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Assessing the Effect of Eco-City Practices on Urban Sustainability Using an Extended Ecological Footprint Model: A Case Study in Xi'an, China

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Abstract: Planning and construction are well-known practical topics; however, eco-city developments and their sustainable effects on the city are less known. Xi'an is a typical city that has a target to become an eco-city. This city is selected in this case study with the aims of (1) framing eco-practices to enhance the understanding of an eco-city development and (2) evaluating the effect of eco-practices to reveal whether they truly enhance urban sustainability. For the first objective, the framework was constructed in accordance with ecological footprint (EF) theory. For the second objective, environmental pollution was added to an extended EF model. The EF of Xi'an from 1999 to 2014 was calculated and analyzed. The results are as follows: (1) Water pollution control and water area development are core issues in the Xi'an eco-city development. Air pollution control and forest land development also play important roles in the eco-city development; (2) Eco-city practices contribute to the decreases of per capita EF and per capita ecological deficit because of the reduction in the EFs of water area, forest land, and arable land, thereby enhancing urban sustainability; (3) The effect of eco-city practices on the improvement of per capita ecological capacity (EC), the ECs of arable land, water area, pasture land, and forest land are not significant. Based on these results, this study provides practical implications for the promotion of urban sustainability through eco-city development.

Keywords: urban sustainability; eco-city; eco-city practices; EF; ED

1. Introduction

Cities play a major role in causing and addressing population–resource–environment crises in the process of rapid urbanization. Thus, the principle and policy of an eco-city has received global attention and became popular in the early 2000s [1]. The proportion of urban population in China increased from 17.9% to 57.4% between 1978 and 2016. The traditional models of cities and high-speed urbanization are attracting attention as contributors to the national or even global problems (e.g., excessive consumption of resources, environmental pollution, and destruction of the ecosystem). The eco-city model has been extensively applied in China to address the challenge of urban sustainability that is induced by eco-environmental problems [2]. Generally, ecological city development in China has been regarded as the result of political and economic transformation and emerged as a new strategy in 2000.

Although researchers or organizers have highlighted the notion or practice of "eco-type urbanization" [1–3], the "city eco-process" that takes place in an actual city remains unclear. Additionally, longitudinal studies evaluating the sustainable performance of eco-practices have not been given sufficient attention. Consequently, the achievements of eco-practices during the eco-city construction period remain unclear.

Thus, to address these research challenges and contribute to existing researches, the present study examined eco-city implementation practices and their effects on urban sustainability based on a case study of Xian, China. With the objective to build an eco-city, various measures such as pollution control, the encouragement of green consumption has been promoted by the whole administrative region of Xian since 1999. The primary goal of this study is to critically frame and evaluate eco-practices, thereby providing implications for the further development of other eco-cities. The objectives of this research include:

(1) To generalize an eco-city practices framework based on ecological footprint (EF) theory, thus understanding China's eco-city development better;
(2) To evaluate the sustainable effects of these practices during the development process of an eco-city by using an extended EF model, thus identifying and assessing the gaps where adaptation and improvement are needed.

2. Literature Review

2.1. Framework of Eco-City Practices

Several countries, such as China and India, have experienced rapid urbanization and have been practicing "eco-urbanism". The concept of an eco-city was first proposed in 1971 [4] and is commonly deemed to be evolved from the concept of a "garden city" [5]. Register (1973) defined an eco-city as an ecologically healthy city, in which human production and livelihood has not exceeded the ecological carrying capacity of the city biotic district [6]. Yanitsky, who was one of the core members of the expert working group of "Man and the Biosphere Program", expounded the profile of an "ecological city" based on the urban ecological problems in the 1970s [7].

The concept of an eco-city in academic researches and practices is still not clearly defined. Most researchers and practitioners have defined the concept from comprehensive or environmental perspectives. From a comprehensive perspective, an eco-city is defined based upon the concept of an eco-system [8], which results in the harmonious co-existence of humans and nature. The definition includes economic sustainability, social harmony, city innovative demonstration effects [9], complete infrastructure, and housing security and management [3].

However, most of the understanding surrounding an eco-city is considered from the ecological–environmental perspective. Roseland (1997) contended that an eco-city can save energy resources and reduce waste to create healthy living conditions [10]. Joss (2010) argued that an eco-city aims to upgrade a low-carbon economy; the growth of new, knowledge-based, creative, and green industries; and environmental improvement [11]. Van Dijk (2015) suggested that an eco-city should manage issues concerning energy, solid waste, transportation, pollution, water, sanitation, and climate change [12]. Flynn et al. (2016) argued that the eco-city development process should cover various aspects, such as enhancing environmental quality, protecting environmental assets and the resource base, improving the efficiency of material use, promoting a low carbon lifestyle, and developing low carbon industries [13].

Other representative literature proposed certain factors that contribute to the eco-process. These factors include synthetic governance strategies (e.g., joint venture partnership and public private partnership) [14], cross-sector administrative management [15], the improvement of environmental performance and adaptable development of infrastructure and industry [16], new policies that can balance economic and environmental targets [17], and an environment-friendly urban dwelling lifestyle [13]. Hu et al. (2016) noted that national capability and policy, local public authority, public participation, and commercial operation are the four transforming factors of eco-city development [18].

2.2. EF

Are eco-city practices effective? Recognizing the performance of these practices during the construction period is critical for policymakers to upgrade urban management strategies and make cities more "ecological". Previous studies have focused on the evaluation of eco-cities using indicators like environmental protection and economic development to find out the gap among different cities [12,19]. These studies are mostly cross-sectional researches and paid little attention to the effects of eco-practices. Environment and sustainability have also been assessed using ecological footprint (EF) analysis, input–output analysis (IOA), life-cycle analysis (LCA), carbon footprint (CF) analysis, and cost benefit analysis (CBA) [20].

The combination of the IOA and EF methods (i.e., the IOA-EF model) is useful for estimating appropriated land areas of economic sectors [21], but it focuses on industry, and doesn't embody the pressure of pollutants and wastes on the ecosystem. CF analysis only quantifies carbon emissions [22], and it doesn't consider the regional ecological carrying capacity. Besides, it is suggested that CBA is more efficient in the project or technology domain, whilst LCA is mainly applied at the micro level (e.g., product and process) [20]. EF analysis is an alternative method for the sustainability performance assessment of eco-city practices, with the features of longitudinal comparison and appraising the sustainability degree of a region at different scales, particularly for cities [23]. The method can also distinguish the extent of impacts of consumption activities (e.g., eating and drinking), productive consumption (industry), and waste types on EF [24], thus establishing logical associations between evaluation outcomes and eco-city activities. Therefore, the EF method was selected to quantitatively assess the sustainable effects of urban eco-practices.

The EF model is an evaluation method based on a quantitative indicator of the biologically productive land area (BPLA) (including land and water), which has the functions of natural resource productivity and waste purification [25]. EF represents a kind of estimated BPLA converted from people's resources consumption and waste production of a region, whereas ecological capacity (EC) refers to the total existing BPLA that a regional or urban natural ecological system can provide [26,27]. The EF model can quantitatively present the sustainable level of a country or a region by comparing its EF and EC, thereby providing valuable advice for further sustainable development.

The EF model was first proposed by Rees (1992) [28]. Wackernagel et al. (1999) improved the model and calculated the EF of 52 countries and regions in the world [29]. McDonald (2004) assessed regional sustainable development from the national, provincial, and county and municipal level using an EF model [30]. Li (2010) calculated the EF of bio-resources and energy consumption in Baotou, China, using an EF model and found that the social and economic development of the city was under an unsustainable state from 2001 to 2007 [31]. The original EF model divides the global biological productive land into six categories (i.e., built-up land, water area, arable land, fossil energy land, pasture land, and forest land) and then converts biological resources and fossil energy consumption into the corresponding biologically productive land. The model contains two accounts, namely, biological resources consumption and fossil energy consumption [32].

However, the original EF model is often criticized for not covering all the land functions (e.g., natural purification), as well as all the effects of human activities (e.g., pollution) on the environment [33,34]. In the past decade, the methodology of EF analysis has been modified numerous times [34]. Some researchers have attempted to add factors (e.g., pollutants) into the EF model. Hong (2007) added wastewater and acid rain into a water EF model [35]. Feng (2011) calculated the EF and intensity of solid waste emissions in Shenyang, China, using an EF model [36]. Hoekstra et al. (2009) included the use of freshwater when considering the standard footprint [37]. These modifications help to assess urban production–consumption holistically [38], thereby capturing the sustainable effects of eco-city practices more comprehensively.

Therefore, this study proposes a new method within which environmental pollution consumption is incorporated into the original EF model to measure eco-related long-term impacts on sustainable urban development.

3. Materials and Methods

3.1. Case Context

Originally known as Chang'an, Xi'an is the capital of Shaanxi Province in Western China. Its urbanization rate increased from 60.8% in 2000 to 72.6% in 2014 [39]. With the expansion of the city population, many environmental and ecological problems emerged. In 1999, a strategy of creating an eco-city in Xi'an was proposed. In 2004, green efforts in Xi'an were strengthened when the Chan-Ba Ecological District (CBED) began its construction of an eco-city. From 2006 to 2011, the bid and hosting of the green event (i.e., the 2011 Xian World Horticultural Exposition) was regarded as an ecological achievement of the city, which showed the further progress of Xi'an as an eco-city, at least from the official view. Therefore, Xi'an was selected as a potentially good case study to explore the impacts of eco-city development on urban EF.

3.2. Methods

3.2.1. Step One: Defining Eco-City

A mixed method case study design, including an EF model and a content analysis of eco-city practices, was adopted to frame the eco-actions and measure their long-term outcomes. Before framing the practices, an eco-city was initially defined as a resource-conserving and environment-friendly city. Then, eco-city practices were defined as the resource-saving and environment-friendly practices of the city, which decrease EF, increase urban EC, and consequently reduce the ecological deficit (ED) or increase the ecological remainder (ER).

3.2.2. Step Two: Framing Eco-City Practices

The content analysis of text materials, including news reports and policy documents from 1999 to 2014 about eco-city development in Xi'an, was conducted to refine a framework that illustrates the eco-efforts of Xi'an based on EF theory. First, a conceptual framework about eco-city practices was developed. Within the framework of extended EF, eco-policies/practices were classified into four basic categories, namely: (1) environment pollution control; (2) fossil energy consumption control; (3) biological resource consumption control; and (4) EC improvement. Then, all statements in relation to green or ecological practices were coded according to the classification in Table 1. In the process, encoded statements with the same meaning were merged into one. Encoded statements with close meanings were classified into several secondary dimensions. Then, the statements were classified into a first-level index. The framework will also guide the study to put forward hypotheses about the effects of eco-city practices on urban sustainability.

Table 1. Classification of eco-city practices based on EF theory.

First-Level Dimensions	Secondary Dimensions	Sources
Environment pollution control	Practices involving environmental protection (e.g., pollution control); waste minimization; water conservation; proper environmental quality standards	Wang et al., 2015 [4]; The Index of Sino-Singapore Tianjin Eco-city (ISSTE) (2008) [3]; Roseland (1997) [10]; Van Dijk (2015) [12]; Flynn et al., 2016 [13]
Fossil energy consumption control	Practices involving industrial transformation (e.g., developing green industries and reducing energy-intensive industries); practices of building green facilities and infrastructure; expansion of the use of clean energy, recycling and re-using; energy efficiency improvement; transportation systems that advocate walking, cycling, and public transport	ISSTE (2008) [3]; Roseland (1997) [10]; Joss (2010) [11]; Van Dijk (2015) [12]

Table 1. *Cont.*

First-Level Dimensions	Secondary Dimensions	Sources
Biological resource consumption control	Practices that advocates green lifestyle (e.g., promoting the pattern of saving and green consumption); adjustment of the structure of daily consumption	Roseland (1997) [10]; Flynn et al., 2016 [13]
EC improvement	Improvement of the yield of arable land (e.g., co-agriculture development); widening the biological productive land area of forest land and water land	McDonald et al., 2004 [30]; Monfreda et al., 2004 [40]

Note: These eco-practice dimensions were integrated from previous studies based on the EF framework; other ecological practices would be added to the catalog in the encoding process.

3.2.3. Step Three: Measuring the Performance of Eco-Efforts

An extended EF model was constructed to measure the impact of eco-efforts. The basic approach is to calculate EF, EC, and ED/ER (i.e., ED or ER = EC − EF). A negative value is ED, whereas a positive value is ER. ED indicates an unsustainable development status, whereas ER indicates a suitable development status for the region. City development status is usually measured by per capita EF, per capita EC, and per capita ED/ER.

Given the heavy pressure of pollution on the urban eco-system, an environmental pollution account was incorporated into the original footprint accounts and certain types of pollution were converted into the amount of biological productive arable lands based on their purification ability. Consequently, the extended EF model consists of three accounts, namely, environmental pollution consumption, biological resource consumption, and fossil energy consumption. Three indicators were considered in the new account, namely, sulfur dioxide, industrial fumes, and wastewater. Sulfur dioxide and fumes are assumed to be purified by forests, whereas wastewater is purified by a natural wetland (water area). The environmental pollution account was calculated as follows:

$$EF_e = \sum_{i=1}^{3} EF_i = \sum_{i=1}^{3} (C_i/Y_i) \times R_j \tag{1}$$

where EF_e is the total footprint caused by pollution, C_i is the ith pollution emission, Y_i is the purification ability of the biologically productive land corresponding to the ith pollutant, and R_j is the equivalent factor that translates a concrete land type into a common unit of BPLA.

The computation of the biological resource EF and fossil energy EF refers to methods stated by Wackernagel et al. (1999) [29] and Xu et al. (2000) [41].

$$EF_{bf} = N \bullet EF_i = N[\sum_{j=1}^{6} R_j (C_i/Y_i)] \tag{2}$$

where EF_{bf} is the total footprint caused by biological resource and fossil energy consumption, N refers to the regional population, i refers to each different consumption item (i = 1, 2, . . . , n), C_i is the per capita consumption of ith item (kg/cap), R_j is the equivalent factor (j = 1, 2, . . . , 6), and Y_i is the average productivity of producing ith consumption item for the corresponding BPLA.

The sum of EF_e and EF_{bf} is referred to as the total EF.

A computational method of EC refers to the formula presented by Tang et al. (2011) [33]. However, the biosphere does not only belong to humans and 12% of BPLA should be used for biodiversity conservation [29]. Therefore, 12% of the EC should be deducted from the total EC when calculating EC. EC is calculated as follows:

$$EC = N \times (EC_i) \times 0.88 = \sum (a_j r_j y_j) \times 0.88 \quad (3)$$

where EC_i is the per capita EC (ha/cap), a_j is the per capita BPLA of jth type land, y_j is the yield factor of jth type land, and r_j is the equivalent factor.

Furthermore, a sustainable effect index was required to evaluate the sustainable effect induced by eco-city practices from 1999 to 2014. The average annual growth rate (AAGR) of variables, such as the AAGR of GDP and population, is a simple and common index used to evaluate the social and economic performance during a period in the statistics. The AAGR of time series data is calculated based on the first and last terms (i.e., $(a_n/a_0)^{1/n} - 1$). However, this method is flawed because it neglects the middle terms between the first and last term in the time-series data. As a result, the method cannot fully describe the changes in economic variables and is more suitable for making an economic development plan rather than being employed as an application in academic papers [42].

All terms should be incorporated into the model to utilize the hidden information in the entire time-series data. Accordingly, an improved comprehensive sustainable effect index (CSEI) was developed based on the fluctuations in time-series data and their annual growth rate. The average of the annual increasing rate of each time series data (i.e., EFs, ECs, or EDs/ERs) was calculated as the overall growth rate. However, the value is still insufficient for reflecting changes in trends, including situations where data increases for several years and then decreases; thus, CSEI should consider the difference between the maximum/minimum value and the last term value. The difference is used as the parameter to adjust the average of the annual increasing rate. For example, if the maximum and most recent value of the EFs is greater than 0, this suggests a downward trend in a certain period. For EFs, this trend indicates a positive effect. Therefore, the CSEI will become smaller through subtracting the ratio between the difference and number of years, thereby reflecting the positive effect more exactly.

The formula for CSEI is

$$\text{CSEI} = 1/n \sum_{t=1}^{n} (a_{t+1} - {}^{a_t}/_{a_t}) - (\text{MAX}(|a_t|) - |a_n|)/n \quad (4)$$

where a_0, a_1, ..., a_t are the time series data and refer to EF, EC, or ED; t denotes the year; and n represents the latest year. The outcomes calculated by Equation (4) reflect the effect of eco-city practices during a certain period. A small EF or |ED| value is suitable; thus, the CSEI of EF/ED value, which is less than 0, denotes a declining trend of EF/ED, suggesting a significant positive effect of eco-city practices on urban sustainability; a positive value represents an increasing trend of EF/ED, which denotes that eco-city practices have no significant impacts on urban sustainability. A high EC value is suitable; thus, positive values represent significant positive impacts on urban sustainability.

3.3. Data Collection

Data are composed of online textual materials and official statistical data. Textual materials (e.g., news reports and policy documents) were all related to the eco-practices in Xi'an. Texts and data were collected from the Xi'an government website [43], the Xi'an Expo official website [44], CNKI.net, and Baidu.com. The dates of these reports were from 1999 to 2014. A total of 93 articles were gathered and copied to MS Word 2007 for further content analysis (see Section 3.2.2).

The quantitative data related to consumption was acquired from the Xi'an Statistical Yearbook (2000–2015) [39]. Part of the pollution emission data was from the China City Statistical Yearbook [45], and part of the land area data was from the land use change survey data of Shaanxi Province (2000–2015) [46]. With the changes in society, economy, and policies, the growth rate of the official data is unstable. For example, wastewater discharge increased at the beginning, and then decreased from a peak in 2007 owing to the more stringent control of pollution discharge.

The EF calculation was mostly based on "hectares with globally average bio-productivity" [40], except that arable land yield factors were expressed in terms of "actual land-use" in Xi'an, and environmental pollution account indicators were expressed in terms of "actual land-use" in China. C_i in the biological resource consumption account includes grain, oil, poultry and poultry products, vegetables and vegetable products, and wine (in occupied arable land); melons, fruits, and timber (in occupied forest land); meat, milk, and dairy products(in occupied pasture land); and aquatic products (in occupied water area).

Grain average yield data were collected from the online database of World Agriculture (FAO) [47]. The equivalence factor of arable land, pasture land, forest land, and water area was 2.8, 0.5, 1.1, and 0.2, respectively [48]. Yield factors of arable land were calculated according to food production, the arable area in Xi'an, and the world average yield (Table 2). The rest of the yield factors considered the average level in China. Forest land, pasture land, and water area were 0.91, 0.19, and 1, respectively.

Table 2. Value of arable land yield factors in Xi'an from 1999 to 2014.

Year	Grain Output (Ten Thousand Tons)	Total Cultivated Area (hm^2)	The Global Average (kg/hm^2)	Arable Land Yield Factors
1999	204.4	300,493.33	2744	2.48
2000	201.9	295,580.00	2744	2.49
2001	197.1	287,793.33	2744	2.50
2002	192.4	282,973.33	2744	2.48
2003	176.3	275,893.33	2744	2.33
2004	195.8	269,913.33	2744	2.64
2005	205.5	266,780.00	2744	2.81
2006	193.5	263,860.00	2744	2.67
2007	189.1	261,180.00	2744	2.64
2008	214.4	260,513.33	2744	3.00
2009	218.2	258,593.33	2744	3.08
2010	221.7	255,546.67	2744	3.16
2011	182.0	251,400.00	2744	2.64
2012	192.6	246,606.67	2744	2.85
2013	183.1	244,153.33	2744	2.73
2014	175.6	240,486.67	2744	2.66

C_i in the fossil energy consumption account includes raw coal, washed coal, other washed coals, briquette, coke, other coking products, coal gas, natural gas, liquefied natural gas, crude oil, gasoline, kerosene, diesel oil, fuel oil, liquefied petroleum gas, other petroleum products, other fuels, heating power, and electricity. Heating power and electricity occupied the built-up land, for which the equilibrium factor was 2.8, and the rest occupied fossil energy land, for which the equilibrium factor was 1.1. The average global energy footprint (GJ/hm^2) and convert coefficient (GJ/t) were as cited from Wackernagel et al. (1999, 1997) [29,49].

According to the China National Biodiversity Research Report (1998), the capabilities of biological productive land to process pollution are as follows: the capabilities of coniferous forest and broadleaf forest to absorb sulfur dioxide are approximately 215.6 kg/ha and 88.65 kg/ha per year, respectively; the capabilities of detaining dust of coniferous forest and broadleaf forest are 33.2 ton/ha and 10.11 ton/ha per year, respectively; and the capacity of natural wetland to process wastewater is approximately 8.11 ton/ha per year [50]. The capability of conifer-broadleaf forest is usually the average of conifer and broadleaf forest.

The area of broad-leaved forest, coniferous forest, and conifer-broadleaf forest accounted for 63.6%, 11.6%, and 24.8%, respectively, of Xian's total forest area in 2005 [51]. Weighted by areas of three types of forest, the weighted average of capabilities of absorbing sulfur dioxide and detaining dust were calculated and provided as the capability of the whole forest in Xi'an. The results show that the capability of forest to absorb sulfur dioxide is 185.13 kg/ha per year, and the capability of detaining dust of forest is 27.66 ton/ha per year.

In the process of calculating the EF, a trade adjustment was not taken into account because the carried proportion of EF induced by international imports and exports was minimal, and the evaluation of the impacts of trade between domestic regions needs more comprehensive and detailed statistics, which are currently unavailable.

4. Eco-Practices Framework and Hypotheses

This section explores the basic framework of the eco-city practices in Xi'an through document analysis and 93 texts were coded and classified. Eco-practices in Xi'an since 1999 were classified into four first-level dimensions (see Table 3).

(1) Environmental pollution control. The main green practices include water and air pollution source control (e.g., clean energy action). Logically, these measures may greatly reduce the footprints of water area, forest land, and fossil energy.
(2) Fossil energy consumption control. This dimension includes two major aspects, one is "greening" facilities, buildings, and industries, and the other is transportation systems renovation. Thus, the consumption of fossil energy footprint was expected to reduce.
(3) Biological resource consumption control. Xi'an encouraged citizens to participate in green consumption through various participatory activities, which positively related to the reduction of pasture land and arable land footprints.

To date, green practices are involved in the process of reducing EF. The following hypotheses (H) were developed to guide this study.

Hypothesis 1 (H1). *Eco-practices or activities in Xi'an since 1999 will significantly contribute to reducing footprints of water area, forest, fossil, pasture, and arable land.*

(4) EC improvement. Eco-practices include eco-agriculture construction and the increase of water area and forest land area. The construction of eco-agriculture may have a positive effect on the improvement of the EC of arable land. Wetland eco-restoring projects, as well as forest plantation and conservation, are expected to increase the ecological carrying capacities of water land and forest land.

Hypothesis 2 (H2). *Eco-practices in Xi'an since 1999 will have a significant positive effect on the growth of arable land, forest land, and water area capacities.*

In synthesizing the two hypotheses above, we can propose H3 and H4:

Hypothesis 3 (H3). *Eco-practices in Xi'an will lead to a reduction in trends in the ED of water area, forest land, pasture land, and arable land.*

Hypothesis 4 (H4). *Overall, eco-practices will cause reduction trends in the per capita EF and ED and have a positive impact on sustainable urban development.*

In the next section, the hypotheses were tested using the extended EF model.

Table 3. Framework of eco-city practices in Xi'an.

First-Level Dimensions	Secondary Dimensions	Eco-City Practices
Environment pollution control	1. Water pollution control	• In improving the capacity of wastewater treatment, more than 360 paper mills were shut down and more than 80 million tons of wastewater had been treated by the end of 2006. Twelve wastewater treatment plants had been built. The annual sewage treatment capacity increased by 565,000 tons. • High water-pollution industries, such as printing and textile were downsized. A total of 105 plating corporations were closed from 2001 to 2006. • Wastewater treatment and reuse engineering in CBED have been conducted since 2004.
	2. Air pollution control	• Diverse measures had been taken for clean energy, such as eliminating or converting coal-burning boilers, promoting the usage of semi-coke, clean coal, and additives for sulfur capture, and promoting the shift from coal to gas. More than 6900 restaurants and hotels had changed to use clean fuels. • Gas emission of vehicles was reduced. Approximately 25,000 vehicles that weren't up to emission standard were rectified and reformed within a given period. Moreover, the campaign of "converting oil to gas" was accelerated. • The above practices reduced the emission of SO_2 and soot.
Fossil energy consumption control	3. Greening industries	• The application of ecological green production technologies was widely promoted. And it can improve the production efficiency and reduce energy consumption. • Modern service industries (especially finance, logistics, tourism, gardening, exhibition and leisure industry) were developed in CBED. It is assumed that service industries development can decrease energy consumption per 10,000 Yuan of GDP, and thereby reducing the total energy consumption. • Green hospitality was developed. Green motels and ecological star hotel clusters were constructed. By doing this, the energy consumption of service industries can be reduced.
	4. Green buildings and facilities	• The sites (e.g., venues) of the 2011 Xian World Horticultural Exposition (WHE) were green. Building green venues is consistent with the idea of energy-saving and emission-reduction. • Ecological communities, such as Yanming Lake energy conservation communities, were built.
	5. Transportation systems renovation	• "Public transportation priority" policy and transportation integration strategies were implemented. For example, urban road networks were improved, rail transits (e.g., subway) were developed, and public bus lanes were increased. Public transit can reduce the use of private cars and decrease energy consumption in transportation industry. • Residents' green commuting was encouraged. People were encouraged to use green vehicles like bicycles, and bicycle paths were built accordingly. These can reduce energy consumption of vehicles. • Traffic stream control. During the WHE, use of private cars were restricted based on the odd and even number rule, and heavy-polluting, high-emission vehicles were forbidden to enter the city traffic control areas. These can also lead to the reduction of energy consumption of vehicles.
Biological resource consumption control	6. Green citizens	• Citizens were established green and energy-saving lifestyle through various participatory activities, such as shopping in green creative supermarkets and participation in green products exhibitions. • The city also promoted the "green rule 10" (e.g., to cherish and economize on the use of grain, to advocate rational consumption). These practices can reduce biological resource consumption in residents' daily life.
EC improvement	7. Eco-agricultural construction	• The construction of ecological agriculture was strengthened comprehensively. Dust prevention measures (e.g., non-tillage with retaining stubble (NT) or planting winter crops) were taken intemporarily bare soilarea. Xian alsopromoted technologies of conservation tillage to reduce pollution of farmland and soil dusts. These can increase the productivity of arable land and improve its EC.

Table 3. *Cont.*

First-Level Dimensions	Secondary Dimensions	Eco-City Practices
EC improvement	8. Expansion of forest land area	• Greening efforts toward the Xi'an Expo site was strengthened. A total of 1.005 km^2 of green area was completed, with more than 70% greening rate of the sites. The urban forest land had increased. • Forestation. Forest land protection and restoration projects were implemented to increase forest land area. Especially, Xi'an became the National Garden City in 2010. The plan of building the China's "National Forest City" has been implemented since 2013.
	9. Expansion of Water area	• The wetland and water areas were restored and enlarged. For example, Wetland eco-restoring projects of the Jingwei Wetland, Yanming Lake, Hu River, Ba River, Wei River, Chan River, etc. had been implemented. From 2012 to 2014, 445.33 ha of new water areas and 900 ha of wetland areas were added.

5. Sustainable Impact Evaluation: Extended EF Model

Per capita EF, EC, ED, and six components of per capita EF in Xi'an from 1999 to 2014 were calculated using Equations (1)–(3). The sustainable performance of eco-city practices, combined with volatility trends and CSEI, were analyzed.

From 1999 to 2014, the footprint curves of arable land (CSEI = −0.012) and forest land (CSEI = −0.036) showed a downward trend. The water area footprint (CSEI = −0.142) initially increased, but began to decrease from 2007, which indicates the decreasing pressure of biological resources and environmental pollution in Xi'an. The EF of fossil energy land (CSEI = 0.099) exhibited an increasing trend, which shows an increasing pressure from fossil consumption. Furthermore, the EF of built-up land (CSEI = 0.03) and pasture land (CSEI = 0.028; mainly led by meat and dairy consumption) increased from 1999 to 2014 (Table 4). This finding suggests that eco-practices did not have significant positive impacts on the decrease of EFs in built-up and pasture lands. The empirical results partially support H1.

Table 4. Six components of per capita EF in Xi'an from 1999 to 2014.

Year	Arable Land	Forest Land	Water Area	Pasture Land	Built-Up Land	Fossil Energy Land
1999	0.2816	0.0846	1.7677	0.0852	0.0077	0.1656
2000	0.2906	0.0742	1.6036	0.0917	0.0068	0.2183
2001	0.2872	0.0721	1.3962	0.0694	0.0073	0.2915
2002	0.2899	0.0657	1.9541	0.0749	0.0083	0.2709
2003	0.2843	0.0629	2.0136	0.0799	0.0083	0.3085
2004	0.2712	0.0779	2.2045	0.0795	0.0092	0.4861
2005	0.3196	0.0741	2.7155	0.1167	0.0094	0.4225
2006	0.2916	0.0706	2.5593	0.1088	0.0117	0.4525
2007	0.2755	0.0735	2.9518	0.1043	0.0106	0.4785
2008	0.3403	0.0728	2.8368	0.1343	0.0107	0.4516
2009	0.3042	0.0636	2.0439	0.1139	0.0124	0.5503
2010	0.3160	0.0592	2.0744	0.0893	0.0141	0.5105
2011	0.2206	0.0701	1.9708	0.0862	0.0137	0.4844
2012	0.2253	0.0607	1.5368	0.0843	0.0120	0.5205
2013	0.2275	0.0467	1.3591	0.0962	0.0127	0.6629
2014	0.2316	0.0461	1.0159	0.1071	0.0108	0.5816
CSEI	−0.012	−0.036	−0.142	0.028	0.030	0.099
Effect	positive	positive	positive	—	—	—

Note: "—" means no significant positive effect.

For the components of per capita EC (Table 5), the arable land capacity (CSEI = −0.029) decreased from 0.272 in 1999 to 0.183 in 2014, indicating the decline of arable land areas in Xi'an. This result indicates that eco-practices did not positively affect the improvement of arable land EC. The CSEI of pasture land capacity was −0.022. The per capita EC of forest land (CSEI = −0.002) presented a negative growth from 1999 to 2014, of which of the water area (CSEI = −0.035) decreased from 0.0008 to 0.0005. This suggests that eco-practices have not resulted in the improvement of the EC of pasture land, forest land, and water area. The CSEI of the built-up land capacity (CSEI = 0.028) from 1999 to 2014 maintained a slight increasing trend, indicating a steady growth of the built-up land area. The results show that four components of EC (i.e., arable land, pasture land, forest land, and water area) decreased from 1999 to 2014, whereas the EC of built-up land increased. The outcomes failed to confirm H2.

Table 5. Five components of per capita EC in Xi'an from 1999 to 2014.

Year	Arable Land	Forest Land	Water Area	Pasture Land	Built-Up Land
1999	0.2721	0.0545	0.0008	0.0002	0.0897
2000	0.2446	0.0496	0.0008	0.0001	0.0836
2001	0.2547	0.0529	0.0008	0.0002	0.0909
2002	0.2459	0.0526	0.0008	0.0002	0.0915
2003	0.2209	0.0517	0.0008	0.0002	0.0865
2004	0.2425	0.0518	0.0008	0.0001	0.1010
2005	0.2287	0.0466	0.0007	0.0001	0.0979
2006	0.2112	0.0457	0.0007	0.0001	0.0944
2007	0.2045	0.0446	0.0007	0.0001	0.0935
2008	0.2299	0.0448	0.0007	0.0001	0.1044
2009	0.2323	0.0505	0.0004	0.0001	0.1266
2010	0.2349	0.0502	0.0004	0.0001	0.1333
2011	0.1920	0.0499	0.0004	0.0001	0.1153
2012	0.2022	0.0496	0.0004	0.0001	0.1266
2013	0.1915	0.0521	0.0005	0.0001	0.1299
2014	0.1828	0.0519	0.0005	0.0001	0.1291
CSEI	−0.029	−0.002	−0.035	−0.022	0.028
Effect	—	—	—	—	positive

Note: "—" means no significant positive effect.

According to Table 6, the ED of the water area increased between 1999 and 2007, but sharply decreased from 2008. The CSEI of water area was −0.142, which indicates that the eco-process in Xi'an had a significant positive impact on water area sustainable development. The CSEI of built-up land ER was 0.029, showing an increasing trend. The CSEI of forest land ED was −0.064, suggesting that the eco-process in Xi'an is positively associated with forest land sustainability. However, the ED of arable land fluctuated with a CSEI of 0.406, indicating that the eco-process in Xi'an did not have a significant positive effect on arable land sustainability. The ED of pasture land stayed at a low level with a CSEI of 0.028, suggesting that the eco-process in Xi'an did not positively influence the decrease of pasture land ED. The empirical results partially support H3.

The extended EF value broadens the contents of EF by adding the environmental pollution account, making the EF values in this study greater than those calculated by Wu et al. (2006) between 1999 and 2004 [52]. The per capita EF and ED in Xi'an fluctuated during this period. They increased from 1999 to 2007, and then decreased from 2008 to 2014. Conversely, EC maintained a relatively stable change (CSEI = −0.01; see Figure 1). The overall increasing trend of EF and ED in Xi'an from 1999 to 2007 indicated an unsustainable state of the ecological environment. However, further observations based on Figure 1 revealed that per capita EF and ED began to decrease in 2007, indicating that 2007 was a turning point in the sustainable development performance of Xi'an. The CSEI values of EF and ED were −0.123 and −0.122, respectively. This result indicates that the eco-process in Xi'an had a significant positive effect on urban sustainable development. Therefore, H4 is proved.

Table 6. Five components of per capita ED/ER in Xi'an from 1999 to 2014.

Year	Arable Land	Pasture Land	Forest Land	Water Area	Built-Up Land
1999	−0.0095	−0.0851	−0.0302	−1.7668	0.0821
2000	−0.0460	−0.0916	−0.0246	−1.6028	0.0768
2001	−0.0325	−0.0692	−0.0192	−1.3954	0.0837
2002	−0.0440	−0.0748	−0.0131	−1.9533	0.0832
2003	−0.0634	−0.0797	−0.0111	−2.0128	0.0783
2004	−0.0286	−0.0794	−0.0261	−2.2037	0.0918
2005	−0.0909	−0.1165	−0.0275	−2.7148	0.0885
2006	−0.0803	−0.1086	−0.0249	−2.5586	0.0827
2007	−0.0710	−0.1042	−0.0289	−2.9511	0.0829
2008	−0.1105	−0.1342	−0.0280	−2.8362	0.0937
2009	−0.0719	−0.1138	−0.0132	−2.0434	0.1142
2010	−0.0811	−0.0892	−0.0090	−2.0740	0.1192
2011	−0.0286	−0.0861	−0.0202	−1.9703	0.1015
2012	−0.0232	−0.0842	−0.0112	−1.5364	0.1146
2013	−0.0361	−0.0961	0.0055	−1.3587	0.1172
2014	−0.0488	−0.1070	0.0058	−1.0155	0.1182
CSEI	0.406	0.028	−0.064	−0.142	0.029
Effect	—	—	Positive	Positive	—

Note: The positive values are ER, the negative values are ED; "—" means no significant positive effect.

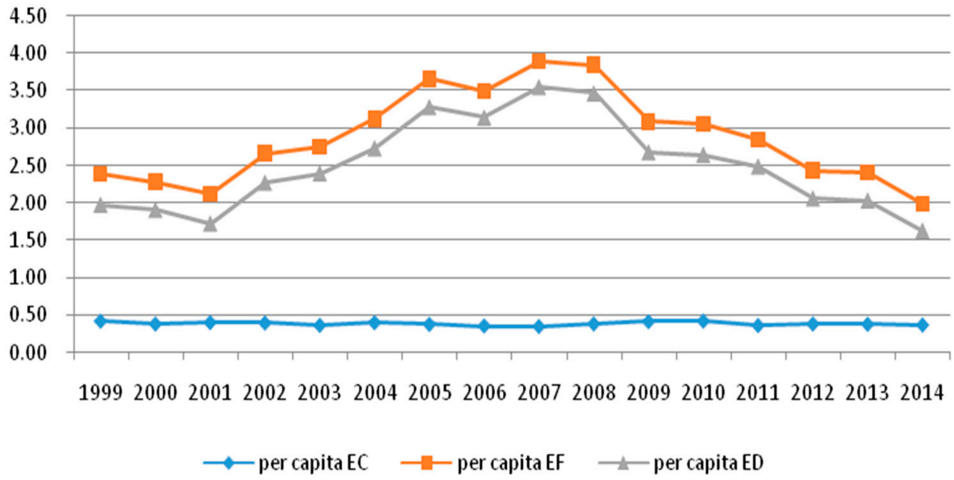

Figure 1. Dynamic Change of per capita EF, EC, and ED in Xi'an from1999 to 2014. Note: Per capita ED was converted into an absolute value for the convenience of graphing.

6. Conclusions

6.1. Discussion

A framework of eco-city practices was generalized following the conceptual framework of an extended EF in the current study. It is revealed that Xi'an City had been paying attention to diverse eco-practices (including water conservation, air pollution control, the development of green industries, green buildings and facilities, green citizens, transportation systems renovation, eco-agriculture construction, and forest land and water area development) from 1999 to 2014. Among all the eco-practices, water pollution control and water area development were the major initiatives taken in the eco-city development. Air pollution control and forest land development also played important roles in the process. The framework helps to understand the process of China's urban eco-practices. In addition, the conceptual framework of extended EF developed in the study can be used as the analytical tool to frame practices of other eco-cities.

The extended EF model with an additional dimension of environmental pollution was constructed to evaluate the sustainable effects of the eco-practices on urban EF (an index of sustainable urban development). A new index, CSEI, was developed to evaluate the sustainable performance of the eco-development process. The assessment results show that eco-city development practices had a significant positive impact on the decrease of the footprints of arable land, water area, forest land, per capita EF, and per capita ED. Thus, eco-practices play a positive role in enhancing urban sustainable development. According to the CSEI values, the reduction of per capita EF was mainly due to the decrease in water area and forest land footprints. This is because that Xi'an had outstanding achievements in terms of environmental pollution control with a decrease of 127.29 million tons of wastewater emission, 35,551.34 tons of sulfur dioxide emission, and 2377.33 tons of industrial soot emission from 2007 to 2014 [39]. However, the footprints of fossil, built-up, and pasture land increased, suggesting that the eco-practices, such as energy conservation (e.g., the development of green industries) and green consumption, had no apparent positive effect.

The impacts of eco-city development practices on the increases of arable land, forest land, and water area capacities were not apparent. This indicates that the eco-development practices related to the improvement of EC had not improved the sustainable performance. Compared with environmental pollution control, efforts to improve the EC seem ineffective. The main reason is that the rapid urbanization process in Xi'an resulted in the expansion of built-up land, whereas the growth of arable land, forest land, and water area was difficult to achieve.

6.2. Implications

More than 80% of China's prefecture-level cities are going through the transformation to "Eco-urbanism" [53]. Xi'an is a typical city, which is moving toward becoming an eco-city with the pressure from environmental and resource problems. Additionally, Xi'an provides an early exploration into the "eco-urbanism" pattern, and the experience provides implications for other cities. The study shows that eco-practices concerning environmental pollution treatment would be effective for urban sustainability, suggesting the need for strict pollution control to improve urban sustainability.

However, the results also indicate the increasing trend of the fossil energy footprint and the indistinctive positive impact of the eco-practices on the EC of arable land, forest land, and the water area. The EC and ED of built-up land rose from 1999 to 2014, indicating that an unreasonable structure of land use limits the improvement of the overall urban EC. The current research also shows that the city exerted more efforts to shape the green environment than resource conservation (e.g., fossil energy, built-up land), suggesting the need to rethink the eco-city model in China. As Pow and Neo (2015) stated, with the social-economic and environmental contradictory tensions in China, eco-projects were often driven by green entrepreneurial objectives [54]. Therefore, this study suggests the importance of making systematic resource conservation and utilization plans to cope with the ecological pressures. The plans include reconstructing the transport system, restricting the increase of automobiles, applying energy-saving technologies, developing green industries, and promoting intensive built-up land utilization to ensure more water areas and forest and arable land. In addition, more effective ways of improving the yield of arable land are also needed.

Theoretically, the extended EF model has broadened the meaning of the EF value, and bridged the gap between eco-practices and the EF model, thereby providing a useful tool for evaluating eco-city practices in the future. More importantly, the new model covered more diverse and comprehensive functions (including waste absorption and resources supply) of BPLA than the traditional model. The model highlights the balance between various consumptions and the supplying capacity of the BPLA of an eco-city. It is suggested that this kind of balance should be taken into consideration when evaluating an eco-city and its practices. The current study also assessed the comprehensive performance of eco-practices from the beginning of an eco-city construction by using a diachronic monitor on eco-city practices in a specified timeframe.

6.3. Limitations and Future Directions

The extended EF model clarifies the sustainable status of the city. However, the three selected pollution indicators only involved the forest land and water area footprint. New items, such as solid waste, could be added in future studies. Besides, the inter-cities trade footprint was not considered due to the lack of official statistics.

Moreover, the present study did not identify the period during which the effects of eco-practices were the greatest on urban EF. Additional researches could be conducted to divide the eco-city development process into different stages in the long-term and evaluate the eco-effects by stage.

Finally, the EF model is only one of the methods to evaluate eco-development performance. There are some challenges for improving the ecological footprint further because of increasing consumption types and the difficulty of embodying all the other ecological and social factors, such as biodiversity, carbon dioxide, and the quantity of water resources. Multiple approaches (e.g., energy analysis) to evaluate the effects of eco-city practices from different perspectives should be adopted to provide deeper insights into urban eco-city development strategies.

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