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School of Economics and Management, Nanchang University, School of Economics and Management, Nanchang University, Faculty of Economics, Kyushu University, School of Economics and Management, Nanchang University

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Evaluation of Chinese provincial ecological well-being performance based on the driving effect decomposition

Shengyun Wang
School of Economics and Management, Nanchang University
Jingjing Zhang
School of Economics and Management, Nanchang University
Meifen Chu
Faculty of Economics, Kyushu University
Jing Li
School of Economics and Management, Nanchang University

Abstract

The focus of this paper is three-fold. First, it recalculates the HDI and EFI, use the ratio of HDI and EF to build the EWP, then evaluate and analyze the EWP of China's provinces. Second, it develops a unique ecological well-being performance (EWP) model, which is divided into two driving effects: the well-being effect of economic growth and the ecological efficiency of economic growth. Third, using the Human Development Index (HDI), it measures the well-being effect and ecological efficiency of economic growth in 31 Chinese provinces. Based on the EWP results, it divides the Chinese provinces into five types from economic leading and upgrading to overall descending. The research results show that China's HDI has greatly improved from 2006 to 2016, displaying a trend of "Beijing, Tianjin and Shanghai take the lead in upgrading, and then the uprising trend expands from east to west". However, during the same period from 2006 to 2016, the growth rate of China's people’s well-being was significantly lower than that of per capita ecological footprint (EF), and the overall

EWP declined. China's growth in people’s well-being is decoupled from economic growth, which indicates that China’s rapid economic growth was not followed by a similar progress in China’s people’s well-being. The above results suggest that China's total factor productivity (TFP) and green total factor productivity (GTFP) were improving but in different degrees during the above period. Other results show that, the carbon footprint has always been the largest component of China's EF, and the GTFP has always been lower than the TFP. According to the technology progress index and scale efficiency driving of change index, China’s provinces mainly focus on provincial TFP rather than GTFP. This paper suggests that the different types of provinces should adopt different strategies to improve their EWP in order to promote high-quality economic development.

Keywords:

Ecological Well-being Performance (EWP), Human Development Index (HDI), Ecological Footprint (EF), Green Total Factor Productivity (GTFP), Driving Effect

Corresponding author: Meifen Chu, assistant professor, faculty of Economics.

E-mail: chu@econ.kyushu-u.ac.jp

Introduction

Since China adopted economic reform policies and opened to the outside world in the late 1970s, it has made remarkable achievements in economic development (Ji, *et al.*, 2017; Lin, 2013). However, at the same time, the burden on China's resources and environment has increased significantly (Bian, *et al.*, 2018; Obrist, *et al.*, 2018; Zhang, *et al.*, 2019). With the large-scale urbanization process and rapid economic growth, the excessive consumption of resources has created serious challenges in recent years (Huo, *et al.*, 2018; Wang, *et al.*, 2015; Yue, *et al.*, 2017; Zhang, *et al.*, 2019). Growing evidence demonstrates that humanity has left yesterday’s "empty world” and entered into a “full world” (Pirgmaier, 2017; Toth & Szigeti, 2016). Improving people’s well-being while simultaneously respecting ecological limits is the main challenge humanity is currently facing. How to promote the coordination and efficient development between economic growth, welfare improvement and resources and environment, and then improve the performance of China's ecological welfare is a vital of academic researchers and government leaders.

With the evolution of the concept of development, development means not only economic prosperity and social progress, but also the improvement of people’s well-being and quality of life (Li, *et al.*, 2019). Sustainable development means how resources, environment, and ecological elements can effectively meet human needs, that is, improving the quality of human life without exceeding the carrying capacity of ecosystems (Munasinghe & Mcneely,1995; Zhang, *et al.*, 2018). Based on the feasibility theory of measuring well-being proposed by Sen (1989), the 1990 human development report pointed out that human development is a process of expanding people's choice opportunities, mainly including three dimensions: access to a long and healthy life, receiving higher education and to have decent standards of living. The

Human Development Index (HDI) is a summary measure of the average achievement of the above three dimensions, and it is widely used to represent people's well-being. The WBCSD (World Business Council for Sustainable Development) (1998) believes that ecological efficiency is "to reduce the pressure on environment to at least the same level as the estimated carrying capacity of the earth when meeting the demand of human high-quality life, which can be carried out by providing goods and services with price advantages". The OECD (Organization for Economic Cooperation and Development) (1998) defines ecological efficiency as "the efficiency of using ecological resources to meet human needs". Zhang, *et al.* (2018) pointed out that EWP refers to the efficiency of transforming natural resource consumption into people's well-being. Improving China's EWP is of great practical significance in implementing the sustainable development stipulated in the 2030 Agenda: Improving people's well-being and promoting high-quality economic development.

In 1974, Daly first proposed measuring the sustainable development level of countries through the increase in the level of welfare generated by a unit natural consumption and expressed it as the ratio of service to flux (Daly, 1974). However, because services and fluxes are difficult to quantify and compare in practice, the concept of ecological welfare performance has not been widely used. The Human Development Index (HDI) released by the United Nations Development Program in 1990 and the concept of ecological footprint proposed by Rees (1992) enabled the numerator and denominator of the ecological welfare performance ratio to be reliably measured. On this basis, further development of ecological welfare performance research can be conducted. Until now, no other indicator of objective well-being has been as popular as the HDI in the academia and policy making circles (Klugman, *et al*., 2011). Fu, *et al*. (2014) defined the EWP as the ratio of HDI to EFI and conducted comparison of the EWP of 24 countries. Zhang, *et al*. (2018) explored the EWP of 82 countries in 2012, suggesting that the developed countries and the G20 countries have relatively low EWP values.

The second category of studies measured the EWP at the regional level. Based on sample data from 105 countries, Knight, *et al.* (2011) constructed ecological welfare performance indicators based on a per capita ecological footprint (a measure of environmental consumption) and average life satisfaction (a measure of subjective well-being). Using the maximum likelihood estimation method, they analyzed the impact of climate, politics, economy and social factors on ecological welfare performance. Jorgenson, *et al.* (2015) compared relevant data between developed and underdeveloped countries and examined the relationship between economic growth and ecological welfare performance. Kumar (2006) analyzed 41 developing and developed countries and examined conventional and environmentally sensitive total factor productivity (TFP). He found that the environmentally sensitive measure of productivity is higher in those countries, which have the higher GDP per capita. Moreover, it also found that the energy intensity of production is negatively related to the environmentally sensitive measure of productivity. However, the conventional measure of productivity remains unaffected by the composition of output growth. The openness of a country increases its TFP when it is measured by the standard Malmquist index (or ML index). Feng & Yuan (2016) analyzed the changing trend of the EWP of 30 provinces during 2005-2010 in China and explored its influencing factors. Bian, *et al* (2020) established an index system in order to evaluate urban EWP. After that, a case study of 30 provincial capital cities in China from 2011 to 2016 was presented, in which the Super-slack-based measure model (Super-SBM) was utilized. Teixidó-Figueras and Duro, (2014) estimated and decomposed different polarization indices for a balanced sample of 119 countries over the period 1961 to 2007. They concluded that the EF distribution is persistently driven by the polarization.

To summarize the existing literature, there are some deficiencies in the extant research. First, most of the existing studies focus on an empirical study of EWP at the national level (Feng & Yuan, 2016). However, each province is a significant entity for considering economic development, conserving energy, reducing emissions, and improving ecological well-being. So far, the existing empirical studies on China's provincial EWP tend to analyze regional differences or temporal and spatial evolution characteristics. However, research results on the driving effect and regional types of China's provincial EWP are rare. Second, the HDI data used in some provincial EWP studies are usually directly derived from China’s human development report. It is well known that the calculation methods of HDI as published in China’s human development report over the years are different; thus, it is difficult to directly apply them to a vertical comparison (Qi, *et al.*, 2017). Third, the existing research on the EWP driving effect usually divides the EWP into two parts: the well-being performance of economic growth and the economic performance of natural consumption (Zhu, 2013). However, the well-being performance of economic growth is expressed by the ratio of well-being level to economic level, without further analysis of the relationship between economic growth and well-being growth. In terms of the economic performance of natural consumption, it only conducts an overall analysis of the total economic output corresponding to a unit of natural consumption. This does not but should include a further analysis which reveals the change of the driving force of economic growth corresponding to a unit of natural consumption.

To compensate for the above deficiencies in the existing literature, we conduct this research in a unique way, by measuring the EWP and classifying the different types of

Chinese provinces in terms of EWP. The contributions of this study are listed below. (1) recalculate the HDI and EFI, use the ratio of HDI and EF to build the EWP, then evaluate and analyze the EWP of China's provinces; (2) decompose the EWP into the two driving effects of economic growth, namely, the welfare effect and the ecological efficiency of economic growth, and then determine the relationship between economic growth and welfare promotion in each province and the driving force change of economic growth; (3) classify the EWP of provinces, provide suggestions for improving the EWP and promoting sustainable development and people's well-being based on the composition of the different types of provinces.

The remaining parts of this paper are organized as follows. Section 2 presents the methods and data description of this study. Section3 focuses on the analysis of the results. Section 4 gives the concluding remarks. Appendices give data tables for the different provinces.

2. Methods

2.1 Evaluation of EWP

In this paper, the ecological well-being performance (EWP) is used to measure the people’s well-being placed on a unit consumption of ecological resources. People’s well-being is measured by HDI, and ecological indicator is measured by EF. As the HDI is a unit-free index with values falling between zero and one and the values of EF vary in a larger range. we normalize the value of EF to make it which can be expressed as:

$$EWP = HDI/EFI \tag{1}$$

where HDI is employed to measure people's well-being (UNDP,1990); EFI is the normalized ecological footprint, which is used to measure humanity's ecological consumption. Following the methods proposed by Wackernagel, *et al.* (1997), we construct the indicator EF, which consists of cropland footprint, forest products footprint, grazing land footprint, built-up land footprint, fish products footprint, and carbon footprint. EF is a ratio of land area required to the population. Using the equivalent factor to adjust the weight of all kinds of land (Shi and Wang, 2016), we can drive the formula for EF as follow:

$$EF = \sum_{i}^{n} (r_{j\times}A_i)/N = \sum_{i}^{n} r_j(P_i/Y_i)/N \; (i = 1, 2, \ldots, n; j = 1,2, \ldots, 6) \qquad (2)$$

Therefore, we can obtain the normalization equation of EF, which can be written as:

$$EFI = \frac{EF}{\max(EF)}, max(EF) \neq 0 \qquad (3)$$

where max (*EF*) represents the maximum EF.

2.2 Decomposition model of EWP

Following the methods used to construct the HDI (Zhu, 2013), this paper decomposes the EWP as follows:

$$EWP = (HDI/GDP) \times (GDP/EFI) \qquad (4)$$

In Eq. (4), HDI/GDP measures the people's well-being induced by one unit of GDP, representing the people's well-being effect from economic growth. GDP/EFI measures how much GDP one unit of EFI can support, which is named ecological efficiency.

Therefore, the growth rate of EWP can be expressed as:

$$\%\Delta EWP = (\%\Delta HDI/\%\Delta GDP) \times (\%\Delta GDP/\Delta\%EFI) \tag{5}$$

Where %ΔHDI, %ΔGDP and $\Delta\%EFI$ represent the growth rate of HDI, GDP, and EFI respectively and can be expressed as:

$$\%\Delta HDI = (\%\Delta HDI/\%\Delta GDP) \times (\%\Delta GDP) \tag{6}$$

$$\%\Delta GDP = (\%\Delta GDP/\%\Delta EF) \times (\%\Delta EF) \tag{7}$$

where %ΔGDP indicates the change in economic growth, and %ΔEF indicates the change of EF.

Based on Eq. (6) and Eq. (7), we analyze people's well-being effect and ecological efficiency, respectively.

2.2.1 Measuring the well-being effects of economic growth

The DI index is used to represent the relationship between people's well-being growth and economic growth as follows:

$$DI = \%\Delta HDI/\%\Delta GDP \tag{8}$$

This is consistent with the decoupling index model proposed by Tapio (2005). Generally, the larger DI is, the greater the balance between economic growth and human well-being is. When the value of DI is larger than 1, it means that the growth rate of HDI is faster than that of GDP and the relationship between economic growth and human well-being is coordinated. Otherwise, the growth rate of HDI will lag behind economic growth. A very small DI value indicates the uncoordinated or decoupled development.

2.2.2 Evaluating the ecological efficiency of economic growth

To evaluate the ecological efficiency, we construct the Solow economic growth model including EF based on the Solow growth model to analyze the ecological efficiency. Therefore, %ΔGDP can be decomposed as follows:

$$\%\Delta GDP = \frac{\%\Delta GDP}{\%\Delta EF} \times (\%\Delta EF) = \frac{\Delta A}{A} + \frac{\Delta \theta}{\theta} + \propto \frac{\Delta L}{L} + \beta \frac{\Delta K}{K} + \gamma \frac{\Delta R}{R} \quad (9)$$

where A, L,K, and R represent technological progress factors: efficiency factor, labor input, capital input and land input, respectively. ΔA,Δθ,ΔL,ΔK, and ΔR represent the changes of technological progress, the change of efficiency, the change of labor input , the change of capital input and the change of land input, respectively. α, β and γ represent the elasticity of labor, capital and land input to GDP growth.

Compared with the concept total factor productivity (TFP) that is used to measure technology changes ($\frac{\Delta A}{A}$), green total factor productivity (GTFP) is used to illustrate ecological efficiency of economic growth (Shi & Wang ,2016). To calculate ecological efficiency ($\frac{\Delta \theta}{\theta}$), DEA-ML index model is adopted.

Suppose the input of economic activity is $x \in E_C^+$, the expected output is $y \in E_B^+$, and the non-expected output is $z \in E_I^+$ (Chung, *et al.*,1997). The production set can be expressed as:

$$GTFP = \{(K, L, R, EF) | (K, L) \in (GDP, EF)\} \quad (10)$$

Based on the direction distance function and the research of Chung, *et al.*, (1997), this paper considers economic growth (expected output) and EF (non-expected output). Considering the non - expected outputs, the detailed direction distance function can be expressed as:

$$\vec{D_t}(\mathrm{K,L,R,GDP},EF) = max\left\{\beta:\left(\mathrm{GDP}+\beta_g,\mathrm{EF}-\beta_g\right)\epsilon p(x)\right\} \tag{11}$$

where β is the value of the distance function, which is the largest multiple of the expected output increase and the non-expected output decrease when the output level moves in the direction B to the front of production. The smaller β is, the closer the production unit is to the production frontier and the higher the efficiency is; When β=0, this means that the production unit is on the production front, indicating that the production is completely efficient.

Therefore, the green total factor productivity index (GTFP) from period t to period t+1 can be expressed:

$$GTFP = \left\{\frac{[1+\vec{D_o^t}(K^t,L^t,R^t;\mathrm{GDP}^t,\mathrm{EF}^t)]}{[1+\vec{D_o^t}(K^{t+1},L^{t+1},R^{t+1};\mathrm{GDP}^{t+1},\mathrm{EF}^{t+1})]} \times \frac{[1+\vec{D_o^{t+1}}(K^t,L^t,R^t;\mathrm{GDP}^t,\mathrm{EF}^t)]}{[1+\vec{D_o^{t+1}}(K^{t+1},L^{t+1},R^{t+1};\mathrm{GDP}^{t+1},\mathrm{EF}^{t+1})]}\right\}^{\frac{1}{2}} \tag{12}$$

GTFP>1 indicates an increase in the improvement of green total factor productivity, while GTFP < 1 indicates the decrease of green total factor productivity.

Furthermore, GTFP can be decomposed into technology progress index (TECH) and technology efficiency change index (EFFCH), which can be expressed as:

$$\mathrm{TECH} = \left\{\frac{[1+\vec{D_o^{t+1}}(K^t,L^t,R^t;\mathrm{GDP}^t,\mathrm{EF}^t)]}{[1+\vec{D_o^{t+1}}(K^t,L^t,R^t;\mathrm{GDP}^t,\mathrm{EF}^t)]} \times \frac{[1+\vec{D_o^t}(K^{t+1},L^{t+1},R^{t+1};\mathrm{GDP}^{t+1},\mathrm{EF}^{t+1})]}{[1+\vec{D_o^{t+1}}(K^t,L^t,R^t;\mathrm{GDP}^t,\mathrm{EF}^t)]}\right\}^{\frac{1}{2}} \tag{13}$$

$$\mathrm{EFFCH} = \frac{[1+\vec{D_o^t}(K^t,L^t,R^t;\mathrm{GDP}^t,\mathrm{EF}^t)]}{[1+\vec{D_o^{t+1}}(K^t,L^t,R^t;\mathrm{GDP}^t,\mathrm{EF}^t)]} \tag{14}$$

$$GTFP = TECH \times EFFCH \tag{15}$$

TECH>1 indicates technological progress, and the production boundary is moved out. TECH<1 indicates that there is technological decline in the process of economic growth, and the production boundary moves towards the origin. EFFCH>1 represents an improvement in technical efficiency. EFFCH<1 represents a deterioration in technical efficiency.

EFFCH can be divided into the pure technical efficiency change index (PECH) and scale efficiency change index (SECH), which can be expressed as:

$$EFFCH = PECH \times SECH \tag{16}$$

3. Data and indicators

3.1 Data sources

According to the United Nations Development Program (UNDP), HDI is used to represent the performance of people's well-being (UNDP, 2016). Based on the method proposed by the UNDP (1990), we recalculate the HDI data from 2006 to 2016, which can be expressed as the arithmetic mean of the income, the life expectancy, and the education index. The data are mainly from the Statistical Yearbook of China (2007-2017), Provincial Statistical Yearbook (2007-2017), the Population and Employment Statistics Yearbook of China (2007-2017), China 2000 Census Data, China 2010 Census Data, and IMF official website (2006-2016).

This paper calculates the EF of China's provinces from 2006 to 2016.The data used to calculate the EF of China from 2006 to 2016 is obtained from the Statistical Yearbook of China, the Energy Statistical Yearbook, and the statistical yearbook of each province from 2007 to 2017. EP includes six kinds of compositions. The carbon footprint is calculated by the consumption of coal, coke, crude oil, gasoline, kerosene, diesel, and natural gas. The cropland footprint is calculated based on the output of eight agricultural products: grains, beans, potatoes, oil, cotton, tobacco, hemp and sugar (Shi & Wang, 2016). The fish grand footprint is calculated from the production of aquatic products. The output of grazing land consumption is used to measure grazing footprint (Shi & Wang, 2016). The grazing footprint is calculated by the consumption of pork, beef, mutton, milk and eggs. The forest products footprint is calculated by the total consumption of various fruits. The built-up land footprint is calculated from the construction land area.

3.2 Indicator analysis

HDI in China has gradually increased from 0.752 in 2006 to 0.849 in 2016. Although an imbalance of HDI between provinces still exists, human well-being in China has improved gradually (Wang, *et al.*,2018) based on the rapid economic growth and improved public services. From 2006 to 2016, the echelon of high human development has been spread from east to west in space, which is conducive to narrowing the gaps in the human well-being level.

The EF in China increased from 2.392 gha (global hectare) per capita in 2006 to 3.329 gha per capita in 2016. Figure 1 shows the values of EF and its compositions during 2006-2016. The footprints of carbon footprint, cropland footprint, grazing land, forest, fish grand and built-up land all increase gradually. Among these, the carbon footprint accounts for the highest proportion and the proportion increased from 67.56% in 2006 to 71.10% in 2016, indicating that China's economic development has become more dependent on fossil fuels. As the carbon footprint is the main part of the EF in most provinces, the change of EF in most provinces of China is determined by the carbon footprint. The carbon footprint accounted for more than 50% of the EF in 27 provinces and accounted for more than 80% of the EF in 11 provinces.

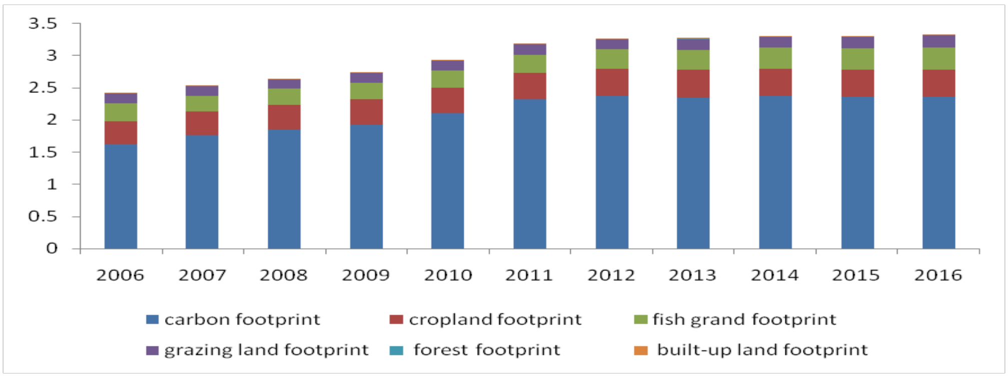

Figure 1. Evolution of EF and its compositions in China from 2006 to2016

Sources: the Statistical Yearbook of China, the Energy Statistical Yearbook of China, and the statistical yearbook of China (from 2007 to 2017)

Based on Eq. (1), EWP is expressed as HDI divided by the normalized EF. The overall EWP of China decreased from 3.01 in 2006 to 2.44 in 2016, indicating that the improvement of China's HDI was slower than the growth of EF. Figure 2 shows the spatial structure of EWP. The northwestern regions have low level of people's well-being, while their per capita ecological footprint is high, which leads to the poor performance of their ecological well-being. For these provinces, the improvement of people's well-being is achieved at the cost of resource consumption, while for eastern provinces, such as Shanghai, Beijing, Guangdong, Zhejiang, and Fujian, the improvement of people's well-being level and economic development quality is achieved with relatively small resource consumption.

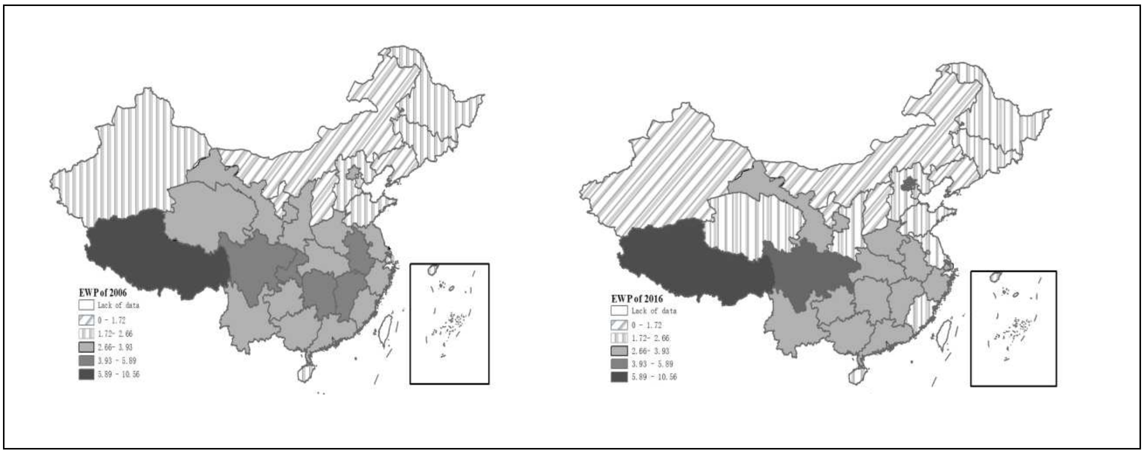

Figure 2. Spatial structure of EWP in China's provinces:2006 and 2016

4. Results analysis

4.1 Analysis on the well-being effect of China's provincial economic growth

This paper decomposes the EWP into two parts: DI index and ecological efficiency. The DI index is used to evaluate the relationship between people's well-being growth and economic growth. According to the DI index, we could illustrate the well-being effects based on China's economic development. To analyze the spatial people's well-being effect, we choose a threshold value and divide the DI index into relatively low well-being and medium well-being. If $0 \leqslant DI \leqslant 0.1$, then the people's well-being is increasing at a relatively low speed with economic growth and this case is low human well-being growth. If $0.1 < DI < 1$, then the people's well-being is increasing at a medium speed and is called medium well-being growth.

Generally, China was in a state of relative decoupling between people's well-being growth and economic growth during 2006-2016, since the growth rate of HDI lagged behind the economic development. Furthermore, the gap between HDI and GDP is narrowing, and they tend to achieve coordinated development. Figure 3 shows the two growth pattern between HDI and GDP.

In 2006, most provinces had low human well-being growth. For these provinces, the economic growth was notably faster than that of human welfare. Among them, Beijing, Tianjin, Hebei and other eastern provinces had relatively higher levels of human well-being and economic development, while the growth rate of HDI was slower than that of GDP, and their DI indices were lower. As the DI indices of 6 provinces were higher than 0.1 in 2006, and these 6 provinces were medium well-being growth type. For theses provinces, the growth gap between HDI and GDP was relatively small. In 2016, about half of the provinces came into medium well-being growth, as the growth gap between HDI and GDP gradually narrowed. The DI index changes for the Chinese provinces from 2007 to 2016 are shown in the Appendices.

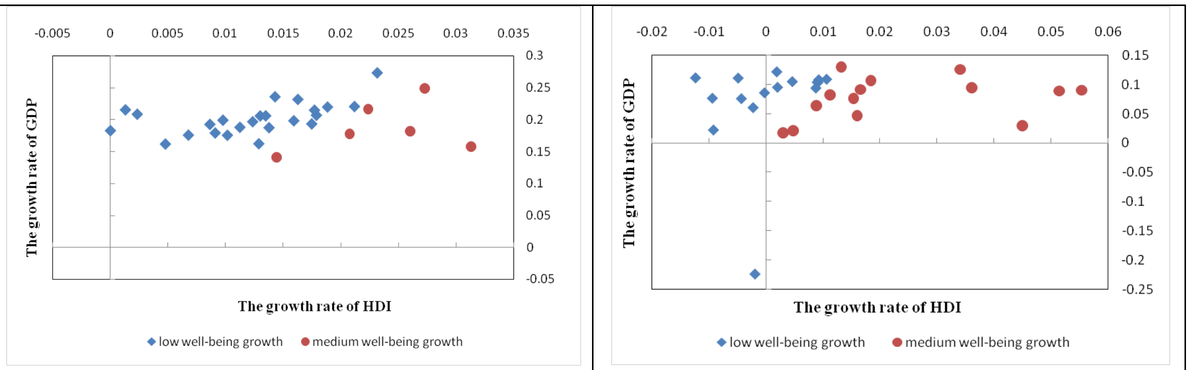

Figure 3. Cases of people's well-being effects

4.2 Ecological efficiency effect in China

GTFP is the green total factor productivity index, which is used to measure another part of ecological well-being: ecological efficiency. Table 1 shows the values of GTFP in China. During 2006-2016, GTFP notably improved in China. The average annual GTFP in China was more than 1, except Guizhou and Guangxi, indicating that the ecological efficiency of economic growth in China's provinces improved. From the spatial perspective, the GTFP of eastern China is larger than those of central China, northeastern China, and western China. From 2006 to 2008, northeast China had the highest GTEP, followed by eastern and central China. Western China had the lowest score, while from 2009 to 2016, the three northeastern provinces saw their GTFP decrease in a fluctuating way as PECH declined. With their improvement of TECH, the GTFP of the six central provinces surpassed that of the three northeast provinces. In eastern provinces, the GTFP has been rising in a fluctuating fashion. Driven by TECH and PECH, the gap of GTFP between the western region and the eastern region is narrowing.

Table 1 GTFP in Chinese provinces

	2006-2007				2015-2016			
	TECH	SECH	PECH	GTFP	TECH	SECH	PECH	GTFP
China	0.957	1.268	1.524	1.849	1.370	1.509	0.663	1.370
Beijing	1.035	1.099	1.033	1.175	1.053	1.001	1.000	1.053
Tianjin	1.124	1.004	1.047	1.181	1.287	0.747	1.338	1.287
Hebei	0.930	1.567	0.899	1.309	4.080	0.208	4.815	4.080
Shanxi	0.933	1.205	1.173	1.320	2.643	0.597	1.675	2.643
Inner Mongolia	1.054	1.033	1.000	1.088	0.165	7.602	0.132	0.165
Liaoning	0.924	1.468	0.956	1.297	1.000	1.000	1.000	1.000
Jilin	0.947	1.755	1.008	1.675	1.125	1.496	0.669	1.125
Heilongjiang	0.946	1.426	0.878	1.184	1.000	3.214	0.311	1.000
Shanghai	1.113	1.001	1.000	1.114	0.910	0.901	1.110	0.910
Jiangsu	1.001	1.354	0.851	1.154	1.449	0.873	1.146	1.449
Zhejiang	1.016	1.144	1.023	1.190	1.999	0.797	1.255	1.999
Anhui	0.966	1.135	0.948	1.040	2.850	0.826	1.210	2.850

Fujian	0.943	1.034	0.973	0.948	2.631	0.880	1.137	2.631
Jiangxi	0.954	1.291	0.950	1.169	3.400	0.779	1.284	3.400
Shandong	1.042	1.207	1.014	1.275	2.274	1.009	0.992	2.274
Henan	0.979	1.297	0.886	1.124	2.228	0.726	1.377	2.228
Hubei	0.966	1.188	0.967	1.109	3.860	0.906	1.103	3.860
Hunan	0.942	1.072	0.861	0.870	3.541	1.000	1.000	3.541
Guangdong	0.914	0.985	0.903	0.814	2.218	0.682	1.466	2.218
Guangxi	0.990	1.293	0.968	1.238	1.279	1.206	0.829	1.279
Hainan	1.036	1.059	0.691	0.758	2.168	0.540	1.851	2.168
Chongqing	1.000	0.771	0.708	0.546	1.778	0.919	1.088	1.778
Sichuan	1.012	1.135	0.885	1.017	1.000	1.039	0.963	1.000
Guizhou	1.000	1.000	1.000	1.000	1.012	1.057	0.946	1.012
Yunnan	0.956	1.257	1.095	1.316	0.477	1.029	0.971	0.477
Tibet	1.904	1.000	1.000	1.904	1.255	0.861	1.162	1.255
Shaanxi	1.016	1.002	0.826	0.841	3.339	0.279	3.589	3.339
Gansu	0.956	0.841	0.867	0.697	1.386	0.276	3.622	1.386
Qinghai	1.123	1.045	1.075	1.261	0.421	1.000	1.000	0.421
Ningxia	0.820	1.000	1.000	0.820	2.047	0.648	1.544	2.047
Xinjiang	1.037	1.113	0.845	0.975	1.959	0.835	1.198	1.959

Generally, from 2006 to 2016, the growth rate of China's GTFP generally showed a trend of "great ups and downs and gradually stabilized". From the perspective of the decomposition of GTFP, except for the TECH, both EFFCH and SECH have shown negative growth. The results show that the contribution of the GTFP to economic growth is as follows: TECH> SECH> PECH. TECH has the primary impact on economic growth. Technological progress is the most important driving factor for China's economic growth. The contribution of SECH to China's economic growth ranks second. The contribution of PECH to China's economic growth is lower than the impact of SECH. The improvement of China's provincial GTFP is mainly driven by the TECH and SECH.

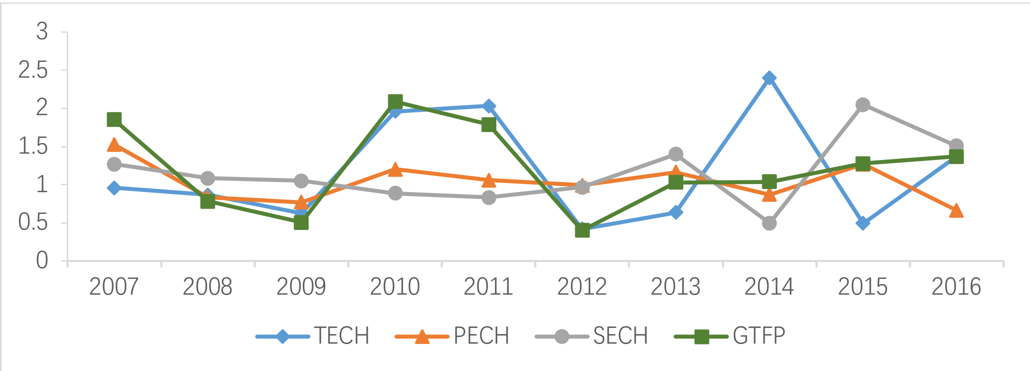

Figure 6. Decomposition of China's GTFP in 2006-2016

From the perspective of the decomposition of GTFP in various regions of China, except for Guangxi, Heilongjiang, and Qinghai, the average TECH for 2006-2016 of all provinces is greater than 1. According to the provincial average, the average annual TECH of the four major regions is also greater than 1, indicating that technological progress has the effect of improving the ecological efficiency of the four major regions. The average annual TECH of the eastern and central regions is greater than that of the northeastern and western regions, and the growth rate of the eastern and central TECH is much higher than that of the northeastern and western regions, indicating that technological progress plays a greater role in improving the ecological efficiency of the eastern and central regions at this stage.

From the perspective of PECH, the average annual PECH of the eastern, central and western regions from 2006 to 2016 was greater than 1, and showed a positive growth, indicating that the resource allocation in three regions was relatively good during the study period. The average annual PECH of the northeastern region was less than 1, which indicates that the resource allocation efficiency of the northeastern region was relatively low. This may be due to the fact that the development of the northeastern region is still dominated by extensive economy, and the allocation of input factors such as capital and energy is not reasonable enough. The ineffectiveness of PECH is the main reason for the poor economic and ecological efficiency in northeast china.

From the perspective of SECH, the average annual change index of scale efficiency in all provinces from 2006 to 2016 was greater than 1, indicating that scale efficiency has a promoting effect on the ecological efficiency of all provinces.

4.4 Type analysis of EWP in China's provinces

In order to further reveal the differences of EWP, we classify different types of EWP in China by considering DI, GTFP and EWP. The 31Chinese provinces are divided into five types with the provincial GTFP mean (1.190) as the threshold value. The details are given in Table 2.

(1) The first type of province is named economic leading and upgrading and includes Beijing, Tianjin and Shanghai. The economic growth of these three municipalities is faster than that of people's well-being, the ecological efficiency of economic growth is high, and the EWP is constantly improving. The GTFP and TECH of Beijing, Tianjin and Shanghai showed an overall upward trend. The improvement of GTFP increases the quality of economic development, promotes the growth of human welfare, and raises the EWP of these three municipalities.

(2) The second type of province is provinces with well-being driven promotion

and includes Yunnan and Tibet. The well-being effect of economic growth in these two provinces is evident. Even if the ecological efficiency of economic growth is low, the EWP is still rising. The economic foundation of Yunnan and Tibet is weak, the growth rate of people's well-being is fast, and the well-being effect of economic growth is prominent. Although Yunnan and Tibet have low GTFP and the quality of their economic development needs to be improved, the growth rate of their people's well-being is still faster than that of per capita ecological footprint, and the performance of ecological well-being is improved.

(3) The third type of province is well-being lags and declines and includes14 provinces. The main features of this type are economic growth is faster than that of the welfare growth, the green total factor productivity is high, and its EWP shows a downward trend. The green total factor productivity and the quality of economic development of this type have significantly improved. However, the demand for fossil fuels such as coal, oil, and natural gas has been increasing in economic development, and the growth rate of per capita ecological footprint is significantly faster than that of people's well-being, so that its EWP has declined.

(4) The fourth type is provinces with economic lags and declines, includes 9 provinces. In this type, people's well-being has increased rapidly, the effect of economic growth on well-being is obvious, the green total factor productivity is low, and the performance of ecological well-being has declined. Since the provinces have a relatively weak economic development, economic growth plays a greater role in promoting people's well-being, and the growth rate of people's well-being is relatively fast. However, the green total factor productivity is relatively low, and the economic growth mode is extensive. Fossil fuel energy consumption is large, the per capita ecological footprint is growing rapidly, and the EWP is significantly reduced.

(5) The last type of province is the overall descending type. This type mainly includes Jilin, Shanxi and Chongqing. The features of this type are the growth rate of people's well-being is slower than that of economic growth, green total factor productivity is low, and EWP is declining. The low green total factor productivity and technological progress index greatly increased the energy consumption in their economic growth, doubled the EF of fossil fuels, and significantly slowed the growth of their people's well-being compared with the per capita ecological footprint.

Table 2. EWP types of Chinese Provinces

Type	Features	Provinces
Province with economic leading	Low well-being growth, high GTFP and improvement of	Beijing, Tianjin, Shanghai
Province with well-being driven	Medium well-being growth, low green total factor	Yunnan, Tibet
Province with well-being lags and declines	Low well-being growth, high GTFP and decline in EWP	Liaoning, Hebei, Jiangsu, Zhejiang, Fujian, Guangdong, Shandong, Henan, Hubei, Sichuan,
Province with economic lags and declines	Medium well-being growth, low GTFP and decline in EWP	Hainan, Guangxi, Guizhou, Gansu, Qinghai, Ningxia, Xinjiang, Heilongjiang, Inner Mongolia
Overall descending type	Low well-being growth, low GTFP, and decline in EWP	Jilin, Shanxi, Chongqing

5. Conclusion and Discussion

(1) Based on the analysis of the temporal and spatial characteristics of China's HDI and EF, this paper finds that the level of human development in China has been significantly improved from 2006 to 2016, and the level of human development in the central and western provinces has been faster than that in the East. Human development

in all regions of China has achieved great progress and distinct convergence in space, and the spatial scope of the high-level echelon of human development has been greatly promoted from eastern China to western China. Meanwhile, China's per capita EF is also growing. The carbon footprint accounts for the highest proportion and shows a growing trend. Economic growth in China still depends on fossil fuel, and the carbon footprint is the main part of the EF of most provinces. In particular, the per capita carbon footprint of northeast China and western provinces is growing faster than that of the eastern and central regions. This needs to be given more attention.

(2) From 2006 to 2016, China's EWP showed a downward trend. The main reason for the decline is that the improvement of people’s well-being is restricted by the high consumption of ecological resources, and the increase of China's EF is mainly due to the increase of per capita fossil fuel footprint. To reverse the declining trend of human welfare output efficiency corresponding to the consumption of ecological resources, we must change the mode of economic growth, reduce the proportion of fossil fuel use, and vigorously promote green development.

There are significant differences in EWP between provinces. The EWP of Beijing, Tianjin, Shanghai, Yunnan, and Tibet is rising. The EF of the central and western provinces is relatively low as a whole, and people’s well-being has significantly improved. The EWP of the central and western provinces is higher than that of the eastern and northeastern regions. The eastern and northeastern regions should give full play to the advantages of technology and capital, vigorously introduce new energy research and development institutions, increase investment in scientific and technological innovations for energy utilization technologies, optimize energy structures, improve energy utilization efficiency, implement fiscal, financial, and other policies to encourage the development of new energy industries, and reduce the proportion of fossil-fuel energy consumption.

The central and western provinces should accelerate the transformation of heavy chemical industries with high consumption and high carbon emissions, formulate and implement financial and tax policies for energy conservation and emission reductions, strengthen the regulation of energy conservation and emission reductions for industries with high energy consumption and high pollution, and form restrictive mechanisms, so that the industries with high consumption and high pollution will greatly reduce their fossil-fuel energy consumption by optimizing the industrial structures.

(3) Most of China's provinces belong to the low well-being growth type, while a few belong to the medium well-being growth type. There are no provinces with high well-being growth. This shows that China's economic growth has promoted the improvement of people’s well-being, but the growth of well-being is slower than the economic growth, and the efficiency of transforming economic output into people’s well-being is still low. The problem of low well-being growth in China should be given more attention.

Economic growth is the material basis for improving people’s well-being. Governments at all levels should formulate relevant policies and actively promote the transformation of economic development achievements into people’s well-being. The government should vigorously increase the proportion of social welfare expenditure, promote the equalization of basic public services, pay attention to the provision of higher-level and more diversified public services and the cultivation of people's own development ability. It should also increase investment in human capital and social capital, and improve the efficiency of the allocation of education, medical and health resources. The government should promote the coordinated development of economic growth and people's well-being, enhance China's people’s well-being in the process of dynamic synergy of economic growth and social development, and encourage provinces to achieve high well-being growth.

(4) The GTFP of China's provinces is significantly lower than the TFP, which shows that the cost of resources and environment for economic growth affects the quality of China's economic development. At present, China's economy has changed from a high-speed growth stage to a high-quality development stage. High-quality development means not only sustained and healthy economic development, but also significant improvement in people's well-being and ecological environment quality. In the context of high-quality development, continuous improvement of people's livelihood and EWP has become an important part of strengthening the construction of ecological civilization and promoting the construction of a moderately prosperous society in an all-round way.

Eastern China has the highest GTFP, followed by central and northeastern China. GTFP is the lowest in western China, which is the key region where GTFP should be promoted. The improvement of GTFP in China is mainly driven by technological progress. Most of the innovator provinces are in the eastern part of the country. The eastern region should give full play to its technological advantages and promote innovations in the northeast, central and western regions. At the same time, the central and western regions should increase investment in R&D funds, integrate all kinds of high-quality scientific and technological resources, build a high-level innovation platforms, actively cultivate innovation subjects, improve and implement tax incentive policies to support enterprise R&D, and encourage enterprises to accelerate their technological innovations.

(5) China's 31 provinces are divided into five types: economic leading and upgrading, well-being driven promotion, well-being lags and declines, economic lags

and declines, overall descending type. Different types should adopt different strategies to improve their EWP according to their own "short board". For the provinces of the “economic leading and upgrading” type, such as Beijing, their social security and infrastructure construction have been relatively perfected. These provinces should enhance the welfare well-being effect of economic growth, further promote the equalization of basic public services, and further improve people's ability to create a happy life.

The provinces of the “well-being driven promotion” type, such as Yunnan and Tibet, should improve their quality of economic development and enhance the capacity of green development by reversing the extensive mode of economic growth.

The provinces of the “well-being lags and declines” type, such as Liaoning and Hebei, should improve the contribution of well-being effect to improve their EWP. These provinces can further improve their public service systems by optimizing the public financial expenditure structure and increasing the proportion of people's financial expenditure.

The provinces of the “economic lags and declines” type, such as Hainan and Guangxi, should vigorously strengthen economic development and implement the economic development strategies that take into account economic benefits.

The provinces of the “overall descending” type, such as Jilin, should actively improve the quality of their economic development, and focus on solving the problems of poor industrial structure, weak innovation ability, and lagging people's well-being that hinder the high-quality economic development.

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Appendix

Appendix 1. Equivalent factor and yield factor of six land types

Factor	Farmland	Forest	Pasture	Construction	Fishrey	Fossil fuel
Equivalent factor	2.21	1.34	0.49	2.21	0.20	1.34
Yield factor	2.80	1.10	0.50	2.80	0.20	1.10

Appendix 2. DI change of Chinese Provinces from 2007 to2016

	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Beijing	0.095	0.039	0.007	0.116	0.015	0.080	0.032	0.891	0.080	-0.043
Tianjin	0.030	0.032	0.026	0.099	0.025	0.049	0.047	0.444	0.084	-0.053
Hebei	0.052	0.064	0.098	0.097	0.031	0.118	0.052	-0.071	0.561	0.202
Shanxi	0.063	0.055	0.063	0.091	0.056	0.063	-0.027	0.481	0.244	-0.415
Inner	0.085	0.083	0.136	0.283	0.050	0.106	0.057	0.098	0.183	0.175
Liaoning	0.059	0.034	0.028	0.126	0.035	0.060	0.001	0.181	3.922	0.009
Jilin	0.061	0.042	0.086	0.165	0.028	0.065	0.013	0.021	0.381	0.314
Heilongjiang	0.102	0.059	0.077	0.172	0.064	0.110	-0.130	-0.120	0.202	0.235
Shanghai	0.013	0.001	0.035	0.066	0.058	0.133	-0.070	0.540	0.182	0.280
Jiangsu	0.073	0.021	0.081	0.133	0.064	0.058	0.100	0.090	0.089	0.086
Zhejiang	0.045	0.042	0.052	0.124	0.043	0.145	0.065	0.271	0.118	0.089

Anhui	0.049	0.088	0.112	0.199	0.102	0.010	0.075	-0.206	0.159	0.084
Fujian	0.006	0.046	0.129	0.281	0.013	0.069	0.087	0.071	0.117	0.097
Jiangxi	0.117	0.053	0.104	0.203	0.042	0.059	0.077	-0.095	0.058	0.173
Shandong	0.058	0.038	0.096	0.143	0.038	0.059	0.103	0.093	0.117	0.141
Henan	0.079	0.058	0.199	0.158	0.052	0.074	0.014	-0.171	0.146	0.093
Hubei	0.087	0.064	0.091	0.172	0.027	-0.009	0.065	-0.023	0.170	0.043
Hunan	0.082	0.044	0.078	0.201	0.011	0.040	0.101	0.025	0.142	0.181
Guangdong	0.066	0.033	0.046	0.08	0.076	0.163	0.062	0.326	0.153	-0.112
Guangxi	0.070	0.064	0.299	0.265	0.141	0.035	0.192	-0.015	0.053	0.614
Hainan	0.080	0.095	0.062	0.211	0.100	0.116	0.089	0.061	0.129	0.381
Chongqing	0.097	0.050	0.046	0.036	0.180	0.035	0.091	0.021	0.094	0.102
Sichuan	0.104	0.065	0.103	0.237	0.034	0.037	0.036	-0.015	0.094	0.021
Guizhou	0.034	0.258	0.211	0.384	0.09	0.070	0.131	0.242	0.069	0.015
Yunnan	0.001	0.170	0.269	0.426	0.062	0.107	0.076	0.683	0.083	-0.004
Tibet	0.249	0.078	0.196	0.395	0.099	0.080	-0.038	0.423	0.271	-0.084
Shaanxi	0.065	0.068	0.068	0.173	0.058	0.071	0.060	-0.013	0.449	-0.123
Gansu	0.139	0.154	0.464	0.298	0.123	0.120	0.079	0.502	1.135	-0.038
Qinghai	0.096	0.169	0.247	0.204	0.120	0.041	0.057	0.735	-0.156	0.136
Ningxia	0.109	0.169	0.110	0.167	0.049	0.139	0.103	0.076	-0.022	0.457
Xinjiang	0.200	0.062	0.700	0.182	0.075	0.107	0.031	0.185	0.013	1.014

Appendix 3. WP change of Chinese provinces from 2006 to2016

	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	Annual average growth rate in 2006-2016 (%)
China	3.01	2.88	2.79	2.72	2.62	2.43	2.39	2.40	2.42	2.43	2.44	-2.12

Eastern China	Beijing	3.54	3.58	3.62	3.78	4.02	4.37	4.45	4.89	5.15	5.37	5.89	6.65
	Tianjin	2.17	2.17	2.29	2.25	2.04	1.96	2.03	2.05	2.24	2.34	2.55	1.74
	Hebei	2.51	2.38	2.33	2.24	2.19	1.98	1.98	1.99	2.08	2.12	2.20	-1.22
	Shanghai	2.66	2.77	2.68	2.8	2.69	2.66	2.74	2.64	2.96	2.89	3.18	1.96
	Jiangsu	2.89	2.80	2.75	2.71	2.57	2.33	2.30	2.27	2.30	2.25	2.26	-2.18
	Zhejiang	2.89	2.88	2.85	2.81	2.78	2.64	2.71	2.70	2.74	2.72	2.88	-0.02
	Fujian	2.86	2.91	2.86	2.65	2.65	2.45	2.46	2.50	2.32	2.34	2.48	-1.35
	Shandong	2.27	2.16	2.06	2.03	1.98	1.91	1.85	1.94	1.87	1.82	1.82	-1.96
	Guangdong	3.88	3.92	3.84	3.70	3.51	3.33	3.39	3.44	3.51	3.56	3.64	-0.61
	Hainan	2.50	2.28	2.21	2.16	2.21	2.03	1.98	2.04	1.94	1.88	1.99	-2.02
Northeast China	Liaoning	1.72	1.72	1.67	1.64	1.57	1.48	1.44	1.47	1.50	1.52	1.54	-1.02
	Jilin	2.54	2.69	2.39	2.47	2.30	2.04	2.06	2.08	2.11	2.19	2.28	-1.04
	Heilongjiang	2.60	2.53	2.29	2.24	2.12	1.98	1.93	1.98	1.92	1.92	1.94	-2.55
Central China	Shanxi	1.40	1.37	1.43	1.47	1.46	1.35	1.30	1.27	1.25	1.27	1.33	-0.51
	Anhui	3.99	3.91	3.62	3.43	3.34	3.25	3.13	2.99	2.88	2.90	3.04	-2.38
	Jiangxi	4.37	4.30	4.26	4.19	4.04	3.82	3.77	3.66	3.53	3.45	3.63	-1.70
	Henan	3.58	3.37	3.35	3.33	3.20	3.00	3.16	3.16	3.11	3.09	3.22	-1.01
	Hubei	3.35	3.19	3.20	3.09	2.92	2.70	2.65	2.92	2.84	2.87	3.02	-0.98
	Hunan	4.17	4.00	4.00	3.89	3.99	3.70	3.69	3.84	3.81	3.74	3.93	-0.57
Western China	Guangxi	3.11	2.98	2.95	3.00	2.84	2.63	2.48	2.50	2.51	2.62	2.77	-1.09
	Chongqing	4.94	4.19	4.07	3.93	3.69	3.57	3.62	4.03	3.85	3.83	4.17	-1.57

	Sichuan	4.95	4.62	4.46	4.20	4.26	4.24	4.17	4.12	3.92	4.11	4.40	-1.12
	Guizhou	2.85	2.90	2.95	2.80	2.95	2.82	2.63	2.61	2.76	2.76	2.76	-0.32
	Yunnan	3.34	3.23	3.11	3.03	3.16	3.05	3.01	3.05	3.47	3.74	3.73	1.17
	Tibet	7.46	8.45	16.61	17.86	18.41	10.45	11.54	12.16	10.59	10.78	10.56	4.15
	Shaanxi	3.69	3.42	3.19	3.02	2.72	2.52	2.25	2.22	2.12	2.14	2.11	-4.28
	Gansu	3.30	3.16	3.17	3.30	3.17	2.87	2.82	2.74	2.84	2.88	3.08	-0.66
	Qinghai	3.27	2.72	2.67	2.72	2.88	2.58	2.25	2.12	2.41	2.59	2.39	-2.69
	Ningxia	1.51	1.43	1.37	1.30	1.18	0.93	0.89	0.86	0.85	0.83	0.91	-3.97
	Xinjiang	2.00	1.95	1.86	1.69	1.64	1.45	1.29	1.19	1.11	1.12	1.16	-4.20
	Inner Mongolia	1.29	1.23	1.07	1.04	1.01	0.83	0.81	0.83	0.81	0.82	0.86	-3.32