Journal of Environmental Engineering and Landscape Management
ISSN 1648–6897 / eISSN 1822-4199
2022 Volume 30 Issue 3: 350–362
https://doi.org/10.3846/jeelm.2022.17407

THE DEVELOPMENT STAGE OF XIAMEN CITY AND RELATED ENVIRONMENT EVOLUTION

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Received 22 September 2021; accepted 30 December 2021

Highlights

- An improved stage model to describe the urban development and environment evolution was proposed.
- Huge and continuous growth of eco-environmental pressure (like EF) along with the rapid industrialization and urbanization stages was obtained.
- Possible approach to support Xiamen City hastening its transition to eco-city was discussed.

Abstract. A model of environmental evolution of cities, especially in East Asia, is said to follow four stages. The pathways to the fourth stage of eco-city are not always clear, but need to be contextual. This research extended the original stage model of environmental evolution to describe urban development and its impact on the environment, especially integrated a model comprise of density, mix and accessibility (DMA) for urbanization and applied Ecological Footprint (EF) concept for pressure on eco-environment. The research analyzed the Xiamen City in China through the first three stages in order to gain insights how the city might be able to hasten its transition to the fourth stage of an eco-city. As expected, the development of Xiamen City and its environmental impacts has very obvious stage characteristic. Before 2010, Xiamen City got through a long time of Stage I (poverty stage); and in the period of 2010 to 2019, Xiamen experienced the Stage II (industrial pollution stage) and Stage III (mass consumption stage) crossly. The new built-up land in the decade of 2000–2010 is much larger than the previous 10 years from 1989 to 2000, 5 times more. Meanwhile, compared with 1980–1995, the ecological deficit also enlarged greatly in period of 1995–2010. Considering up to 2019 Xiamen still has large amount of energy consumption and high level output of industry solid waste, Xiamen should take measures of adjusting the industrial structure, promoting the green industry and planning the urban growth boundary to achieve the eco-city stage.

Keywords: Xiamen, urbanization, environment, stage, ecological footprint.

Introduction

Urbanization, indeed promoted the social and economic development (Bai et al., 2012) but it also brought a series of ecological and environmental problems, such as ecological degradation, environmental pollution (including air, water, solid waste, and noise pollution, etc.), resource depletion and land in short supply (Huang et al., 2016). Since the 1980s, sustainable development of balancing urbanization and ecological environment draw great attention (Vernberg, 1997; Hancock, 1996; Shin et al., 1997; Parker, 1996). Scholars like Register and Roseland introduced the concept, primary principles and heading approach of eco-city (Roseland, 1997a, 1997b; Register, 1987).

China's urbanization could be divided into two distinct phases by the Opening Up policy in 1978. Before 1978, China's urbanization ratio was pretty low and the progress was also slow. After 1978, with the continuous and rapid economic development, China's urbanization entered a new stage, urbanization ratio increased from 17.92% in 1978 to 37.7% in 2001 (Bai et al., 2014). In 2000, the national 10th Five-Year Plan took urbanization

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as a key national development strategy for the first time. Since then, a new round of China's urbanization got into the accelerated development stage (Jin et al., 2018, 2019). By 2011, China's urbanization ratio got over 50%, reaching 51.27%. In 2014, the government released the National New-type Urbanization Plan, which set targets for China's urban population fraction to reach 60% by 2020. Urbanization along with industrialization has become the two engines of modernization and economic growth (Bai et al., 2014).

Rapid urbanization leads to huge expansion of the urban area and population, inevitably consuming large amount of arable land, resources and energy, resulting in increased pressure on natural resources and the eco- environment (Zhu et al., 2002a, 2002b; Wang, 2001; Wang et al., 2001). Thus, the contradictions between urbanization, protection of natural resources and ecological preservation became greatly marked (Bai et al., 2014; Grimm et al., 2008; Chen et al., 2013). Such situation brings increasingly threaten to the regional sustainable development and national policy of ecological civilization.

Xiamen, known as English name Amoy, has a long history linking China with western countries, especially when it became one of the first five opening ports based on the Treaty of Nanjing in 1842. Xiamen is also well known for its sustainable development and low pollution (Zhao, 2011), especially the beautiful and livable reputation of Gulangyu Island. Actually, 13 countries had ever built consulates, churches and hospitals on Gulangyu Island by the beginning of the 20th century. In 2004, Xiamen even obtained "UN-Habitat Award". While as part of the Opening-Up Policy in 1980, Xiamen became one of China's original four Special Economic Zones (SEZs) opened to foreign investment and trade (Zhao et al., 2010). Since then, three decades of development greatly modernized the Xiamen's urban landscape (Tang et al., 2013).

Tang et al. (2013) and Lin et al. (2013) firstly observed Xiamen's historical footprints and tremendous achievements in different period. Baohong et al. (2021), Chen et al. (2019), and Hao et al. (2017) noticed the changes of ecosystem health by observation of red tide outbreaks, the suspended sediment concentration (SSC) in Xiamen tidal cycles, or ecological security of Xiamen estuary. These researches generally show that the urban spatial expansion with rapid socioeconomic development in Xiamen already caused various eco-environment problems and couple of scholars provided suggestions in different perspective for sustainability, such as Shi and Yuan focused on Compact City, Shao suggested multiple approach of Sponge City and Zhu supported local legislations, regulations and rules for a better coast (Shi et al., 2016; Yuan et al., 2017; Shao et al., 2018; Zhu et al., 2019).

For environmental problems in East Asian cities, many studies have been done on this subject. The research in Bai et al. (2000) proved common characteristics in the development of East Asian cities and proposed a stage model to describe different environmental problems at different stages of urban development (Bai & Imura, 2000). In this stage model, Bai divided urban environmental evolution into four stages: Poverty Stage, Industrial pollute on stage, Consumption stage, Eco-city stage. However, the stage model mainly describes the evolution of the environment and the indicators used for description of the urbanization are quite few, actually only one indicator of population urbanization ratio. Thus, this research set a hypothesis that, for urban development, there's not only stage characteristics in environmental evolution, but also in the two main engines of industrialization and urbanization that promote urban development as well as impact environmental evolution.

Generally, this paper extended the observation by Tang et al. (2013) and Lin et al. (2013) about Xiamen's development but focuses on a general view of the Xiamen's development and its impact upon environment. Further, in order to highlight the temporal stage characteristic along with environmental pressure in Xiamen and gain insights how the city might be able to hasten its transition to an eco-city, this research extended the stage model for environment evolution by Bai and Imura (2000) to description of three aspects of urban development: industrialization, urbanization and environment evolution (IUE). Multiple indicators are added to describe the two engines (urbanization and industrialization) for economy growth, especially a DMA concept (density, mix and access) for better understanding of the urbanization. While the environmental impacts of these changes are calculated mainly following the Ecological Footprint. Based on these analysis and calculation, using the frame work of the stage model, the development stage of Xiamen City was defined and approach for eco-city was discussed finally.

1. Methodology

1.1. Stage model of IUE

Like the stage model in Bai and Imura (2000) and DMA theory in Dovey et al. (2014), the stage model of IUE here is not a model based on a rigorous data analysis in this research, but sets a concept, theoretical basis and framework for general observation and statistical data analysis of what is the trend as well as what is possible. Specifically, the improved stage model proposed in this research has three basis of IUE, as shown in the bottom of Figure 1. Based on these three aspects, the corresponding index system is set up and Figure 1 shows the relationship of these three aspects, specific indicators and urban development stages.

Though this research chose main representative categories and typical indicators from the indicator system in Bai and Imura (2000), for a better understanding of the urbanization, a new concept of DMA model were introduced and integrated to the stage model to describe the physical change of urbanization, including the land use, road network expansion and population increase, as shown in the following section.

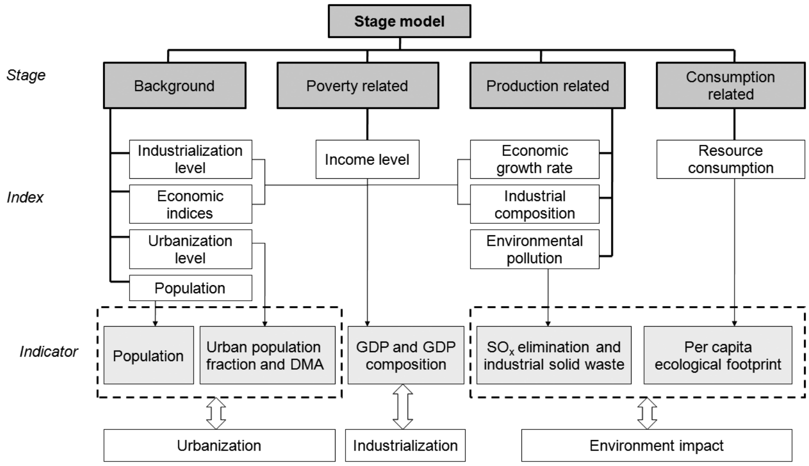

Figure 1. Reconstruction of indicator system integrated three aspects of IUE (figure drawn by the author)

1.2. DMA

DMA, density-mix-access, are primary categories used for urbanization analysis at multiple scales. Like biological DNA, it does not determine outcomes but sets a framework for what is possible (Dovey et al., 2014). The theoretical framework of this intersection has been developed from two primary sources, "assemblage" (Deleuze & Guattari, 1987) and "resilience" theory of complex adaptive systems (Gunderson & Holling, 2002; Walker & Salt, 2006). Dovey et al. (2014) have used these primary categories of DMA for analysis of social, spatial and environmental at multiple scales (Dovey et al., 2014).

This paper chose corresponding indicators for each of the DMA aspects. These indicators were categorized to the final four, population density, road density, land use mix and connectivity. The whole process is shown in Figure 2.

Because the analysis of land use mix only need statistic, so the final calculation is about the following three indicators:

1) Formula of population density is the following (Bourdic et al., 2012):

$$\text{Human density} = \frac{\text{population}}{\text{area of the selection (m}^2\text{)}}. \quad (1)$$

2) Formula of road density is the following (Pont & Haupt, 2009):

$$N_f = (\sum l_i + (\sum l_e)/2)/A_f, \quad (2)$$

where, l_i = length of the interior network (m); l_e = length of edge network (m); A_f = area of fabric (m^2).

3) Formula of connectivity is the following (Bourdic et al., 2012):

$$\text{Connectivity} = \frac{\text{number of intersections}}{\text{seletion area (m}^2\text{)}}. \quad (3)$$

1.3. Ecological Footprint

Ecological footprint (EF) represents human demand for ecosystem products and services through identifying the amount of six bio-productive land use types (including farm land, grazing land, forest land, fishing ground, built-up land and energy land). EF is a synthetic method and comprehensive indicator to trail human impacts on eco-environmental system. For the past few years, a growing number of scholars had employed it to capture environmental degradation effectively (Wackernagel, 1996, 1999a, 1999b, 2002; Borucke et al., 2013; Lin et al., 2018). Global Footprint Network began its National Footprint Accounts (NFA) program in 2003. In the recent edition of EF guidebook issued in 2018, NFAs give the newest standard definition for EF (Lin et al., 2018).

1.3.1. Ecological Productive Area

Ecological Productive Area represents the ability of an ecosystem to produce useful biological materials and to

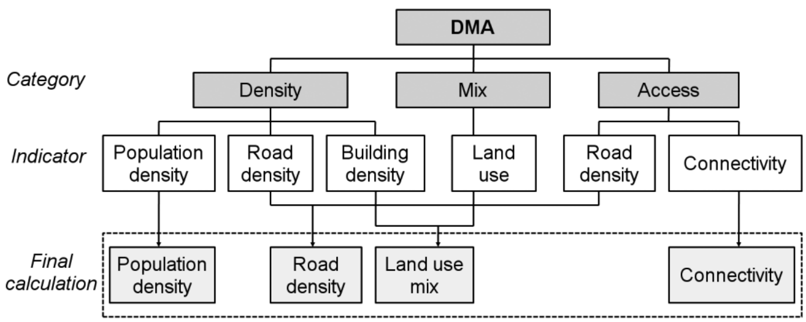

Figure 2. Simplification process of DMA indicator system (figure drawn by the author)

absorb carbon dioxide emissions, usually referring to the supply of land available to serve each use (Ewing et al., 2010).

1.3.2. Bio-capacity

As defined in NFA Guidebook 2018: a measure of the amount of biologically productive land and sea area available to provide the ecosystem services that humanity consumes – our ecological budget or nature's regenerative capacity.

1.3.3. Ecological deficit/reserve

This indicator described the difference between the bio-capacity and Ecological Footprint of a region or country. An ecological deficit (ED) occurs when the Footprint of a population exceeds the bio-capacity (BC) of the area available to that population. Conversely, an ecological reserve exists when the bio-capacity of a region or country exceeds the footprint of its population.

1.3.4. EF equations

This research mainly calculated the Ecological Footprint of Consumption. All the consumption data is obtained from the yearbook of Xiamen and the Xiamen Bureau of Statistics. These consumption data already integrated the production data with both imports and exports data (consumption = production + imports – exports). The bio-resource products in this research include 15 types like cereals, potato, beans, mutton et al. and all the energy resources (relate to carbon dioxide emitted) were sort out to electricity, coal and heating power.

Based on traditional EF model by Rees, WWF started to carry out dynamic analysis of long time series since the report in 2004, mainly adding a new adjustment factor (average inter temporal yield factor, IYF), so as to improve the traditional calculation method, reduce the error caused by temporal accumulation, and strengthen the accuracy in time series calculation (Lin et al., 2018). Thus, this research uses the newest analysis frame, methods and steps in NFA 2018 to do the EF calculation. In addition, for comparison among different regions, this research uses the world average yield (Y_w) and the world average Inter-temporal Yield Factor (IYF_W) in calculation of six land area including crop land, grazing land, forest land, fishing area, built-up land and energy land, expressed in units of average biological productivity (or global hectares, gha). "EQF" (Equivalence factor) contains the equivalence factor for given land use type throughout NFA 2018. The calculation equations refer to NFA Guidebook 2018 and Borucke et al. (2013).

The Ecological Footprint time series are calculated as follows:

$$EF_C = \sum \frac{C_{N,i,j}}{Y_{N,i,j}} \times YF_{N,i,j} \times IYF_{W,i,j} \times EQF_{i,j} = \sum \frac{C_{N,i,j}}{Y_{W,i,j}} \times IYF_{W,i,j} \times EQF_{i,j}, \quad (4)$$

where, for any product i (bio-resource or carbon dioxide emitted, like cereals, potato or coal) produced by given land type, in a given year j, EF_c = Ecological Footprint associated with consumption, global hectares (gha); C_N = consumption amount, $t \cdot yr^{-1}$; Y_N = National-average yield for product extraction or waste absorption, $t \cdot nha^{-1} \cdot yr^{-1}$, nha means national-average hectares (for a given land use type); YF_N = Yield factor of a given land use type within a country, $wha \cdot nha^{-1}$, wha means world average hectares (for a given land use type); EQF = Equivalence factor for given land use type, $gha \cdot wha^{-1}$; IYF_W = World average Inter-temporal Yield factor of a given land use type, (unitless); Y_W = World-average yield for product, $t \cdot wha^{-1} \cdot yr^{-1}$.

Similarly, bio-capacity time series are calculated in terms of constant gha as follows:

$$BC = \sum A_{N,i,j} \times YF_{N,i,j} \times IYF_{W,i,j} \times EQF_{i,j}, \quad (5)$$

where, for any product i, in a given year j, BC is the total bio-capacity, gha; A_N represents the bio-productive area available at the country level, nha; YF_N, IYF_W and EQF, are the country-specific yield factor, the world average Inter-temporal Yield Factor, and the equivalence factor for the land use type producing that product, respectively.

The ecological deficit could be worked out using the following formula:

$$ED = EF - BC, \quad (6)$$

where, EF is the ecological footprint, BC is the bio-capacity.

1.4. Study area and data processing

1.4.1. Study area

Xiamen is one of the major coastal ports in Fujian Province, China. As early as 1995, Xiamen identified itself as "China's Special Economic Zone, an important central city in the southeast coast, a port and a scenic tourist city". The topography of Xiamen inclines from higher northwest to lower southeast, composes of mountains, hills and seaside lowland (Figure 3). The whole city has a total administrative area of 1617 km^2 (including both land and surrounding sea areas).

In 1988, Xiamen was promoted to sub-provincial status and began to be considered in China's state planning specially. In 1989, the State Council approved its two administration districts of Xinglin and Haicang as Taiwan investment zones. Up to then, the second expansion of Xiamen SEZ has been completed. The scope of the Special Economic Zone had expanded from 2.5 km^2 of Huli Export Processing Zone to 131 km^2 of the whole island, with another expansion from the island inside to outside. In 2010, Xiamen SEZ was expanded to the whole Xiamen administrative area, including four districts outside Xiamen Island, Jimei, Haicang, Tong'an and Xiang'an. After this expansion, the area of Xiamen SEZ reached to 11 times larger than before.

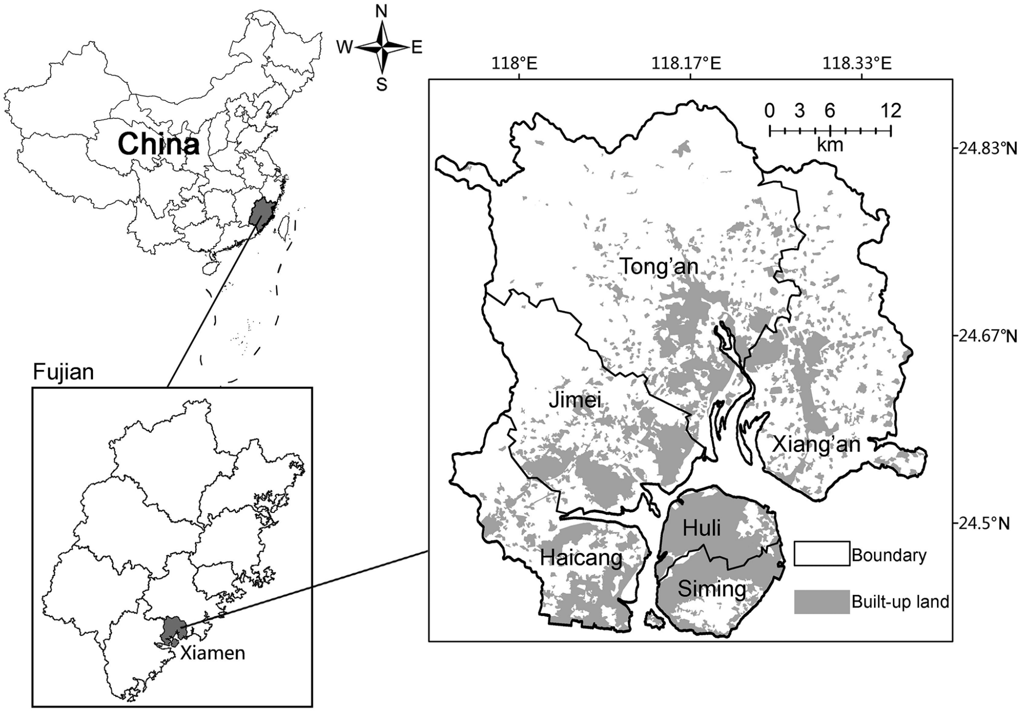

Figure 3. Study area of Xiamen City located in coastal Fujian Province, China (figure drawn by the author)

1.4.2. Data processing

Based on the introduction of Xiamen in the section "Study area" above, it could be seen that the very key time nodes for Xiamen development since 1980 would be around 1980, 1989 and 2010. This research try to capture the change of Xiamen in decades normally, so data collection is based on two standards: one is the end year of decade and the second is availability of data collection. Thus, finally the data used for DMA includes three time nodes of 1989, 2000 and 2010 and data for EF had one more node of 1980.

Detailed data used in this research includes land use, transportation network, bio-resource and energy consumption where land use data from the data repository in the Institute of Urban Environment, Chinese Academy of Sciences, road network data from the vectorization of maps, resource consumption data from year book of Xiamen Bureau of Statistics (n.d.).

Data used to calculate global average yield and harvested area comes from the production yearbook of Food and Agriculture Organization (n.d.). Equivalence factor is obtained from the articles (Wackernagel, 1996, 1999a, 1999b, 2002).

2. Results

2.1. Background of the urbanization and industrialization

The first set of results is around the overview of Xiamen's development in the past half more century, from 1952 to 2010. Population, GDP and investment continued to grow in the period of 6 decades after 1952, in which population growth began to accelerate after 1995 (Figure 4a). While total construction land area (industrial and residential land) and road length almost have no increase until 1981 (the next year of Opening Up for Xiamen), from then on, they have a sustained growth for 30 years and especially began to accelerate in 1995 (Figure 4b).

It's obvious that the development of Xiamen City has a stage characteristic. Actually the general development

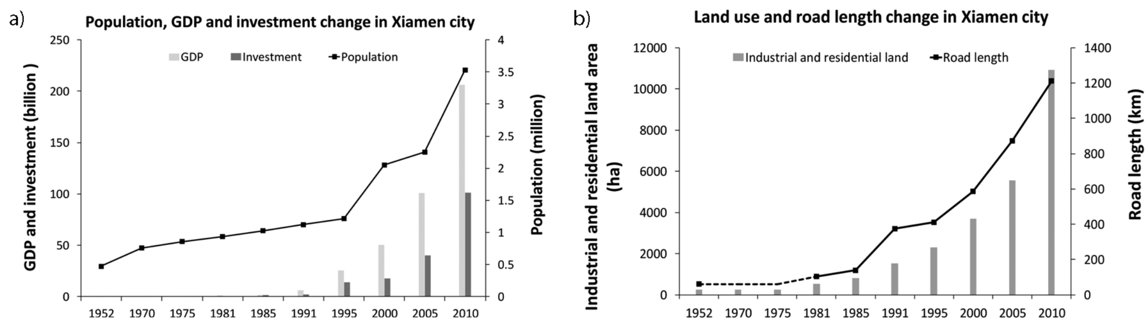

Figure 4. Background of the urbanization and industrialization change in Xiamen City (figure drawn by the author)

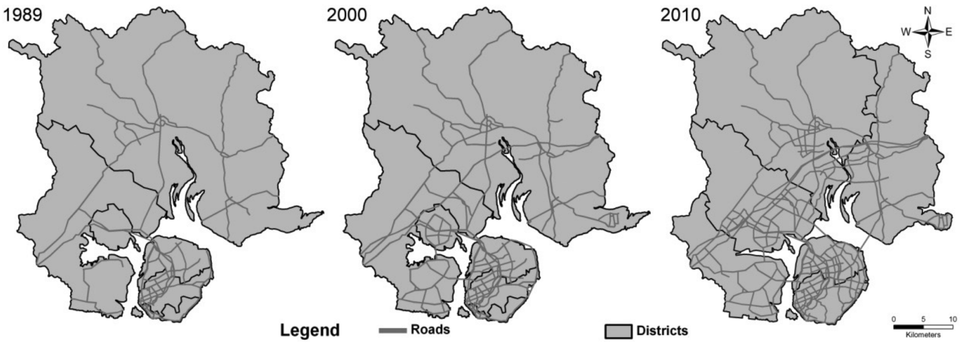

Figure 5. Road expansion from1989 to 2010 (figure drawn by the author)

kept steady slow before 1981 but accelerate from 1995, extremely rapidly from 2000. So the following analysis of DMA focused mainly on the period of 1990 to 2010.

2.2. DMA

2.2.1. D&A: Density and Access

In the final calculation, population density and road density is for "Density", connectivity is for "Access". Calculation of road density and connectivity is around road network, as shown in the following Figure 5. The expansion of the road networks shows an obvious spatial pattern that new roads almost were constructed along the coastal areas.

Calculation results of population density, road density and connectivity is shown in the following Figure 6.

The Figure 6 above shows that, Xiamen's population density, road density and connectivity have a continuous increase through the three time nodes, especially during the period 2000–2010, the population density shows an obvious stage characteristic. That means, from 1989 to 2000, the population density increased by only 136 persons/km^2, but from 2000 to 2010, the change amount enlarged to 1395 persons/km^2, more than 10 times of that in former period.

2.2.2. M: Mix

Description about the "Mix" is in land use. The land use mix of Xiamen City at the three time nodes is shown in the Figure 7.

Figure 7 shows that Xiamen's land use change in the 20 years from 1989 to 2010 mainly occurred on the increase

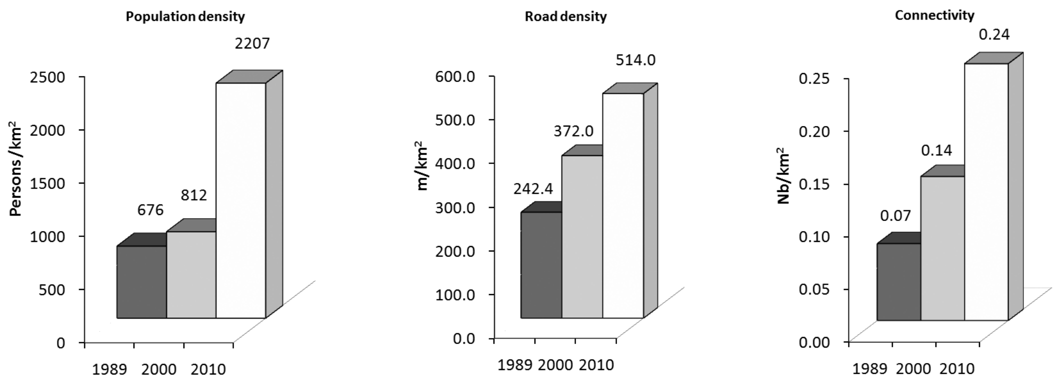

Figure 6. Population density, road density and connectivity from 1989 to 2010 (figure drawn by the author)

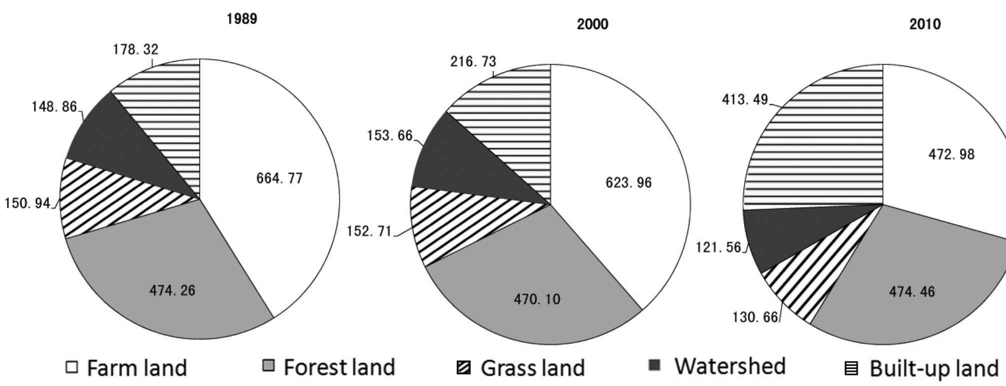

Figure 7. Land use mix in Xiamen City from 1989 to 2010 (km^2, figure drawn by the author)

of built-up land and reduction of farm land. Watershed or grass land changed slightly while forest land nearly had no change. The built-up land, with change of biggest amount, increased from 11% in 1989 to 25.6% in 2010, increased by 235.2 km^2 totally. The built- up land in 2010 is 231.9% of that in 1989. Meanwhile, farm land proportion decreased from 41.1% to 29.3%, with a total reduction amount of 191.8 km^2. Although the forest increased a little bit (0.4 km^2) from 1989 to 2010, benefiting the ecosystem health maintaining, the sharp decrease of farm land, grass land and watershed reduced the bio-resource production and bio-capacity, as shown in the following section.

About the speed of land use change, obviously the later decade runs significantly faster than the previous 10 years, demonstrating a stage characteristic. The change amount of built- up land from 2000 to 2010 is 196.8 km^2, as much as 512% of that from 1989 to 2000 (only 38.4 km^2). This indicates that Xiamen's main stage of accelerated urbanization process is the later 10 years.

2.3. Resource consumption and environmental impact

2.3.1. Resource consumption

Per capita ecological footprint is a typical resource consumption related indicator in the stage model. The calculation results of ecological footprint (EF), bio-capacity (BC) and ecological deficit (ED) is shown in Figure 8.

In Figure 8, it's obvious that the EF per capita of Xiamen City showed an increasing trend with a net increase of 1.85 gha from 1980 to 2010. On one hand, such change indicates the improvement of people's living standards; on the other hand, it also indicates the increasing pressure on the eco-environment.

Further observation reveals that the evolution of EF per capita of Xiamen City from 1980 to 2010 shows a temporal stage characteristics, which means that, taking the time period of 1980 to 1990 as the first stage, the EF per capita increased 0.25 gha; the second stage is from 1990 to 2000, with net change of 0.70; the third stage is from 2000 to 2010, with net increase of 0.90 gha, which is approximately equal to the sum growth of the first and the second stage.

While for BC change, the stage pattern is obvious as well. Figure 8 shows that BC per capita of Xiamen City decreased by 0.22 gha from 1980 to 2010, accounting for 62.9% of 1980. In the stage of 1980 to 1990, the BC per capita almost has no change, but decreased sharply by 42.1% in the stage of 1990 to 2000. Four land use types of forest, farmland, grass land and watershed mainly provide the bio-resource production. While compared with the big loss of other three land use types, the forest increase from 1980 to 2010 is quite small (0.4 km^2). Thus, the reason for the decrease of BC is due to the loss of farmland, grass land and watershed.

Based on the change of EF and BC per capita shown above, the ED per capita enlarged more than 10 times of that in 1980, also presenting temporal stage pattern. For the whole increasing period, ED per capita increased yearly 0.005 gha, but began to enlarge sharply from 1990 to 2010, yearly 0.07gha, 12 times of that in previous decade. The stage performance of all EF, BC and ED indicates that the economic production activities in Xiamen had the greatest pressure on the ecosystem during period 2000–2010.

For a better understand of the EF development in Xiamen City, its per capita EF value in 2009 was chosen to compare with the that of China's mean value and provinces in mainland (Huang et al., 2015; Xie et al., 2012), as shown in Figure 9.

The comparison reveals that the per capita EF in Xiamen ranked 8th in the list, nearly equals to the national average (2.2 gha). But its per capita BC (0.1 gha) is pretty low, only 10% of the national average (1.0 gha), ranked last. Meanwhile, the proportion of construction land (industrial land and residential land) in Xiamen City is the highest, much higher even than the four municipalities of Beijing, Tianjin, Chongqing and Shanghai, indicating that the Xiamen's urbanization process run extremely fast. Demographically, Xiamen's urbanization ratio reached 88.4% in 2010, far higher than the national ratio 49.68% (in sixth national census at 0:00 on November 1st, 2010 as the standard time, Xiamen had a resident population of 3.53 million with urban population of 3.12 million). Xiamen City, on one hand had a high

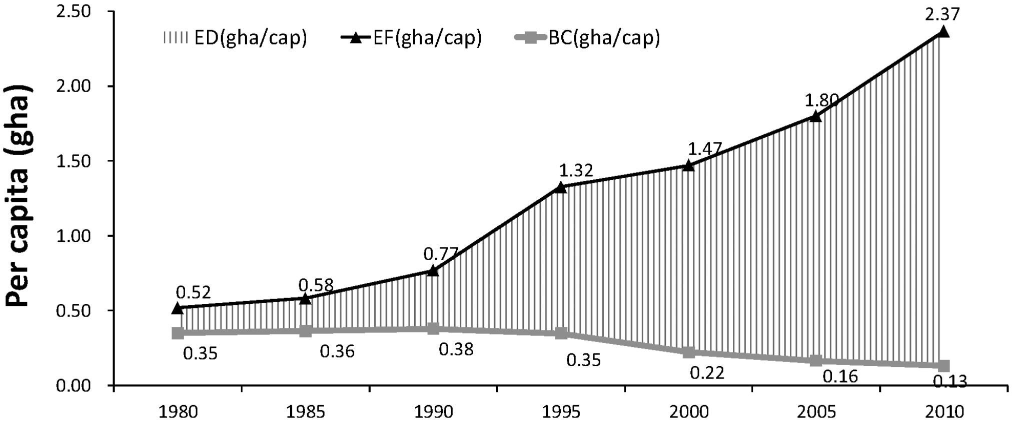

Figure 8. The per capita EF, BC and ED change from 1980 to 2010 in Xiamen City (figure drawn by the author)

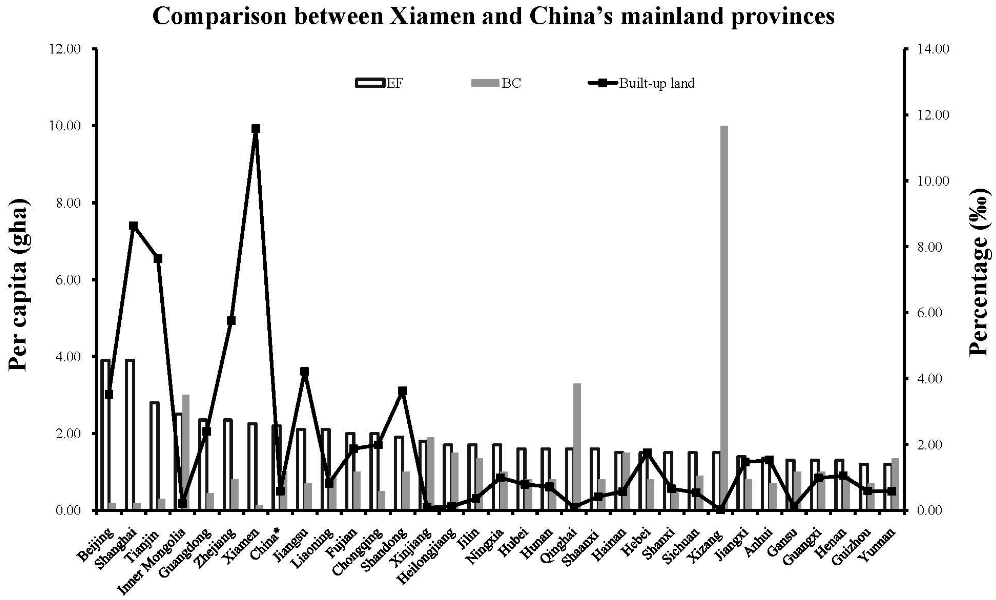

Figure 9. Comparison between Xiamen City and China's provinces and municipalities (figure drawn by the author)

urbanization ratio and per capita EF, while on the other hand had the lowest per capita BC, revealing the contradictions of supply-demand and urbanization – ecological environment.

2.3.2. Change trend of EF with DMA and GDP

Based on the observation of the data changes of IUE indicators, exactly GDP for industrialization, DMA for urbanization and EF for environment evolution, it is found that all these indicators performed very rapid increase during the main period from 1989 to 2010. For a better understanding of the relationship between EF and economy development, this section integrates indicator changes of both them two into one graph, where representative indicators were selected for IUE as well as DMA. Specifically, the per capita GDP presents the industrialization, population density, proportion of built-up land and road connectivity are for DMA respectively. While the ecological deficit presents the pressure on environment, and the final result is shown in the Figure 10 below.

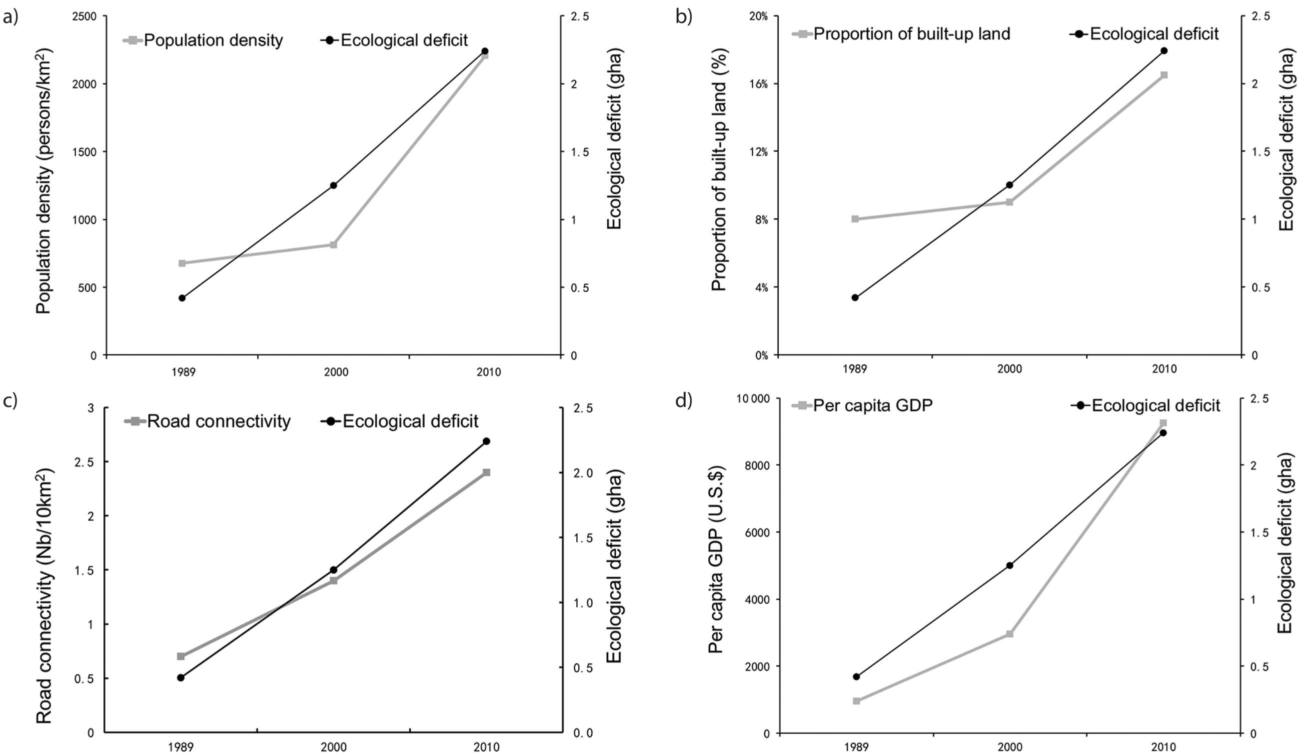

Figure 10. Change trend of EF with DMA and GDP factors from 1989 to 2010 in Xiamen City (figure drawn by the author)

It can be seen in Figure 10 that, for the data of the three time nodes (1989, 2000 and 2010), the ecological deficit is generally consistent with the changes of DMA and GDP, especially the road connectivity and ecological deficit tend to rise linearly (Figure 10c). While the population density, proportion of built-up land and per capita GDP shows obvious stage characteristics: the rising speed from 2000 to 2010 is much higher than that from 1989 to 2000 (Figure 10a, b, d). This increase trend demonstrate that the rapid urbanization and industrialization in this period of 1989–2010 caused large-scale of infrastructure construction along with big population pouring into the city, leading to the rapid growth of build-up land and the huge consumption of biological resources as well as fossil energy, which finally performed great pressure on the ecological environment and natural resource capacity.

2.3.3. Environmental pollution

Emissions of industrial solid waste and waste gas of SO_2 were selected to describe the pollution impact upon environment. These two indicators are the production related ones in stage model by Bai and Imura (2000). The statistic result is shown in Figure 11.

In Figure 11, the two emissions have a slow growth from 1981 to 1991, followed a slight increase from 1991 to 2000, but significant acceleration from 2000 to 2005, finally down sharply after 2006. As explained on the website of Xiamen Bureau of Ecological Environment (n.d.), in the 11th Five-year Plan released by the government, there is a strict emission reduction plan of 27.2% lower compared with the emission of 2005. Finally the emission amount of SO_2 in 2010 is indeed much lower than that in 2005, actually by a percentage of 33.56%.

2.4. Development stage of Xiamen City

After both the long term overview and focused 3-decades analysis of Xiamen's industrialization, urbanization and environmental change, the urban development along with its environmental problems showed the following phases.

Phase I (1952 to 1980). Xiamen had low level of industrialization (GDP and investment) with insignificant pollution.

Phase II (1980 to 2000). The first 20 years after national policy of Opening-Up, booming new enterprises accelerated the urbanization and industrialization process, but also poses serious urban environmental issues (pollution of water, soil, noise and air). Ecosystem began to deteriorate, large amount of farm land had been converted into built-up land, emission of industrial solid waste and waste gas have been increasing nearly all the years.

Phase III (2000 to 2010). In 2000, Xiamen had a per capita GDP of U.S. $ 2,953 (year book of Xiamen), and the 2010 data of Xiamen is close to that of Korea in Stage II (year of 1998). The analysis in this paper proved the description in Bai et al. (2014), a rapid urbanization process is often coupled with rapid industrialization and economic development. Under such background, large-scale projects of industrial development and infrastructure construction move on (like Taiwan Investment Zone, Free Trade Zone and logistics parks), resulted in rapid expansion of road network and urban area, as well as huge consumption of energy, enlarging the EF, ED and pressure on eco-environment.

Phase IV (2010 to present). In 2019, per capita GDP of Xiamen increased to 2 times more of that in 2010 (Table 1), and the 2019 data is between that of Korea in Stage II (in 1998, industrial pollution stage) and Japan in Stage III (in 1998, consumption stage). All these data indicates that before 2010, Xiamen City got through a long time of Stage I; and in the period of 2010 to 2019, Xiamen experienced the Stage II and Stage III crossly (Bai & Imura, 2000).

In 2019, Xiamen's built-up land increased to 508 km^2 and population increased to 4.3 million with urbanization rate of 89.2%. Such rate is much higher than that of national data (60.6%) and even higher than the most developed city of Shanghai (88.1%) in China. Data from Fujian Provincial Bureau of Statistic show that, although the emission amount of SO_2 in 2019 already reduced to only 1 thousand ton, the emissions of industrial solid waste is still 927.2 thousand ton, as high as that in 2008

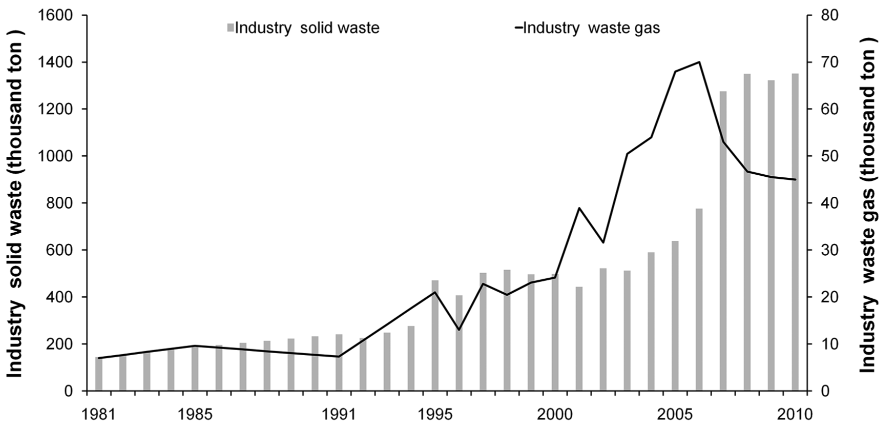

Figure 11. Environmental pollution change in Xiamen City

Table 1. Comparison of economy indicators in different stages

	Xiamen	Korea	Japan
Per capita GDP	U.S.$9,254 (2010)	U.S.$ 10,644 (1998, Stage II*)	U.S.$ 36,575 (1998, Stage III*)
	U.S.$20,691 (2019)	U.S.$31,762 (2019**)	U.S.$ 40,247 (2019**)
Industrialization Ratio (primary: secondary: tertiary)	1:50:49 (2010)	7:43:50 (1998, Stage II*)	2:41:57 (1998, Stage III*)
	0:42:58 (2019)	2:33:65 (2019)**	1:29:70 (2019)**

Note: data for Xiamen come from the Xiamen Bureau of Statistics; * means the data come from the paper of Bai and Imura, 2000; ** means the data come from the World Bank, 2019.

(Fujian Provincial Bureau of Statistic, n.d.). Further, the energy consumption in 2019 is also doubled that of 2010, like the coal consumption increased from 11.7 million ton in 2010 to 23.6 million ton in 2019 and electricity power consumption increased from 16.9 billion kW·h in 2010 to 37.4 billion kW·h in 2019 (Xiamen Bureau of Statistics, n.d.), indicating that the carbon footprint pressure is still increasing rapidly and at a very high level.

3. Discussion

Based on stage model, Xiamen should find its way to target the eco-city.

As Bai described, there are 4 scenarios of urban environmental evolution for city targeting an eco-city (Bai & Imura, 2000). For Xiamen, considering that it has entered the Stage III in 2019, the only scenario it could shift to Sustainable eco-city stage could be:

Scenario 1: Stage I —> Stage II —> Stage III —> Stage IV.

The problem is that how can Xiamen City enter Stage IV and become an eco-city? This section discussed the possible way around both industrialization and urbanization based on Xiamen resource and self-identification.

Bai and Imura (2000) provided some evidences showing that structural changes in the economy relate to different sets of environmental problems and take Japan as an example that first to enter the high-growth era and has the most advanced economic structure and highest per capita income. This enlightened Xiamen possible approaches to the eco-city based on the structural changes in the economy.

As analyzed above, around the year of 2010, Xiamen got into Stage II, accordingly, its tertiary industry ratio is also very close to that of Korea in Stage II (7:43:50). In 2019, the secondary and tertiary industry ratio in Xiamen is also just as Japan ever had in Stage III (1998). However, Xiamen still has a high secondary industry ratio but a low tertiary industry ratio compared with Japan and Korea in 2019 (Table 1). Therefore, GDP of Xiamen mainly increased in the section of secondary and tertiary industries. While it's obvious that EF growth mainly focused on the fossil energy consumption (Figure 12) and such growth mainly comes from the secondary industry. Thus, if Xiamen tries to reduce the ecological footprint but simultaneously keep the GDP growth, it would be reasonable to reduce the secondary industry but meanwhile promote the tertiary industry and primary industry, so as to slow down the rapid increase of fossil energy consumption and head to eco-city.

If the ratio of secondary industry be reduced, which sort of tertiary industry or primary industry could be suitable for Xiamen development?

As Xiamen identified itself as "a port and a scenic tourist city" and Xiamen is a coastal city that has advantages around the marine, culture and tourism resource, it's reasonable for Xiamen to put development priority for couple of environmentally sound eco-industries, like seafood, culture creativity, finance, hi-tech and tourism. Even the original agriculture or fishing could be integrated with IT industry and convert to very high output as well as high

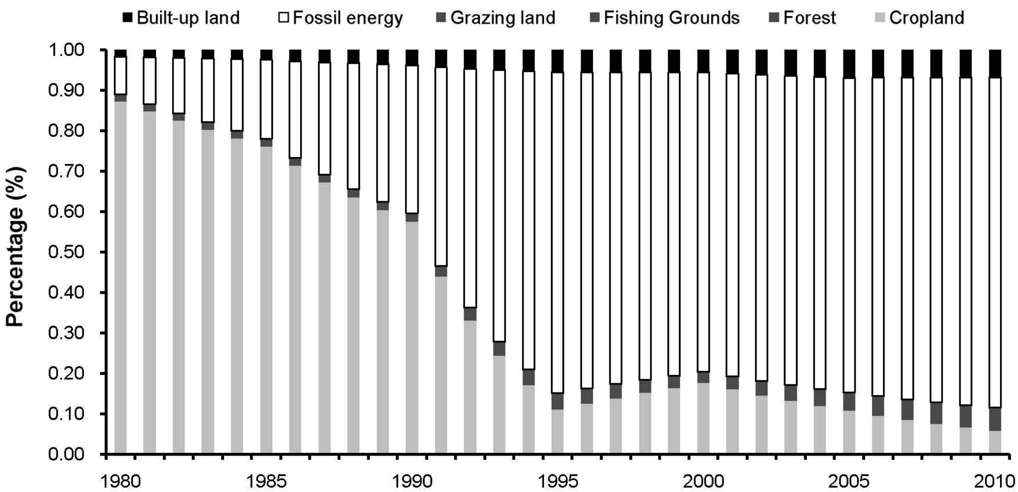

Figure 12. The proportion of EF per capita over years (figure drawn by the author)

technology industry, like the new emerging industry of live broadcasting of planting, harvesting, fishing and related products sale. Actually, with the value boosting of short video and live broadcasting in China, it seems that the primary industry is going to face more opportunity along with some sort of tertiary industry like e-commerce, tourism and multiple IT measures. Indeed, Xiamen seems already recognized its limitation of resources and set up three high-tech industry parks. Therefore, the enhancement of such eco-industries, green industry or circular economy above can reduce the energy consumption, the pressure on the environment and optimize the industrial structure. Further, promotion of solar and wind power generation along with related products and industry would also reduce the consumption of fossil energy and carbon footprint.

In addition to the industrial approaches, on the urbanization aspect, Xiamen City could follow the sustainable urbanization way, like planning urban growth boundary, so as to make itself more compact due to its small and hilly topography (Tang et al., 2013; Yuan et al., 2017; Shi et al., 2016). Some other measures like construction of urban greening, building greening, lake and river wetlands from concept of sponge city would also be reasonable (Shao et al., 2018).

Conclusions

This research extended an original stage model for environment evolution to describe urbanization, industrialization and environment evolution. In this improved stage model, a DMA index system are integrated for better understanding of the urbanization and Ecological Footprint is calculated for the urban development impacts on environment. The result reveals that development in Xiamen City has obvious stage characteristics and there is sharp conflict between rapid urban development and eco-environment.

For the stage characteristics, from 1952 to 2019, Xiamen development could be defined as four phases and data mainly focused in the period 1989–2010 around, especially about the DMA indicators for urbanization change. Result reveals that in the later 10 years (2000–2010), the new built-up land is much larger than the previous 10 years (1989–2000), 5 times more. Compared with 1980–1995, the ecological deficit also enlarged greatly in period of 1995–2010. As the division reference in research of Bai and Imura (2000), before 2010, Xiamen City got through a long time of Stage I (poverty stage); and in the period of 2010 to 2019, Xiamen experienced the Stage II (industrial pollution stage) and Stage III (mass consumption stage) crossly. Up to 2019, Xiamen still has large amount of coal and electricity power consumption, as well as release high level of industry solid waste. These results indicate that Xiamen should take couple of measures to achieve the eco-city, like adjusting the industrial structure, promoting the green industry and circular economy, planning the urban growth boundary for a compact city.

Although this research analyzed Xiamen's development in many aspects, due to the availability of enough data source, the description of Xiamen development maybe still not comprehensive. And, some other issues also need further analysis, like:

For the spatial pattern of the urbanization, why the land changes mostly occurred along the coastline? What factors drive this spatial pattern? Such issues should be the work of next step.

Acknowledgements

This work was supported by the China Scholarship Council, the National Key Research and Development Program (No. 2019YFB2102004) of China, the Education Foundation of Sichuan province, China (No. 18ZB0492), Sichuan Mineral Research Center (No. SCKCZY2021-YB001) and the Key projects from Academy of global governance and area studies, Sichuan Normal University (No. GJZD2020003).

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