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Research paper

Assessing urban sustainability of Chinese megacities: 35 years after the economic reform and open-door policy

Selected as Editor's Choice by Landscape and Urban Planning

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HIGHLIGHTS

- GDP has increased much faster than GPI in Chinese megacities in recent decades.
- Chinese cities have improved human welfare greatly at the expense of environment.
- Western Chinese cities lag in development and have smaller ecological footprints.
- Eastern Chinese cities are challenged by more and greater environmental problems.
- Chinese megacities are faced with increasing problems of socioeconomic inequality.

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ABSTRACT

Driven by unprecedented economic development for more than three decades, China's urbanization level rose from 17.9% in 1978 to 54.8% in 2014. This breakneck speed of urbanization has resulted in myriad environmental problems and social inequities. To gauge the urban sustainability of China, our study focused on ten megacities which are socioeconomic centers of the country. We evaluated the three dimensions of sustainability using a set of sustainability indicators, including Genuine Progress Indicator (GPI), Ecological Footprint (EF), Biocapacity, Environmental Performance Index (EPI), City Development Index (CDI), Human Development Index (HDI), Gini coefficient, and Urban–rural income ratio. Based on time-series data from 1978 to 2012, our study has produced the following findings: (1) The values of GPI for the ten megacities started to increase since 2006 after a relatively constant period between 1994 and 2005; (2) The pressures of economic growth on the environment (EF) increased while biocapacity decreased for the ten megacities, with smaller biocapacity deficits for western cities; (3) The overall level of human wellbeing (HDI) increased; (4) Socioeconomic inequality (Gini and urban–rural income ratio) widened, but the widening trend seemed to have ceased in recent years for most of the ten megacities; and (5) Certain aspects of urban environment and city development (EPI and CDI) improved gradually, particularly in waste treatment and infrastructure development. Our findings suggest that, to achieve overall urban sustainability, China must move away from maximizing economic development and focus on improving environmental quality of its megacities.

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1. Introduction

After thousands of years of being predominantly agrarian, China has become urban as about 55% of its population now live in urban areas, surpassing the global average urbanization level for the first time (Wu, Xiang, & Zhao, 2014). Although China has the longest urban development history in the world, its urbanization rate has picked up the pace only during the past three decades. Since the economic reform and open-door policy in 1978, China's rapid urbanization has been driven by the exponential growth of national GDP (Bai, Chen, & Shi, 2012; Wu et al., 2014). China's urban population increased from 170 million (17.9%) in 1978 to 730 million (53.7%) in 2013, with an annual growth rate of 1.02%. Three main urban agglomerations (the Beijing–Tianjin–Tangshan, the Yangtze

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River Delta, and the Pearl River Delta) gathered 18% of Chinese total population, and made up of 36% of national GDP in merely 2.8% of the country's land area (CPC Central Committee and State Council, 2013).

Such a record speed and scale of China's urbanization has induced a series of environmental problems, including landscape fragmentation caused by the drastic change in land use, regional climate change from the altered surface radiation regimes, biodiversity loss, and ecosystem degradation (Bai et al., 2012; Gaubatz, 1999; Liu, Zhan, & Deng, 2005; Liu, He, Zhou, & Wu, 2014). By 2050, the urbanization level of China is projected to be 77.5% (Wu et al., 2014). So China is faced with continued rapid urbanization in the next thirty-five years, and thus must deal with the issue of urban sustainability.

In addition to several related models of urban development (e.g., Garden city, Healthy City, Eco-city, Low-carbon City, Smart City), "Sustainable City" is a relatively new but increasingly popular concept (Alberti, 1996; Mega & Pedersen, 1998; Mori & Christodoulou, 2012; UN-Habitat, 1996; Wu, 2008). In response to the calling of Agenda 21, a number of urban sustainability indicators have been developed since 1992 to assess the progress in developing sustainable cities (Huang, Wu, & Yan, 2015). China is one of the most active countries in promoting eco-cities and low-carbon cities (Qiu, 2013). By 2011, 230 of the 287 prefecture-level cities in China had proposed to build eco-cities, and 133 of them had initiated low-carbon city plans. Our literature search reveals that there have been at least 11 national-level sustainable city movements in China (Table 1, Part I), with 8 guiding indicator sets provided by different organizations (Table 1, Part II). While such efforts are well-intended, gauging their actual progress in urban sustainable development is challenging. Many of the proposed assessment methods do not seem adequate, and some of these efforts are yet to be evaluated.

Therefore, the main purpose of this study was to assess the sustainability of ten Chinese megacities in the 35 years after the economic reform and open-door policy in 1978, using a set of widely used sustainability indicators and following the Triple Bottom-Line principle of sustainability. These megacities are the political, economic, and cultural centers in China, together capturing the salient features of the rapid urbanization in China during the past several decades.

2. Methods

2.1. Study cities

There are 16 megacities with a municipal district population exceeding 5 million, as defined in the "Integrating Farmers in Cities Plan (2014–2020)" released by the CPC Central Committee and State Council. Of the 16 megacities, we chose 10 provincial capitals because they, as capital cities, have higher levels of comparability, geographic representation, and data availability. In the "National Urban System Planning (2005–2020)", the Ministry of Housing and Urban–Rural Development of China classified Chinese cities hierarchically into several categories: "globally functioning cities", "regional central cities", and other cities. In this study, four megacities – Beijing, Tianjin, Shanghai, and Guangzhou – are globally functioning cities, and the other six – Chongqing, Shenyang, Nanjing, Wuhan, Chengdu, and Xi'an – are regional centers (Fig. 1).

Differing from North American and European cities, these Chinese cities are metropolitan regions that include both urban and rural areas. For example, Beijing City (short for Beijing) includes 14 urban districts and 2 counties. Also, in this study urban population refers to resident population, not registered population, as the former better reflects the actual level of city's production, consumption and waste emission. For instance, the electricity power is consumed by the resident population of a city, and then its carbon footprint considers all the carbon emissions by all the people residing in the city, even some released in other areas.

Fig. 1. Locations of the ten study megacities in China, which fall into four regions: Western Region (Chengdu, Chongqing, and Xi'an); Central Region (Wuhan); Eastern Region (Beijing, Guangzhou, Nanjing, Shanghai, and Tianjin); and Northeastern Region (Shenyang). Unnamed dots denote the other 24 megacities or provincial capital cities in China. The classification of four regions is from "National Urban System Planning (2005–2020)", released by the Ministry of Housing and Urban–Rural Development of China.

Table 1
Sustainable city movements in China and associated indicators.

Number	City movement (initiation time–end time)	Number of winning cities (up to 2013)	Target	Indicator System (publish year, newly-revised year)
Part I: National city movements and assessment systems				
1	National Garden City (1992) and National Ecological Garden City (2004)	Former: 113; Latter: 0	National Garden City: Focus not only on garden greening, but involving multiple aspects, including sanitation, transport, housing security, and urban management National Ecological Garden City is the updated version of National Garden City: Use ecological principles to reduce pollution, implement clean production, green transportation, and green buildings	National Garden City Standard (1992, 2010)
2	China-Habitat Scroll of Honour Award (2000–)	33	Echoed with "UN-Habitat Scroll of Honour Award" and "Dubai International Award for Best Practices to Improve the Living Environment", to encourage and recognize the cities, towns, organizations and individuals who have made great contributions to the improvement of environmental quality and human settlements	China-Habitat Scroll of Honour Award evaluate indicator system (2010)
3	Eco-city (2003–)	19	Realize the rational exploitation of natural resources and improvements of the ecological environment, meanwhile ensure socioeconomic development and meet increasing mass material and cultural life needs	Construction indicators of Ecological County, Municipality, and Province (2003, 2007)
4	National Model City for Environmental Protection (1997–)	84	Take sustainable urban development as the principle to set models of coordinating social and economic development with healthy environment quality	National Model Cities for Environmental Protection Assessment Indicator and Implementing Detailed Rules (1997, 2011)
5	National ecological civilization pilot demonstration zone (2008–)	Approximately 37	Upgrade eco-city construction (mentioned in number 3) to ecological civilization construction	National Ecological Civilization Pilot Demonstration Zone Indicator (tentative standard) (2013)
6	National ecological civilization pioneer demonstration zone (2013–)	–	Build a resource-saving and environment-friendly society, seek the path to ecological civilization construction based on its own realities	National Ecological Civilization Pioneer Demonstration Zone Indicator System (tentative standard) (2013)
7	Ecological civilization demonstration project in western area (2011–)	13	Reinforce ecological construction and environmental protection, quicken the pace of switching the way of economic development	Not yet
8	National pioneer demonstration zone in sustainable development (1986–)	5	Carry out China's agenda 21and the national strategy of sustainable development	No
9	National civilized city (1980–)	19	Achieve coordinated development among material, political and spiritual civilization while at the same time achieving economic growth, so as to enhance the overall citizen's ideological quality	National Civilized City Assessment System (2005, 2011)
10	National Hygienic City (1990–)	Approximately 155	Improve the urban (including villages in cities, the urban and rural fringe) hygiene level provide the residents with a clean and comfortable living environment	National Hygienic City Assessment and Naming, Supervision and Management Methods (1990, 2009)
11	Healthy City (2007–)	–	Improve environmental and sanitary conditions to provide a better health service	Differ from WHO Healthy City assessment system, the establishment of China's healthy city assessment system started in 2009 and is currently in the preassessment phase
Part II: Guiding indicator sets provided by different departments or organizations				
12	Evaluation of the performance of urban developmental strategy (2002)		Design a performance index for Changsha, Zhuzhou, Xiangtan, et al. to help assess the improvement of living standard and the performance of urban governance on key issues	Chinese urban developmental strategy Performance Index (2002)
13	Livable City (2005–)		Build livable cities with fresh air, and beautiful environment	Livable City Scientific Evaluation Standards (2007)
14	–		Assess circular economy for urban and industrial park.	Circular economy assessment system (2007)
15	–		Evaluate Chinese cities' new path of urbanization	Chinese cities' developmental ability indicator system (2005), China's new urbanization strategy indicator system (2008)
16	–		Lower urban carbon emission	Low-carbon city standard (2011)
17	The Urban China Initiative (2010)		Evaluate the environmental stability, the services offered by each city, and each city's resource efficiency. Assess 112 cities between 2005 and 2008	Urban Sustainability Index (2010)
18	Sino-Singapore Tianjin Eco-city (2008)		Explore a livable eco-city model of scientific development, social harmony and ecological civilization in water-deficient area	Sino-Singapore Tianjin Eco-city indicator system (2008)
19	Caofeidian Area ·Tangshan Bay Eco-city (2008)		Explore an eco-city model with low-carbon, resource-saving and human-nature harmony	Caofeidian Area ·Tangshan Bay Eco-city indicator system (2008)

Note: In part I, the symbol "–" denotes a sustainable city movement that has not been assessed yet. In 2012, the total number of Chinese cities was 657 (National Bureau of Statistics of the People's Republic of China, 2013).

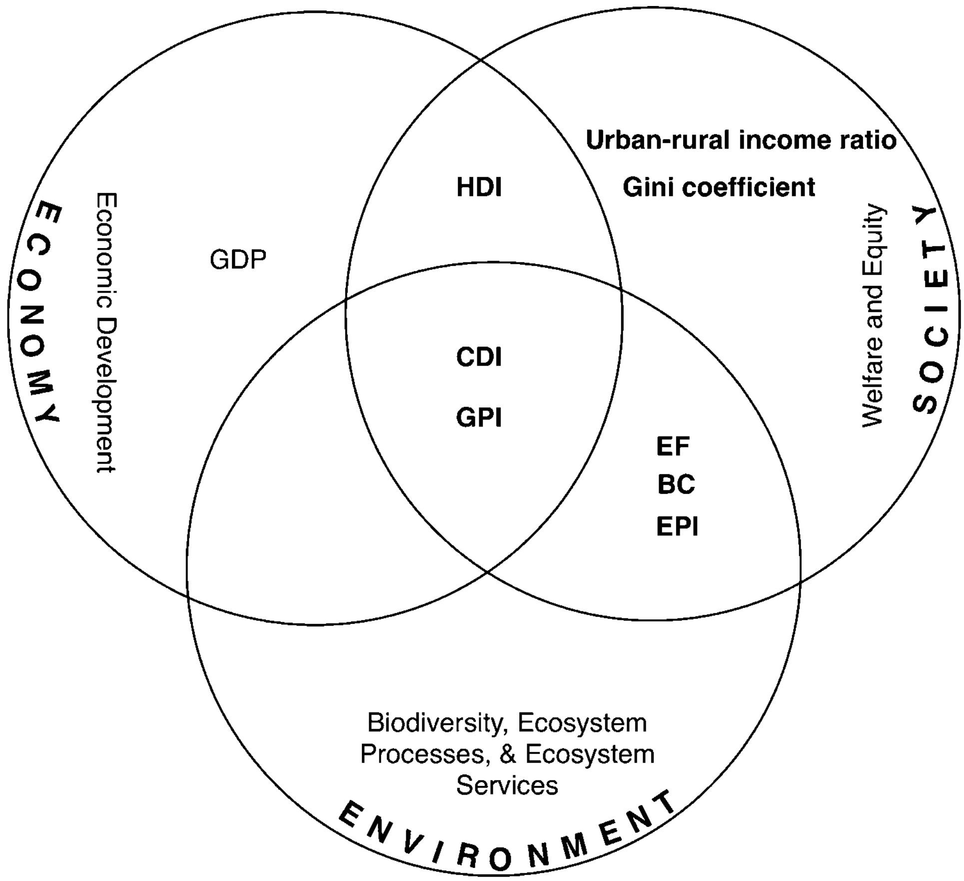

Fig. 2. Indicators used in this study to assess the three dimensions of sustainability—environment, economy, and society.

2.2. Selection and calculation of urban sustainability indicators

The Triple Bottom-Line concept of sustainability emphasizes the balance among the three dimensions—environment, economy, and society (Wu, 2013), and has been widely used as a guiding principle for sustainability assessment (Alberti, 1996; Huang, Wu, & Yan, 2015). In this study, we followed this principle, and selected the following indicators to assess the three dimensions of sustainability: Genuine Progress Indicator, Ecological Footprint, Biocapacity, Environmental Performance Index, City Development Index, Human Development Index, Gini coefficient, and Urban-rural income ratio (Fig. 2). In a recent article (Huang, Wu, & Yan, 2015), we have reviewed these and other urban sustainability indicators in detail. Thus, we only briefly describe these indicators here as follows.

2.2.1. Genuine Progress Indicator (GPI)

GPI measures the economic welfare generated by economic activities, essentially adding the positive components and subtracting the negative components left out of GDP (Kubiszewski et al., 2013; Wen, Yang, & Lawn, 2008). In this study, the negative components included fifteen items and the positive included four (Table 2). We used the mathematical formulation of each item in Wen, Zhang, Du, Li, & Li (2007) and Wen, Yang, & Lawn (2008), with some modifications. First, China's urban–rural dual land system leads to the division of statistical data, so we had to calculate Gini coefficient for the urban area and rural area separately, instead of the whole city. Second, we assumed that the net loss of forests was zero in the megacities under study.

2.2.2. Ecological Footprint (EF) and Biocapacity (BC)

EF measures the environmental pressure of resource consumption and waste disposal while BC measures the amount of biologically productive land and sea area available to bear this environmental pressure (Rees & Wackernagel, 1996). We followed the Global Footprint Network's accounting framework (Borucke et al., 2013; Eqs. (1) and (2)),

$$\mathrm{EF}_C = \sum_i \frac{C_i}{Y_{W,i}} \cdot \mathrm{EQF}_i \tag{1}$$

where $\mathrm{EF_C}$ is the Ecological Footprint of consumption; C is the amount of each primary product i that is consumed (or carbon dioxide emitted) in the city; $Y_{W,i}$: the average world yield for commodity i (or carbon uptake capacity in cases where C is CO_2); and EQF_i is the equivalence factor for the land use type producing products i;

$$\mathrm{BC} = \sum_i A_{U,i} \cdot \mathrm{YF}_{P,i} \cdot \mathrm{EQF}_i \tag{2}$$

where $A_{U,i}$ is the bioproductive area that is available for the production of each product i at the urban scale; and $\mathrm{YF}_{P,i}$ is the province-specific yield factor for the land producing products i. Key parameters in EF were adopted from peer-reviewed literature and published books: $Y_{W,i}$ (Xie, Wang, & Chen, 2008; Yang, He, Mao, Yu, & Wu, 2004), Carbon Emission Factor (World Resources Institute, 2013), Carbon uptake capacity (Xie et al., 2008), EQF_i (Kitzes, Peller, Goldfinger, & Wackernagel, 2007), and $\mathrm{YF}_{P,i}$ (Liu, Li, & Xie, 2010).

2.2.3. Environmental Performance Index (EPI)

Environmental Performance Index (EPI) evaluates the state of protection of human health from environmental harm and protection of ecosystems (Hsu et al., 2014). The eight steps of EPI calculations are: (1) input raw data, (2) transform indicators, (3) set targets and low performance benchmarks, (4) transform targets and low performance benchmark,

Table 2
GPI components among the ten Chinese megacities in 2012. The unit was 100 million dollars (in 2005 US$) or specified otherwise. Blank spaces are missing values.

GPI component	Beijing	Tianjin	Shanghai	Chongqing	Nanjing	Guangzhou	Chengdu	Wuhan	Xi'an	Shenyang
GPI's starting point-consumer expenditure	861.26	441.60	1210.85	555.88	328.66	663.63	323.73	243.31	213.85	239.47
Adjustment for unequal income distribution (for rural residents)	0		0	0		0				
Adjustment for unequal income distribution (for urban residents)	−295.56	−177.74	−567.96	−84.68	0.00	−150.64	−86.10	−46.85	−61.78	−82.48
Cost of consumer durables	−17.87	−10.24	−22.10	−35.14	−17.59	−12.50	−9.61	−7.36	−7.76	−12.00
Economic costs-proportion to GDP (%)	**−12.28**	**−10.50**	**−21.06**	**−7.56**	**−1.76**	**−8.80**	**−8.47**	**−4.88**	**−12.01**	**−10.66**
Services of consumer durables	80.40	46.08	99.47	158.13	79.14	56.25	43.24	33.14	34.93	54.00
Economic benefits-proportion to GDP (%)	**3.15**	**2.57**	**3.55**	**9.98**	**7.92**	**3.04**	**3.83**	**2.98**	**6.03**	**6.09**
Cost of crime	−14.18	15.54	−30.69	−19.62	−6.78	−14.53	−8.50	−7.70	−4.33	−6.25
Cost of automobile accidents	−0.04	−0.05	−0.02	−0.02		−0.01	−0.01	−0.01	−0.01	−0.01
Cost of commuting	−159.58	−73.26	−114.67	−30.00	−22.73	−82.72	−34.25	−12.62	−17.55	−39.59
Cost of family breakup	−0.55	−0.29	−0.58	−0.70	−0.20	−0.23	−0.42	−0.22	−0.15	−0.23
Cost of underemployment	−0.89	−2.69	−3.97	−1.53	−0.54	−3.44	−0.80	−1.01	−1.02	−0.82
Social costs-proportion to GDP (%)	**−6.86**	**−3.39**	**−5.35**	**−3.28**	**−3.03**	**−5.45**	**−3.89**	**−1.94**	**−3.98**	**−5.29**
Value of leisure time	413.21	216.11	274.72	324.28	126.30	206.33	132.71	108.42	95.75	25.14
Value of housework and parenting	47.16	32.53	48.56	113.04	19.86	24.13	41.38	26.05	21.19	23.07
Value of volunteer work	5.03	2.63	3.34	3.95	1.54	2.51	1.62	1.32	1.17	0.31
Social benefits-proportion to GDP (%)	**18.23**	**14.04**	**11.66**	**27.86**	**14.77**	**12.57**	**15.55**	**12.22**	**20.40**	**5.47**
Cost of pollution (air pollution is not included)	−47.57	−21.87	−18.62	−25.95	−37.14	−2.91	−2.77	−2.21	−1.88	−0.96
Cost of air pollution	−48.51	−34.01	−53.24	−30.10	−19.00	−35.20	−21.47	−21.11	−11.00	−16.85
Cost of wetland loss	0.01	0	−0.45		−0.06			−0.07	−0.02	−0.38
Cost of farmland loss	−0.37	−0.05	−0.03	−0.16	−0.03	−0.02	0	−0.13	−0.23	0.63
Loss of old-growth forests	0	0	0	0	0	0	0	0	0	0
Depletion of nonrenewable resources	−119.18	−167.91	−219.96	−82.56	−186.55	−146.24	−12.10	−54.60	−22.71	−34.13
Cost of long-term environmental damage	−5.61	−5.04	−7.14	−9.35	−4.56	−5.33	−1.89	−5.08	−1.14	−2.23
Environmental costs-proportion to GDP (%)	**−8.66**	**−12.79**	**−10.69**	**−9.35**	**−24.74**	**−10.24**	**−3.38**	**−7.49**	**−6.39**	**−6.15**
GPI	697	261	598	835	260	499	365	253	237	146
GPI/capita ($/capita)	3369	1849	2510	2837	3200	3887	2573	2503	2774	1775
GPI/GDP	0.27	0.15	0.21	0.53	0.26	0.27	0.32	0.23	0.41	0.16

Table 3
The framework of EPI used in this study.

Index	Objectives	Objective Weight (% of EPI)	Policy Categories	Indicators	Indicator Weight in EPI %	Target	Low performance benchmark	Statistical transformation	Transformed targets	Transformed low performance benchmark
EPI	Environmental Health	30	Environmental burden of disease	Child mortality	15.00	0.001	0.11	Natural logarithm	-6.91	-2.18
			Air pollution (effects on humans)	Indoor air pollution	3.75	0%	100	Natural logarithm	-2.30	4.61
				Particulate matter	3.75	20 μg/m^3		Natural logarithm	3.00	6.80
			Water (effects on humans)	Access to drinking water	3.75	100%	36	None		
				Access to sanitation	3.75	100%	13	None		
	Ecosystem Vitality	70	Air Pollution (effects on ecosystem)	Sulfur dioxide emissions per capita	4.96	0 kg	105.63	Natural logarithm	-1.30	4.66
				Sulfur dioxide emissions per GDP	4.96	0 g	11.39	Natural logarithm	-2.59	2.44
			Water (effects on ecosystem)	Wastewater treatment	9.33	100%	14.09	None		
			Biodiversity & Habitat	Biome protection area	18.08	17%	0	None		
			Agriculture	Pesticide use intensity	6.41	3 kg/ha		Natural logarithm	1.10	4.34
			Forestry	Forest cover change	6.41	0.9988 of forest cover change in time2 to time1	0.89	Natural logarithm	0.00	-0.12
			Climate Change	CO_2 per capita	6.71	1262 kg CO_2	19588.33	Natural logarithm	7.16	9.88
				CO_2 per GDP	6.71	0.0784 kg CO_2	1.53	Natural logarithm	-2.04	0.46
				CO_2 emissions per electricity generation	3.2	0	845.33	Natural logarithm	-0.69	6.74
				Access to electricity	3.2	100%	0	None		

Note: The main body of this framework was from 2012 EPI report (Emerson et al., 2012). Words in blue were from 2014 EPI report (Hsu et al., 2014), and words in red were modified based on the characteristics of Chinese cities and data availability.

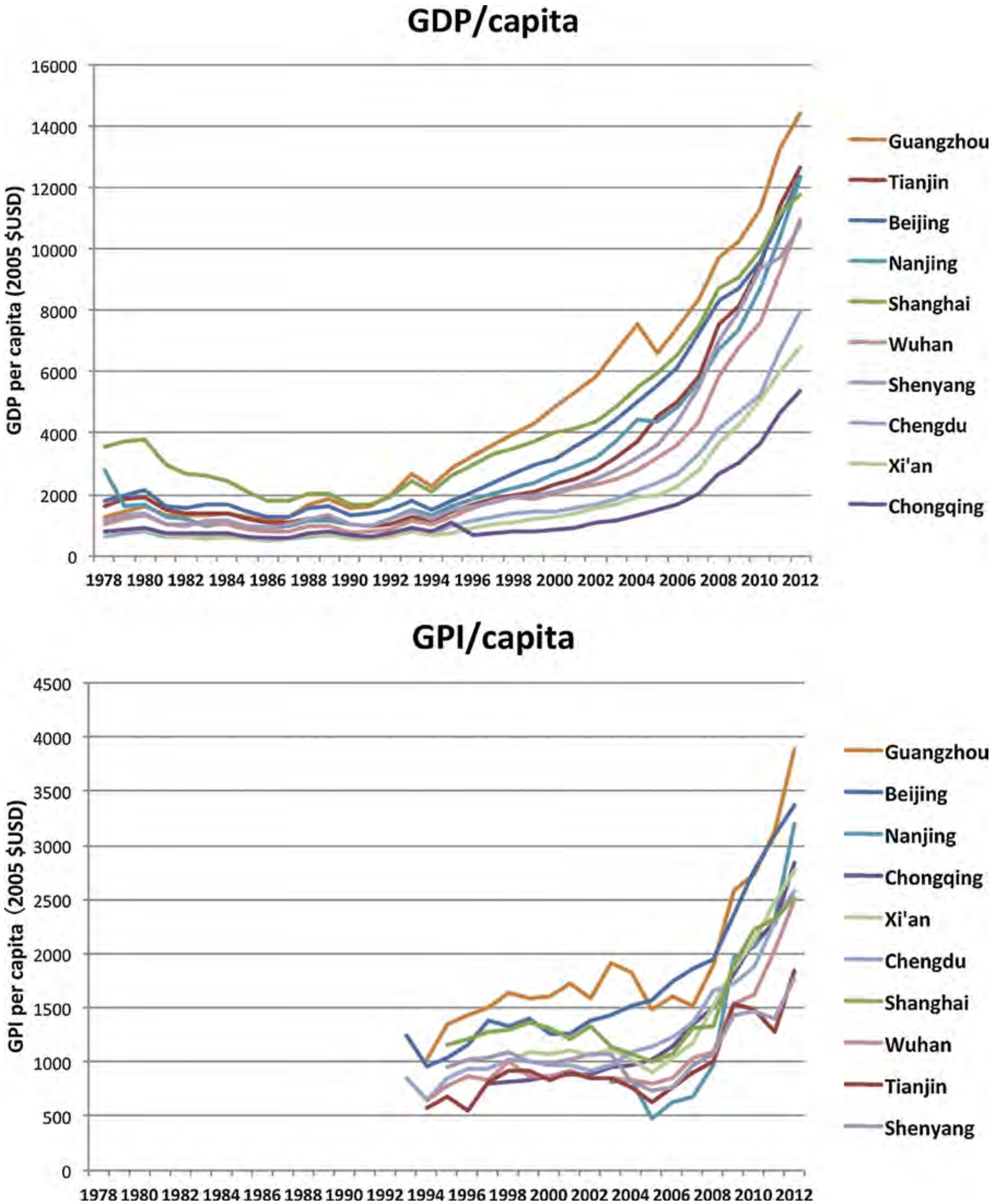

Fig. 3. GPI/capita, GDP/capita, and annual growth rates of GPI/capita and GDP/capita of ten megacities during 1978 to 2012. GPI/capita and GDP/capita were in 2005 US$.

(5) calculate proximity-to-target value which equals [(low performance benchmark – target) – (indicator – target)] × 100/(low performance benchmark – target), (6) aggregate to policy category, (7) aggregate to objective, and (8) aggregate to EPI index (Emerson et al., 2012). On the basis of 2012 and 2014 EPI frameworks (Emerson et al., 2012; Hsu et al., 2014), we modified some parameters according to the characteristics of Chinese cities and data availability (Table 3): (1) We replaced $PM_{2.5}$ with PM_{10} because of the lack of data availability; (2) If some indicators were not available at the urban level, the other indicators in the same category receive the corresponding weight; and (3) Most Targets were the default values from the EPI 2012 or 2014 report, except for the target of PM_{10} which was set to 20 $\mu g/m^3$ (daily mean of PM_{10} in a year) according to WHO, and the "Protection area" which was set to 17% according to Eco-city (Table 1, number 3). The low performance benchmarks of "Pesticide use intensity" and "PM_{10}" were the lowest values among the ten megacities within the 35 years.

2.2.4. *City Development Index (CDI) and Human Development Index (HDI)*

City Development Index (CDI) is a measure of average well-being and access to urban facilities by individuals (UN-Habitat,

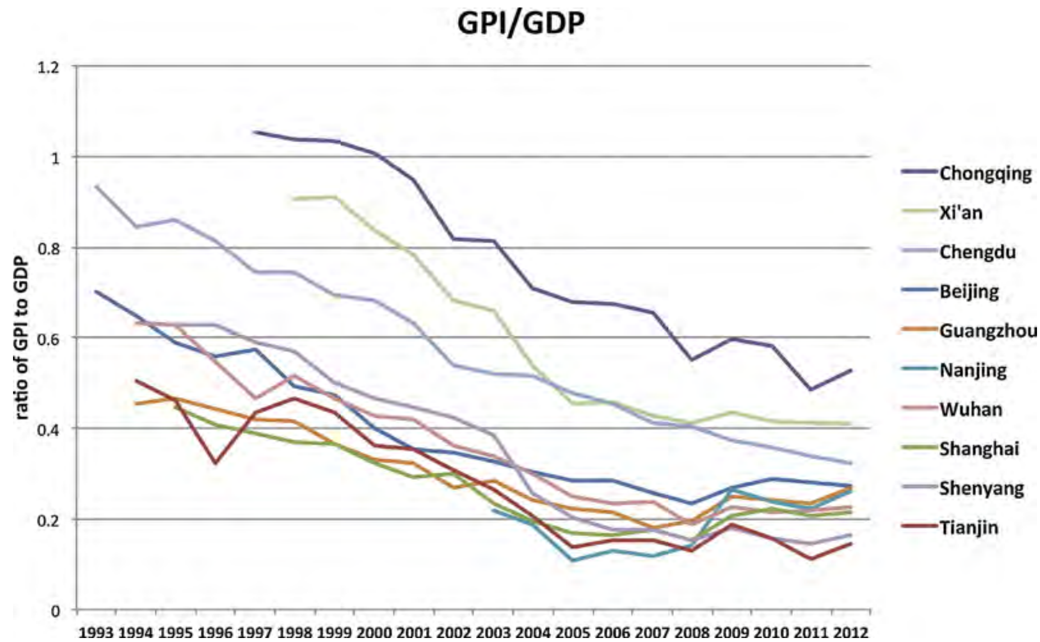

Fig. 4. The ratio of GPI to GDP for the 10 study megacities, showing a generally declining trend. The three cities in the Western Region – Chongqing, Xi'an, and Chengdu in a descending order – had much higher values than other cities.

2002). The sub-indices, waste, health, and infrastructure, only reflects urban environmental conditions indirectly. As one of the most widely-used sustainability indicators, Human Development Index (HDI) is a measure of life expectancy, income, and education (UNDP, 2009). Because of the limitation in data availability and quality, this index was computed only for four megacities—Beijing, Tianjin, Shanghai, and Chongqing.

2.2.5. Gini coefficient and Urban-rural income ratio

As the most widely used index of inequality, the Gini coefficient measures the extent to which the distribution of income among individuals within an economy deviates from a perfectly equal distribution (Atkinson, 1970). As mentioned earlier, we could only compute the Gini coefficient for urban households and rural households, separately, because of the data availability. We further used the urban–rural income ratio to measure the income inequality between urban and rural populations based on disposable income.

2.3. Data acquisition and processing

Social and economic data were mainly from each city's Statistical Yearbook, China City Statistical Yearbook, China Energy Statistical Yearbook, China Statistical Yearbook, and Statistical Communiqué on Economic and Social Development. Environmental data were obtained from the published literature, each city's Statistical Yearbook, and China Statistical Yearbook on Environment (the data sources of each indicator were listed in the Appendix). For missing values, we used the first order regression to fill the gaps within a series based on closest available data points (Emerson et al., 2012).

3. Results

3.1. GPI and GDP

For all the ten megacities, both GPI/capita and GDP/capita showed an upward trend in time, but the increase of GDP/capita was generally faster than GPI/capita (Fig. 3). GDP/capita remained relatively unchanged up to 1994 and then increased dramatically. By contrast, GPI/capita remained relatively constant between 1994 and 2005, and increased rapidly since 2006 (Fig. 3). The gap between GPI and GDP, as represented by the GPI/GDP ratio, had been widening from a historical perspective, but became relatively stable in recent years for most megacities (Fig. 4). The ranking of the megacities in 2012 in a descending order of the GPI/GDP ratio was: Chongqing, Xi'an, Chengdu, Beijing, Guangzhou, Nanjing, Wuhan, Shanghai, Shenyang, and Tianjin. Major costs included income inequality, commuting cost, pollution cost and nonrenewable resource depletion (Table 2). Benefits of leisure time, housework and parenting, and volunteer work contributed a lot in GPI calculating.

3.2. EF and BC

EF/capita varied among cities in 2012 (Fig. 5). The highest EF/capita was 4.45 global hectares (gha) (Nanjing), whilst the lowest was 1.54 gha (Chengdu). Carbon footprint and farmland footprint were the main components of the total EF. Ten megacities' EF/capita increased remarkably in the past 20 years (Fig. 6). In the recent five years, the values of EF/capita for Nanjing and Wuhan were between 3.5 and 4.5 gha; the values of EF/capita of Guangzhou, Tianjin, Beijing, Shanghai and Shenyang were between 2 and 3 gha; while the values of EF/capita of Chongqing, Xi'an and Chengdu were below 2 gha. Western cities, especially Chengdu and Xi'an, had lower values of EF/capita than eastern cities.

Chongqing's biocapacity ranked the highest, 0.75 gha per capita in 1995, and then dropped to 0.40 gha in 2000. The biocapacity of other cities also decreased, but not as sharply as that of Chongqing (Fig. 6). The ranking order of cities by BC/capita from large to small is as follows: Chongqing, Shenyang, Nanjing, Guangzhou, Wuhan, Chengdu, Xi'an, Beijing, Tianjin, and Shanghai. The BC/capita values of Guangzhou, Wuhan, and Chengdu were close to each other, while those of Xi'an and Beijing were similar before 2003.

3.3. EPI

The overall EPI of the ten megacities all show an increasing trend, with values ranging from 27.8 (Beijing in 1994) to 66.7 (Xi'an

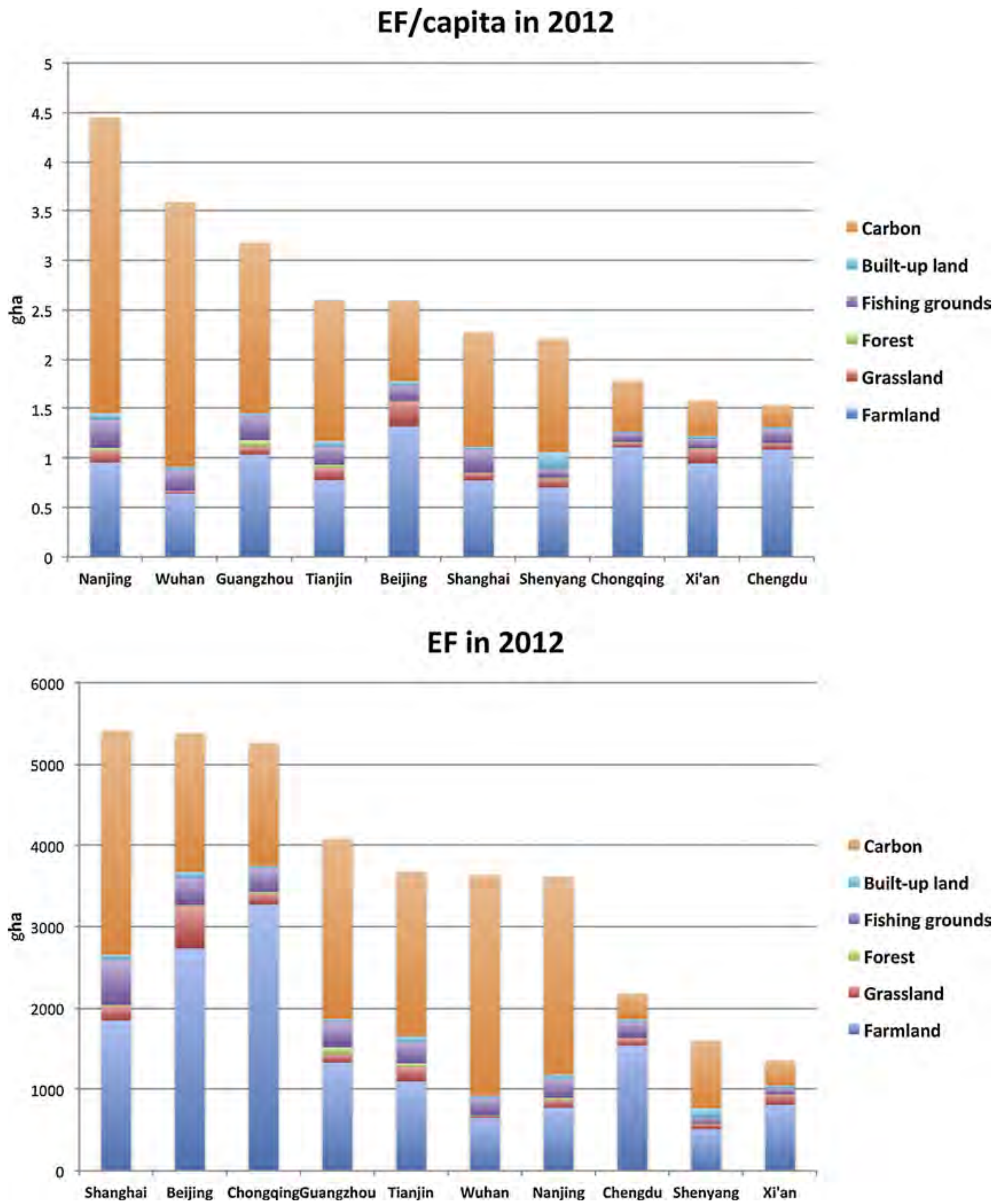

Fig. 5. Per capita EF and the total EF in 2012. Nanjing, Wuhan, and Guangzhou were the top three by per capita EF, and Shanghai, Beijing, and Chongqing were the top three in terms of the total EF.

in 2012) (Fig. 7). An examination of EPI's component indicators reveals that only CO_2 Emission Per Capita was moving away from the target in the ten cities, while three other indicators (Biome Protection Area, Pesticide Use Intensity, and Forest Cover Change) showed inconsistent changes among cities.

In 2006, the only year with complete data of all cities, the ranking order by the scores of EPI was: Chengdu, Xi'an, Tianjin, Guangzhou, Shanghai, Shenyang, Beijing, Nanjing, Chongqing, and Wuhan (Fig. 8). All cities performed well in Access to Electricity, Forest Cover Change, Access to Sanitation, and Access to Drinking Water; while all cities performed poorly in CO_2 Emissions Per Electricity Generation, CO_2 Per GDP, SO_2 Emissions Per GDP, and SO_2 Emissions Per Capita. Cities performed diversely in Indoor Air Pollution, Wastewater Treatment, Biome Protection Area, Pesticide Use Intensity, and CO_2 Per Capita. In general, environmental health performed better than ecosystem vitality for all cities but Shenyang.

3.4. CDI, HDI and Urban-rural income ratio

In 1998, the scores of CDI of Beijing, Tianjin, and Shanghai were between 60 and 70, and that of Chongqing was 46.1 (Fig. 9). In 2012, the scores of the four cities were all higher than 80. Beijing and Tianjin improved noticeably on waste and infrastructure, Shanghai on waste, and Chongqing on waste, health and infrastructure. However, they all had a large room for product improvement (Fig. 9).

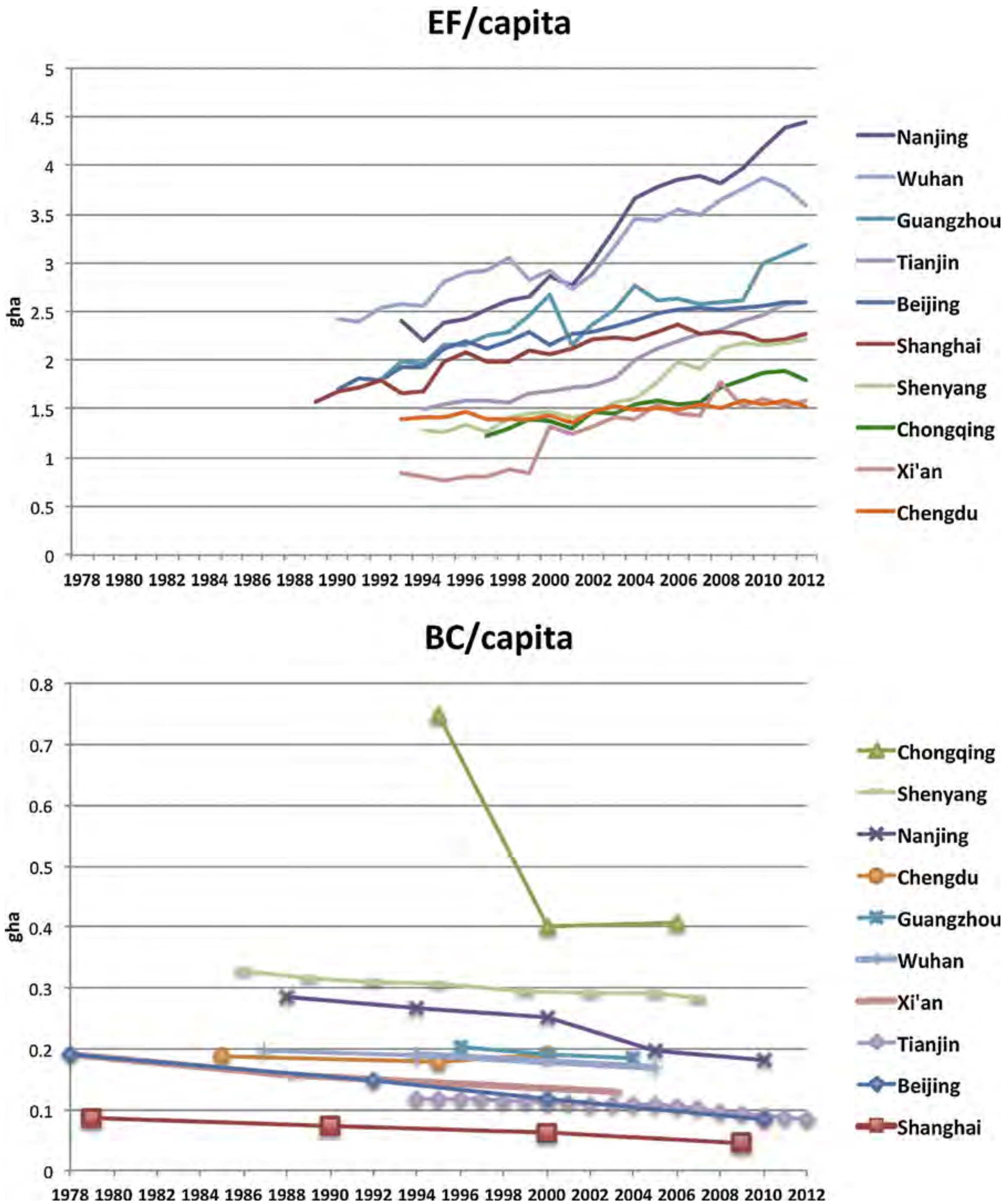

Fig. 6. Temporal dynamics of EF/capita and BC/capita for the ten megacities in this study.

Similar to CDI, in 1998 the scores of HDI for Beijing, Tianjin, and Shanghai ranged from 0.73 to 0.79, with Chongqing having a low score of 0.64. A large room existed for GDP/capita improvement (Fig. 10).

The Gini coefficient of urban households increased to the peak around the year 2002 for most megacities, and decreased gradually afterward. However, the urban–rural income ratio of the ten megacities showed a generally increasing trend, with fluctuations over the study period between 1978 and 2012 (Fig. 11). The ratio had its smallest values between 1983 and 1984, and the largest values between 1993 and 1994 and between 2006 and 2008 again (Fig. 11). Chongqing had the highest urban–rural income ratio among the ten megacities, while the five eastern megacities, Guangzhou, Tianjin, Nanjing, Beijing, and Shanghai had relatively low urban–rural income ratios. The urban–rural income ratio remained relatively steady or decreased slightly in recent years for the other 9 megacities, except for Tianjin. However, the urban–rural income ratio was still higher than 2 in 2012 for all the ten megacities (Fig. 11).

4. Discussion

4.1. Have Chinese megacities made "genuine progress"?

Our results indicate that the ten Chinese megacities had two distinct growth phases of GPI/capita since 1994: Phase I (1994–2005)

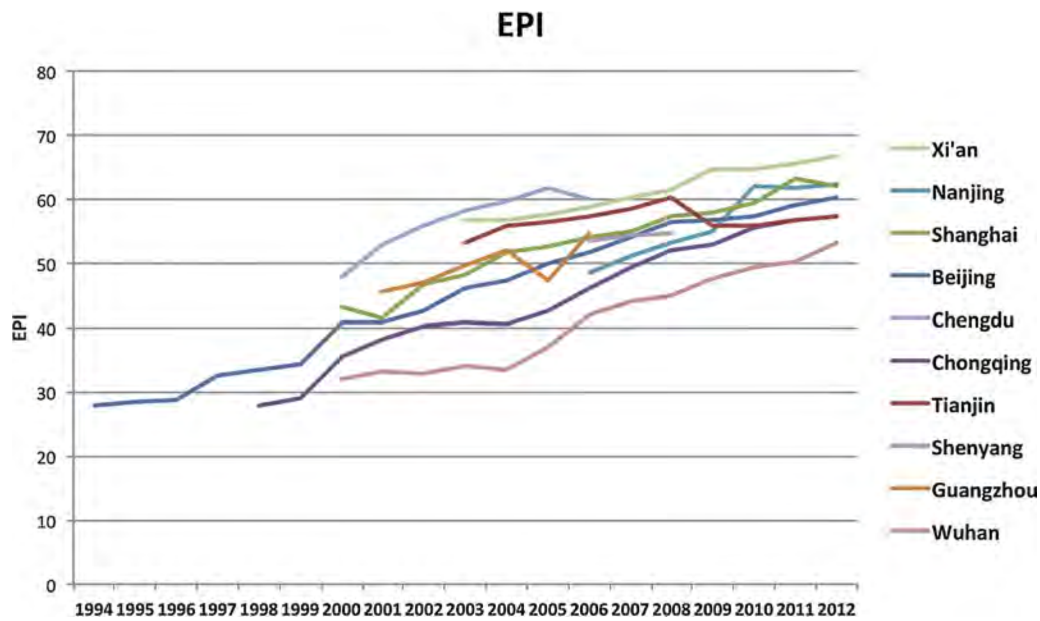

Fig. 7. Temporal trend of EPI for the ten study megacities from 1978 to 2012.

characterized by a rapid increase in GDP and little change in GPI, and Phase II (2006–2012) characterized by rapid increases in both GDP/capita and GPI/capita. For the ten megacities in our study, the rapid increase in GPI/capita started in 2006. In general, eastern and northeastern megacities had higher GDP/capita and GPI/capita than those in the central and western regions.

In an assessment of sustainable development of China from 1970 to 2005, Wen, Yang, & Lawn (2008) identified five GPI growth phases. GPI/capita rose gradually during the first three phases (1970–1993), and increased rapidly in phase four (1994–1998), with a growth rate comparable to that of GDP/capita. In phase five (1999–2005), GPI/capita stopped increasing due largely to increasing income inequality, crime rate, family breakdown, and high environmental externality costs (Wen, Yang, & Lawn, 2008). As we followed the method in Wen, Zhang, Du, Li, & Li (2007) and Wen, Yang, & Lawn (2008) to calculate GPI, our results are comparable with those in Wen, Yang, & Lawn (2008). Two findings emerge from such comparison: (1) GPI/per capita for megacities and for China as a whole has shown different growth phases since China's economic reform in 1978; and (2) For both megacities and China as a whole, the growth of GPI/per capita seems to have stalled since the early 2000s.

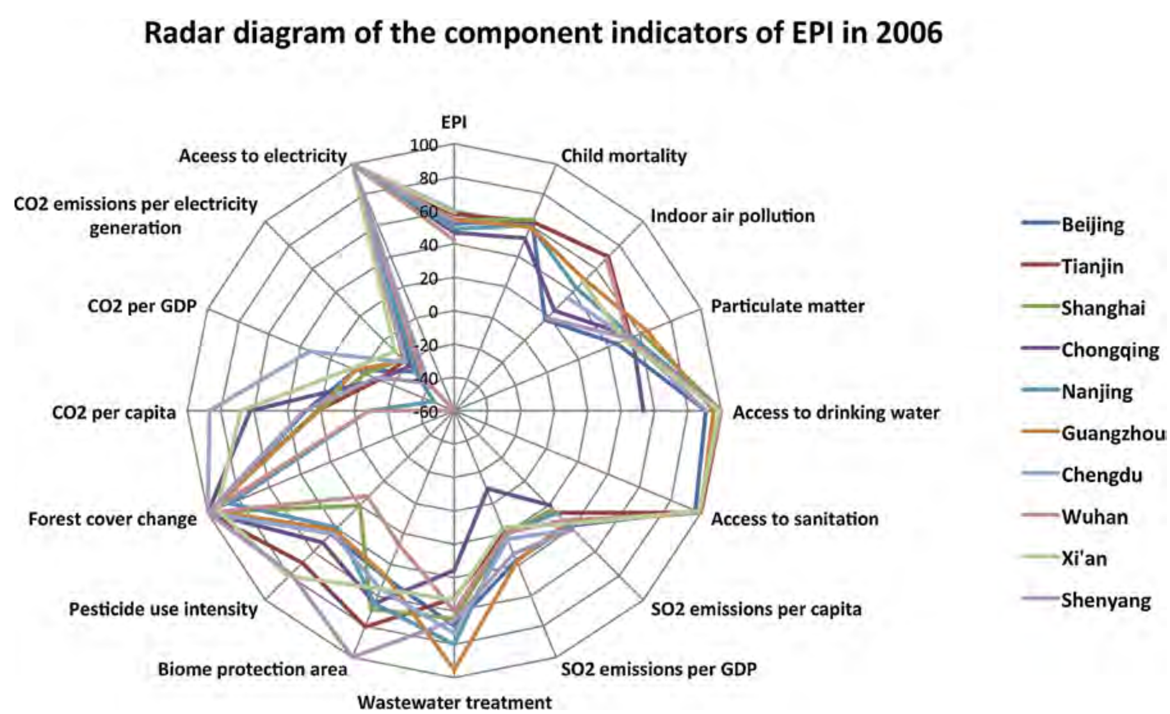

Fig. 8. Radar diagram of the component indicators of EPI in 2006 for the ten study megacities. Values were rescaled to 100, and negative values denote conditions worse than the low performance benchmark.

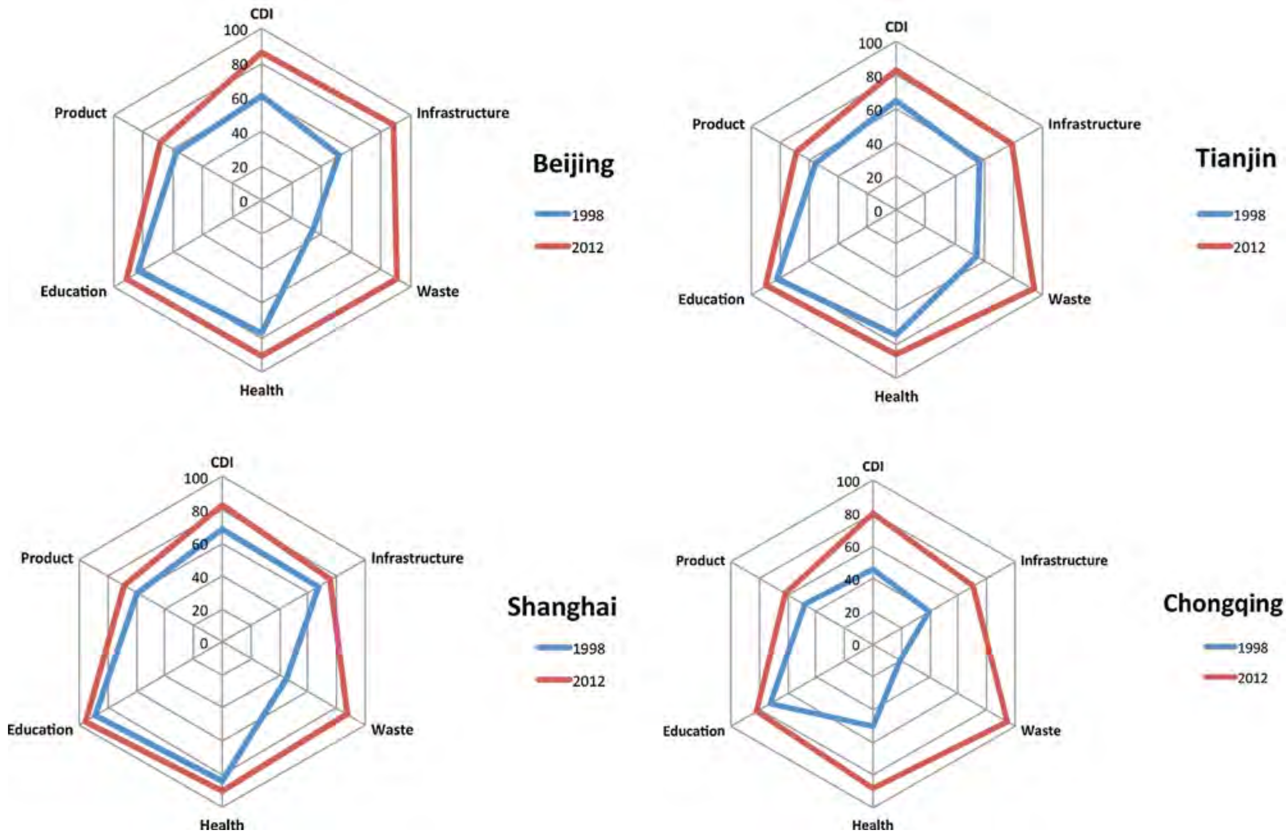

Fig. 9. Changes in CDI between 1998 and 2012 for four selected Chinese megacities.

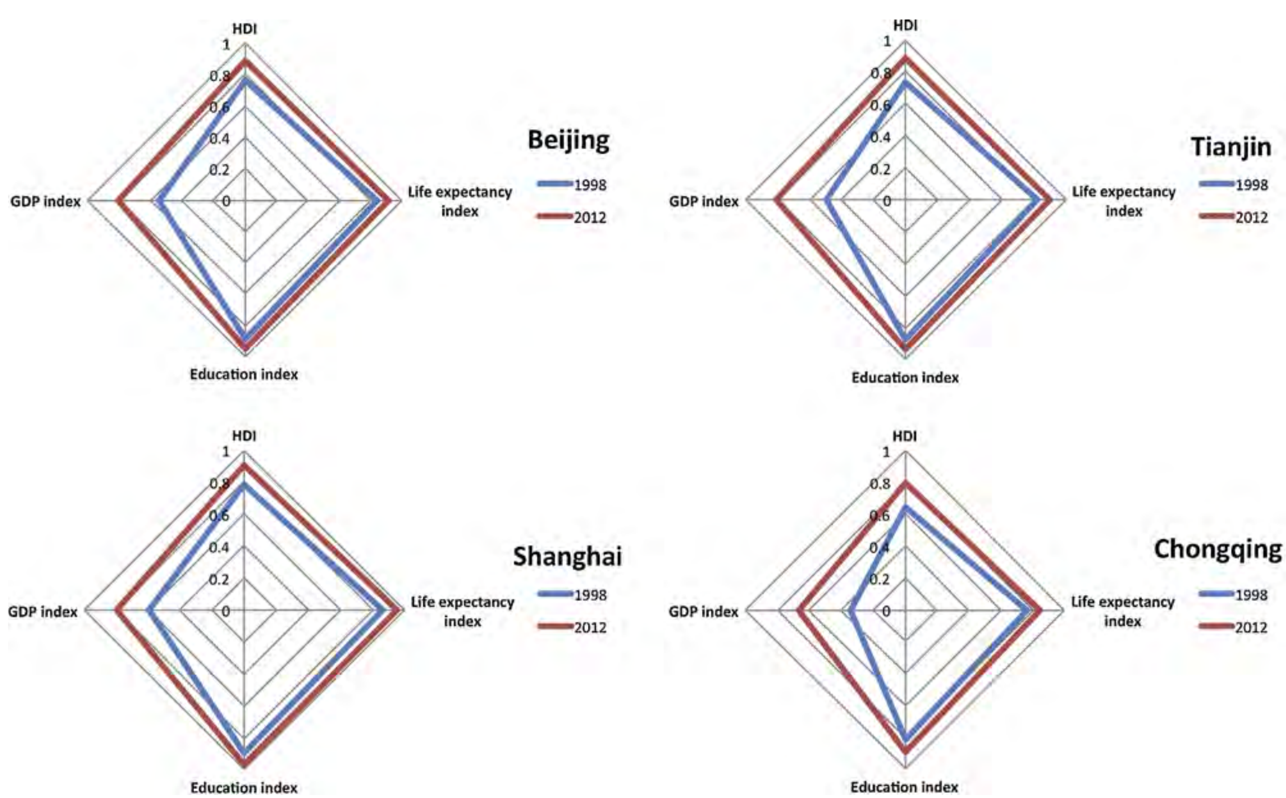

Fig. 10. Changes in HDI between 1998 and 2012 for four selected Chinese megacities.

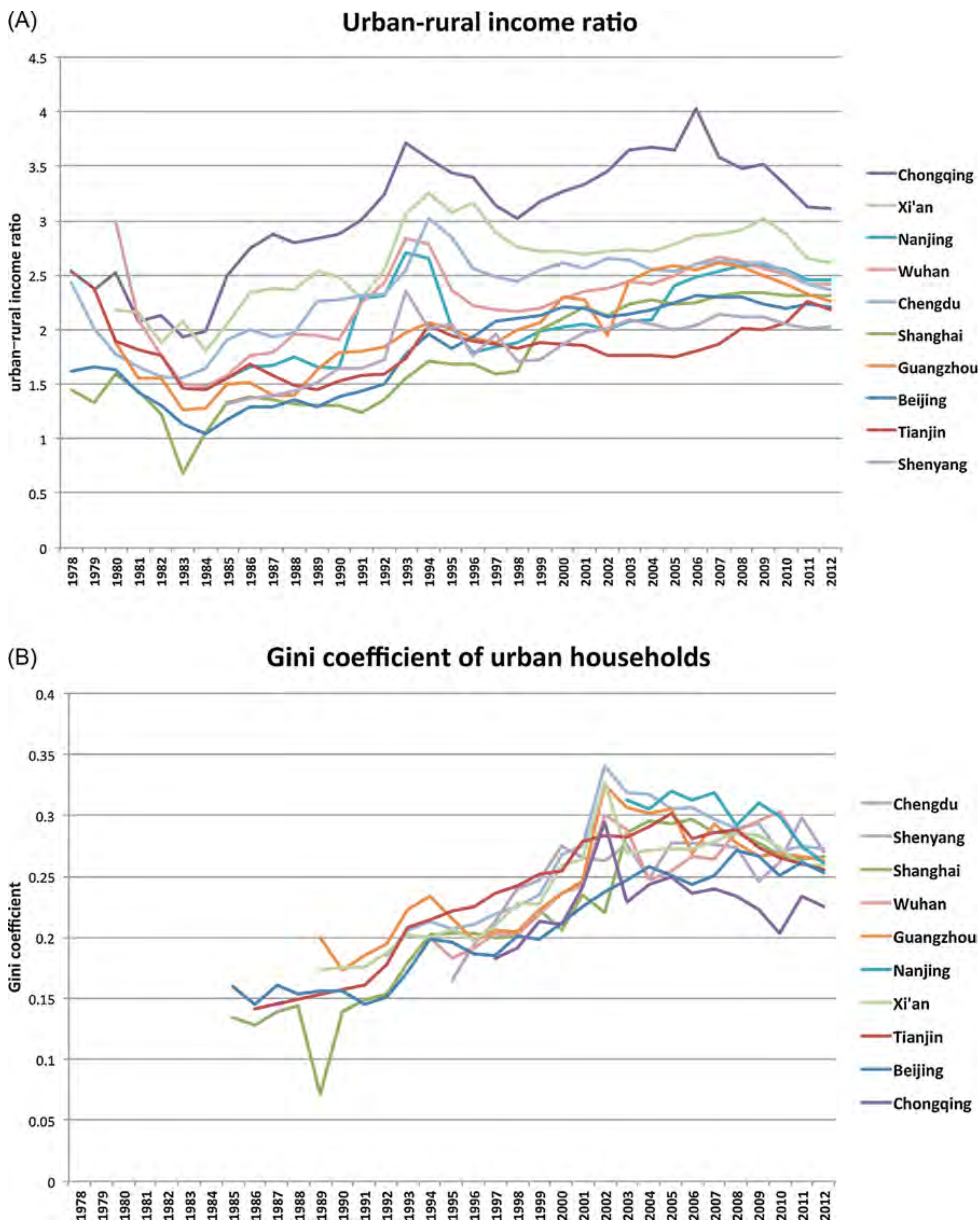

Fig. 11. Socioeconomic inequality of the ten study megacities from 1978 to 2012. (A) Urban–rural income ratio; and (B) Gini coefficient of urban households.

4.2. Has the environmental quality of Chinese megacities improved?

In the 2012 EPI Report, Switzerland had the highest score (76.69), Iraq was at the bottom (25.32), and China (42.24) ranked at the 116th out of 132 countries. Our results show that seven Chinese megacities had EPI scores between 53.3 (Wuhan) and 66.7 (Xi'an) in 2012 (Fig. 7), which were larger than the overall score of China. Also, the EPI scores for all the ten megacities continued to increase, indicating that the overall environmental quality was improving during the study period.

The trend shown by EPI, however, may not be an accurate reflection of the reality because EPI is incapable of capturing several important environmental problems that widely occur in China. First, 420 of the 661 Chinese cities suffer from water shortage (Niu, 2012), but the formulation of EPI only considers "wastewater treatment", not "water scarcity". Second, EPI does not consider soil pollution and groundwater pollution which are common environmental problems in Chinese megacities. In addition, EPI uses $PM_{2.5}$ to assess outdoor air quality, but China did not begin to monitor $PM_{2.5}$ until 2012. As a result, we had to use PM_{10} in lieu of $PM_{2.5}$, which may have further inflated the values of EPI. Finally,

Table 4
Three categories by city performance according to EF/capita, GPI/GDP, and Urban-rural income ratio.

Megacities	EF/capita in recent five years	GPI/GDP	Urban–rural income ratio (in average)
Chengdu, Xi'an, Chongqing	<2 gha	Relatively high	>2
Shanghai, Beijing, Guangzhou, Tianjin, Shenyang	2–3 gha	Relatively low	<2
Nanjing, Wuhan	>3.5 gha	Relatively low	>2

inconsistent quality of the diverse data required by EPI may have introduced additional errors into the results.

Nevertheless, the upward trend of EPI seems to corroborate that Chinese cities have made great progress in drinking water supply ("access to drinking water"), sanitation support ("assess to sanitation"), gas supply ("indoor air pollution"), waste treatment system ("wastewater treatment), and electricity supply ("access to electricity"). These indicators make large contributions to the high scores of EPI for the Chinese megacities under study. Huang et al. (2008) also showed that the state of the environment (air, water, and sound) of Beijing was far away from the target, but the indicators pertaining to resource consumption, pollutant emission, public green space, and waste treatment were all improving in recent years. However, as indicated by the expanding EF, declining biocapacity, and degrading urban ecosystem vitality, Chinese megacities are faced with grand challenges in achieving environmental sustainability in years to come.

In addition, our study indicates that the urban green spaces in Chinese megacities have increased (also see Cheng, Li, & Deng, 2011). This is partly a consequence of the Chinese government's emphasis on improving urban livability and building "eco-cities" or "green cities" (Table 1). While increasing urban green spaces usually leads to enhanced urban ecosystem services that are crucial to the wellbeing of urban residents, cities that are ecologically sound or "green" are not necessarily sustainably environmentally, economically, and socially (Wu, 2013, 2014).

4.3. Have Chinese megacities become more socially equal?

Our analysis with CDI and HDI shows that four of the ten Chinese megacities improved from "medium human development" to "very high human development" during the study period, according to standards established by UN-Habitat (2002) and UNDP (2009) for cities and countries around the world. However, social inequality measured by the Gini coefficient and the urban–rural income ratio also increased with urban development. The urban–rural income ratio was below 1.6 for most countries in 2005, but China was one of the only three countries with a value of larger than 2 (Pan & Wei, 2011). The phenomenon that "the rich gets richer and the poor gets poorer" seems wide-spread in Chinese megacities. The widening urban–rural gap has negative impacts on the socio-economic sustainability of these megacities.

Our study also shows promising examples of narrowing this gap. For example, of more than 650 cities in China, Chengdu and Chongqing were chosen as the pilot cities of "National Urban and Rural Reform Pilot Area" in 2007. Known as the "Heavenly Land of Abundance" of China, Chengdu has accelerated urbanization under the "Go West" policy since 1999. In 2003, Chengdu enlarged its size greatly by annexation of surrounding small cities and rural areas. Moreover, the spatial pattern of the whole city was rearranged as three circular zones from the city center outward: modern services zone, new industry zone, and modern agriculture zone (National Information Center, 2010; Niu, 2012). In 2009, the government of Chengdu proposed to develop a "Garden City of the Modern World", with an emphasis on environmental protection, social equity, and urban–rural balanced development. As a result, the urban–rural income ratio of Chengdu has been decreasing since 2003 (Fig. 11).

5. Conclusions

Our study shows that, of the ten major Chinese megacities, Chengdu, Xi'an, and Chongqing have relatively lower development pressures on the environment (EF/capita under 2 gha in recent years) and better performance in economic sustainability (relatively high GPI/GDP ratios), but with a higher degree of social inequality (urban–rural income ratio above 2) (Table 4). The remaining seven cities all perform poorly in economic sustainability, with Nanjing and Wuhan creating larger ecological footprints and wider urban–rural income gaps than Shanghai, Beijing, Guangzhou, Tianjin, and Shenyang. Our findings support the recent urban development policy shift in China, which moves away from maximizing production and consumption to improving overall urban sustainability with more emphasis on environmental quality. Sustainability assessment using multiple indicators with a "strong sustainability" framework (Huang, Wu, & Yan, 2015) will be necessary to gauge the effectiveness of this policy shift, and to guide urban planning and management in China so as to achieve urban sustainability.

Acknowledgments

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at http://dx.doi.org/10.1016/j.landurbplan.2015.09.005.

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