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RESEARCH ARTICLE

Spatiotemporal analysis and multiple scenarios prediction of sustainable ecosystem in China based on ecological footprint method

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Abstract: Dynamic changes of sustainable ecosystem in China have been assessed with long-term series from 1949 to 2006, and the ecosystem sustainability of 30 provinces in 1986, 1996, 2002 and 2006 are analyzed with ecological footprint index (EFI) and ecological footprint efficiency (EFE). The two indices are proposed based on ecological footprint (EF) method. Then, the fluctuant cycles of per capita EF and bicapacity (BC) in China 1949-2006 are decomposed and extracted based on EMD method, and series nonlinear dynamic predictive models are presented with the cycles. Three Forecasting scenarios are analyzed based on their predictive models according to three EF scenarios presented in Living Planet Report 2006 published by WWF *et al.* (2006). Over last 57 years, China's EFI has reduced sharply with fluctuation. The change of EFE is very slowly before 1980, subsequently, is sharply increased. There are 6, 5, 12, and 7 provinces which are running ecological surplus in 1986, 1996, 2002, and 2006, respectively. There are 14, 16, 11, and 16 provinces which EFI are smaller than -100% in 1986, 1996, 2002, and 2006, respectively. The provinces with the highest EFE are Shanghai, Beijing, and Tianjin, and the lowest are Xinjiang, Guizhou, Hainan, Ningxia, *et al.* in 1986, 1996, 2002, and 2006, respectively. The obvious undulation cycles of per capita EF in China are 4.8 years and 10.9 years, and the periods of per capita BC are 3.03 years, 8.35 years, 14.25 years, and 28.15 years. The business-as-usual scenario looks at the consequence that per capita ED would be 11.200 hm^2 and EFI would be -1307.19% in China in 2050. The slow-shift scenario shows per capita ED would be 0.728 hm^2 and EFI would be -84.96% in 2050. The rapid-reduce scenario shows per capita ED in China would be 0.498 hm^2 in 2050 and 0.261 hm^2 in 2100, respectively. EFI of rapid-reduce scenario would be -58.11% in 2050. China could denote sustainability at the global level if slow-shift scenario and rapid-reduce scenario are implemented.

Keywords: ecological footprint, ecological footprint index, ecological footprint efficiency, empirical mode decomposition, nonlinear dynamic prediction model, China

1 Introduction

Managing natural capital is the core of sustainable development, while effective management depends on reliable measurement of those who need to be managed.[1] As a bio-physical quantitative assessment tool to estimate the sustainable utilization of natural resources, the EF method proposed by Rees[2] and Wackernagel[3,4] has gained much attention and positive response from international scientists, world's governments and non-government organizations.[5–13] Dynamic changes of sustainable ecosystem in China have been assessed with long-term series from 1949 to 2006, and the ecosystem sustainability of 30 provinces in 1986, 1996, 2002 and 2006 are analyzed based on ecological footprint index (EFI) proposed by Wu[14] and ecological footprint efficiency (EFE) proposed by Xu.[15] Then, the fluctuant cycles of per capita ecological footprint and bicapacity in China 1949-2006 are decomposed and extracted based on EMD method, and series nonlinear dynamic predictive models are presented with the cycles. Forecasting numerical values of the three scenarios are analyzed based on their predictive models according to three ecological footprint scenarios presented, in *Living Planet Report 2006* published by World Wide Fund for Nature.[12] Furthermore, we analyze and evaluated the feasibility and difficulties of the above three scenarios, and propose some solutions and suggestions. We hope that our analysis will be useful to study of rational natural resources utilization in order to eliminate global and

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regional ecological overshoot. This research could be meaningful for predicting global and regional sustainable development status; at the same time, we hope it would provide new access to effective methodology in predicting and interpreting the EF in long time series.

2 Methodology and data

Due to EF model simplicity and easy interpretation, the applications of this approach can be found in an abundant literature.[5,6,8,10–12,16–18] Its calculation details are readily obtained in many references.[3,4,19,20] In order to make calculation results in accordance with long time series, some modified methods of ecological footprint and biocapacity in China 1949-2006 calculations are as following:

Thinking data availability, the ecological footprint account in China 1949-2006 includes biologic resource production, built-up space (non hydro-power), and energy consumption (*e.g.* fossil fuels, hydro-power, embodied energy in trade, nuclear energy). The biocapacity account involves biologic resource, built-up space (non hydro-power), and hydro-power. Biologic resource footprint is calculated with output data instead of consumption, and fossil energy footprint calculation is reverse.

Alterable equivalence factors are used to calculate EF and BC in China 1949-2006 (Table 1). That is equivalence factor in 1961 for 1949-1965, in 1971 for 1966-1975, in 1981 for 1976-1985, in 1991 for 1986-1995, in 1999 for 1996-2000, in 2001 for 2001-2002, and in 2003 for 2003-2006. Hydro-power equivalence factor is constantly 1 from 1949 to 2006.

Table 1. Equivalence factors

	1961[a]	1971[a]	1981[a]	1991[a]	1999[a]	2001(WWF)[b]	2003(WWF)[c]
Built-up land	2.23	2.23	2.23	2.23	2.17	2.19	2.21
Primary cropland	2.23	2.23	2.23	2.23	2.17	2.19	2.21
Marginal cropland	1.76	1.77	1.74	1.71	1.76	1.8	1.79
Pasture	0.5	0.49	0.48	0.47	0.47	0.48	0.49
Forest	1.31	1.32	1.32	1.32	1.35	1.38	1.34
Water area	0.35	0.35	0.35	0.36	0.35	0.36	0.36
Fossil energy land	1.1	1.1	1.1	1.1	1.1	1.1	1.1

Source: [a] Wackernagel *et al*. (2004); [b] WWF *et al*. (2004); [c] WWF *et al*. (2006)

Biologic footprint in China is calculated with invariable average output per unit. The invariable average output per unit for a biologic resource is defined as its average output per unit from 1949 to 2006. This treatment could indirectly reflect dynamic influences of factors on EF such as management, technology, policy, society, economy.

Alterable yield factors of arable land and pasture are used to calculate BC in China 1949-2006, and ones of forest and water area are invariable. The main interest of this paper is to analyze long term series BC components in China 1949-2006 rather than compare to other countries. Thus, global average productivity data are not used to determine yield factors of arable land and pasture. A modified method is proposed to calculated alterable yield factors of arable land and pasture in China. For example, the calculation formula of arable land yield factors can be obtained as:

$$\mathrm{y}_{arable,j} = \frac{1}{n}\sum_{i=1}^{n}\left[output_{i,j} \Big/ \left(\sum_{j=1}^{57} output_{i,j}\right)/57\right] \tag{1}$$

Where $y_{arable,j}$ is arable land yield factor in j^{th} year, n is biologic resource item (*e.g.*, grain, cotton), j is a year, and $output_{i,j}$ is output per unit of i^{th} biologic resource item in j^{th} year. Outputs per unit of forest and aquatic products are often influenced by natural factor, as well as data confine. So yield factors of forest and water area are constantly used as 1 in China 1949-2006. Yield factors of built space are the same as arable land.

Figures 1 tracks per capita EF and BC in China 1949-2006. Over last 57 years, the per capita EF in China is constantly increased with fluctuation, and the per capita BC is decreased. The average growth rate of EF is 4.519%, and the average decreased rate is 0.237%. The CO_2 footprint, from the use of fossil fuels, was the fastest growing component, increasing more than sixteen fold from 1953 to 2006. The results are basically in accordance with the calculation of China 1961-2001 by WWF *et al.* (2005).

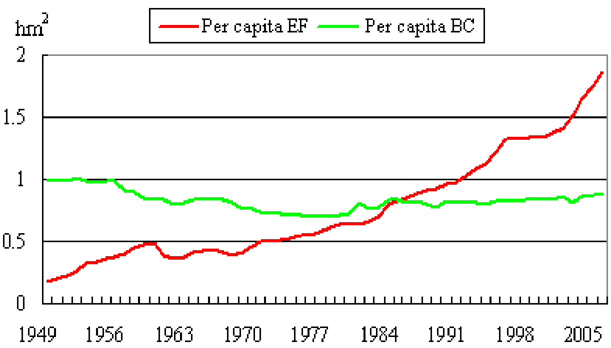


Figure 1. The trends of per capita EF and BC in China 1949-2006

3 Results

3.1 Spatiotemporal analyses

The spatiotemporal analyses are processed with EFI and EFE indices in this paper. EFI is defined as a percentage that the amount of biocalacity minus EF accounts for the biocalacity of a given region (Wu, 2005).

It reflects the potential of future regional sustainable ecosystem. The calculation formula is:

$$EFI = [(BC - EF)/BC] \times 100\% \qquad (2)$$

EFE is defined as the ratio of total gross domestic production (GDP, 10,000 yuan) of a regional economy system divides its total ecological footprint (Xu et al., 2003). The calculation formula is:

$$EFE = GDP/EF \qquad (3)$$

3.1.1 Dynamic changes of EFI and EFE 1949-2006

The basic dynamic trend of EFI is demonstrated in Figures 2. The results show that over the 57 years, the China's EFI had reduced sharply with fluctuation. EFI dropped from 83.30% in 1949 to -112.99% in 2006, declining 196.233% in all with an average annual rate of 3.443%. EFI was negative 4.83% in 1986 when humanity's footprint grew larger than biocapacity for the first time. Since the late 1980s, this overshoot has been increasing each year till EFI reached negative 112.99% in 2006. This trend suggests that China are degrading natural ecosystem at a rate unprecedented in human history.

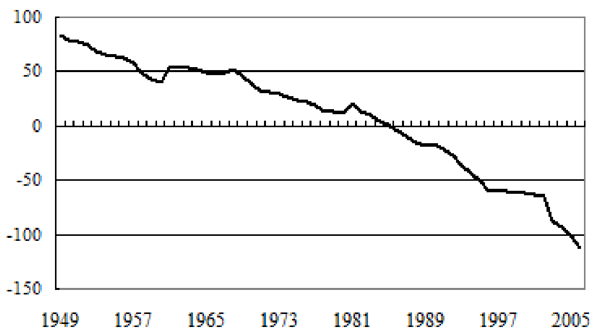


Figure 2. Trend of China's EFI from 1949 to 2006

The change of EFE is shown in Figures 3. The result shows that the change of EFE is very slow before 1980. It is 0.0458 10,000yuan/hm^2 in 1952, and 0.0661 10,000yuan/hm^2 in 1979, respectively. Later, EFE is rapidly creased. It is 0.8599 10,000yuan/hm^2 in 2006. This may be strongly correlated to many practical factors such as society, economy, technology and management in China. For example, implementing China's initiating reforms since 1978, advocating circulation economy, constructing saving society in recent years.

Although EFE is rapidly increased in the last 57 years, EFI fell down constantly. The change shows China has been confronted with the great environment challenges. There is still a considerable room for further saving natural resource in China.

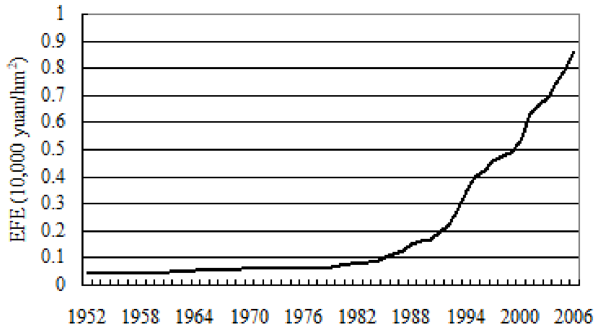
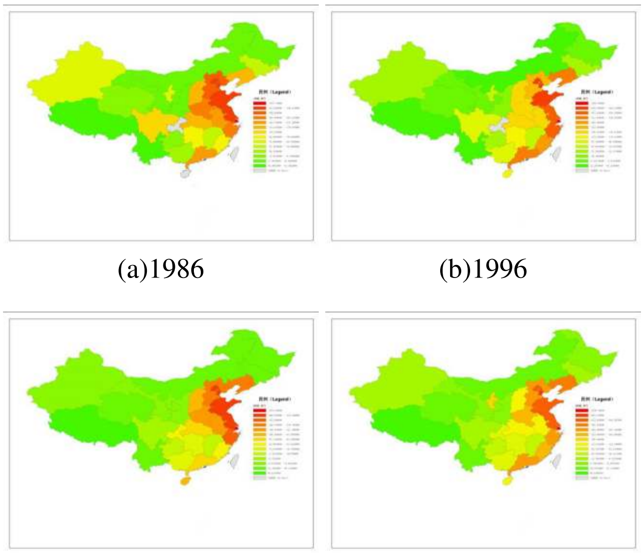


Figure 3. Trend of China's EFE from 1952 to 2006

3.1.2 Spatial changes of EFI and EFE of provinces

Four sketch maps of ecological sustainability of provinces are shown in Figures 4 based on EFI. There are 6 provinces running ecological surplus in 1986. Their EFI are Heilongjiang 4.518%, Gansu 7.446%, Shannxi 7.519%, Neimenggu 10.000%, Yunnan 49.309%, and Tibet 91.493%, respectively. There are 14 provinces which EFI are lower than -100%. For example, Shanghai is -1397.692%, Beijing is -531.818%, Tianjin is -529.767%, Jiangsu is -470.0658%, Shandong is -436.314%, and Hebei is -358.028%. There are 5 provinces running ecological surplus in 1996. Their EFI are Heilongjiang 3.437%, Gansu 5.515%, Neimenggu 35.297%, Yunnan 40.809%, and Tibet 93.318%, respectively. There are 16 provinces which EFI are lower than -100%, e.g. Shanghai is -1385.821%, Beijing is -678.095%, Tianjin is -664.545%, Shandong is -425.143%, Jiangsu is -357.525%, Zhejiang is -355.352%, Guangdong is -341.053%, and Liaoning is -328.273%. There are 12 provinces running ecological surplus in 2002. There EFI are Guizhou 0.5927%, Sichuan 13.723%, Xinjiang 24.044%, Ningxia 30.276%, Shannxi 31.558%, Gansu 34.063%, Jilin 43.339%, Heilongjiang 44.666%, Qinghai 45.047%, Yunnan 59.241%, Neimenggu 68.111%, and Tibet 96.048%. There are 11 provinces which EFI are lower than -100%. Shanghai is -2594.760%, Tianjin is -960.650%, Jiangsu is -482.785%, Shandong is -441.396%, and Beijing is -437.547%. There are 7 provinces running ecological surplus in 2006. Their EFI are Shannxi 6.796%, Gansu 17.149%, Jiangsu 22.963%, Qinghai 29.979%, Neimenggu 38.331%, Yunnan 42.42%, and Tibet 96.048%, respectively. There are 16 provinces which EFI are lower than -100%. Shanghai is -2528.299%, Tianjin is -879.429%, Jiangsu is -612.82%, Beijing is -536.448%, Shandong is-504.367%, and Liaoning is -328.459%. In comparison with Figures

1, EFI could reflect the importance of a given region biocapacity playing role in sustainable development. Sustainabilities of different regions are distinct because of their various biocapacities if they have the same as ecological deficit. Those provinces which have bigger biocapacity than others may be running more sustainable status. Therefore, EFI could avoid limitation of only using ecological footprint or ecological deficit (ED).

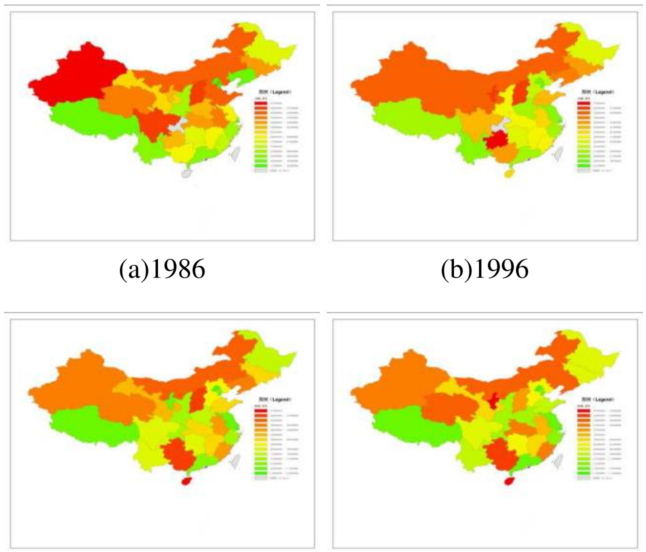


(a)1986 (b)1996

(c)2002 (d)2006

Figure 4. Varies of China's EFI in 1986, 1996, 2002, and 2006

Four sketch maps of province EFE are shown in Figures 5. The provinces with the highest EFE in 1986 are Shanghai 0.205 10,000yuan/hm^2, Beijing 0.198 10,000yuan/hm^2, and Tianjin 0.177 10,000yuan/hm^2. The provinces with the lowest EFE in 1986 are Xinjiang 0.037 10,000yuan/hm^2, Shannxi 0.046 10,000yuan/hm^2, and Sichuan 0.047 10,000yuan/hm^2. The provinces with the highest EFE in 1996 are Shanghai 1.027 10,000yuan/hm^2, Beijing 0.785 10,000yuan/hm^2, and Tianjin 0.689 10,000yuan/hm^2. The provinces with the lowest EFE in 1996 are Guizhou 0.278 10,000yuan/hm^2, Ningxia 0.303 10,000yuan/hm^2, and Xinjiang 0.316 10,000yuan/hm^2. The provinces with the highest EFE in 2002 are Shanghai 1.650 10,000yuan/hm^2, Beijing 1.386 10,000yuan/hm^2, Tibet 1.143 10,000yuan/hm^{2}and Tianjin 1.064 10,000yuan/hm^2. The provinces with the lowest EFE in 2002 are Hainan 0.375 10,000yuan/hm^2, Guizhou 0.411 10,000yuan/hm^2, Guangxi 0.413 10,000yuan/hm^2, and Shannxi 0.406 10,000yuan/hm^2. The provinces with the highest EFE in 2006 are Beijing 2.760 10,000yuan/hm^2, Shanghai 2.448 10,000yuan/hm^2, Tibet 1.895 10,000yuan/hm^{2}and Tianjin 1.635 10,000yuan/hm^2. The provinces with the lowest EFE in 2006 are Hainan 0.387 10,000yuan/hm^2, Ningxia 0.424 10,000yuan/hm^2, Guizhou 0.570 10,000yuan/hm^2, and Qinghai 0.649 10,000yuan/hm^2. The main factors of Tibet with high EFE in 2002 and 2006 may be its lower per capita EF and population growth than other provinces, and with higher GDP growth.



(a)1986 (b)1996

(c)2002 (d)2006

Figure 5. Varies of China's EFE in 1986, 1996, 2002, and 2006

3.2 Multiple analyses of per capita EF and BC

EMD method is introduced to study the fluctuation and causes of per capita EF and BC in China at multiple timescales. The data of EF are decomposed into two IMFs and one residual trend term (Figures 6). Figures 6 shows that IMF$_1$ponderance expresses the 4.8 years period fluctuation, while IMF$_2$ expresses 10.9 years period (Table 2). The data of BC are decomposed into four IMFs and one residual trend term (Figures 7). Figures 7 shows that IMF$_1$ponderance expresses the 3.03 years period fluctuation, while IMF$_2$, IMF$_3$, and IMF$_4$ express 8.5 years period, 14.25 years, and 28.15 years, respectively the fluctuation periods (Table 3).

3.3 constructed and adjusted Models

The dynamic prediction models are constructed based on our above analysis as follow:

Where $x(t)$ means per capita EF or BC (hm^2), $R(t)$ is the original value of residual trend of EF or BC (hm^2), t is the time (year), r is the average annual change rate of EF or BC, T$_i$ is period, A_i is amplitude, φ_i is original phase, IMF_{0i} is original value of IMF$_i$.

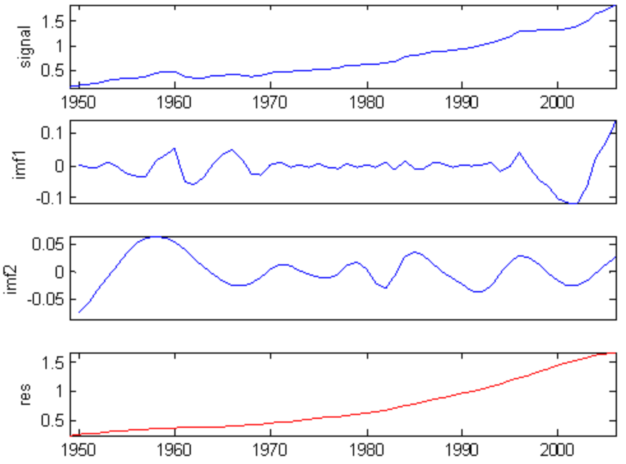


Figure 6. IMF and residual trend R of variations of per capita EF in China

Table 2. Statistical values of IMF_{1-2} of per capita EF in China by Hilbert Transform

IMF_i	IMF_1	IMF_2	RES
Periods (Ti, Years)	4.8	10.9	∞
Variance contribution (k_i, %)	0.882	0.501	98.627
Average amplitude	0.065	0.05	
Center frequency	0.185	0.096	
Original value	0.0015	0.0008	0.1647

The average annual change rates are 4.519% for per capita EF, -0.237% for BC in China 1949-2006 according to Figures 1. Taking x_0, r, and A_i, T_i of Table 2 and Table 3 into Formula (11), we get:

$$EF(t) = 0.1647e^{0.04519t} + 0.065\sin\frac{2\pi t}{4.8} + 0.0015 + 0.05\sin\frac{2\pi t}{10.9} + 0.0008 \quad (4)$$

$$BC(t) = 0.4694e^{-0.00237t} + 0.018\sin\frac{2\pi t}{3.03} + 0.0454 + 0.029\sin\frac{2\pi t}{8.35} + 0.3173 + 0.02\sin\frac{2\pi t}{14.25} + 0.0360 + 0.02\sin\frac{2\pi t}{28.15} + 0.1320 \quad (5)$$

If their average changed annual rates are constant, the

Table 3. Statistical values of IMF_{1-2} of per capita BC in China by Hilbert Transform

IMF_i	IMF_1	IMF_2	IMF_3	IMF_4	RES
Periods (Ti, Years)	3.03	8.35	14.25	28.15	∞
Variance contribution (k_i, %)	4.536	31.725	3.599	13.201	46.94
Average amplitude	0.018	0.029	0.02	0.02	
Center frequency	0.33	0.118	0.07	0.036	
Original value	0.045	0.317	0.036	0.133	0.469

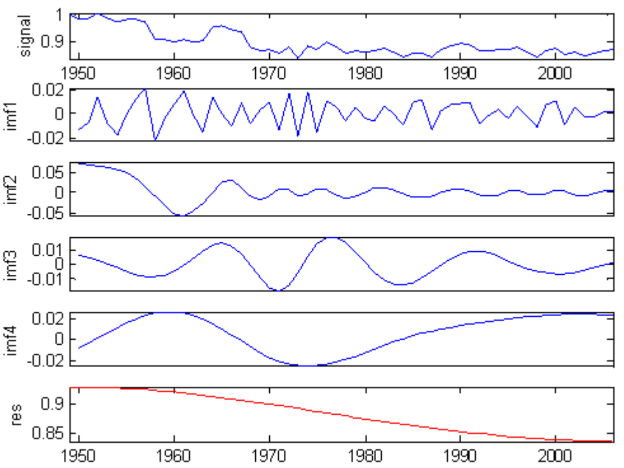


Figure 7. IMF and residual trend R of variations of per capita BC in China

predictive results of per capita EF and BC 1949-2006 are shown in Figures 8 and Figures 9 according to Equation 4 and Equation 5, respectively.

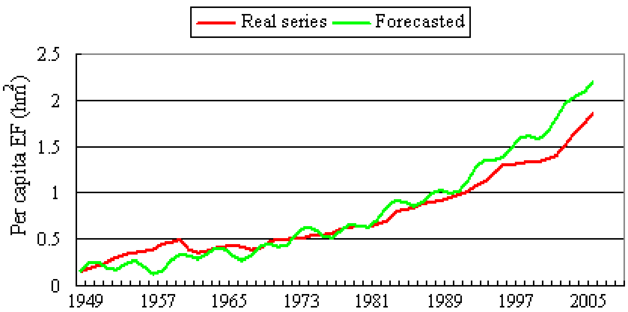


Figure 8. Fitting diagram of forecast and real per capita EFin China 1949-2006

The relative errors of the real and predicted values of per capita EF and BC from 1949 to 2006 are calculated. The average relative errors of per capita EF and BC over the past 57 years are 5.51%, 5.28%, respectively. Their revisory average changed annual rates are 4.27%, -0.249%, respectively. The Equation 4 and Equation 5 are revised as:

$$EF(t) = 0.1647e^{0.0427t} + 0.065\sin\frac{2\pi t}{4.8} + 0.0015 + 0.05\sin\frac{2\pi t}{10.9} + 0.0008 \quad (6)$$

$$BC(t) = 0.4694e^{-0.00249t} + 0.018\sin\frac{2\pi t}{3.03} + 0.0454 + 0.029\sin\frac{2\pi t}{8.35} + 0.3173 + 0.02\sin\frac{2\pi t}{14.25} + 0.0360 + 0.02\sin\frac{2\pi t}{28.15} + 0.1320 \quad (7)$$

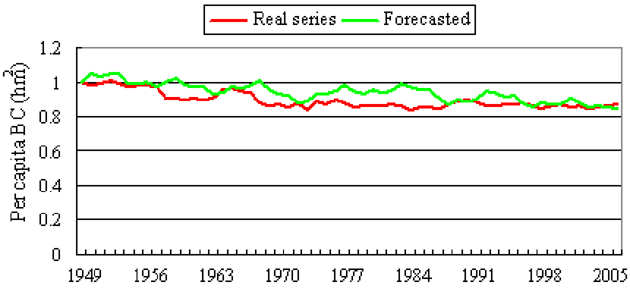


Figure 9. Fitting diagram of forecast and real per capita BC in China 1949-2006

The predictive results of per capita EF and BC 1949-2006 are shown in Figures 10 and Figures 11 according to Equation 6 and Equation 7, respectively.

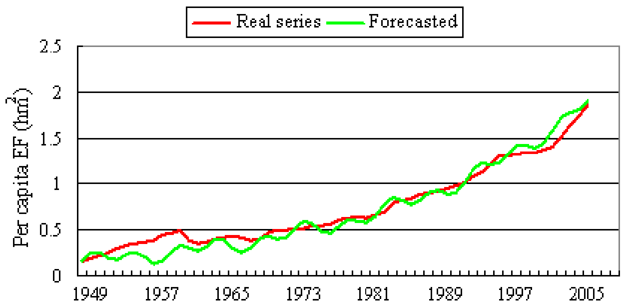


Figure 10. Revised fitting diagram of forecast and real per capita EF in China 1949-2006

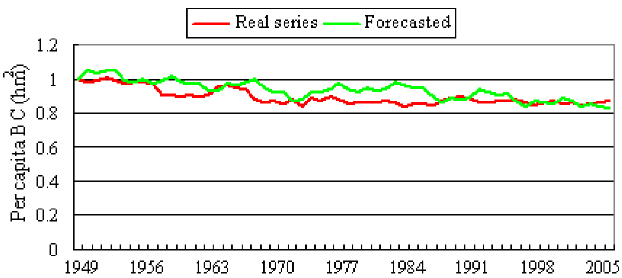


Figure 11. Revised fitting diagram of forecast and real per capita BC in China 1949-2006

3.4 Multiple scenarios forecasting

3.4.1 Business-as-usual scenario

If their average annual change rates keep constantly over last 57 years ($r_{EF} = 4.27\%$, $r_{BC} = -0.249\%$), and 1.853hm^{2}of per capita EF, 0.870hm^{2}of per capita BC in 2006 are regarded as their original values, Equation 6 and Equation 7 are revised as:

$$EF(t) = 1.8276e^{0.0427t} + 0.065\sin\frac{2\pi t}{4.8} + 0.0162 + 0.05\sin\frac{2\pi t}{10.9} + 0.0092 \tag{8}$$

$$BC(t) = 0.4084e^{-0.00249t} + 0.018\sin\frac{2\pi t}{3.03} + 0.0395 + 0.029\sin\frac{2\pi t}{8.35} + 0.2760 + 0.02\sin\frac{2\pi t}{14.25} + 0.0313 + 0.02\sin\frac{2\pi t}{28.15} + 0.1148 \tag{9}$$

The prediction of per capita EF and BC from 2007 to 2050 are shown in Table 4 according to Equation 8 and Equation 9.

Table 4. Forecasting of per capita EF and BC 2007-2050 of business-as-usual scenario (hm^2)

Year	EF	BC	ED	Year	EF	BC	ED
2007	2.023	0.918	1.105	2030	5.166	0.783	4.383
2010	2.174	0.921	1.253	2035	6.305	0.847	5.458
2015	2.619	0.875	1.744	2040	7.897	0.9	6.998
2020	3.365	0.816	2.549	2045	9.711	0.787	8.924
2025	4.072	0.897	3.175	2050	12.056	0.857	11.2

Table 4 shows per capita EF would reach to 12.056 hm^2 in 2050 if its average increased annual rate is 4.27% constantly. Per capita BC would fall to 0.857 hm^2 in 2050 if its decreasing trend does not change. Per capita ED would rapidly grow, and increase to 11.200 hm^{2}in 2050. At this level of ecological deficit, ecological assets exhaustion and large-scaled ecosystem collapse will become increasingly alike (WWF *et al.*, 2006) before 2050. The increased BC could not compete with human ecological deficit within the regional biocapacity limits though it may take effect in some way. Thus, the essential access to eliminating ecological deficit in China is to reduce total EF and per capita EF.

3.4.2 Slow-shift scenario

The slow-shift scenario of *Living Planet Report 2006* (WWF *et al.*, 2006) shows that overshoot would end about two decades before the close of the century when about 10 per cent of the planet's biological productivity could be spared for the use of wild species. But a hypothesis of this trend is that global per capita EF should be 2.051 gha in 2025, 1.798 gha in 2050, and BC should be 1.538 gha in 2025, 1.461 gha in 2050, respectively. The average annual change rates of global per capita EF should be 0.365% 2003-2025, 0.493% 2025-2050 according to global per capita EF is 2.23 gha in 2003. If the change of per capita EF in China 2006-2050 keeps the same trend of contemporaneous world and per capita BC keeps constantly the trend over last 57 years ($r_{BC} = -0.249\%$), and 1.853 hm^{2}of per capita EF in 2006 is regarded as its original value, Equation 8 is revised as:

$$EF(t) =1.8276e^{-0.00365t} + 0.065\sin\frac{2\pi t}{4.8} + 0.0162 + 0.05\sin\frac{2\pi t}{10.9} + 0.0092 \quad (10)$$

The prediction of per capita EF 2007-2025 and BC 2007-2050 are shown in Table 5 according to Equation 9 and Equation 10. Per capita EF will be 1.664 hm^2 in 2025. If the change of per capita EF 2025-2050 keeps 0.493% of the average annual reduced rate consistently, and 1.664 hm^{2}of per capita EF in 2025 is regarded as its original value, Equation 8 is revised as:

$$EF(t) =1.6411e^{-0.00493t} + 0.065\sin\frac{2\pi t}{4.8} + 0.0147 + 0.05\sin\frac{2\pi t}{10.9} + 0.0082 \quad (11)$$

The prediction of per capita EF 2025-2050 is shown in Table 5 according to Equation 11.

Table 5. Forecasting of per capita EF and BC 2007-2050 of slow-shift scenario (hm^2)

Year	EF	BC	ED	Year	EF	BC	ED
2007	1.936	0.918	1.019	2030	1.654	0.783	0.871
2010	1.807	0.921	0.886	2035	1.593	0.847	0.746
2015	1.704	0.875	0.829	2040	1.628	0.9	0.728
2020	1.778	0.816	0.962	2045	1.523	0.787	0.736
2025	1.664	0.897	0.767	2050	1.585	0.857	0.728

Table 5 shows per capita EF would reach to 1.585 hm^2 in 2050 if its change keeps the same trend of contemporaneous world. Per capita ED would fall to 0.728 hm^2 in 2050. Per capita ED would cut down 10.471 hm^2 in 2050 comparing to business-as-usual scenario. This may be owed to the numerous policies and measures which have been put into practice such as controlling population growth, implementing recycle economy, and innovation of renewable or cleaner energy use by Chinese central government in recent years. For example, in order to release the pressure of the growing demand for fossil fuel energy (Table 6), Chinese State Council has taken energy development as a central role in the coming decades. Therefore, per capita ED could be cut down with economy constant growth in future. An inspiring prospect with great challenges in China is depicted by the slow-shift prediction scenario.

3.4.3 Rapid-reduce scenario

The rapid-reduction scenario of *Living Planet Report 2006* shows that humanity's footprint in 2100 would be 40 per cent less than that in 2003. It assumes per capita EF falls to 1.348 gha in 2050, 1.053 gha in 2100, and an optimistic growth in biocapacity which per capita BC reach to 1.461gha in 2050, 1.474 gha in 2100. Thus, 30% of biocapacity would have been allowed for the use of wild species. The average annual decreasing rates of global per capita EF should be 0.842% 2003-2050, and 0.438 % 2050-2100, respectively. The average annual change rates of global per capita BC should be -0.381% 2003-2050, and 0.018% 2050-2100, respectively.

Table 6. Renewable energy targets in China

	Capacity in 2005 (MW)	Target in 2020 (MW)
Hydro-power	100,000	300,000
Wind power	1200	30,000
Biomass	2000	30,000
Solar energy	50	1000

Source: Lema and Ruby (2007)

If the change of per capita EF in China 2006-2050 keeps the same trend of contemporaneous world and per capita BC keeps constantly the trend over last 57 years ($r_{BC} = -0.249\%$), and 1.853 hm^2 of per capita EF in 2006 is regarded as its original value, Equation 8 is revised as:

$$EF(t) =1.8276e^{-0.00842t} + 0.065\sin\frac{2\pi t}{4.8} + 0.0162 + 0.05\sin\frac{2\pi t}{10.9} + 0.0092 \quad (12)$$

The prediction of per capita EF 2007-50 and BC 2007-2050 are shown in Table 5 according to Equation 9) and Equation 12. Per capita EF will be 1.355 hm^2 in 2050. If per capita EF and BC 2050-2100 keep -0.438%, 0.018% of the average annual change rates consistently, and 1.355 hm^{2}of per capita EF and 0.857 hm^2 of per capita BC in 2050 are regarded as their original values, Equation 8 and Equation 9 are revised as:

$$EF(t) =1.3364e^{-0.00438t} + 0.065\sin\frac{2\pi t}{4.8} + 0.0119 + 0.05\sin\frac{2\pi t}{10.9} + 0.0067 \quad (13)$$

$$BC(t) =0.4023e^{0.00018t} + 0.018\sin\frac{2\pi t}{3.03} + 0.0388 + 0.029\sin\frac{2\pi t}{8.35} + 0.2718 + 0.02\sin\frac{2\pi t}{14.25} + 0.0309 + 0.02\sin\frac{2\pi t}{28.15} + 0.1132 \quad (14)$$

The prediction of per capita EF and BC 2050-2100 are shown in Table 7 according to Equation 11 and Equation 12.

Table 7. Forecasting of per capita EF and BC 2007-2100 of rapid-reduce scenario (hm^2)

Year	EF	BC	ED	Year	EF	BC	ED
2007	1.928	0.918	1.01	2055	1.356	0.86	0.496
2010	1.773	0.921	0.852	2060	1.305	0.899	0.406
2015	1.629	0.875	0.755	2065	1.351	0.827	0.524
2020	1.666	0.816	0.85	2070	1.256	0.858	0.399
2025	1.516	0.897	0.619	2075	1.327	0.843	0.485
2030	1.566	0.783	0.784	2080	1.205	0.853	0.352
2035	1.432	0.847	0.585	2085	1.276	0.906	0.37
2040	1.465	0.9	0.565	2090	1.153	0.84	0.313
2045	1.364	0.787	0.577	2095	1.198	0.87	0.328
2050	1.355	0.857	0.498	2100	1.099	0.837	0.261

Table 7 shows per capita EF would reach to 1.355 hm^2 in 2050 if its change keeps the same trend of contemporaneous world. Per capita ED would fall to 0.498 hm^2 in 2050. Per capita ED would cut down 10.701 hm^2 in 2050 comparing to business-as-usual scenario. Per capita EF and BC would reach to 1.099 hm^2, 0.837 hm^2 in 2100 if their change rates are -0.438%, 0.018%, respectively. Per capita ED would fall to 0.261 hm^2 in 2100. The achievement of the rapid-reduce prediction scenario need to make great efforts by Chinese government and resident.

3.5 Prediction of EFI 2007-2050

Figures 12 shows change trends of EFI based on the above three prediction scenarios. EFI will fall to -136.01% in 2010, -559.91% in 2030, and -1307.19% in 2050 according to the business-as-usual scenario. EFI will be grow slowly with -96.18% in 2010, -111.25% in 2030, -84.96% in 2050 if per capita EF is decreased and BC is increased But this change should owe to some effective measures implement. EFI may rapidly grow with -92.49% in 2010, -100.09% in 2030, -58.11% in 2050 according to rapid-reduce prediction scenario. China should strictly control population growth, implement recycle economy, construct saving society, innovate in renewable or cleaner energy use, and make rational international trade structure, etc. Therefore, China could denote sustainability at the global level.

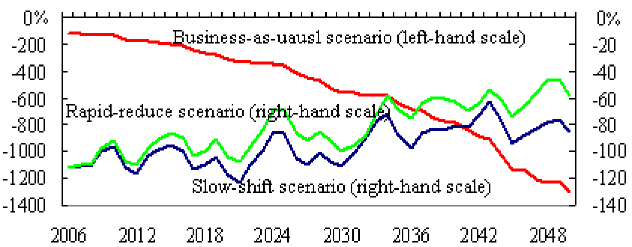


Figure 12. The trends of EFI 2007-2050 of three prediction scenarios

4 Conclusions and discussion

Over last 57 years, the China's EFI has reduced sharply with fluctuation. The change of EFE is very slowly before 1980, subsequently, is sharply increased. There are 6, 5, 12, and 7 provinces which are running ecological surplus in 1986, 1996, 2002, and 2006, respectively. There are 14, 16, 11, and 16 provinces which EFI are smaller than -100% in 1986, 1996, 2002, and 2006, respectively. The provinces with the highest EFE are Shanghai, Beijing, and Tianjin, and the lowest are Xinjiang, Guizhou, Hainan, Ningxia, et al. in 1986, 1996, 2002, and 2006, respectively.

The fluctuant cycles of per capita EF and BC in China from 1949 to 2006 are decomposed and picked-up based on EMD method. Nonlinear dynamic prediction models are presented with the cycles. Three prediction scenarios are proposed according to *Living Planet Report 2006*. The results show that: Over last 57 years, the obvious undulation cycles of per capita EF in China are 4.8 years and 10.9 years, and the periods of per capita BC are 3.03 years, 8.35 years, 14.25 years, and 28.15 years. The business-as-usual scenario looks at the consequence that per capita ED would be 11.200 hm^2 and EFI would be -1307.19% in China in 2050. The slow-shift scenario shows per capita ED would be 0.728 hm^2 and EFI would be -84.96% in 2050. The rapid-reduce scenario shows per capita ED in China would be 0.498 hm^2 in 2050 and 0.261 hm^2 in 2100, respectively. EFI of rapid-reduce scenario would be -58.11% in 2050.

The nonlinear dynamic predictive model proposed with the cycles and multiple scenarios forecasting are analyzed in this paper. The purpose is to offer an access to the prediction study on Ecological Footprint Method. It is meaningful in reducing humanity's EF, increasing BC and for policy-makers by simulating the parameter. The variations of EF and BC could be simulated if the values of r and T are appropriate. Theoretical references for policy-makers from the public, government, and environment departments could be offered. Of course, the multiple scenarios prediction of this paper need to be perfected since they are calculated at various hypothesis premises (e.g., the annual change rates of per capita EF and BC would be consistent). In fact, the variations of EF and BC are very complicated as they are influenced by social, economic and natural factors such as population, consumption, land use, climate, technology, management etc Solutions to these questions will provide further perception into Ecological Footprint Method prediction.

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