i) The changes in area of four land-cover types: urban land, green land, cropland, and water, from 1975–2005.

Air and water quality changes

Urbanization places a heavy burden on local air and water quality. Air quality monitoring data obtained from different observatories showed that concentrations of SO_2, TSP, and NO_x, along with acid rain frequency, varied considerably in different areas along the urbanization gradient. Concentrations of air pollutants were consistently highest in urban areas, lower in suburban areas, and lowest in rural areas over the study period, indicating a strongly negative influence of major urban development on air quality (Figure 3). The temporal variations in air pollutants suggest that SO_2, TSP, and acid rain were largely the result of coal combustion, since levels of these pollutants decreased from 1983 to 2004 in all three areas, while NO_x concentration increased (Figure 3). The falling concentrations were mainly related to the decline in the use of coal, both by industry and in private households (Yuan and James 2002). The increase in green lands may also have helped to mitigate air pollution. The rising concentrations of NO_x are attributed primarily to a rapidly increasing number of motor vehicles in recent years; for example, vehicles in Shanghai numbered less than 100 000 in the early 1980s, but rose to more than 2 million by 2004 (www.shtaq.com/

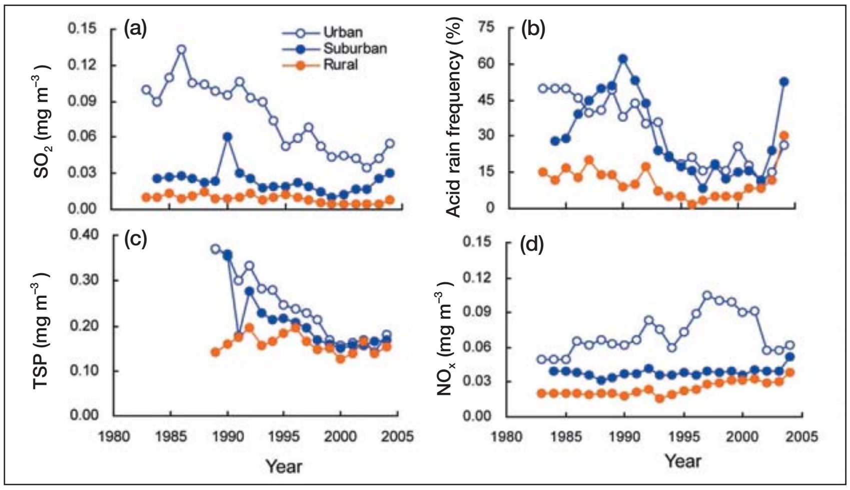

Figure 3. *Changes in major components of air quality between 1983 and 2004 in the different areas of Shanghai: (a) sulfur dioxide (SO_2); (b) acid rain frequency; (c) total suspended particles (TSP); and (d) nitrous oxides (NO_x).*

showcontent/contentdetail_old.asp?id=39703). A similar result was seen in Beijing (He *et al.* 2002).

There have been two exceptions to these general trends. First, as shown in Figures 3a and 3b, SO_2 pollution and acid rain have tended to increase in the suburbs in recent years, which may be attributed to a growing number of factories in suburban areas. In the late 1990s, the municipal Government of Shanghai initiated an environmental improvement program, aimed at moving industrial units from urban centers to suburban areas in order to improve urban air quality (Shanghai Environmental Protection Bureau 2001).

The second exception is that NO_x pollution has decreased in urban areas, since the late 1990s, a result of the Clean Vehicle Program which was implemented in 1999 as a means of controlling air pollution due to vehicle emissions (He *et al.* 2002).

Water pollution levels show similar patterns, being consistently more severe in the central urban areas than in suburban and rural areas (Figure 4). During the study period, different pollutants varied over time in the central urban areas; concentrations of COD, BOD, KN, and volatile phenols increased from the early 1980s to the early 1990s, and then began to decrease, while DO, total phosphorus, oils, and total mercury did not exhibit significant changes over the same period. This suggests that water quality in the city center has been improving since the 1990s. However, water quality in the suburban and rural areas has deteriorated over the past decade, although generally much better than in the central urban area. For example, BOD, KN, and TP pollution has increased in recent years, probably as a result of the transfer of factories from the city center to suburban and rural areas (Shanghai Environmental Protection Bureau 2001).

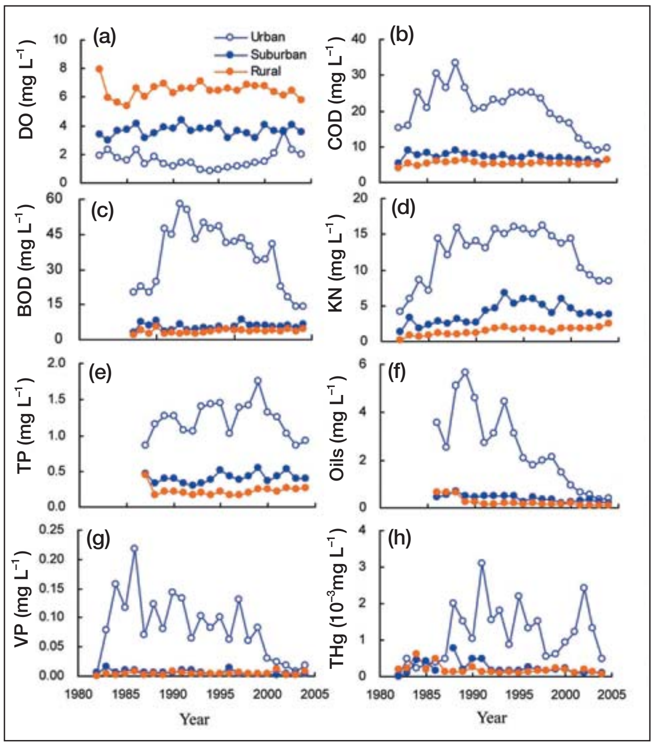

Figure 4. *Changes in major components of water quality between 1983 and 2004 in the different areas of Shanghai: (a) dissolved oxygen (DO); (b) chemical oxygen demand (COD); (c) biochemical oxygen demand (BOD); (d) Kjeldahl nitrogen (KN); (e) total phosphorus (TP); (f) oils; (g) volatile phenols (VP); and (h) total mercury (THg).*

Local climate change and the heat island effect

As illustrated in Figure 5, a substantial urban heat island effect was found in Shanghai. The difference in MAT between urban and rural areas increased from 0.1 °C in the late 1970s (average for 1975–1979; a mean MAT of 15.7°C vs 15.6°C at urban and rural stations) to 0.7°C in the early 2000s (average for 2000–2004; 17.3°C vs 16.6°C), with an increase of 0.24°C per decade (Figure 5a). Similarly, MT_{max} and MT_{min} did not show a difference between urban and rural areas in the late 1970s (28.2°C vs 3.4°C for MT_{max} and MT_{min}, respectively), although the differences increased to 0.7°C (29.2°C vs 28.5°C for the urban and rural area) and 0.5°C (5.0°C vs 4.5°C) in the early 2000s, respectively, with a decadal increase of 0.26°C and 0.21°C (Figures 5b and 5c).

The correlation analysis of the relationship between the differences in mean temperatures in urban vs rural areas, and the amount of urban land, indicate that the differences in temperature between urban and rural areas increased substantially as the city expanded, and that this increase was faster for MT_{max} than for MT_{min} (Figure 5d). This strongly suggests that rapid urbanization can increase temperatures considerably in the city and adjacent areas (Zhou *et al.* 2004).

Changes in biodiversity

The area around Shanghai is rich in biodiversity. There are 1904 spermatophyte plants, representing 981 genera and 168 families. However, there are more non-native species than native (968 and 936, respectively; Xu *et al.* 1999). Seven hundred and sixty vertebrate species are found in Shanghai, of which 40 are mammals, 424 birds, 32 reptiles, 14 amphibians, and 250 fish (Shanghai Agriculture and Forestry Bureau 2004).

Urban expansion and the associated increase in human activities have led to a considerable loss of biodiversity in the study area. The number of native plant species has fallen rapidly in the relatively wild regions; for example, the number of plant species in the Sheshan area fell from 535 in the 1980s to 254 by the end of the 1990s (Xu *et al.* 1999), while on Dajinshan Island plant species declined from 254 in the 1980s to 145 in 2000 (Yang *et al.* 2002). At the same time, the number of non-native plant species has increased greatly due to the introduction of many species into the managed green spaces; about 300 alien plant species were introduced to the Shanghai area between 1980 and 2005, for instance. In 2004, a comprehensive investigation by the authors recorded a total of 206 woody plant species within the green spaces in the city, of which only 64 (31.1%) were native to Shanghai and adjacent areas (Da *et al.* 2005). The proportion of native species is even lower in recently established green areas within the city. For example, in the newly created Yanzhong green land, only 26 (18.4%) of 142 woody plants are native, while a much higher proportion (28 out of 69 species) of woody plant species were found in the green spaces established in the 1950s on the campus of East China Normal University (Table 1).

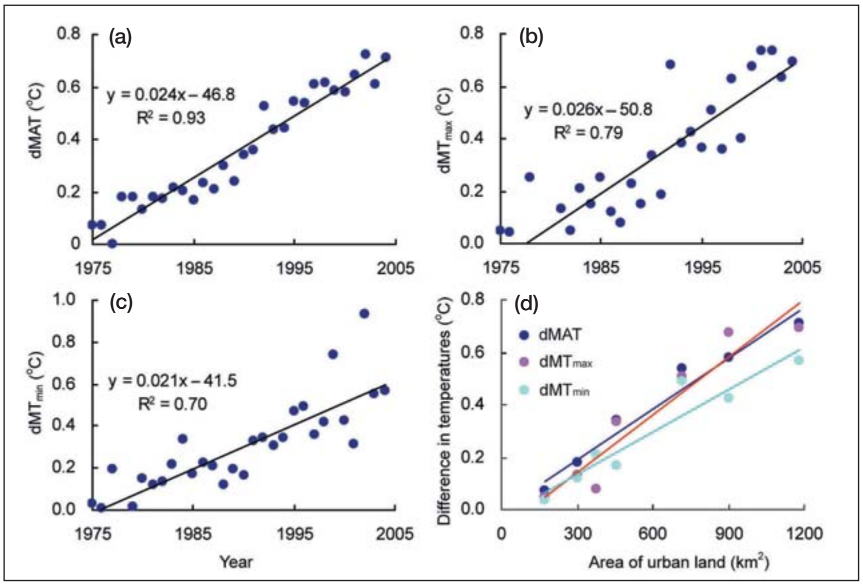

Figure 5. *Changes in temperature differences between urbanized and rural areas in the years 1975–2004. (a) Difference in mean annual temperature (dMAT); (b) difference in monthly mean maximum temperature (dMT_{max}); (c) difference in monthly mean minimum temperature (dMT_{min}); and (d) relationships between the temperature differences and degree of urbanization.*

Conclusions

Shanghai has experienced rapid urbanization over the past three decades, accompanied by large-scale economic development. However, this urban growth has caused a number of ecological problems, including degradation of air and water quality, alteration of the local climate, a decline in native species, and an increase in numbers of alien species. This, together with an improvement in public awareness of environmental issues, has been the basis for attempts to achieve both socioeconomic and environmental sustainability in the urbanization process. In recent years, the Shanghai Government has implemented a series of measures specifically designed to protect the local environment. First, a number of policies have been developed which are aimed at promoting clean energy use to reduce water and air pollution; over the past 10 years, these have involved improvement of the sewage treatment infrastructure, removal of exhaust emission sources, improvement of transportation systems, and control of vehicle density. As a result, air and water quality have begun to improve, beginning in the 1990s (Figures 3 and 4). Second, afforestation and the establishment of parks within Shanghai have been incorporated into city planning, leading to an increase in vegetation coverage. For example, the area occupied by green land in Shanghai has risen from 870 ha in 1975 to 25 300 ha

Table 1. Comparison of the number and proportion of native woody plant species in three different green lands in Shanghai

Site	*No. of woody plants*	*No. (%) of species native to Shanghai*	*No. (%) of species native to the adjacent areas*	*No. (%) of native species*
All green lands in the urban center	206	43 (20.9%)	21 (10.2%)	64 (31.1%)
Newly established Yanzhong green land	142	11 (7.8%)	15 (10.6%)	26 (18.4%)
Green land on the East China Normal University campus, established in the 1950s	69	16 (23.2%)	12 (17.4%)	28 (40.6%)

Based on Da *et al.* (2005)

in 2005 (Figure 2). Third, nature reserves and forested parks have been established to protect biodiversity and provide recreation sites. The first nature reserve in Shanghai was established in the early 1990s, followed by four more reserves and a national forest park. Finally, in 2003, Chongming Island, the third largest island in China and the largest alluvial island in the world, was declared an "ecological island" by the Shanghai Government. Chongming Island, situated at the estuary of the Yangtze River in northern Shanghai, covers an area of 1100 km^2 and includes a large coastal wetland and tidal flats that provide habitat for a wide variety of species. All development activities that conflict with the protection of the environment will be prohibited on the island. At the same time, the Shanghai Government provides monetary compensation to local communities and encourages local resident participation in the protection of the island (Yuan *et al.* 2003).

In summary, China is facing many challenges as its urban growth rate continues to accelerate. Rapid urbanization has greatly accelerated economic and social development, but has also created severe environmental problems. Maintaining a balance between environmental sustainability and the continuing process of urbanization is a major issue facing the Chinese Government. A national strategy for sustainable development – China's Agenda 21 (Department of Planning Committee of China 1994) – has been established, aimed at reducing the negative environmental impacts of economic development while at the same time maintaining economic and social benefits. This involves land-use management strategies and the development of greener cities, thereby providing a healthier environment for both humans and wildlife.

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