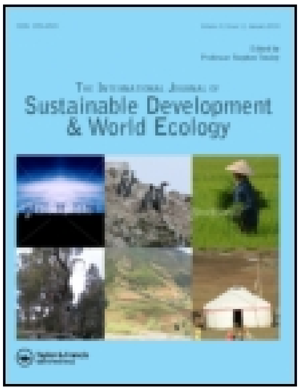

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Does large-sized cities' urbanisation predominantly degrade environmental resources in China? Relationships between urbanisation and resources in the Changjiang Delta Region

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Does large-sized cities' urbanisation predominantly degrade environmental resources in China? Relationships between urbanisation and resources in the Changjiang Delta Region

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Outward expansion of urban lands in the developing nations is often associated with a substantial loss of environmental resources such as forests, wetlands, freshwater and cash crop fields. Yet, determining how different aspects of urbanisation – such as city population size and spread pattern of built-up lands – contribute to the cumulative loss of resources remains controversial. In this study, data sets were constructed describing changes to land cover across 65,200 grid cells at 1 km^2 spatial resolution for China's Changjiang Delta Region over the past 60 years. The results showed that the region lost 12.2% of total resource sites. The distribution of resource degradation showed a highly dispersed pattern and was not confined to a few intense areas associated with large cities. No empirical evidence was found that city population size alone accurately predicts the distribution of resource loss. Very large cities ($N = 4$) contributed 35% to the total loss, demonstrating impacts similar to those of much more scattered towns ($N = 230$). Urban expansion of large cities may lead to extensive resource loss; however, a set of non-linear mechanisms, such as the diminishing effects of per-unit area urban spread on resources and interactions between urban patterns and the size of urban spread, can also play a significant role in downsizing the negative effects of large cities on resource sites. Thus, effective urban policies should carefully weigh the cumulative urban spread mechanisms of both large and small cities responsible for spatially dispersed degradation of environmental resources.

Keywords: environmental resources; urbanisation; land-cover change; urban patterns; Changjiang Delta Region; China

Introduction

The fertile lands of coastal regions produce some 77% of global ecosystem services, for example, food, water, climate control and disaster prevention (Burke et al. 2001; Martínez et al. 2007). These regions also provide different-sized urban settlements for more than one-third of the world's population within only 4% of the Earth's total surface area (United Nations Environment Programme 2006; World Bank 2010). Yet, in the face of large-scale urbanisation, outward expansion of urban lands is causing a substantial transformation of urban–rural fringe lands, especially in the coastal areas of predominantly rural nations such as China. Although major Chinese cities have taken steps to protect land and water resources, beginning with Shanghai in the 1980s (Information Office of Shanghai Government 2010), this does not indicate that all remaining important sites have been safeguarded (Zhao et al. 2006; Lin et al. 2010) and places a priority on investigating spatial and temporal variation in the cumulative resource loss generated by the expansion of urban lands. In short, several important questions remain: Is the rapid expansion of a few major cities predominantly responsible for a region's loss of resources, or is resource loss a fundamentally dispersed process that involves a number of different-sized cities? What aspects of urbanisation, for example, city population size or certain quantitative components of urban spread, better explain the degradation? In approaching these questions, the impact of different-sized cities on resources was divided into two parts: (i) increases in urban land, or a 'size factor' and (ii) resource loss per unit area of urban land, or an 'efficiency factor' of urban spread.

There are many benefits of environmental resources near cities. For instance, food, water, wood and minerals and by-products of urbanisation, such as wastes and pollutants, can be transported to and from cities at reduced time and cost. Flood control, water purification, climate regulation and maintenance of species habitats can more directly benefit human settlements. Also, recreational amenities and cultural heritage sites located in proximity to cities tend to attract large crowds, generating measurable and non-measurable economic value (Forman 1995; Millennium Ecosystem Assessment 2005; Li et al. 2010). This study focused on forestlands, freshwater sites, wetlands and cash crop fields located in China's lower Changjiang Delta Region. These resources were clearly discernible from classified remote-sensed imagery and were available from multiple sources of spatial data and planning documents. All four resources occupied a significant portion of the study area (>5% each) and corresponded to international and local land-cover standards (Liu et al. 2002; Lillesand et al. 2004). The four land types are referred to as 'environmental resources', defined as natural or human-modified land capital that produces valuable ecological services and environmental benefits (Dasgupta and Mäler 1995; Forman 2008).

The Changjiang Delta Region covers 65,200 km^2 of terrestrial land and 10,200 km^2 of freshwater bodies (30° 06′–32° 30′N, 118° 39′–121° 58′E), with the highest

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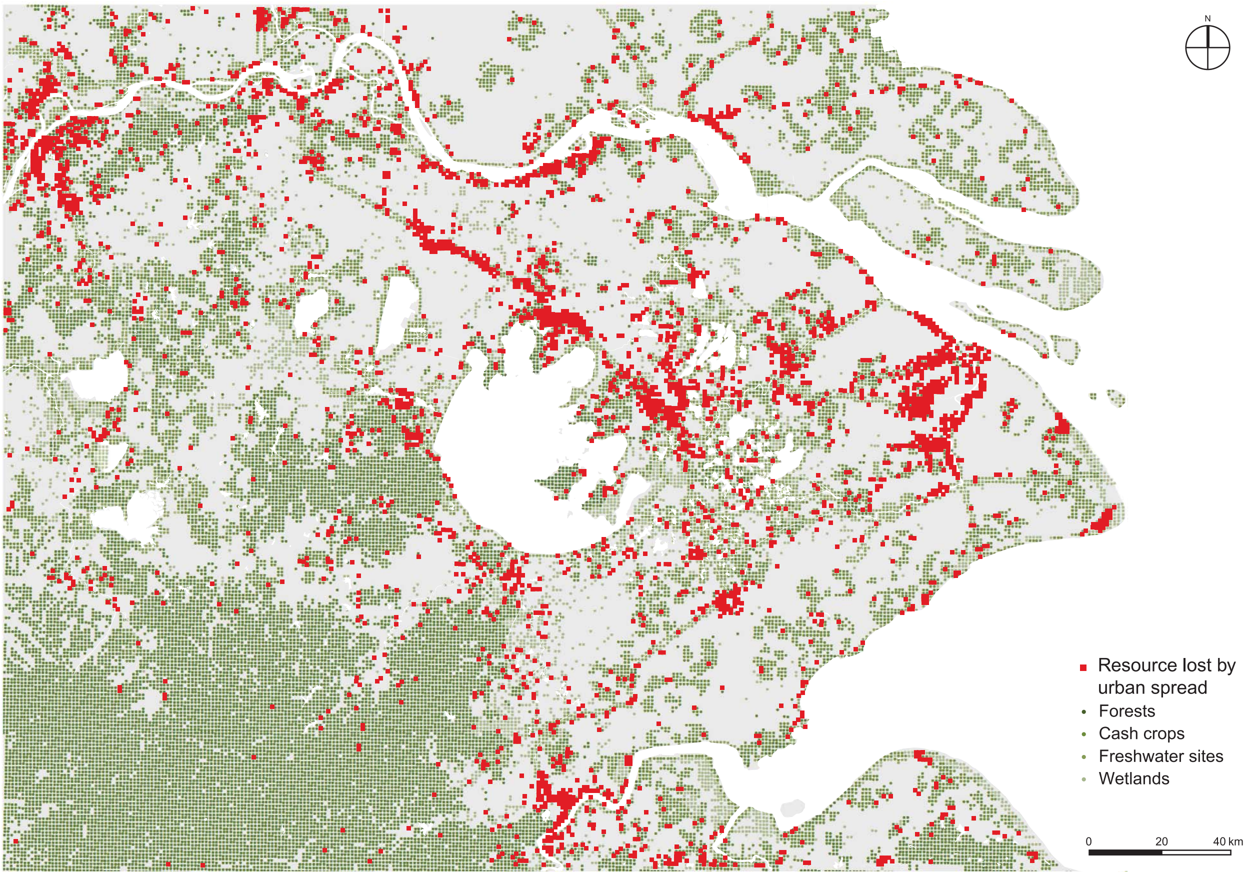

Figure 1. Regional distribution of four types of environmental resource and cumulative resource loss through urban spread between 1950 and 2010.

Note: Coastal lines and waterbodies were drawn based on the year 2010.

elevation at 1587 m above sea level (a.s.l.) (Figure 1). It includes 16 regional-level cities, 30 county-level cities and 1730 towns, with a total of some 62 million household-registered inhabitants in 2005. The region is composed of alluvial flat land located in a transition zone between the Changjiang (Yangtze River) and the East China Sea, large waterbodies such as Taihu and Gehu Lakes, as well as mountainous regions in Zhejiang and Anhui Provinces. Some 7000 years ago, the deltaic land grew gradually seaward due to the accumulation of sediment trapped by the extensive floodplains, forming Shanghai's eastern boundary in the early twentieth century (Sit 1998). Taihu Lake, China's third largest freshwater body, is located at the centre of the region, with some 55.3% of its watershed made up of lowlands less than 3 m a.s.l. (Sun and Mao 2008). Urban built-up land has expanded remarkably in the region, from approximately 804 km^2 in the 1950s to 6726 km^2 in 2010. Between 1979 and 2000, the rate of urban-land expansion was fairly high at about 4.7% per year, which was faster than the annual urban population growth rate of 3.5% between 1985 and 2005 (author calculation for 16 regional-level cities in the region; China City Statistical Yearbooks 1986, 2006).

This paper attempts to make methodological advances in the findings of previous studies (e.g. Wang et al. 2008), which were limited largely to the non-spatial, cross-sectional estimation of the delta region's resource sites and its ecosystem service values. Spatial aspects of the land-cover changes since 1950 were investigated through locating fine-scale vector data points on a consistent coordinate system. Also included was the eastern part of Anhui Province, representing 15.7% of the region's total terrestrial lands, which has an extensive forest zone that was selected as one of China's 33 priority conservation areas (Xie 2009). A regression method using stratified sampling was applied to determine influential urban aspects linked to resource degradation. However, non-physical effects of urbanisation, such as air pollution or climatic change, were not included.

Methods

Time-series land-cover data sets were created for the years 1950, 1979, 1990, 2000 and 2010 based on multi-band remote-sensed images, high-resolution aerial photographs and digitised historic and land-use planning maps. To identify seven standardised land-cover classes – urban built-up land, agricultural land, rangeland, forest, waterbodies, wetland and barren land (Anderson et al. 1976) – on-screen visual interpretation was carried out using images from the Landsat Orthorectified Multispectral Scanner (MSS; 57 m resolution, recorded in August 1979), Thematic Mapper (TM; 30 m resolution, recorded in August 1989) and Enhanced Thematic Mapper Plus (ETM+; 30 m resolution, recorded in July 2001) acquired from the US Geological Survey (USGS) Earth Resources Observation and Science Center. Before analysis, these images were geometrically rectified, re-projected and re-sampled using ERDAS Imagine (Hexagon Group, Stockholm, Sweden) with a 100 m resolution. A supervised classification of the maps was conducted using the maximum likelihood classifier in Multispec to produce consistent land-cover information. To complement any missing information, over 200 spatially referenced historic maps and aerial photographs (ca. 1963 and 2010) were compiled, as well as some 100 urban planning reference maps published by local municipalities. Consultations were also held with four Chinese institutions in May and June 2011: Fudan University Historical Geography Institute, Tongji University College of Architecture and Urban Planning, Suzhou Bureau of Construction and the Segacn Real Estate Group in Changzhou. All data sets were georeferenced in ArcGIS to the Xian 1980 GK Zone 19 coordinate system.

The distribution of environmental resources – forests, freshwater sites, cash crop fields and wetlands – and the location of urban spread were mapped using the established database. Land in the region was subdivided into 1 km^2 grid cells and a dominant land-cover type within each cell was recorded. This size of grid cells was chosen based on the coarse resolution of historic maps that were at best accurate to approximately 0.5 km. Areas of forest were predominantly occupied by secondary evergreen–broadleaf and mixed deciduous trees (Xu et al. 2010). Freshwater sites included lakes ($>$1 km^2), rivers ($>$100 m width), aquaculture sites ($>$1 km^2) and the vegetated buffer zones (d = 1–5 km) along the waterbodies. Waterbodies that were not open to any type of hydrological change were excluded. The vegetated buffer distances were chosen based on the slope of the land and soil texture (d = 1 km if slope was $<2°$ and sandy soil; d = 5 km if slope was $>5°$ and clay soil), according to the landscape ecology theory that a vegetated buffer zone prevents pollutants from entering streams and improves the in-stream processing of pollutants (Allan et al. 1997; Wang et al. 2001; Allan 2004). Cash crop fields included cotton, oil crops, flax, medicinal plants and tobacco, which were digitised from GJDT (1993). Finally, to identify areas of wetland, satellite maps, aerial photos and recent Geographic Information System (GIS) vector data of the 2000 Wetland Map of China created by Gong et al. (2010) were integrated. There was a wide variability in the accuracy of spatial data, given the scarcity of land-cover information before the 1980s and the difference in resolution of the original references. In some instances, reference maps were used to supplement remote-sensed images, or land-cover information in 1950 was rounded based on the data sets for the 1970s. In other cases, data accurate enough to rank as sound for the purpose of working estimates at a 100 m resolution (maps after 1979) and 1 km resolution (maps before 1979) were found. Once all data sets were vectorised, the locations of resource sites with urban spread sites were overlapped to illustrate cumulative resource loss through urban spread. To qualify as a resource site converted to urban land, the proportion of urban land within the cell must exceed all other types of land cover that once dominated the cell.

The spatial correlation between city size and resource loss was tested using both the scaling function formula suggested by Bettencourt et al. (2007) and a buffer graph method. First, the scaling function method uses population (N_t) as a measure of city size (at time t) that explains various urban indicators (Y_t), expressed as $Y_t = Y_0 N_t^{\beta}$. In our study, Y_t was defined as the log of the area of resources lost to urban spread within a sample boundary. Second, the buffer graph method calculates the percentage of resource area lost to urban spread within multiple buffer rings drawn from city and town centres. The radii of buffers were incrementally increased at 500 m intervals until the buffer areas reached 100% of the region's total land. The four largest cities in the region ($N = 4$: Shanghai, Wuxi, Nanjing and Hangzhou), together with mid-sized cities ($N = 12$: cities with a population between 200,000 and 500,000 in 2000), and much smaller towns ($N = 230$: towns with a population $>$50,000 in 2000) were tested in this manner.

Once a general relationship between city size and resource loss was investigated, stratified sampling of 94 subregions was conducted for multiple regression analyses. Two components of city size effects – increases in urban spread (size factor) and pattern metrics of urban spread (efficiency factor) – were the main variables of interest related to the region's resource loss, controlling for other variables such as soil group. Stratified sampling is known to reduce the variance of its estimation when analysing spatially non-homogeneous phenomena (Richards et al. 2000; Achard et al. 2002). Thus, sampling boundaries were drawn based on three criteria: (i) areas with a population density $>$1000 people per km^2, measured based on Population Grid Data 2000 (grid size = 1 km × 1 km); (ii) areas surrounded by major geographic barriers such as mountain ridges or large waterbodies; and (iii) if delineating a boundary between two cities was difficult because of the agglomeration of dense urban settlements, their relative population sizes were used to define their boundaries. Different population density criteria were tested for comparison, as the model outcomes could be sensitive to the specifications of the sample boundaries: any density substantially larger than 1000 people per km^2 included only highly urbanised areas near urban districts; sample subregions with a density lower than 1000 people per km^2 covered too much rural land, which substantially limited the variation in resource loss ($<<$10%). Consequently, a 1000 people per km^2

definition was selected because it helped to retain densely populated urban districts, adjacent urban settlements with heterogeneous land-cover patterns and extended rural sites directly linked to dense urban settlements. This avoided the problem of 'over-bounded' or 'under-bounded' sample boundaries. This density criterion was higher than that used in Wolman's comparable study (Wolman et al. 2005), since Chinese urban regions are far denser than metropolitan regions of the United States. Any samples less than 10 km from another sample boundary or without any significant land-cover changes were excluded. Using the selected samples, the following variables were measured: (i) the average percentage of resource sites lost to urban spread (dependent variable); (ii) the natural logarithm of total population in 2000 (acquired from the University of Michigan China Data Center (2007)) and total population growth ratio between 1997 and 2005 as a proxy for pressure on resources; (iii) increases in the number of cells with urban spread between 1950 and 2010; (iv) Moran's coefficient (Moran's I) for measuring degree of clustering of urban spread; (v) urban characteristics such as the length of expressways, distances to major cities, the number of nearby towns, density of industrial enterprises and per capita gross domestic product (GDP) in 2010; and (vi) multiple geophysical variables such as soil groups (clay/silt/sand), average land slopes, the presence of timber and metal mining sites, land subsidence and flood. Tsai (2005) tested the validity of Moran's I for measuring the relative clustering (or scattering) of urban forms, showing that the index could distinguish compact urban patterns from scattered forms. While Galster et al. (2001) proposed what is probably the most comprehensive sprawl index, it was not applicable to this study because its calculation was based on residential forms and the standardised parameter of the index did not offer direct interpretation. For Moran's I, fixed distance bands of 3 km were used where the z-score of spatial clustering peaked. Stepwise multiple regression analyses were conducted with the backward elimination method (maximum p-value to retain the variables = 0.05). When all variables were tested for multicollinearity, urban spread and Moran's I showed a correlation; however, they were not excluded in order to be inclusive of interaction effects of major variables on resources.

Results

A highly dispersed pattern of environmental resource loss

The region lost some 12.2% of total environmental resource sites between 1950 and 2010 (the total number of resource cells decreased from 45,817 to 40,211; Table 1). Forests decreased by 13.6%, freshwater sites by 13.3%, cash crop fields by 9.8% and wetlands by 7.9% (Figure 1). The cumulative losses showed a highly dispersed pattern across the region, rather than being confined to a few major areas of intensity near large cities. The buffer graph method showed that only 35% of the region's total losses have

Table 1. Changes in the area of resource sites by region in 1950, 1979 and 2010 (unit = 1 km^2).

Urban regions	Forests			Wetlands			Freshwater sites			Cash crop fields			Total		
	1950	1979	2010	1950[a]	1979	2010	1950	1979	2010	1950	1979	2010	1950	1979	2010
Shanghai	18	17	11	201	320	510	1,475	1,330	1,130	1,086	1,014	865	2,780	2,681	2,516
Suzhou	227	218	146	935	850	773	2,724	2,636	2,199	1,052	1,016	872	4,938	4,720	3,990
Wuxi-Changzhou	1,084	1,074	814	1,031	888	764	2,627	2,549	2,192	599	582	519	5,341	5,093	4,289
Zhenjiang-Yangzhou[b]	751	758	407	220	185	155	1,754	1,706	1,547	481	468	441	3,206	3,117	2,550
Nanjing[b]	954	952	554	336	288	247	2,204	2,112	1,899	787	766	727	4,281	4,118	3,427
Taizhou-Nantong[b]	17	22	1	131	158	191	1,000	972	869	1,637	1,631	1,576	2,785	2,783	2,637
Huzhou	2,768	2,760	2,565	639	513	411	1,981	1,941	1,847	251	234	214	5,639	5,448	5,037
Jiaxing	94	86	40	229	173	130	909	884	800	923	914	886	2,155	2,057	1,856
Hangzhou-Ningbo[b]	3,142	3,153	2,940	272	399	586	1,491	1,442	1,289	693	681	627	5,598	5,675	5,442
Xuancheng[b]	5,955	5,957	5,493	373	309	256	2,024	2,032	2,006	739	731	712	9,091	9,029	8,467
Total	15,010	14,997	12,971	4,370	4,083	4,023	18,189	17,604	15,778	8,248	8, 037	7,439	45,817	44,721	40,211

Notes: Each value was calculated based on the number of resource sites within the sample boundaries of each regional-level city (above 'urban regions' column). The right-side column 'Total' is the summation of the cells for forests, wetlands, freshwater and cash crop sites for each year.

[a]Wetland data in 1950 were not available. Thus, the trend between 1950 and 1979 was linearly extrapolated based on the changes between 1979 and 2010, although this assumption is likely to underestimate the size of wetlands in 1950.

[b]Only parts of Yangzhou, Nanjing, Taizhou, Nantong, Hangzhou, Ningbo and Xuancheng were included for the calculation, since the outer boundary of the defined region does not cover all these cities' administrative areas. Thus, the size of resource sites in these cities is likely to be underestimated.

taken place within 30 km of the four largest cities, or 15% of the total land surface. The remaining portion, or 65% of the region's resource losses, was associated with urban spread located away from the immediate fringes of very large cities. The same proportion of land near much smaller towns ($N = 230$) accounted for some 30% of the total resource loss, demonstrating very similar degradation effects between large cities and small towns.

Sensitivity analysis was conducted to test whether the dispersion of resource loss was a result of the definition of the buffer area around cities and towns. However, even when the area definition of the buffer rings changed, the extent of the percentage of resource areas lost to urban spread between very large cities and small towns remained similar (Figure 2). For example, redefining 30% of the total land surface as buffer areas made only a small percentage difference between the four largest cities (51%) and small towns (45%). Thus, it can be safely inferred that a few large cities did not consume a disproportionately large amount of resource sites in the region. By contrast, effects of mid-sized city urban spread were smaller than the other groups: 15% of the total land near mid-sized cities ($N = 12$) explained only 21% of the total resource losses.

There was a low spatial association among the losses of different resources insofar as a high ratio of one type of loss was not always matched by a high ratio of other types of resources. Pearson's correlation analyses revealed that the pairwise correlation coefficients of four resources

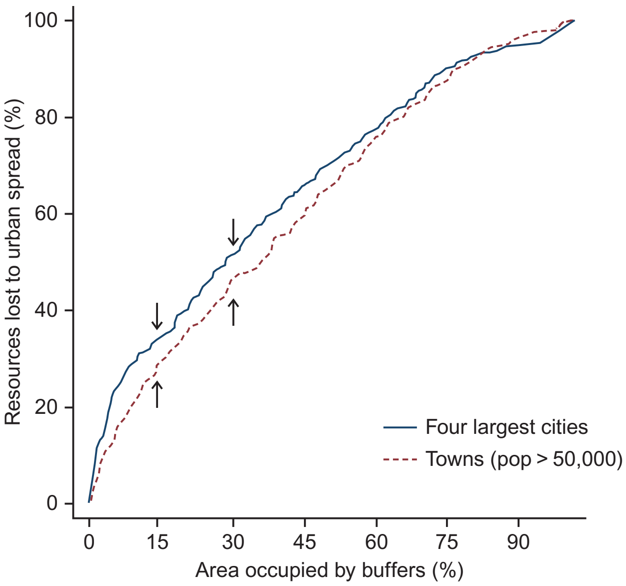

Figure 2. Percentage of resource sites lost to urban spread (1950–2010).

Notes: Relationship between buffer areas (x-axis) and the extent of resource sites lost to urban spread (y-axis) is compared between the four largest cities and 230 towns. Buffer area is the percentage of aggregated buffer rings drawn from the centres of cities/towns to the total land surface. Extent of the lost resource sites is based on the percentage of the number of resource losses (red dots) to the total resource sites. Vertical arrows show 15% buffer area and 30% buffer area criteria, respectively.

were fairly small (<0.3), with the exception of the relationship between cash crops and freshwater sites. The cities of Shanghai, Nanjing, Suzhou and Xuancheng presented considerably uneven proportions of losses. For example, urban spread in Shanghai comprised 27.1% of the region's total of lost cash crop fields, whereas its forest loss comprised only 0.4%; Nanjing's forest loss comprised 30.6%, while wetland loss comprised 5.5%; Xuancheng's forest loss comprised 9.2%, while freshwater site loss comprised only 0.1%. By contrast, the Changzhou-Wuxi-Zhenjiang region showed a relatively even proportion of loss: 21% of total lost forests, 24.5% of wetlands, 21.2% of freshwater sites and 13.9% of cash crop fields. The Huzhou and Jiaxing regions also showed a similar congruence ratio of 15.1%, 12.8%, 10.2% and 9.3%, respectively, across the same resources.

A non-linear relationship between city size and resource degradation

City size showed a weak, statistically insignificant correlation with resource loss. The scaling function test of city size showed that the log of resource loss (Y) was positively associated with the log of city size (N), but the predictive capability of city size was fairly small (adjusted $R^2 = 0.30$, $\beta = 0.535 \pm 0.201$, $N = 94$). A scaling exponent value of this formula, or β, was far less than 1, indicating that a mechanism of economies of scale shows up relative to the loss of environmental resources as the size of a city increases. When multiple variables were controlled for in the stepwise regression, city size was eliminated as being non-significant. On the other hand, increases in urban spread and its degrees of spatial clustering, measured with Moran's I, were retained as significant when soil type and rate of total population growth were held constant (Table 2). These results showed that city size could be an underlying but not singularly significant cause of land-cover change associated with resource loss in the region. A probable interpretation of this result is that the multiplication of a 'size factor' and an 'efficiency factor' explains some unanticipated outcome of city size effects on resource loss.

The log of increases in urban spread, or a size factor, was significantly associated with resource loss. The best-fit equation was as follows:

$$Y = -1.9 + 4.8 \log X \,(\text{adjusted } R^2 = 0.34), \qquad (1)$$

where Y is the average percentage loss of resource sites and X is the number of increased urban spread cells between 1950 and 2010, when one cell unit is equivalent to a 1 km^2 resolution. The level–log relationship has an intuitively clear meaning, that is, larger urban spread consumes increased levels of resources, but the effects of additional per-unit area urban land decrease as city size increases. In other words, resource loss is a saturating function of

Table 2. Regression result: significant factors associated with resource losses.

Dependent variable: resource loss (%)	Regression coefficients	Standardised coefficients	$p > \|t\|$
Moran's I	13.53	0.282	0.013
Urban spread	0.025	0.286	0.001
Soil texture (silt)	4.67	0.219	0.006
Population growth	−1.07	−0.150	0.043

Notes: Correlation coefficients of each listed variable were analysed using multiple regression analysis with backward elimination with the percentage variance in resource losses. The four variables were retained at 5% significance level. Initial independent variables were per square kilometre lengths of expressways (km/km^2), distances to the four largest cities (km), number of towns within 50 km from the centre of each sampling boundary, density of industrial enterprises, presence of land subsidence, presence of timber or mining sites, average land slope (degrees), soil group (clay/silt/sand; above), natural logarithm of total population (2000), row-standardised Moran's I of urban spread patterns (above), relative increases in urban spread (above) and population growth ratio (total population in 2005 divided by total population in 1997; above). The above regression model is statistically significant, $F = 17.5$, $N = 94$, $R^2 = 0.35$, $p < 0.0001$.

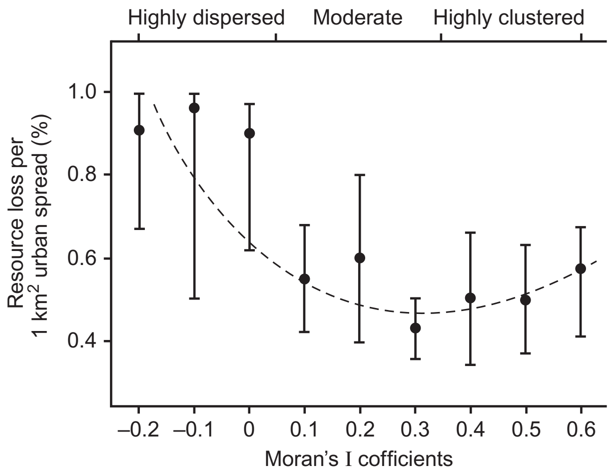

Figure 3. Relationship between resource loss per unit area of urban spread and Moran's I coefficient.

urban spread because, in largely developed areas, an additional expansion of urban land is more likely to be similar to existing urban forms. Moreover, in small urban settlements, the progressive increases in urban land should have far greater negative impacts on resources than in larger cities.

The Moran's I value of urban spread patterns, or efficiency factor, ranged from –0.4 (highly dispersed) to +0.6 (highly clustered). The regression coefficient was positive, meaning that, in general, more clustered urban patterns were associated with increased resource loss ($p < 0.001$). This outcome is counter-intuitive, since sprawl-like urban forms are frequently associated with increased land consumption (Johnson 2001). One likely explanation for the result here is that Moran's I strongly interacts with urban spread, thus its effects vary widely depending on the magnitude of the spread. Pearson's correlation test supported this, with a correlation coefficient that was fairly high (0.47), while multicollinearity in other variables was not significant (all other correlation coefficients were <0.2). Why then do urban patterns depend on the size of urban spread? In extensively built-up cities, developing new land far away from previously developed areas is often avoided, thus Moran's I is expected to increase because of the benefits of sharing existing infrastructure, social service facilities and the proximity between housing and places of employment. Thus, in general, increases in urban size result in more clustered urban patterns. However, this trend may be reversed, or Moran's I can be lowered during the process of urbanisation if continuous urban development is discouraged. For example, the presence of dense villages on the urban fringes or socially valued resource lands can be resistant to urban development, since the estimated return of urban lands may not be obviously higher than the sum of current land productivity and total cost for development in the long term. This interactive relationship between size and pattern of urban spread leads to a skewed U-shape graph between Moran's I and resource loss per unit area urban spread (Figure 3). The graph indicates that a highly dispersed urban pattern, as well as a highly clustered pattern to some extent, is more associated with increased resource loss per unit area of urban spread than moderately compact patterns. Therefore, despite a relatively small urban spread, a city may have amplified negative effects on resources if its spatial pattern is associated with both ends of the graph. Shizhuangzhen in Rugao, for example, shows a highly dispersed spread pattern (Moran's I = –0.19), which is associated with its fairly high resource loss of 30.9%. Similarly, the clustered urban spread of Haining (Moran's I = 0.41), a small city with a population of 64,000 in the year 2000, has affected the inner-city resource sites (total resource loss = 27.7%) such as severe pollution of Xiashizhen groundwater sources (Class V in 2005) and the large decreases in size of the Dongshan forest because of newly developed industrial buildings (HSDF 2006).

Complex forces behind land-cover change

Urban spread, despite its statistical significance, led to varying degrees of resource degradation when individual resources were examined separately. For example, the loss of forest and wetland had no significant relationship with the relative increases in urban land, as measured by the ratio of urban land in 2010 to that in 1950. On the other hand, the loss of cash crop and freshwater sites was a strongly positive function of urban spread. This inconsistency among resources is due partly to the uneven distribution of resources and human intervention in community-specific land cover. For example, cash crop fields were located adjacent to mid- to large-sized cities in the eastern part of the region, as well as in rural areas away from cities to the west of Taihu Lake. This bifurcated distribution led to a relatively high clustering of cash crop losses near Shanghai and Suzhou. For example, some 38.5% of Shanghai's total cropped area, including grain and cash crop fields, was eliminated between 1990 and 2008 (Editorial Committee of Expo Shanghai Atlas 2010). Yet, the amount of net loss in the region was not surprisingly high (9.8%), since it was offset by the creation of newly cultivated cash crop fields in Jiangsu and Zhejiang Provinces. The ratio of cash crop to other types of sown area, for example, increased from 13% to 16% in Jiangsu Province and from 9.5% to 11.5% in Zhejiang Province between 1998 and 2002 (Yuan et al. 2005). Lost wetlands and freshwater sites were scattered to the east, north and south of Taihu Lake, and along the coasts of the Changjiang and the East China Sea. The annual rate of wetland loss was estimated at only 0.14% over the last 60 years. Between 1990 and 2000, the rate was the highest at 0.6%. Interestingly, the region's net wetland loss was far slower than the national average of 1.5% (Gong et al. 2010), because of the natural growth of marshlands, estuaries and constructed wetlands in the study area. Also, the region was not as strongly affected by macro-climatic fluctuations like temperature change and drought as other areas such as China's Northern plain (Qian and Zhu 2001).

Environmental policies designed to protect natural lands may also have affected the non-linear relationship between urban spread and resource loss. An aggregate area of 13,525 km^2, or 3.8% of the total surface of the region's four provinces, was protected as nature reserves as of 2009 (Ministry of Environmental Protection of the People's Republic of China 2010). Shanghai has the highest proportion of these, with 14.3% of the total land surface protected. Forests and wetlands are the major land types within these reserves; for example, 84% of Jiangsu's nature reserves consist of either wetlands or forests (26 of 31 sites; Jiangsu Province 2009). In effect, the urbanisation process may have had a reduced or indirect impact on the protected lands of some forests or wetlands.

Discussion

In this analysis, resource degradation in the Changjiang Delta Region does not appear to be confined to the urban fringes of large cities. Further, city size alone does not explain the distribution of resource loss. The extensive urban spread of large cities may truly lead to a substantial loss of resources, but a set of non-linear factors, such as the diminishing effects of per unit area urban spread on resources, interactions with spatial patterns and high variations amongst different resource types linked to the interventionist regime, play a significant role in downsizing the effects of large cities on resource degradation. More conceptually, the effects of population growth on resources, and the associated spread of urban land, are offset by the increased efficiency factor during the urbanisation process. This non-linear mechanism of urban growth may explain why city size is not proportionally associated with increased resource degradation, despite the sustained regularity of city size on a broad set of urban indicators, such as wealth creation, employment, housing provision and energy use (Bettencourt et al. 2007). The more centralised expansion of larger cities may incorporate both inner-city redevelopment opportunities and new development away from important resource sites. On the other hand, urban spread in smaller cities may lead to increased susceptibility of resources to disturbances due to dispersed or polycentric patterns of expansion. Also, small cities may have limited institutional capacities, widespread poverty and low functional specialisation for maintaining the environmental quality, leading to immature coping when faced with the rapid degradation of common-pool resources.

Following on from this analysis, it is clear that the simultaneous growth of small and large cities poses challenges to the conservation efforts of local governments. A singular approach of protecting only hotspots of environmental threats is difficult to achieve in a region where different-sized urban settlements are affecting the land-cover patterns. Additionally, policies designed to minimise the development of urban lands may have the unintended effect of suppressing reasonable supplies of developable land in well-managed cities, despite a policy's practical role in saving resource land. This may in turn lead to the depletion of productive lands by motivating the rapid spread of much smaller cities and villages with highly duplicative and land-consumptive urban patterns. No causal relationship should be inferred, but the region's resource loss and its spatial dispersion seem to be highly attributed to the diminished efficiency factor of urban land use in small cities and towns. In short, land-use control in an urbanising region is necessary but not sufficient to ensure conservation of the most valuable resource land located between interconnected cities.

From a more historical perspective, during the boom period of urbanisation in China since 1978, on-ground environmental management efforts hardly achieved their intended goals and were overshadowed by other urgent goals of economic development and poverty reduction. The growth of small cities and towns was promoted as a national policy at China's 1980 *National Conference on Urban Planning*. Small cities and towns came to be vigorously linked with larger cities to export industrial production to larger markets, to channel surplus population into rural industries and to transfer basic social services to underdeveloped villages (Kwok 1982). Simultaneously, larger cities were designated as growth centres under urban reform, although overly concentrated urban growth was curtailed to some extent (Rowe 2005). A series of government policy interventions, including the first *National Land Survey* (1984–1996), the *Land Administrative Law* with several amendments (1986) and the designation of nature reserves, were met with scepticism because of their lack of capital investment, conflicts with localised economic gains and the vague definition of preservation goals (Lin and Ho 2003; Liu et al. 2003). More recently, at least six key forestry programmes were initiated, beginning in the late-1990s. However, the central government's total investment in the programmes was less than 0.2% of national GDP in 2005, which was very minor compared to the nation's enormous environmental damage (Wang et al. 2008; National Bureau of Statistics of China 2009).

Nevertheless, the region's priority on urbanisation and economic growth scarcely resulted in unmitigated destruction of productive resource land, despite some cases of large-scale arable land loss. China's institutional players – from rural collectives to municipal governments – appear to have valued productive land resources for very practical reasons. In Dongshanzhen, Suzhou, for example, cultivating aquaculture products (e.g. crabs) and cash crops (e.g. waxberry and pipa) generated the dominant sources of rural income, which in turn stabilised the livelihood of rural villages and generated high tax revenues from increased agricultural outputs. Thus these lands were expanded up to 36.6% of the town's total land, whereas the lowland forests were selectively converted into urban settlements for the booming tourism industry (Dongshanzhen Government 2007; author interview with Professor Rongsan Ruan). Additionally, land-cover conversions from resource sites to urban land occurred in a very selective process and were generally under the control of local governments and collectives. During the mid-1980s, local governments were empowered with fairly strong control over land development, such as preparing annual land-use plans and issuing licenses for land conversions under the central quota allocation system. At a metropolitan scale, Shanghai was the first Chinese city that protected its drinking water sources under the *Regulations on the Water Source Protection of the Upper Reach of Huangpu River* of 1985. Shanghai's government constructed sewage pipes, relocated enterprises that did not meet pollution standards, closed 173 livestock farms and reforested some 44 km^2 of land along the river (Information Office of Shanghai Government 2010; Krantzberg et al. 2010). Due to these efforts, there were minimal land developments along the 5 km buffer of the river's upper reaches, with an annual rate of urban spread $<2\%$, which was far slower than the city's overall rate of 3.1% between 1979 and 2010.

This trend of rising administrative power of cities, collective demand for well-maintained environmental resources and continued land consumption by urban households will pose both challenges and opportunities in the Changjiang Delta Region. Rigid regulatory controls on urban development or a complete freeze on the transfer of land-use rights may not be realistic, because of the region's economic contribution to the production of 19% of national GDP and 29% of the nation's export commodity value (Rowe 2011). A large portion of resource land will be outbid by land developers, since the economic value per area of urban land far exceeds the value of natural resource land. Also, the region is already one of the areas with the highest conservation costs in the light of rehabilitating its cumulative damage and relocating existing villagers living in dense rural settlements, together with the Northeast Plain, the Pearl River Delta and the Sichuan Province (Xie 2009). It is true that the rate of China's urbanisation will probably stabilise in the next few decades, bottom-up demands for environmental remediation will come into play and the decommissioning of aging infrastructure will be carried out for both economic gain and ecological restoration. However, the region's environmental threats and instances of scarcity are in expanding rather than in contracting phase. Per capita arable land was no more than 0.04 ha per person in 2005 and is rapidly shrinking. Indeed it was less than half of the national average of 0.11 ha per person, and less than one-quarter of the world average of 0.23 ha per person, or of the US average of 0.62 ha per person (World Bank 2004). More broadly, Asia's consumption of resources has been soaring over the last five decades. In 1961, 55% of the world's population lived in Asia, consuming 22% of world's fertiliser, 13% of world's meat and 27% of world's domestic materials, including construction materials. In 2007, Asia's population percentage increased only slightly to 60%, while resource use increased sharply to 55% (fertiliser), 43% (meat) and 54% (domestic materials), respectively (Galloway et al. 2008; Food and Agriculture Organization of the United Nations 2009; Schandl and West 2010). Thus, the multiplier effects of increased resource consumption, including per capita land and water, are likely to reshape both the regional and global environment.

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