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Research article

The evolution of the ecological footprint and its relationship with the urban development of megacities in Western China: The case of Xi'an

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ABSTRACT

Although China's western cities have developed rapidly in recent years, their ecosystems remain fragile. The conflict between urban development and environmental protection must be resolved to achieve the goal of sustainability. This study examines Xi'an as a case study of a megacity in Western China, calculating the city development index (CDI) and per capita ecological footprint (*ef*) from 2005 to 2016 to comprehensively calculate Xi'an's eco-efficiency. The E-C elasticity coefficient, which refers to the ratio of the rate of change in CDI to the rate of change in *ef*, is proposed to characterize the degree to which urban development responds to changes in the *ef*. The CDI and *ef* both showed an upward trend from 2005 to 2016. Xi'an's environmental efficiency has grown rapidly, and resource efficiency is the main factor driving its fluctuations in eco-efficiency. The energy consumption and pollution emissions are highly correlated with the CDI, and they are the main factors affecting the development of Xi'an. The relationship between CDI and *ef* is consistent with the law of diminishing marginal utility, the level of urban development rises and then decreases with the increase in *ef*.

1. Introduction

The development of cities is usually accompanied by an increase in the urban population. The global urban population is larger than the global rural population. In mid-2018, 55% of the world's population lived in urban areas, whereas this figure was only 30% in 1950 (UNPD, 2018). Historically, increased density has brought productivity to cities and benefitted urban social and economic development. However, given congestion, energy shortages, and environmental destruction during urban development (Hong et al., 2017; Wolf et al., 2013), among other factors, the conflict between environmental protection and urban development has intensified (Zhang et al., 2015). For example, London's Great Smog of 1952 (Met Office, 2015), the Photochemical Smog in Los Angeles from 1940 to 1960 (Sarah, 2014), and the outbreak of Minamata disease in Japan in 1956 (People's Network, 2004) were all consequences of this conflict. Although these cities have experienced difficult periods due to environmental problems, they have become vibrant cities by protecting ecological resources, improving their energy structures, promoting clean technology, and strengthening investment in ecosystem restoration (Hamlin and Clapp, 1996; Takaaki and Feng, 2012; Chinese Social Science Net, 2014). However, this process may take decades or more. Unlike in these cities in developed countries, urban development in China as a developing country, began later but has proceeded rapidly, it remains in the stage of rapid expansion. China's megacities are typical examples of this development. In China, megacities refer to cities with a permanent population of 5–10 million, and they represent centres of the country's society, economy, culture and population (Central People's Government of the People's Republic of China, 2014). The levels of urban development in Western China are generally lower than those in the eastern region (Li et al., 2012). However, the development rate of western cities has been much faster than that of eastern cities because of the former's low starting point. Rapid urban development has led western cities to become more ecologically fragile. Therefore, the megacities in Western China represent the most prominent conflict between environmental protection and urban development in China. On the one hand, a city optimizes the use of the environment by exerting scale effects, optimizing industrial structure, and improving the quality of life of the urban population and the level of urban management. On the other hand, the environment is deteriorated by population growth, resource consumption and urban development. Accordingly, it is necessary to coordinate urban development and the ecological environment.

The development of a city is usually evaluated from the perspective of sustainability, which has consistently attracted considerable attention from scholars in various countries (Kaklauskas et al., 2018; Wang et al., 2018). The existing research has evaluated development mainly

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through the establishment of an indicator system (Hara et al., 2009). For the purposes of evaluating development, the United Nations Development Programme (UNDP) adopted the human development index (HDI) in 1990 to measure the level of social and economic development in countries around the world (UNDP, 1990). The academic community applied it to urban development research (Liu et al., 2013), and considered it suitable for measuring urban development (Huang and Zhang, 2002). Subsequently, in 1996, the United Nations Human Settlements Programme (UN-Habitat) proposed the city development index (CDI) as an indicator system to evaluate the sustainability of cities around the world (UN-Habitat, 2002). Compared with the HDI, which evaluates human well-being, the CDI is a comprehensive indicator of the state of urban development. To evaluate sustainability, in 1992, Rees (1992) proposed the concept of the ecological footprint (EF), which was extended by Wackernagel (1999) to quantify the consumption and occupation of the ecological environment by human society. The EF can represent the resources needed for the activities of the population within a specific region and the biological productive land area required to absorb the waste from its activities. The use of EF to measure the sustainability of urban environments is widely used (Rashid et al., 2018; Verhofstadt et al., 2016). At present, combining the indicators for measuring development with the EF to measure sustainability is one of the mainstream methods for evaluating the level of urban development (Huang et al., 2016). By combining CDI and EF to analyse urban development, it is possible not only to evaluate the sustainability of the economic, social and ecological development of a city (Guo and Yan, 2016), but also to reveal the main factors affecting ecological changes (Yang et al., 2017b). In this way, we present countermeasures and suggestions to solve the conflict of urban development.

2. Study area

Xi'an is the capital city of Shaanxi Province, and it has a warm temperate continental monsoon climate. It is located in Northwest China, between east longitude 107°40’ −109°49′and north latitude 33°39’ −34°45’ (Fig. 1). It lies south of the Qinling Mountains and north of the Weihe River. The city has jurisdiction over 11 districts and 3 counties, with a the total area of 1,075,200 hm^2, accounting for only 5.2% of the province's land area (Xi'an Municipal People's Government, 2018). As of 2016, the resident population was 8,832,100, increasing by nearly 10% over the past 10 years, of which the urban population reached 6,485,400, accounting for 23.2% of the province's population (Shaanxi provincial bureau of statistics, 2017). In 2016, its gross domestic product (GDP) was 746.99 billion RMB, and the total fiscal revenue was 136.47 billion RMB, accounting for 32.4% and 35% of the province's total, respectively (Xi'an Statistics Bureau, 2017). Only 5% of the land area is responsible for more than 30% of the province's output.

Xi'an is the political, economic and cultural centre of Shaanxi Province. Over the past ten years, it has developed rapidly. From 2005 to 2016, Xi'an's urbanization rate increased from 60.77% to 73.43% (Shaanxi provincial bureau of statistics, 2017). As the only megacity in Northwest China, Xi'an has been playing an increasingly leading role in urbanization. However, this urbanization has had some negative effects. The city's urban area increased by 28,424 hm^2, while its forest area decreased by 41,910 hm^2. Affected by the strong smog from Northern China, the air quality in Xi'an has greatly decreased. Air quality in Xi'an reached the level of excellent on less than 90 days in the past five years. The proportion of energy-intensive heavy industry has increased, resulting in an increase in energy consumption and a decline in resource efficiency in Xi'an. In response, Xi'an has issued a series of treatment plans such as the “Special Action Plan for Coal Reduction and Smog treatment for Protecting the Blue Sky” in 2017 and accelerated pollution control by converting coal use to gas or electricity. These efforts will slow the rate of ecological destruction and promote the development of an ecologically friendly society (Xi'an Municipal People's Government, 2017). However, Xi'an still faces problems such as increased demand for land for construction, among others.

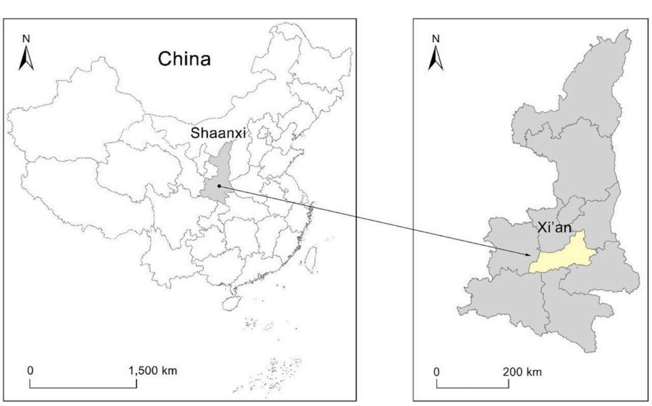

Fig. 1. Location of Xi'an.

3. Materials and methods

3.1. Data sources and description

The main sources of research data are the *Shaanxi Statistical Yearbook (2006-2017)*, *Xi'an Statistical Yearbook (2006-2017)*, and *Statistical Bulletin of the National Economic and Social Development in Xi'an (2005-2016)*. Due to the long time series considered in this study, to maintain the consistency and availability of data, the following indicators have been replaced:

In the CDI indicator system, in terms of infrastructure, official statistics for the “Coverage rate of sewerage” are not available in China, and there is no substitute indicator to replace it. Therefore, it was counted as 0 (Guo and Yan, 2016). There was no suitable data source for “Electricity”, so it was replaced by the indicator “Gas consuming popularization”, which is more representative of the development of urban infrastructure. “Telephone” was calculated as the ratio of the number of mobile phones to the number of residents. In terms of waste, the “Rate of solid waste disposed” was calculated by weighting the “rate of no harm disposal of garbage” and the “rate of industrial solid wastes utilized”. In terms of health, there were no available data on “life expectancy” for 2005 and 2006; thus, the data from 2007 to 2016 were subjected to a linear regression to interpolate data for 2005 and 2006 by fitting the trend line. Based on *Urban Indicators Guidelines* (UN-Habitat, 2004), *the Millennium Development Goals*, and the given domestic data availability, “Child mortality rate” was replaced with “Mortality rate in children under 5 years”. In terms of education, “Literacy” incorporated data from Shaanxi Province corresponding to the “Non-literacy rate of population over 15 years old” in the *Shaanxi Statistical Yearbook*, calculated as $1-\frac{\text{number of illiterate people aged 15 and above}}{\text{population of 15 years and above}}$. “Combined enrolment” was calculated as $(\text{Primary enrolment} + \text{Primary enrolment}) \times \frac{1}{2}$. “City product” is the per capita GDP converted by the purchasing power of the US dollar, and the exchange rate of the RMB against the US dollar was based on the annual average exchange rate from 2005 to 2016.

In the EF accounts, to unify the statistical calibre of the data, consumption was replaced with output in the calculation of the biological resources account. The data in the yearbook do not directly meet the statistical conditions needed to compute the energy consumption. Replacing energy consumption with energy production would result in inaccurate and incommensurable measurement results because the latter does not consider the energy import and export flows between regions. Finally, we decided to use the statistical data for “Energy consumption per unit of GDP”, “Composition of energy consumption”, “GDP” and “Indices of GDP” from the *Shaanxi Statistical Yearbook* to calculate Xi'an's energy consumption. First, the “Indices of GDP” were

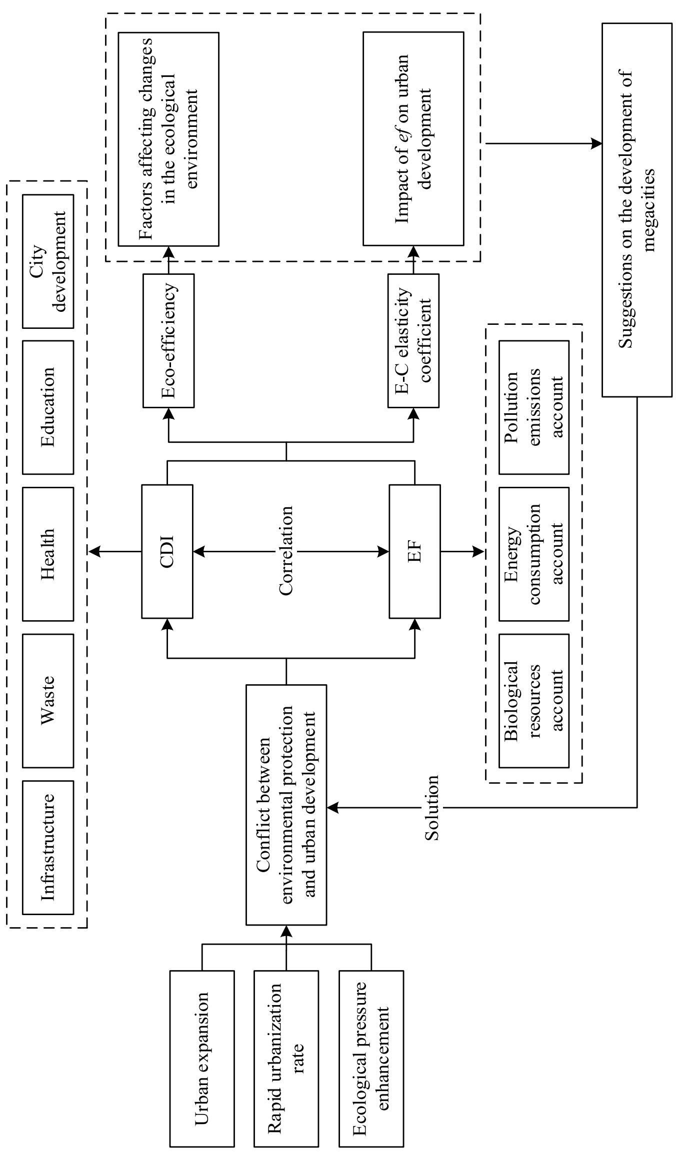

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Fig. 2. Research framework.

used to calculate the indices of GDP for which the value was designated at 100 in 2010, and then, we converted the "GDP in Xi'an" from 2005 to 2016 into 2010 prices. Then, these values were multiplied by the "Energy consumption per unit of GDP" to obtain energy consumption in 2010 prices. The consumption of raw coal, oil, natural gas and hydropower were calculated using Shaanxi Province's energy consumption ratio.

3.2. Methods

This paper measures the CDI and per capita EF (*ef*) of Xi'an from 2005 to 2016 and analyses the correlation between CDI and *ef*. We calculated the environmental efficiency, resource efficiency and eco-efficiency by combining *ef* and CDI. Finally, we propose the E-C elasticity coefficient, which assesses the influence of the rate of *ef* change on that of the CDI (Fig. 2).

3.2.1. CDI indicator system

The CDI indicator system issued by UN-Habitat is used to measure the level of urban development. Combined with the statistical evidence available for Shaanxi Province, an urban development indicator system suitable for Xi'an's development characteristics was established (Table 1). The CDI indicator system comprises five primary indicators – infrastructure, waste, health, education and city development - ranging from 0 to 100, with each indicator being accorded a 20% weight. The CDI represents various aspects of social and economic development in the region. Among them, city development is used to measure the regional economic level, health and education represent the basic public service level available in the region, and infrastructure and waste reflect the city's basic management level.

The calculation of CDI was based on UN-Habitat's *Global Urban Indicators Database Version 2* (UN-Habitat, 2002), and it was combined with the CDI indicator system of Xi'an. The formulas for the indicators are defined as follows (Table 2).

3.2.2. EF model

The EF model is used to measure urban ecological sustainability, and the "equivalence factor" and "yield factor" were introduced to transform regional resource demand, energy consumption and pollution emissions demand into comparable productive land areas. The EF is divided into biological resources account, energy consumption account, and pollution emissions account. The equivalence factor and yield factor of various types of land published in the Working Guidebook to the National Footprint Accounts released by the Global Footprint Network were used (Global Footprint Network, 2016). The revised average production was used to calculate the biological resources account (Yang and Jia, 2015). The formula for calculating the EF of the biological resources account and pollution emissions account is as follows:

$$EF = N \times ef = \sum Efi = \sum \left(ri \times \frac{C_i}{p_i} \right) \tag{7}$$

where *EF* is the total ecological footprint. *N* is the overall population, *ef* is the per capita EF, and *i* is the category of consumer goods. P_i is the average production capacity of the *i*-th consumer goods category, which represents the ability of the land to absorb pollutant emissions in the calculation of the pollution emissions account. C_i is the consumption of the *i*-th commodity, which represents the emissions of the *i*-th pollutant in this calculation of the pollution emissions account. r_i is the equivalence factor, Ef_i is the *EF* of the *i*-th type of consumer goods.

The EF of energy resources is measured as the fossil energy land, which is converted from the heat released from the burning of raw coal, crude oil, and natural gas, hydro-power and other energy resources in the energy resource account according to the average calorific value of fossil energy. Its calculation formula is as follows:

$$A_k = C_k \times b_k / ae_k \tag{8}$$

where A_k is the EF for the *k*-th energy source, *k* is the type of energy, C_k is the consumption of the *k*-th energy source, b_k is the conversion factor for the *k*-th energy source, and ae_k is the average calorific value of the fossil energy land per unit area of the world.

3.2.3. Eco-efficiency

The concept of eco-efficiency was first defined by Schaltegger and Sturm (1990) as the ratio of added value to increased environmental impact. As a tool for sustainability analysis, it has received substantial attention in the study of sustainable urban development (Zhang et al., 2008). Some scholars combine eco-efficiency with the EF model to analyse the relationship between EF and economic development (Huang et al., 2018). Some also studies have also constructed an urban sustainability model based on eco-efficiency through the EF and HDI to analyse urban sustainability (Lin et al., 2010).

The World Business Council for Sustainable Development (WBCSD) believes that eco-efficiency is the environmental impact of human production and activity that resources can support. The Organization for Economic Co-operation and Development (OECD) defines eco-efficiency as the ratio between the added value of the consumed product and the impact on the ecological environment (WBCSD, 2000). The formula to calculate eco-efficiency is as follows:

$$E = S/I \tag{9}$$

where *E* is eco-efficiency, *S* is product service value, and *I* is the impact on the ecological environment. Product service value can be characterized by the city product and level of infrastructure; the impact on the environment is characterized by the status of resource consumption and pollution emissions. The impact on the ecological environment includes resource impacts and environmental impacts. Therefore, eco-efficiency can be divided into resource efficiency and environmental efficiency, in other words, resource efficiency is the ratio of product service value to resource use, and environmental efficiency is the ratio of product service value to environmental pollution (Wang and Shi, 2018).

To achieve a common scale for comparison, according to formula (9) and the measurement of resource use and environmental impact, CDI and *ef* are calculated as multiples of the base year in the formula. Urban eco-efficiency can be calculated by the following formula:

$$CE = \lambda(\text{CDI})/\lambda(ef) \tag{10}$$

$$CR = \lambda(\text{CDI})/\lambda(ef_r) \tag{11}$$

$$CP = \lambda(\text{CDI})/\lambda(ef_P) \tag{12}$$

Table 1
CDI indicators.

	CDI Indicator System of UN	CDI Indicator System of Xi'an
First Grade Indexes	Second Grade Indexes	Second Grade Indexes
Infrastructure	Water connections	Water consuming popularization
	Sewerage	Coverage-rate of sewerage
	Electricity	Gas consuming popularization
	Telephone	Penetration rate of mobile phones
Waste	Wastewater treated	Rate of sewerage disposal
	Formal solid waste disposal	Rate of solid waste disposal
Health	Life expectancy	Life expectancy
	Child mortality	Mortality rate in children under 5 years
Education	Literacy	Literacy rate of population over 15 years old
	Combined enrolment	Combined enrolment rate
City Development	City product	Per capita GDP

Note: The data in the table are from 2005 to 2016.

Table 2
CDI formulas.

Indexes	Formulas
Infrastructure	25 × Water - Consuming popularization + 25 × Coverage rate of sewerage + 25 × Gas - Consuming popularization + 25 × Penetration rate of mobile phones) (1)
Waste	Rate of sewerage disposal × 50 + Rate of industrial solid waste disposal × 50 (2)
Health	(Life expectancy - 25) × 50/60 + (32 - Mortality rate in children under 5 years) × 50/31.92 (3)
Education	Non-literacy rate of population over 15 years old × 25 + Combined enrolment rate × 25 (4)
City Development	(log GDP per capita - 4.61) × 100/5.99 (5)
CDI	(Infrastructure index + Waste index + Education index + Health index + City product index)/5 (6)

where *CE* is eco-efficiency, *CR* is resource efficiency, *CP* is environmental efficiency, λ(CDI) is the ratio of CDI change compared with the base year, λ(*ef*) is the ratio of change in *ef* compared with the base year, λ(ef_r) is the ratio of change in the resource *ef* compared with the base year, and λ(ef_p) is the ratio of change in the pollution emissions *ef* compared with the base year.

3.2.4. E-C Elasticity coefficient

The concept of elasticity in economics was proposed in 1890 by Alfred Marshall in his book *Principles of Economics*, which refers to a certain proportion of change in one variable relative to another. Wang et al. (2009) applied it to the field of ecological research and proposed a model that defines the ratio of the rate of EF change to the rate of change in an economic variable as eco-economic resilience to reflect the impact of economic development on the ecological environment. Yang et al. (2017a) evaluated the ecological development of urban agglomeration in the Guanzhong Plain using the ecological pressure elasticity coefficient, which comprises the EF and ecological carrying capacity. Deriving an elasticity coefficient by combining EF with other indicators increases the practical value of the EF and lays the foundation for discussing the relationship between the sustainability of cities and ecology.

The elasticity coefficient can express the numerical relationship between the degree of increase in one variable and the degree of increase in another variable within a certain period of time. Thus, E-C, which refers to the ratio of the rate of change in CDI to the rate of change in *ef*, is expressed as the degree of response in the change in a city's CDI to the change in the *ef* of the city over a certain period of time. The formula is as follows:

$$E-C=\frac{\Delta c_{(i,i-1)}/c_{(i-1)}}{\Delta ef_{(i,i-1)}/ef_{(i-1)}} \tag{13}$$

where *E-C* is the *ef* elasticity coefficient of CDI, $\Delta ef_{(i,i-1)}$ is the change in the *ef* from the *i*-1-th year to the *i*-th year, $ef_{(i-1)}$ is the *ef* in the *i*-1-th year, $\Delta C_{(i,\ i-1)}$ is the change in CDI from the *i*-1-th year to the *i*-th year, and $C_{(i-1)}$ is the CDI in the *i*-1-th year.

3.2.5. Pearson correlation coefficient

Using Excel and SPSS 20, after confirming that *ef* and CDI meet the conditions for analysis, the correlation between *ef* and CDI was analysed by the Pearson correlation coefficient (Liu et al., 2017) to reflect the linear correlation between the *ef* accounts and CDI indicators.

4. Results and discussion

4.1. Analysis of CDI

The CDI of Xi'an in the period 2005–2016 was calculated according to formula (1) (Fig. 3).

From 2005 to 2016, the CDI of Xi'an increased from 62.11 to 80.68, with an average annual growth rate of 2.41% and a cumulative increase of 30.90%. In general, except for a small decrease in 2015, it increased each year. Comparing the slopes of the two points on the CDI fold line, the period 2005–2009 growth rapidly. In 2015, the CDI decreased slightly and then rebounded again in 2016. According to the bar graph, the health and education indicators remained basically stable from 2005 to 2016; the city's development increased each year, but the upward trend slowed over time; the infrastructure and waste indicators exhibit consistent trends from 2005 to 2013, both of which showed an upward trend, however, after 2013, they changed in the opposite direction. Calculating the contribution rate of the five indicators to CDI from 2015 to 2016, the contribution rate of health and education indicators to CDI was only 1.31% and 1.50%, respectively. The contribution rates of city product, infrastructure and waste indicators reached 30.28%, 34.23% and 32.68%, respectively, showing that the overall trend of CDI changes is determined mainly by the changes in city development, infrastructure and waste indicators.

4.2. Analysis of ef

According to the calculation results of formulas (7)–(8), the *ef* of Xi'an showed an overall growth trend. From 1.740 hm^2/cap in 2005 to 2.463 hm^2/cap in 2016, the cumulative increase was 41.50%, with an average annual growth rate of 3.21%. From 2005 to 2013, the *ef* exhibited rapid growth; after 2013, the *ef* entered a period of slow growth and exhibited a downward trend from 2016 on. In 2010, the national average *ef* was 2.43 hm^2/cap (Huang et al., 2016), and the *ef* of Xi'an was 2.097 hm^2/cap, lower than the national average.

Regarding the composition of the *ef* and the composition of each account (Fig. 4 (a)), the fluctuation of the biological resources account is relatively low, with an overall decrease of 9.04% in the period 2005–2016. The pollution emissions account exhibited slight fluctuation from 2005 to 2008; since 2008, it has been declining annually. In 2016, it decreased significantly by 21.88% compared with 2015. The energy consumption account changed significantly and continued to grow from 2005 to 2016, from 0.922 hm^2/cap to 1.858 hm^2/cap. The overall growth was 101.44%, with an average annual growth of 6.57%, which was basically consistent with the change in *ef*, and the contribution of energy consumption account to the *ef* of Xi'an far exceeded that of other accounts. Changes in energy consumption are one of the main reasons for Xi'an's *ef*.

Regarding the composition of each *ef* account, agricultural products and grass products account for a large proportion of the biological resources account (Fig. 4 (b)). In 2007, the *ef* of this account decreased sharply because of the lack of rain in spring 2007 and high the temperatures and drought during the wheat irrigation season and pollination period, as dry and hot winds caused wheat to grow abnormally and severely reduced production. The pollution emissions account fluctuated considerably (Fig. 4 (c)), and water pollution and air pollution accounted for an absolute majority of this account before 2014. The surge in *ef* caused by water pollution in Xi'an from 2006 to 2009, which resulted from the substantial increase in domestic sewage discharge, increased from 286.62 million tons in 2006 to 364.7 million tons in 2009. Then, it decreased each year because of the vigorous implementation of the water ecological construction project, and the goal of a three-year clearing of the Xi'an section of the Weihe River was completed on schedule (Xi'an Municipal People's Government, 2016). Air pollution exhibited the largest decline, from 0.132 hm^2/cap in 2005

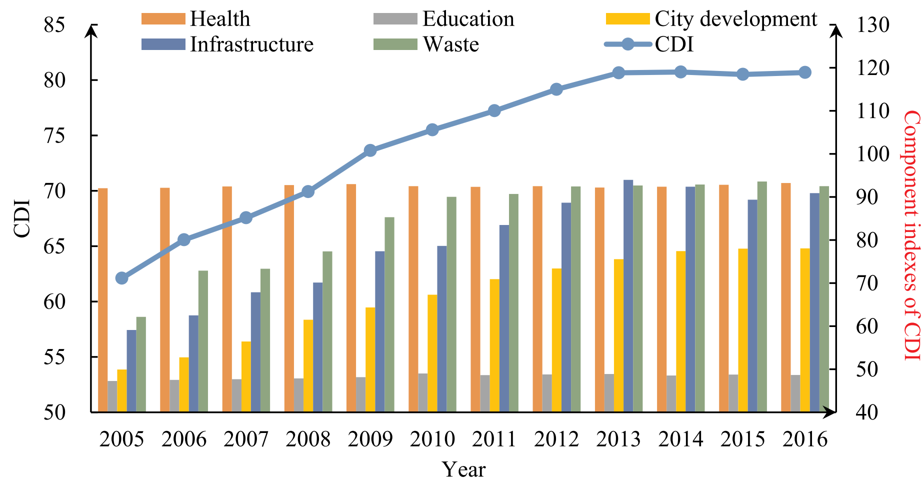

Fig. 3. CDI variations in Xi'an from 2005 to 2016.

to 0.006 hm^2/cap in 2016, which was due to the vigorous implementation of smog treatment in Xi'an, the creation of pollution emissions standards for industry and residences, the forced dismantling of large-scale coal-fired boilers, the introduction of vehicle restriction measures, and the implementation of strict monitoring mechanisms. Contrary to the overall trends for water pollution and air pollution, solid waste pollution increased each year, from 0.03 hm^2/cap to 0.06 hm^2/cap, and the growth of domestic waste was the main cause of this increase. The energy consumption account increased rapidly (Fig. 4 (d)), with the *ef* of raw coal accounting for the largest share and rising rapidly, from 0.76 hm^2/cap in 2005 to 1.56 hm^2/cap in 2016, followed by crude oil and natural gas, hydro-power accounted for the smallest proportion.

4.3. Analysis of eco-efficiency

Taking 2005 as the base year, the efficiency ratios of the resources, environment and ecology of Xi'an from 2005 to 2016 were calculated in

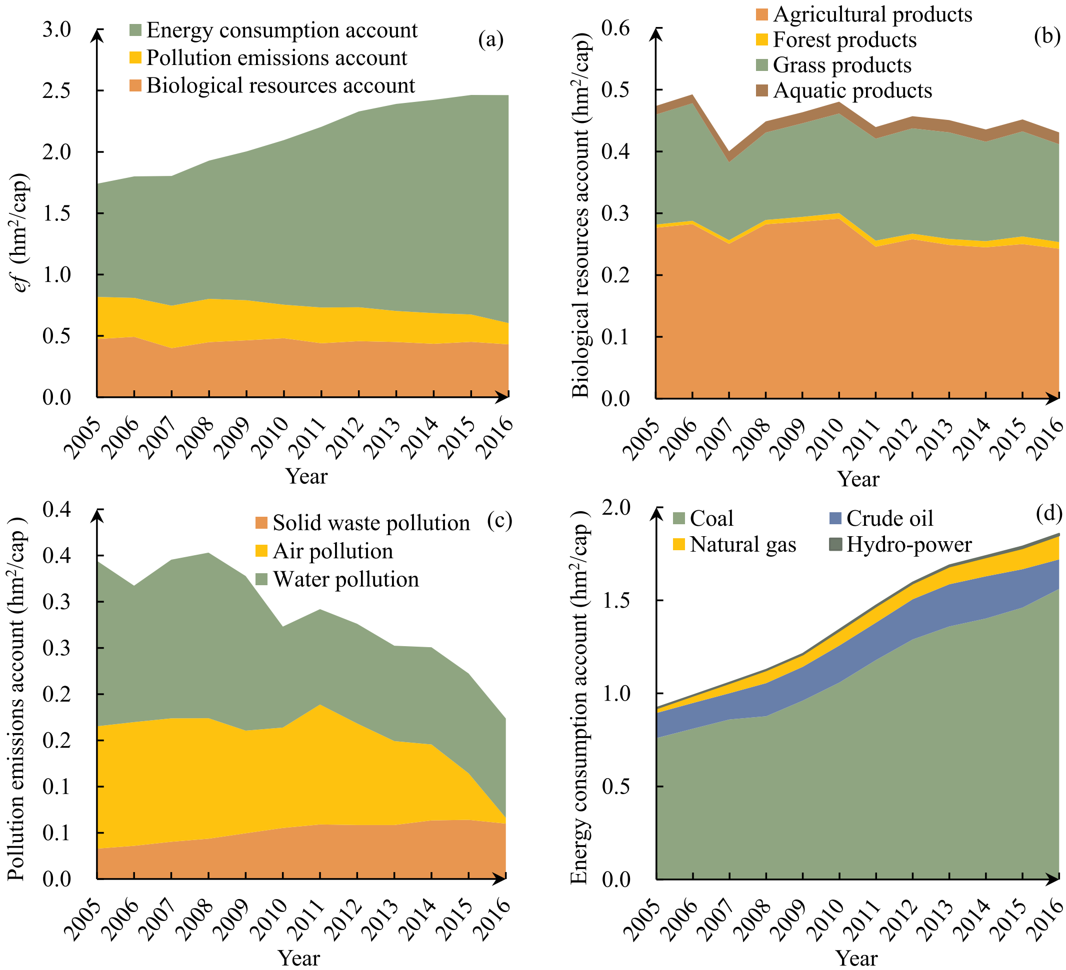

Fig. 4. The composition of *ef* in Xi'an from 2005 to 2016.

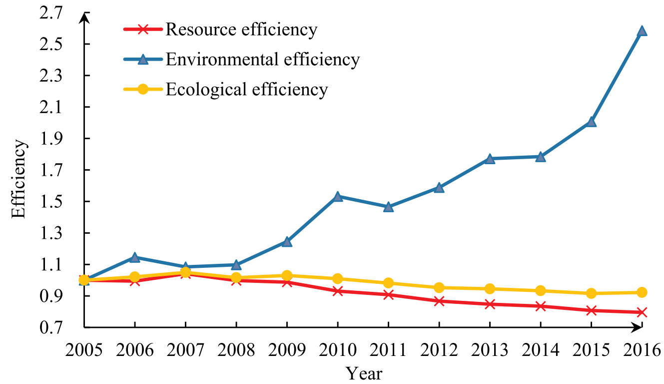

Fig. 5. Efficiency variations in Xi'an from 2005 to 2016.

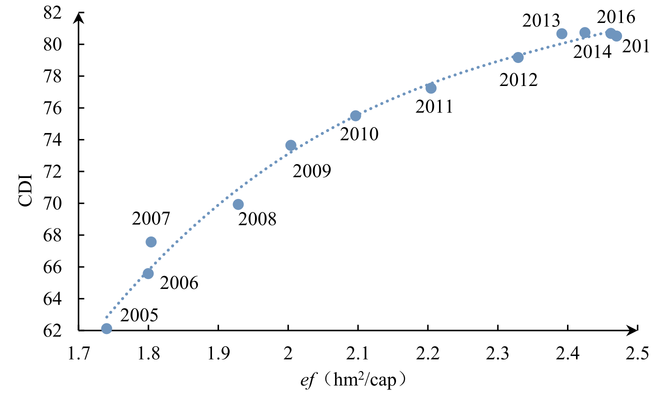

Fig. 6. Relationship between *ef* and CDI in Xi'an from 2005 to 2016.

formulas (10)–(12) (Fig. 5).

(1) Resource efficiency

Resource efficiency is evaluated in terms of biological resources and energy consumption. From 2005 to 2016, the resource efficiency of Xi'an showed a trend of rising first, then falling. The increase in resource efficiency from 2006 to 2007 was due to the reduction in the consumption of biological resources. In the 2007–2016 period, the resource efficiency decreased annually, with a total decline of 20.77%. Before 2016, although the CDI is on the rise overall, the growth rate of resource consumption still outpaced the growth of the social economy, resulting in a continuous reduction in resource efficiency. The development of secondary industry in Xi'an exhibits a tendency towards heavy industrialization. In 2005, the output value of heavy industry accounted for 68.83% of the total industrial output value. By 2016, it had risen to 82.11%. The increase in the *ef* of energy caused by the increase in the proportion of energy-intensive heavy industries is the main reason for the decrease in resource efficiency. Compared with biological resources, the *ef* generated by energy consumption still accounts for an absolute majority, up to 84.04%, which indicates that the rationalization of resource utilization in Xi'an should be based on controlling energy consumption growth.

(2) Environmental efficiency

Environmental efficiency is mainly evaluated based on three pollution emissions accounts. The environmental efficiency of Xi'an showed a fluctuating upward trend from 2005 to 2016 and increased sharply. In 2016 (Fig. 5), it increased by 157.42% compared with 2005, with an average annual growth rate of 8.98%. According to the analysis of the pollution emissions account, the changes in air pollution and water pollution emissions from 2005 to 2016 are the main reasons for the improvement in Xi'an's environmental efficiency. Simultaneously, the amount of solid waste generated by industrial development increased, and the *ef* of solid waste increased from 0.033 hm^2/cap to 0.060 hm^2/cap. Therefore, although environmental efficiency has increased annually, pollution control for solid waste should still be taken seriously.

(3) Eco-efficiency

Fig. 5 shows that the eco-efficiency of Xi'an from 2005 to 2016 showed a small fluctuation, first increasing and then decreasing, with an overall downward trend. In the 2005–2016 period, the overall decline was 8.20%, with an average annual decline of 0.77%. In 2016, eco-efficiency increased because of a significant increase in environmental efficiency that year.

Overall, the social and economic development of Xi'an has increased the consumption of resources, and the pressure on the ecological environment is increasing. Although the CDI continues to increase, the growth of resources and the environmental load is greater than that of social and economic growth. Based on the above analysis, the resource efficiency changes in the 2005–2016 period are small, and the changes in environmental efficiency are more obvious. Changes in eco-efficiency follow increases and decreases in resource efficiency and environmental efficiency. However, resource efficiency and environmental efficiency in Xi'an have opposing trends, and the increase in environmental efficiency is significantly greater than the decrease in resource efficiency, however, the change in eco-efficiency follows the changes in resource efficiency. The impact of environmental efficiency on eco-efficiency is less than that of resource efficiency, which is the main driver of eco-efficiency change in Xi'an.

4.4. Correlation analysis

After testing, *ef* and CDI were in accordance with the bivariate normal distribution. Therefore, a bivariate correlation analysis of the *ef* and CDI was performed using the Pearson correlation coefficient method. From 2005 to 2016, when the significance level was 0.01, there was a high positive correlation between *ef* and CDI, and the correlation coefficient was 0.972 (Table 3). This finding confirms the view that the development and expansion of urbanization are accompanied by the deterioration of the ecological environment (Lv et al., 2018). There was a significant positive correlation between energy consumption account and the education, city development, infrastructure, and waste indicators of the CDI when the significance level was 0.01. This result indicated that the relationship between urban development and the environment is mainly caused by the interaction

Table 3
Pearson correlation coefficient between *ef* and CDI from 2005 to 2016.

Evaluation index	Infrastructure	Waste	Health	Education	City Development	CDI
Biological resources account	−0.310	−0.190	−0.293	−0.103	−0.307	−0.273
Pollution emissions account	−0.815**	−0.771**	−0.447	−0.741**	−0.846**	−0.820**
Energy consumption account	0.967**	0.906**	0.434	0.847**	0.981**	0.962**
ef	0.976**	0.921**	0.408	0.864**	0.987**	0.972**

**. Correlation is significant at the 0.01 level (2-tailed).

Table 4
The E-C elasticity coefficient of Xi'an from 2005 to 2016.

Year	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
E-C elasticity coefficient	/	1.63	13.33	0.51	1.36	0.55	0.45	0.44	0.70	0.07	−0.16	−3.61

between energy consumption and education, urban output value, infrastructure and waste treatment, indicating that energy consumption is one of the main factors promoting urban development. In turn, the development of the city has further exacerbated the extent of energy consumption. In addition, there was also a significant negative correlation between the pollution emissions account and the education, city development, infrastructure, and waste indicators of the CDI when the significance level was 0.01, and it had the highest negative correlation with the city development indicator. This finding shows that pollution emissions seriously hindered cities' economic development. These results further indicate that energy conservation and pollution emissions reduction are current development priorities in Xi'an.

4.5. Analysis of the E-C elasticity coefficient

First, based on the conclusion that there is a significant correlation between the CDI and *ef* in Xi'an from 2005 to 2016, Fig. 6 presents a scatterplot and a trend line, with the *ef* on the X-axis and the CDI on the Y-axis. The figure shows that with the passage of time and an increase in the *ef*, the increase in CDI per unit increase in the *ef* continues to decrease, showing a marginal decreasing effect. Since 2014, a unit increase in *ef* has not caused an increase in CDI. *ef* is greater in 2015 than in 2016, but CDI is less in 2005 than in 2016, thus, an "inverted U-shaped" relationship can be inferred between the CDI and *ef*; that is, the level of urban development rises and then decreases with an increase in *ef*.

Next, according to the definition of elasticity, the E-C elasticity coefficient can be used to characterize the relationship between the EF and urban development, by dividing urban development into three stages. In the first stage, when the E-C elasticity coefficient is greater than 1, the city is characterized by a low urbanization rate and rapid urban development, and increasing the *ef* can generate excess urban development. In this stage, urban expansion is a more suitable mode of urban development. In the second stage, when the E-C elasticity coefficient is in the range [0, 1], the city is characterized by a stable urbanization rate, and the rate of urban development is slowing. Increasing the *ef* can no longer generate an equivalent urban development return. In the third stage, when the E-C elasticity coefficient is less than 0, the city is already experiencing reverse development, and any increase in the use of the ecological environment must be stopped.

The E-C elasticity coefficient is obtained from formula (13) (Table 4). Xi'an was in the first stage of urban development before 2009, the E-C elasticity coefficient of other years were greater than 1 except for 2008, and there was an abnormally high value in 2007 due to the steady growth of the CDI in 2007 and the lack of growth in the *ef*. The E-C elasticity coefficient was in the range [0, 1] from 2010 to 2014, indicating that Xi'an was in the second stage of urban development, and the CDI responded positively to the *ef*; a 1% increase (decrease) in the *ef*, was associated with an increase (decrease) in CDI of less than 1%. The E-C elasticity coefficient for 2015 and 2016 was less than 0, indicating that the change in urban development generally reversed in response to an increase in the *ef*, which is consistent with the negative marginal utility in CDI due to the increase in the *ef* since 2015, as shown in Fig. 6. At this time, Xi'an was already in the third stage of urban development. In view of the long-term development of Xi'an, the road to promote urban development through the exploitation of the ecological environment has ended because continued endless expansion of the *ef* will inhibit urban development. Therefore, for urban development, Xi'an must abandon the development trends of sacrificing resources and harming the environment and instead insist on intensive development.

5. Conclusion

The CDI, EF models, eco-efficiency and E-C elasticity coefficient were analysed for Xi'an as a case study of megacities in Western China, and the following conclusions were drawn.

First, both CDI and *ef* of Xi'an gradually increased. Although the growth rate of *ef* has decreased each year, the occupation and consumption of natural resources for social and economic development have continued to increase. Second, there is a significant correlation between the CDI and *ef* in Xi'an from 2005 to 2016. The correlations between energy consumption, pollution emissions account and CDI indicators are extremely significant, thus, it is necessary to address both urban energy consumption and pollution emissions to alleviate ecological pressure. Third, the overall eco-efficiency of Xi'an in the 2005–2016 period showed a trend of volatile decline. Resource efficiency was the main factor leading to such fluctuations, indicating that the high consumption of resources had a substantial impact on urban development. Fourth, the change in the E-C elasticity coefficient shows that as *ef* increases, the CDI of Xi'an will increase first and then decrease, and blind encroachment of the ecological environment will inhibit urban development. Xi'an should establish a so-called "compact city", restricting the infinite expansion of the built-up area of the central city.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2019.05.016.

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