Ecological consequences of rapid urban expansion: Shanghai, China

Shuqing Zhao¹, Liangjun Da², Zhiyao Tang¹, Hejun Fang³, Kun Song², and Jingyun Fang¹*

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 (e.g., urban parks, street trees, lawns) have increased dramatically, at the expense of cropland. Concentrations of major air pollutants (e.g., \( \text{SO}_2 \), \( \text{NO}_x \), and total suspended particles) were higher in urban areas than in suburban and rural areas. Overall, however, concentrations have decreased (with the exception of \( \text{NO}_x \)), due primarily to a decline in coal consumption by industry and in private households. Increased \( \text{NO}_x \) 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.


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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 km² (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 (i.e., 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 (SO₂), acid rain frequency, total suspended particles (TSP), and nitrous oxides (NOₓ); 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;
We analyzed the differences in mean annual temperature (MAT), monthly mean maximum temperature (MT\text{max}), and monthly mean minimum temperature (MT\text{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).

**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 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/...
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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).

**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$_{\text{max}}$ and MT$_{\text{min}}$ did not show a difference between urban and rural areas in the late 1970s (28.2 °C vs 3.4 °C for MT$_{\text{max}}$ and MT$_{\text{min}}$, 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$_{\text{max}}$ than for MT$_{\text{min}}$ (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).

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

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

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 km² 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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References


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Biodiversity in China’s mountains

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China spans a huge geographical area, ranging from tropical to boreal zones and from very low altitudes (156 m below sea level in the Turpan Desert, Xinjiang) to the world's highest mountain, Mount Qomolangma (Everest), on the border of Tibet and Nepal. Almost all of the different types of biomes found on Earth, from rainforests to deserts, are found in China. This geographic diversity provides abundant habitats for plants and animals. Home to more than 30,000 vascular plants (surpassed only by Brazil and Colombia) and 6,300 vertebrates, China is one of the world’s “megabiodiversity countries” (McNeely et al. 1990). However, this biodiversity has suffered severe degradation due to the density of the human population, a long history of cultivation, and an increase in the intensity and extent of human disturbances in the plains and lowland areas.

The mountain regions of China provide rich habitats for much of the country's remaining biodiversity, owing to the heterogeneity of climates and soils, rapid elevational changes, varying aspects of slope direction, abundant microhabitats, and limited suitability for cultivation (Körner and Spehn 2002). Thus, China's mountains are likely to be especially important for preserving its remaining biodiversity (Chen 1998).

In this study, we used well-developed county level species distribution databases to explore patterns of biodiversity and to identify biodiversity hotspots within China. Ten hotspot ecoregions were identified, containing 3110 plant genera (92.0% of the country's total), 220 (90.5%) endemic plant genera, 366 (94.3%) endangered plants, and 254 (72.2%) endangered vertebrates, 427 (91.0%) terrestrial mammal species, and 65 (85.5%) endemic mammals. All 10 hotspot ecoregions are located in the mountainous areas of China. Although high richness of overall, endangered, and endemic plants and animals co-occurred in many of the same hotspot ecoregions, they often occurred in different counties within these ecoregions and showed low spatial congruence. In conclusion, China's mountain regions are critical for protecting biodiversity and should be made conservation priorities in the future.

Data sources

There are 2383 counties in China. A county level map was digitized and overlaid with a Digital Elevation Model (DEM) with 1 km x 1 km resolution, obtained from the United States Geological Survey (USGS), to document the topographic attributes of each county.
The overall numbers of plant genera and mammal species, endemic plant genera and mammal species, and endangered plant and vertebrate species for each county were derived from the following resources: “Seed plants of China” (Wu and Ding 1999), “Mammal species in China” (Zhang 1997), “China red data book of endangered plants” (Fu 1992) and “China red data book of endangered animals” (Wang 1998).

The “Seed plants of China” database (Wu and Ding 1999) is the main product of a national project spanning 10 years (1990–1999) that described county-level distributions for each of the 32 308 native and cultivated seed plants, representing 363 families and 3428 genera (including 243 genera endemic to China). For each genus, the geographic distribution was resolved to the county level, and habitat type, elevational range, and longitudinal and latitudinal range were documented based on national flora, local reports, and other scientific literature. Because this database is derived primarily from plant specimen records, it is potentially biased by regional differences in levels of investigation. In the study presented here, genera (or family) richness was used instead of species richness to measure plant diversity, because it is less likely that these higher taxa would be overlooked in surveys (Qian 1998).

To help reduce the possibility of bias in the records as a result of regional differences in investigation intensity, we explored the patterns of seed plant density at the genus, as opposed to species, level in this study.

“Mammal species in China” (Zhang 1997) was compiled based on the scientific literature as well as observations of local fauna over the past 50 years. This book includes information on the county level distribution and habitat type for each of the 537 mammals in China. In our study, 68 marine mammals whose distributions are not clear were excluded from the analysis. We therefore included only the data for 469 terrestrial mammal species (of which 77 are endemic to China) to investigate patterns of mammal diversity.

The “China red data book of endangered plants” (Fu 1992) and the “China red data book of endangered animals” (Wang 1998) provided information on the distributions of endangered plant and vertebrate species. These two datasets record the geographic distribution, habitat type, and elevational range for each of China’s 388 endangered plant species and 352 endangered vertebrate species (including 134 mammals, 95 reptiles, 92 fishes, and 31 amphibians). Endangered birds were also not included in this study as most avian species are migratory, thus making their distributions unclear.

Methods

We first calculated the animal and plant richness per county for the three aspects of biodiversity mentioned above (overall, endemic, and endangered). Geographic information system (GIS) software (ArcView GIS 3.2) was used to calculate the area covered by each county. The administrative division atlas of China (Editorial Committee for the Administrative Division Atlas of China 2002) was digitized to obtain information on county boundaries. The area covered by the different counties in China varies greatly; we used the following area-adjusted species (genera for overall and endemic plants) density as a measure of diversity, to eliminate the influence of county size (Qian 1998):

\[
D = \frac{S}{\ln (A)}
\]

where \(D\) is the species density for a county, \(S\) is the number of species, and \(A\) is the area of the county.

We then used ArcView GIS 3.2 to map different aspects of biodiversity in order to identify biodiversity hotspots across the country. Here, we defined hotspot counties as the top 5% of land area with the highest density of each of the three aspects of biodiversity. We first selected the county that contained the highest density of species, then added the county with the second highest density, then the third, and so on, until the total area of selected counties equalled 5% of China’s total land area. All of the counties ranked within the top 5% for each aspect of biodiversity were designated as the hotspot counties. Because ecoregions can be used as conservation units at regional scales (Olson and Dinerstein 1998), we assigned all the counties to different ecoregions, according to their physical geography (Editorial Committee for China’s Physical Geography 1985). We then calculated the percentage of the area covered by hotspot counties within each ecoregion. An ecoregion was designated as a hotspot if 5% of its total area was covered by hotspot counties.

The topographic attributes (maximum and minimum elevation, average elevation, elevational range, and slope) of each county were derived from the DEM by using ArcView GIS 3.2. The UNEP-WCMC (2002) criterion was used to identify mountainous areas versus plains. According to the criterion, areas that fit any of the following four descriptions are defined as mountainous: (1) an elevation of 300–1000 m and a local elevational range of > 300 m; (2) an elevation of 1000–1500 m above sea level (asl), and a slope of > 5’ or a local elevational range of > 300 m asl; (3) an elevation of 1500–2500 m asl, and a slope of > 2°; or (4) an elevation of > 2500 m asl.

Results and discussion

Macrotopography in China

According to the UNEP-WCMC (2002) definition, mountains cover a total area of approximately 4.6 million km² in China (48% of the total land area). Figure 1 shows the macrotopography and a frequency distribution of the mean elevation per county, together with major geographic regions. Low-lands with an elevation of < 500 m asl covered 2.63 million km² (27.4% of the total land area), while areas with an altitude of > 1000 m asl encompassed an area of 5.42 million km² (56.5% of the total land area). Another 1.93 million km² (20.1% of the
country’s total area) was covered by altitudes of >4000 m asl.

**Patterns of overall plant genera and mammal species densities**

The density of plant genera was higher in eastern compared to western China, higher in southern compared to northern China, and also in the mountainous areas compared to the plains and plateaus (Figure 2a). One hundred and seventy-three counties were assigned as hotspot counties for plant genera; they contained densities of >65 genera ln⁻¹ (km²). In total, 2948 genera of seed plants (86.0% of China’s total) grow in these counties. The counties were located mostly within eight regions: the Hengduan Mountains, the Xishuangbanna area, the upper reaches of the Hongshui River (the Wumeng Mountains), the Nanling Mountains, the Wuling Mountains, the East China Mountains, Hainan Island, and Taiwan Island. Compared to the mountainous areas listed above, counties in the North China Plain, Loess Plateau, Sichuan Basin, and Qinghai-Xizang Plateau contained very low densities of plant genera (<20 genera ln⁻¹ [km²]).

Mammal species densities showed a slightly different pattern from that of plant genera. One hundred and fifty-four counties were designated as hotspot counties, with mammal species densities of >5.8 species ln⁻¹ (km²). These counties contained 384 mammals (81.9% of China’s total) and were mostly located in the following eight regions: the Hengduan Mountains, the Nanling Mountains, the Xishuangbanna Area, the Qinling Mountains, the upper reaches of the Hongshui River, the East China Mountains, Hainan Island, and Taiwan Island. Densities of mammal species were lower in the North China Plain, the Central Yangtze Plain, the Loess Plateau, the western part of the Qinshui-Xiaotang Plateau, the Northeast China Plain, and the Sichuan Basin (Figure 2b).

The distribution of overall richness is positively associated with habitat diversity (Orme et al. 2005). In the present study, we used the elevation range (ie the difference between the highest and the lowest elevation in a county) as a surrogate of habitat heterogeneity, and found positive relationships between elevation range and the densities of both plant genera (Pearson correlation coefficient, r = 0.32, P < 0.01), and mammal species (r = 0.36, P < 0.01). Statistical analysis also suggested a positive relationship between the density of overall plant genera and mammal species (r = 0.36, P < 0.01; Table 1).

**Patterns of endemic plant genera and mammal species densities**

The density of endemic plant genera was also higher in mountainous areas than in other areas. Altogether, 161 counties were assigned as hotspots for endemic plants (>0.85 genera ln⁻¹ [km²]). These counties contained 204 endemic plant genera (84.0% of the total), with most located in the following seven regions: the Hengduan Mountains, the Wuling Mountains, the Nanling Mountains, the Qinling Mountains, the East China Mountains, Hainan Island, and Taiwan Island (Figure 2c). On the other hand, the 123 hotspot counties for endemic mammals (a density of >0.75 species ln⁻¹ [km²]) contained 56 endemic mammals (73.7% of the total), which were located primarily in the Hengduan Mountains, the Qinling Mountains, and the eastern part of the Qinghai-Xiaotang Plateau (Figure 2d). These mammal hotspot counties were located either in the ecotones between different biomes or in areas with high environmental heterogeneity, and have not suffered the influences of the last period of glaciation.

**Table 1. Correlation between densities of overall and endemic plant genera, overall and endemic mammal species, and endangered plant and vertebrate species in different counties of China**

<table>
<thead>
<tr>
<th>Aspect of diversity</th>
<th>Endemic plant genera</th>
<th>Endangered mammals</th>
<th>Overall mammal species</th>
<th>Endemic mammals</th>
<th>Endangered vertebrates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall plant genera</td>
<td>0.41*</td>
<td>0.42*</td>
<td>0.36*</td>
<td>0.07</td>
<td>0.41*</td>
</tr>
<tr>
<td>Endemic plant genera</td>
<td>0.44*</td>
<td>0.31*</td>
<td>0.39*</td>
<td>0.26</td>
<td>0.45*</td>
</tr>
<tr>
<td>Overall mammals</td>
<td>0.38*</td>
<td>0.57*</td>
<td>0.54*</td>
<td>0.31*</td>
<td></td>
</tr>
</tbody>
</table>

*P < 0.01. For all correlations, n = 2383 counties.
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Hotspots for endangered plants included 185 counties (> 1.1 species ln⁻¹ [km²]). These counties contained a total of 333 endangered plants (85.8% of the total) and were located in the following five regions: the Hengduan Mountains, upper reaches of the Honghe River area, the Xishuangbanna area, the Qinling Mountains, the Nanling Mountains, the East China Mountains, Hainan Island, and the east part of the Qinghai-Xizang Plateau. Low densities of endangered vertebrates were found in the northern and northeast plains and plateaus in China (Figure 2f).

Endangered species richness is widely used as a proxy for conservation priority identification because of the significant and positive relationship between endangered species and overall species richness (Dobson et al. 1997). As in previous studies (eg Dobson et al. 1997), we observed a positive correlation between densities of overall mammals and endangered vertebrates (r = 0.54, P < 0.01), and between densities of overall plant genera and endangered plants (r = 0.42, P < 0.01; Table 1). Further, positive correlations were found between the densities of endangered plants and endemic plant genera (r = 0.44, P < 0.01) and between endangered and endemic animals (r = 0.31, P < 0.05; Table 1), as most of the endemic plants and vertebrates in China are endangered because of their limited geographic distributions (Wang 1998).

We also found that the densities of endangered plant and vertebrate species were positively correlated (r = 0.45, P < 0.01; Table 1). Richness of endangered species is shaped by the interaction between the biological mechanisms promoting species diversity and the anthropogenic mechanisms eroding that diversity (Orme et al. 2005). To explore the influence of human threat on the distribution of endangered species richness, we calculated the ratio of endangered compared to overall densities (endangered plants to overall plant genera and endangered vertebrates to overall mammals). This ratio was high in the North China Plain for plants, and in the East China Mountains, the Wuling Mountains, and the Nanling Mountains for animals. The North China Plain, the east (including the East China Mountains), the central (where the Wuling Mountains are located), and the southern (including the Nanling Mountain) regions of China have high human population densities, suggesting the influence of humans on species endangerment (Dobson et al. 1997).

Patterns of endangered plant and vertebrate densities

Hotspots for endangered plants included 185 counties (> 1.1 species ln⁻¹ [km²]). These counties contained a total of 225 endangered vertebrates (63.9% of the total). They were located in the following eight regions: the Hengduan Mountains, upper reaches of the Honghe River area, the Xishuangbanna area, the Qinling Mountains, the Nanling Mountains, the East China Mountains, Hainan Island, and the east part of the Qinghai-Xizang Plateau. Low densities of endangered vertebrates were found in the northern and northeast plains and plateaus in China (Figure 2f).

Endangered species richness is widely used as a proxy for conservation priority identification because of the significant and positive relationship between endangered species and overall species richness (Dobson et al. 1997). As in previous studies (eg Dobson et al. 1997), we observed a positive correlation between densities of overall mammals and endangered vertebrates (r = 0.54, P < 0.01), and between densities of overall plant genera and endangered plants (r = 0.42, P < 0.01; Table 1). Further, positive correlations were found between the densities of endangered plants and endemic plant genera (r = 0.44, P < 0.01) and between endangered and endemic animals (r = 0.31, P < 0.05; Table 1), as most of the endemic plants and vertebrates in China are endangered because of their limited geographic distributions (Wang 1998).

We also found that the densities of endangered plant and vertebrate species were positively correlated (r = 0.45, P < 0.01; Table 1). Richness of endangered species is shaped by the interaction between the biological mechanisms promoting species diversity and the anthropogenic mechanisms eroding that diversity (Orme et al. 2005). To explore the influence of human threat on the distribution of endangered species richness, we calculated the ratio of endangered compared to overall densities (endangered plants to overall plant genera and endangered vertebrates to overall mammals). This ratio was high in the North China Plain for plants, and in the East China Mountains, the Wuling Mountains, and the Nanling Mountains for animals. The North China Plain, the east (including the East China Mountains), the central (where the Wuling Mountains are located), and the southern (including the Nanling Mountain) regions of China have high human population densities, suggesting the influence of humans on species endangerment (Dobson et al. 1997).
The various types of biodiversity hotspot counties (those based on the density of all, endemic, and endangered taxa) tended to be clustered in a few key regions such as the Hengduan Mountains, the upper reaches of the Hongshui River, the East China Mountains, Hainan Island, and Taiwan Island (Figure 2). However, there remains some spatial dissimilarity among the different types of hotspot counties: for example, although the co-occurrence of high richness of overall, endangered, and endemic plants and animals was apparent in many of the same ecoregions, there was little plant–animal richness overlap, as they were often found in different counties within these ecoregions.

The three aspects of plant hotspot counties occupied a total area of 977 450 km², of which only 11.5% (112 281 km²) was common to all three measures (Figure 3a). An additional 21.1% (206 025 km²) was shared between pairs of aspects. However, 22% (215 497 km²), 23.7% (231 801 km²), and 21.7% (211 846 km²) were idiosyncratic to individual aspects of overall, endangered, and endangered hotspots, respectively (Figure 3a).

Similarly, the animal hotspot counties also showed low spatial congruence between different aspects. The cumulative area of the three types of animal hotspot counties was 1 001 709 km², of which only 8.2% (82 080 km²) was common to all three aspects (Figure 3b). The idiosyncratic hotspot counties occupied a total of 220 797 km², 54 266 km², and 54 266 km² for the overall, endemic, and endangered animal hotspots, respectively. The remaining 24.3% (243 652 km²) was shared between pairs of the different aspects (Figure 3b). Similarly low spatial congruencies between different aspects of hotspots were observed with the global pattern of avian richness (Orme et al. 2005).

**Ten hotspot ecoregions in major mountain ranges**

High densities of plant genera and mammal species, endemic plant genera and mammal species, and endangered plant and vertebrate species appeared in different counties, which were aggregated in several ecoregions (Editorial Committee for China’s Physical Geography 1985). These encompassed the Hengduan Mountains, the Wuling Mountains, the Nanling Mountains, upper reaches of the Hongshui River area, the Xishuangbanna area, the Qinling Mountains, the East China Mountains, the Qinghai-Xizang Plateau, Hainan Island, and Taiwan Island. According to the criteria of UNEP-WCMC (2001), all of these ecoregions are located in mountainous areas and should be considered as the hotspot ecoregions (with a “hotspot ecoregion” determined by an area having at least 5% of its land area composed of hotspot counties) for biodiversity in China. These 10 biodiversity hotspot ecoregions cover an area of ca 2.3 million km², or 24.2% of China’s total land area. Table 2 illustrates the plant diversity of these areas. In total, they contained 3110 plant genera (92.0% of the country's total), 220 (90.5%) endemic plant genera, 366 (94.3%) endangered plants, 427 (91.0%) terrestrial mammal species, 65 (85.5%) endemic mammals, and 254 (72.2%) endangered vertebrates. It is worth noting that the alpine areas of the Tibetan Plateau contain globally unique ecosystems and their species are highly endemic, despite low overall taxonomic richness (Table 2).

These hotspot ecoregions are generally the same as those proposed by Chen (1998) and Olson and Dinerstein (1998), who used relatively descriptive and approximate species information. Chen (1998), using estimated species richness and number of endemics, proposed 11 terrestrial critical regions for the conservation of China’s biodiversity, eight of which were located within the hotspot ecoregions identified in this study. Of the WWF’s Global 200 most critical and endangered ecoregions, 17 are located in or around China, with 11 consistent with the priority areas identified in this study. Several of the others are either located in aquatic ecoregions or along China’s borders (Olson and Dinerstein 1998).

**Conclusions**

The patterns of biodiversity, as well as the mechanisms that cause these patterns, are a primary focus of biodiversity research (Gaston 2000). We explored the distribution patterns of different aspects of biodiversity at a county level, and identified ten biodiversity hotspot ecoregions that should serve as conservation priorities in China. All of the identified hotspot ecoregions for overall, endemic, and endangered diversity for plants and animals in China are located in the mountainous areas. These mountainous areas are therefore critical for protecting China’s biodiversity.

By the end of 2004, China had established more than 2000 national and local nature reserves, which collectively...
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cover approximately 1.7 million km², or 17.8% of the country’s total land area (Chinese Species Information Service 2005). Of these, 1498 (or 73.8% of all of the protected areas) are located in mountainous regions, covering a total area of 1.5 million km² (83.0% of all protected areas). Although these reserves play a key role in China’s plan for biodiversity conservation, most are located in remote and poorer areas and are often viewed as obstacles to human welfare and economic development (Liu et al. 2003). Therefore, maintaining the functionality of these reserves is, and will continue to be, a critical but difficult issue. Increasing financial support to reserves and local residents, and assisting local communities in sharing the benefits derived from tourism and natural resources are important factors in addressing this problem (Liu et al. 2003).

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References


Table 2. Plant species richness of China’s major mountain ranges and the Qinghai-Xizang (Tibetan) Plateau

<table>
<thead>
<tr>
<th>Mountain range</th>
<th>Area (10³ km²)</th>
<th>Area (10³ km²) of hotspot counties (%)</th>
<th>Summit (m asl)</th>
<th>Seed plants (family/genus/species)</th>
<th>Genera/species endemic to China (local)</th>
<th>Reference*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hengduan Mts</td>
<td>~ 500</td>
<td>409 (81.7%)</td>
<td>7556</td>
<td>175/1348/7962</td>
<td>56/5079 (12/2988)</td>
<td>Wang 1994</td>
</tr>
<tr>
<td>Upper reaches of Hongshui River (Wumeng Mts)</td>
<td>110</td>
<td>76 (69.1%)</td>
<td>2900</td>
<td>178/1293/5061</td>
<td>55/2555 (8/468)</td>
<td>Wu 1996</td>
</tr>
<tr>
<td>East China Mts</td>
<td>~ 600</td>
<td>213 (35.5%)</td>
<td>2158</td>
<td>174/1180/4259</td>
<td>54/2147 (5/425)</td>
<td>Zhang and Lai 1993</td>
</tr>
<tr>
<td>Wuling Mts</td>
<td>~ 100</td>
<td>97 (96.8%)</td>
<td>2570</td>
<td>20/1005/4119</td>
<td>65/2682 (0/126)</td>
<td>Chen et al. 2002</td>
</tr>
<tr>
<td>Nanling Mts</td>
<td>45</td>
<td>44 (98.0%)</td>
<td>2142</td>
<td>200/1045/3854</td>
<td>41/na (2/na)</td>
<td>Chen and Zhang 1994</td>
</tr>
<tr>
<td>Taiwan Island</td>
<td>35</td>
<td>35 (100%)</td>
<td>3997</td>
<td>186/1201/3656</td>
<td>17/1275 (4/1070)</td>
<td>Ying and Hsu 2002</td>
</tr>
<tr>
<td>Qinling Mts</td>
<td>70</td>
<td>67 (96.1%)</td>
<td>3767</td>
<td>198/1007/3446</td>
<td>46/1428 (0/192)</td>
<td>Ying 1994</td>
</tr>
<tr>
<td>Xishuangbanna</td>
<td>20</td>
<td>20 (100%)</td>
<td>2500</td>
<td>197/1140/3336</td>
<td>8(0)/na (121)</td>
<td>Zhu et al. 2001</td>
</tr>
<tr>
<td>Hainan Island</td>
<td>35</td>
<td>35 (100%)</td>
<td>1867</td>
<td>204/1266/3315</td>
<td>19/1110 (8/505)</td>
<td>Xing et al. 1995</td>
</tr>
<tr>
<td>Alpine Qinghai -Xizang Plateau (&gt; 4200 m)</td>
<td>~ 800</td>
<td>255 (31.9%)</td>
<td>8848</td>
<td>67/339/1816</td>
<td>14/636 (10/604)</td>
<td>Wu et al. 1995</td>
</tr>
</tbody>
</table>

*for detailed data source, see Web Only material; na = not available