Energy Ecological Footprint Changes and Its Influencing Factors at the Provincial Scale in China

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Abstract. The energy ecological footprint is an important theory and method for quantitative measurement of the coordinated development of the socio-economic-ecological environment. This research indicated the following: (1) the energy ecological footprints of China and the provinces showed significant linear increases (except Beijing). China’s economy developed rapidly over 1999-2015, but the economic development had a high dependence on energy consumption, which induced an increase in the energy ecological footprint. Optimizing industrial structure and reducing energy consumption are effective ways to reduce the energy ecological footprint. (2) Forest land was the most important land use type for per capita energy ecological footprint capacity, accounting for 50% or more of the total. The energy ecological footprints of China and the provinces were mainly in a state of deficit, and only Sichuan, Qinghai, Guangxi, Shaanxi, Inner Mongolia and Xinjiang were in surplus. In addition, the ecological pressure in the eastern developed provinces was higher than in the central provinces, and the lowest pressure was in the west. (3) The energy ecological footprint of China and the provinces was mainly affected by the secondary industry output value, followed by population, total investment in fixed assets, and then the tertiary and primary industry output values. The results showed that reduction of industrial energy consumption is still the main issue for addressing carbon emissions in China.

1. Introduction
Global environmental change, especially global warming, has received extensive attention [1]. The IPCC (Intergovernmental Panel on Climate Change) attributed the problem of climate warming mainly to carbon dioxide emissions caused by fossil fuel combustion and land use changes [2]. Compared with developed countries, developing countries are experiencing rapid economic development. They have a strong demand for fossil fuels and a large amount of carbon emissions from energy consumption. The reduction of carbon emissions has become an important political issue, as well as an economic and ecological environmental task, faced by developing countries [3]. China is a typical developing country, and the rapid economic development is closely related to the large energy consumption. A scientific assessment of the inter-provincial energy consumption and economic, social and ecological environment in China will help with the formulation of fair and reasonable policies for regional reductions in carbon emissions.

The concept of the energy footprint is derived from ecological footprint theory. It is the application and development of ecological footprint theory in the energy field, as well as an important method for coordinating energy consumption and socio-economic development [4]. The current application directions include research on the spatial temporal dynamics of the energy footprint [5], research on
factors affecting the energy footprint [6], and research on the improvement of the energy footprint method [7]. The traditional energy footprint assessment methods have given less consideration to natural ecological footprints, making the energy footprint larger overall.

2. Materials and methods

2.1. Materials
Data used in the research include the following: (1) land use data of China as a whole and each province from 1999 to 2015. The farmland (cultivated land and garden land), pasture and grassland data were collected from the China Statistical Yearbook and the China Land and Resources Statistic Yearbook, and forest area data were collected from the Chinese Forestry Database (http://data.forestry.gov.cn/lysjk/). (2) Data on energy consumption in China and each province was collected from the China Energy Statistical Yearbook. (3) Data on population, GDP, and the output values of primary, secondary, and tertiary industries in China and each province, as well as the total investment in fixed assets, were collected from the China Statistical Yearbook.

2.2. Methods
The quantitative methods mainly include two parts. The first part is the energy footprint measurement method [8], including energy footprint (EEF), energy footprint per capita capacity (PEEF), energy footprint ecological pressure (EPIEF), and energy footprint output (VEF):

\[
EEF = \frac{F \times 7000 \times 4.18 \times 10^6}{A \times 10^6 \times P}
\]  
(1)

\[
PEEF = \sum_{j=1}^{A_j} r_j \times y_j
\]  
(2)

\[
EPIEF = EEF / PEEF
\]  
(3)

\[
VEF = PGDP / EEF
\]  
(4)

where the units of EEF are ghm\(^2\)/person; \(F\) represents the amount of energy consumption, kg C (standard coal); \(A\) indicates the global average footprint of coal energy, 55 GJ/ghm\(^2\); and \(P\) is population. The units of PEEF are ghm\(^2\)/person; \(A_j\) is the \(j\)th land use per capita area, ghm\(^2\)/person; and \(r_j\) and \(y_j\) are an equilibrium factor and a production factor, respectively [9]. The units of VEF are RMB/ghm\(^2\); and PGDP indicates GDP per capita, RMB/person.

The second was the influencing factors analysis method based on the STIRPAT model [10]:

\[
EEF = kP^a A^b B^c C^d D^e Q
\]  
(5)

\[
\ln EEF = \ln k + a \ln P + b \ln A + c \ln B + d \ln C + e \ln D
\]  
(6)

where \(P\), \(A\), \(B\), \(C\) and \(D\) represent the population (10000 person), the output of primary, primary, secondary, and tertiary industries, and the total investment in fixed assets, respectively; \(k\) is a constant; and \(a\), \(b\), \(c\) and \(d\) are coefficients. Using \(\ln Q\) as the dependent variable, \(\ln P\), \(\ln A\), \(\ln B\), \(\ln C\) and \(\ln D\) are the independent variables used to perform linear stepwise regression analysis [11].

3. Results

3.1. Energy footprint changes
Nationally, the energy footprint from 1999 to 2015 increased from 0.59 ghm\(^2\) per person to 1.73 ghm\(^2\) per person (a 2.93-fold increase), indicating that the national energy footprint was constantly increasing. The linear trend analysis also showed that the country’s energy footprint showed a
significant growth trend from 1999 to 2015, with a linear growth rate of 0.083 ghm² per person \((P<0.001)\) per year (Table 1).

Except for the small changes in the Beijing energy footprint from 1999 to 2015, the linear trend was not significant \((P>0.05)\), and the energy footprint of other provinces showed significant linear growth \((P<0.001)\). The provinces with the highest average energy footprints in the country were Ningxia, Inner Mongolia, Shanghai, Tianjin and Shanxi. The energy footprints increased by 5.19, 4.67, 1.34, 2.01 and 2.61 times, respectively, from 1999 to 2015. The five provinces with the lowest average energy footprints were Yunnan, Anhui, Hainan, Guangxi, and Jiangxi. Their energy footprints increased by 2.76, 2.68, 3.77, 3.86 and 3.67 times, respectively, from 1999 to 2015 (Table 1).

Table 1. Energy footprint and trends in China and the provinces a.

| Region          | Energy footprint | Linear change |        |
|-----------------|------------------|---------------|-------|
|                 | 1999  | 2000  | 2010  | 2015 Av | CR   | \(R^2\) | \(P\)   |
| China           | 0.59  | 1.07  | 1.55  | 1.73   | 1.22 | 0.083 | 0.967 | \(<0.001\) |
| Ningxia         | 0.83  | 2.27  | 3.10  | 4.31   | 2.60 | 0.215 | 0.988 | \(<0.001\) |
| Inner Mongolia  | 0.86  | 2.14  | 3.63  | 4.02   | 2.59 | 0.245 | 0.941 | \(<0.001\) |
| Shanghai        | 1.88  | 2.32  | 2.59  | 2.51   | 2.30 | 0.049 | 0.757 | \(<0.001\) |
| Tianjin         | 1.42  | 2.09  | 2.80  | 2.85   | 2.28 | 0.111 | 0.925 | \(<0.001\) |
| Shanxi          | 1.08  | 2.03  | 2.51  | 2.82   | 2.16 | 0.123 | 0.941 | \(<0.001\) |
| Qinghai         | 0.98  | 1.64  | 2.43  | 3.74   | 2.11 | 0.196 | 0.961 | \(<0.001\) |
| Liaoning        | 1.20  | 1.72  | 2.55  | 2.63   | 2.04 | 0.111 | 0.929 | \(<0.001\) |
| Xinjiang        | 0.97  | 1.46  | 2.02  | 3.53   | 1.89 | 0.167 | 0.914 | \(<0.001\) |
| Beijing         | 1.69  | 1.91  | 1.89  | 1.68   | 1.79 | 0.005 | 0.048 | \(>0.05\) |
| Hebei           | 0.76  | 1.54  | 2.04  | 2.11   | 1.63 | 0.098 | 0.922 | \(<0.001\) |
| Shandong        | 0.54  | 1.39  | 1.93  | 2.05   | 1.47 | 0.107 | 0.918 | \(<0.001\) |
| Zhejiang        | 0.65  | 1.28  | 1.65  | 1.89   | 1.37 | 0.081 | 0.960 | \(<0.001\) |
| Jiangsu         | 0.60  | 1.21  | 1.75  | 2.02   | 1.35 | 0.105 | 0.969 | \(<0.001\) |
| Heilongjiang    | 0.85  | 1.12  | 1.56  | 1.70   | 1.29 | 0.067 | 0.944 | \(<0.001\) |
| Jilin           | 0.74  | 1.04  | 1.61  | 1.58   | 1.28 | 0.071 | 0.906 | \(<0.001\) |
| Guangdong       | 0.64  | 1.04  | 1.37  | 1.48   | 1.11 | 0.065 | 0.932 | \(<0.001\) |
| Fujian          | 0.45  | 0.92  | 1.42  | 1.69   | 1.10 | 0.086 | 0.987 | \(<0.001\) |
| Hubei           | 0.54  | 0.94  | 1.41  | 1.49   | 1.09 | 0.073 | 0.939 | \(<0.001\) |
| Chongqing       | 0.64  | 0.94  | 1.45  | 1.58   | 1.08 | 0.082 | 0.907 | \(<0.001\) |
| Gansu           | 0.61  | 0.91  | 1.23  | 1.54   | 1.06 | 0.067 | 0.983 | \(<0.001\) |
| Guizhou         | 0.58  | 0.81  | 1.25  | 1.50   | 1.03 | 0.067 | 0.964 | \(<0.001\) |
| Shaanxi         | 0.39  | 0.80  | 1.27  | 1.65   | 0.99 | 0.086 | 0.992 | \(<0.001\) |
| Henan           | 0.42  | 0.83  | 1.21  | 1.30   | 0.93 | 0.066 | 0.940 | \(<0.001\) |
| Sichuan         | 0.40  | 0.77  | 1.19  | 1.29   | 0.90 | 0.067 | 0.958 | \(<0.001\) |
| Hunan           | 0.33  | 0.82  | 1.21  | 1.22   | 0.87 | 0.070 | 0.905 | \(<0.001\) |
| Yunnan          | 0.42  | 0.72  | 1.00  | 1.16   | 0.82 | 0.056 | 0.973 | \(<0.001\) |
| Anhui           | 0.40  | 0.57  | 0.87  | 1.07   | 0.71 | 0.048 | 0.969 | \(<0.001\) |
| Hainan          | 0.30  | 0.53  | 0.83  | 1.13   | 0.68 | 0.056 | 0.986 | \(<0.001\) |
| Guangxi         | 0.28  | 0.56  | 0.92  | 1.08   | 0.68 | 0.059 | 0.976 | \(<0.001\) |
| Jiangxi         | 0.27  | 0.53  | 0.76  | 0.99   | 0.62 | 0.047 | 0.996 | \(<0.001\) |
| Tibet           | —     | —     | —     | —      | —    | —     | —     | —      |

a The units of energy footprint are ghm² per person; Av is the average value; CR is the change rate (ghm² per person per year).
b “—” indicates that there was no energy consumption data for the Tibet Autonomous Region.

### 3.2 Energy footprint ecological pressure

At the national level, the type of the land use with the highest average energy footprint per capita was forestland (with an average carrying capacity of 0.48 ghm²/person), followed by grassland and
farmland. The overall energy footprint was in the state of deficit (−0.33 ghm²/person). The energy ecological footprint pressure was 1.39, indicating that China’s overall energy consumption was too large and exceeded the level of energy footprint per capita that land use can provide (Table 2). The resulting deficit in the energy footprint also reflected the current unsustainable pattern of China’s economic development, which relies on a large amount of energy consumption. This pattern had an unfavorable impact on the sustainable development of the social economy and the protection of the ecological environment. An important goal for the current period and the future is to either improve the industrial structure, lower the level of energy consumption, or increase the per capita capacity of the energy footprint of land use.

Table 2. Results of the energy footprint ecological pressure calculation for China and the provinces a.

| Region          | PEEF | EEF  | PEEF-EEF | EPIEF |
|-----------------|------|------|----------|-------|
|                 | Farmland | Forest land | Grassland |       |
| China           | 0.13 | 0.48 | 0.27     | 0.89  |
| Shanghai        | 0.01 | 0.01 | 0.00     | 0.02  |
| Tianjin         | 0.03 | 0.01 | 0.00     | 0.04  |
| Beijing         | 0.02 | 0.02 | 0.00     | 0.04  |
| Zhejiang        | 0.03 | 0.04 | 0.00     | 0.07  |
| Shanxi          | 0.06 | 0.10 | 0.01     | 0.16  |
| Jiangsu         | 0.14 | 0.01 | 0.00     | 0.15  |
| Hebei           | 0.11 | 0.05 | 0.05     | 0.20  |
| Shandong        | 0.15 | 0.05 | 0.00     | 0.20  |
| Liaoning        | 0.11 | 0.17 | 0.01     | 0.29  |
| Guangdong       | 0.09 | 0.08 | 0.00     | 0.17  |
| Chongqing       | 0.08 | 0.09 | 0.03     | 0.20  |
| Hubei           | 0.11 | 0.11 | 0.00     | 0.22  |
| Anhui           | 0.12 | 0.06 | 0.00     | 0.18  |
| Guizhou         | 0.04 | 0.20 | 0.02     | 0.26  |
| Henan           | 0.22 | 0.05 | 0.00     | 0.27  |
| Ningxia         | 0.21 | 0.41 | 0.19     | 0.80  |
| Hunan           | 0.13 | 0.17 | 0.00     | 0.30  |
| Fujian          | 0.04 | 0.39 | 0.00     | 0.44  |
| Jiangxi         | 0.11 | 0.18 | 0.00     | 0.30  |
| Heilongjiang    | 0.16 | 0.56 | 0.07     | 0.79  |
| Jilin           | 0.21 | 0.65 | 0.01     | 0.87  |
| Gansu           | 0.08 | 0.39 | 0.37     | 0.83  |
| Hainan          | 0.22 | 0.35 | 0.00     | 0.57  |
| Yunnan          | 0.11 | 0.64 | 0.03     | 0.79  |
| Sichuan         | 0.12 | 0.25 | 0.58     | 0.95  |
| Qinghai         | 0.07 | 0.70 | 1.45     | 2.22  |
| Guangxi         | 0.49 | 0.30 | 0.01     | 0.81  |
| Inner Mongolia  | 0.27 | 1.95 | 1.56     | 3.79  |
| Xinjiang        | 0.39 | 1.03 | 1.82     | 3.24  |
| Shaanxi         | 0.05 | 0.25 | 1.72     | 2.02  |
| Tibet b         | 0.10 | 5.76 | 0.57     | 6.44  |

a PEEF-Energy footprint per capita capacity; EEF-Energy footprint; EPIEF-Energy footprint ecological pressure.

b “—” indicates that there was no energy consumption data for the Tibet Autonomous Region.

The provinces with the highest energy footprint per capita in the country (in decreasing order) were Inner Mongolia, Xinjiang, Qinghai, Shaanxi, and Sichuan, which are western provinces. The five provinces with the lowest energy footprint per capita were Jiangsu, Zhejiang, Tianjin, Beijing and Shanghai, all of which were in eastern China. This reflects a distinct difference in the spatial
distribution of the per capita capacity of energy footprint. The high values concentrated in the economically underdeveloped western provinces, whereas the low values concentrated in the developed eastern provinces.

In addition, there were six provinces with a surplus of energy footprint in the country, namely Sichuan, Qinghai, Guangxi, Shaanxi, Inner Mongolia, and Xinjiang, which are located in western China. All other provinces had deficits. The five provinces with the highest negative of energy footprint in the country were Shanghai, Tianjin, Shanxi, Ningxia, and Liaoning. Of these, the eastern provinces were the main ones, indicating that the energy footprint deficit was mainly distributed in the central and eastern provinces, whereas the surplus was mainly distributed in the western provinces. In terms of energy footprint ecological pressure, the top five provinces in the country were Shanghai, Tianjin, Beijing, Zhejiang and Shanxi, whereas the lowest five provinces were Qinghai, Guangxi, Inner Mongolia, Xinjiang and Shaanxi (Table 2).

### 3.3. Influencing factors

The national average energy footprint was positively correlated with population and secondary industry output value, but it was negatively correlated with the tertiary industry output value (Table 3). As the population increased, the output value of the secondary industry increased, and the energy footprint showed an increase. With the increase in the output value of tertiary industry, the national average energy footprint tended to decrease.

| Region               | Coefficient of variable | Region               | Coefficient of variable |
|----------------------|-------------------------|----------------------|-------------------------|
| lnP                  | 14.6*                   | lnP                  | 1.0*                    |
| lnA                  | 1.3*                    | lnA                  | -0.4*                   |
| lnB                  | -1.1*                   | lnB                  | -0.8*                   |
| lnC                  |                         | lnC                  |                         |
| lnD                  |                         | lnD                  |                         |
| China                |                         | Henan                |                         |
| Beijing              |                         | Hubei                |                         |
| Tianjin              | 0.7*                    | Hunan                | -6.3*                   |
| Hebei                | 1.2*                    | Guangdong            | -1.1*                   |
| Shanxi               | 0.4*                    | Guangxi              | -0.3*                   |
| Inner Mongolia       | -20.2*                  |                     |                         |
| Liaoning             |                         | Haimen               |                         |
| Jilin                |                         | Chongqing            | 0.4*                    |
| Heilongjiang         | -21.5*                  | Sichuan              | -3.5*                   |
| Shanghai             | 0.3*                    | Guizhou              | 0.7*                    |
| Jiangsu              | -6.9*                   | Yunnan               | -1.0*                   |
| Zhejiang             | -0.7*                   | Tibetb               |                         |
| Anhui                | 0.4*                    | Shaanxi              | -0.7*                   |
| Fujian               | 10.7*                   | Gansu                | 0.5*                    |
| Jiangxi              |                         | Qinghai              | 0.5*                    |
| Shandong             | -1.1*                   | Ningxia              | 6.9*                    |
|                     | 1.4*                    | Xinjiang             | -1.3*                   |

* (P<0.05), ** (P<0.01), *** (P<0.001). lnP, lnA, lnB, lnC and lnD were the natural logarithm of the population, the output value of the primary, secondary, and tertiary industries, and total social investment in fixed assets, respectively.

b "—" indicated that there was no energy consumption data in the Tibet Autonomous Region.

There were nine provinces with close relationships between energy footprint and population, including Inner Mongolia, Heilongjiang, Jiangsu, Fujian, Hunan, Guangdong, Sichuan, Yunnan and Ningxia. Of these, Fujian, Yunnan and Ningxia had positive relationships between energy footprint and population, and the other provinces had negative relationships. There were six provinces that had close relationships between energy footprint and primary industry, namely Zhejiang, Shandong, Hunan, Guangdong, Shaanxi, and Ningxia, all of which had negative relationships between the two factors (that is, as the output value of the primary industry increased, the level of energy footprint...
decreased). There were 22 provinces with positive relationships between energy footprint and secondary industry output. This shows that the secondary industry output value had increased, and it had greatly contributed to the increase in the energy footprint of most provinces in China. There were seven provinces with negative relationships between energy footprint and the tertiary industry output value, namely Tianjin, Shanghai, Jiangsu, Henan, Guangdong, Sichuan and Guizhou. There were nine provinces with negative relationships between energy footprint and total social fixed asset investment, namely Hebei, Inner Mongolia, Liaoning, Shanghai, Jiangxi, Hubei, Chongqing, Sichuan and Xinjiang.

The above analysis shows that the energy footprint of China and the provinces was mainly affected by the output value of the secondary industry, followed by population, total social investment in fixed assets, and the output values of tertiary and primary industry.

4. Conclusions
(1) The energy ecological footprints of China and the provinces showed a significant linear increasing trend (except for Beijing). China’s economy developed rapidly in 1999-2015, but the economic development had a high dependence on energy consumption, which caused energy consumption to rise and the level of energy ecological footprint to increase. Optimizing the industrial structure and reducing the energy consumption are the effective approaches to reducing the energy ecological footprint.

(2) Woodland is the most important land use type for energy ecological footprint capacity per capita, accounting for 50% or more of the total. The energy ecological footprint of China and the provinces were mainly in deficit, and only Sichuan, Qinghai, Guangxi, Shaanxi, Inner Mongolia and Xinjiang were in surplus. In addition, the ecological pressure in the eastern developed provinces was higher than in the central provinces, and it was the smallest in the west.

(3) The energy ecological footprint in China and the provinces was mainly affected by the secondary industry output value, followed by population, total investment in fixed assets, and then the tertiary and the primary industry output values. The results showed that reduction of industrial energy consumption is still the main issue for reducing carbon emissions in China.

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