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RESEARCH ARTICLE

Ecological sustainability assessment of the carbon footprint in Fujian Province, southeast China

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Abstract China's rapid economic development has initiated the deterioration of its ecological environment, posing a threat to the sustainable development of human society. As a result, an assessment of regional sustainability is critical. This paper researches China's most forested province, Fujian Province, as the study area. We proposed a grid-based approach to assess the regional carbon footprint in accordance with the Intergovernmental Panel on Climate Change's (IPCC) carbon emission guidelines. Our method of assessment also introduced carbon emission indicators with our improved and published Net Primary Production (NPP) based on process simulation. The carbon footprint in Fujian Province from 2005–2017 was calculated and examined from a spatio-temporal perspective. Ecological indicators were used in the sustainability assessment. The research draws the following conclusions: 1) the carbon footprint in the eastern regions of Fujian Province was higher due to rapid economic development; 2) that of the western regions was lower; 3) an uptrend in the carbon footprint of Fujian Province was observed. All five ecological indicators based on carbon emissions and economic and social data showed an ecologically unsustainable trend over 13 years in the research area due to unsustainable economic development. Therefore, it is urgent to balance the relationship between economic development and environmental protection. Our research provides scientific references for achieving ecological civilization and sustainability in a similar region.

Keywords Fujian Province, carbon emission, carbon footprint, ecological index, sustainable development

1 Introduction

Sustainability assessment is a valuable method for resolving global environmental and ecological issues, such as forest vegetation protection, reduction in greenhouse gas emissions, and sustainable development, all of which involve environmental, economic, political, and diplomatic actions (Qi and Dong, 2004; Wang et al., 2014; Wang et al., 2015a; Wang et al., 2018a). Global warming, directly related to human activity, will escalate over the next 100 years, resulting in adverse effects on natural ecological systems and social economy (Solomon et al., 2009; Qin and Stocker, 2014). Low-carbon efficiency in human activities is one of the key contributors to rising CO_2 concentrations (Canadell et al., 2007). Carbon emissions from energy use is the primary cause of greenhouse-gas emissions, causing great concern in both academic and scientific fields (Quadrelli and Peterson, 2007; Gu et al., 2009; Cao et al., 2010; Xie et al., 2009). Some scholars look into comprehensively direct and indirect carbon emissions to trace the carbon footprint (Ramaswami et al., 2008; Hillman and Ramaswami, 2010; Kennedy et al., 2010). However, most previous studies were conducted at a large spatial scale, which is ineffective for guiding policy.

Carbon footprint originates from the concept "Our Ecological Footprint" (Wackernagel and Rees, 1997). It takes into account global warming potential (GWP) as a representation of greenhouse gas emissions (Finkbeiner, 2009). Research on carbon footprint assessment has been

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under way in Japan, the United Kingdom, and the United States (Giurco and Petrie, 2007; Welch et al., 2008; Johnson, 2008 and 2009; Benjaafar et al., 2013). Internationally, there are two different understandings of carbon footprint: one defines it as carbon emissions from human activities (Bahl and Dhami, 2007; Hammond, 2007); and the other considers it as part of the ecological footprint, i.e., the ecological carrying capacity required to absorb CO_2 emissions from burning fossil fuels (Danish et al., 2019).

At present, studies on carbon footprint primarily focus on emissions caused by manufacturing plants (Johnson, 2008; Kim and Neff, 2009; Iribarren et al., 2010; Pathak et al., 2010), households, and businesses (Weber and Matthews, 2008; Druckman and Jackson, 2009; Huang et al, 2009; Berners-Lee et al., 2011). Using a concept-based calculation and case-based methods (Hertwich and Peters, 2009), the fields of research cover individuals, manufacturing plants, households, organizations, cities, and countries (Burnham et al., 2006; Giurco and Petrie, 2007; Qiang et al., 2008; Kenny and Gray, 2009; Brown et al., 2009; Wang et al., 2015; Chacko et al., 2019), and ranges across various sectors of the economy, including industries, transportation, construction, water supply, medical care, etc. (Burnham et al., 2006; Cole, 2009). However, minimal research has been conducted on the spatiotemporal evolution of carbon footprint based on pixel assessment.

There are three common methods for estimating carbon footprint: 1) input-output (I-O), 2) life cycle assessment (LCA), and 3) assessments provided by the Intergovernmental Panel on Climate Change (IPCC) (Geng and Liu, 2010; Wang and Lin, 2010). The input-output analysis was developed by the famous American economist Wassily Leontief (Fabricant, 1952), providing a top-down approach. Life cycle assessment, a bottom-up approach, analyzes and assesses carbon footprint associated with all stages of product life (Zhang et al., 2015). The third approach refers to the Guidelines for National Greenhouse Gas Inventories prepared by the UN IPCC (Hulme, 2017). As an internationally recognized and common approach for measuring carbon footprint, these guidelines provide step-by-step instructions for calculating greenhouse gas emissions. IPCC methodologies look into all substantial sources and explain the emission mechanisms, as well as the calculation methods. Therefore, the IPCC methodology frame, with greater comprehension and recognition, should be adopted for carbon footprint estimation. Based on the frame, the ecological footprint, and methodologies proposed by William E. Rees and Mathis Wackernagel, (Rees, 1992; Wackernagel et al., 1999) were in line with the carbon footprint of Browne's definition (Browne et al., 2009). Carbon footprint is estimated by calculating the implicit energy and greenhouse gas emissions in consumption. It can also be expressed in terms of the area of land (hectares) that absorbs greenhouse gases; areas that are a part of the ecological footprint assessment (Danish et al., 2019). Net Primary Production (NPP) is an important measure of ecosystem function that quantifies carbon allocation of CO_2 in the atmosphere in green plants per unit area, per unit time, through photosynthesis (Field et al., 1995; Running et al., 2004; Crabtree et al., 2009; Li et al., 2013; Xie et al., 2014).

The aim of our study is to propose a feasible method to assess ecological sustainability at grid scale. The IPCC guidelines' frame was adopted to calculate the annual total carbon emissions from 2005 to 2017 in the study area. First, we employed the Normalized Difference Vegetation Index (NDVI), climate data (precipitation, temperature, radiation, etc.) and land cover data to simulate the NPP by using our improved CASA (Carnegie-Ames-Stanford-Approach) model (Wang et al., 2017; Wang et al., 2018b; Wang et al., 2019). Secondly, we combined the statistical Yearbook data, and simulated NPP data to estimate the carbon footprint at grid scale. At last, spatial-temporal evolution characteristics of carbon footprint were investigated. Our research provides insights on the sustainable development of the man-land areal system at both regional and global scale.

2 Study area and data sources

2.1 Study area

Fujian, abbreviated as Min, is a coastal province in southeastern China, with coordinates 15°50′–120°40′E, 23°33′–28°20′N. Over 80% of the terrain is characterized by mountains and rolling hills. The climate in the southeastern area of Fujian is subtropical, subject to monsoons, with average annual precipitation from 800 mm to 1900 mm. Forests cover approximately 65.95% of the area, the highest in China, serving as an important ecological corridor in southern China. Statistical yearbooks show that Fujian's economic activities are primarily concentrated in the southeastern coastal area and in the Triangle area in the south. The GDP value has shown an 41% increase from 78468 million yuan in 1992 to 3.22 trillion yuan in 2017.

2.2 Data sources

Basic energy consumption, population, land area and GDP data are sourced from the Statistical Yearbooks of Fujian. The 2005–2017 monthly NDVI values (1 km × 1 km spatial resolution; MOD13A3) and annual land cover data (1 km × 1 km spatial resolution; MCD12A1) are collected from the National Aeronautics and Space Administration of the United States. The monthly data of meteorological elements (temperature, precipitation, and solar radiation) are collected from the China Meteorological Data Service Center. The standard coal equivalent data are collected from the China Energy Statistical Yearbook, and the carbon emission coefficient is taken from the 2006 IPCC Guidelines for National Greenhouse Gas Inventories.

3 Methods

3.1 Carbon footprint simulation

A carbon emission measurement model for a socio-economic system based on energy consumption (Rong et al., 2016):

$$CE_{it} = \sum_{j}^{n} E_{ijt} \times cv_j \times \delta_j, \tag{1}$$

where CE_{it} is the total carbon emissions from energy use (G·C/a) in Zone i over t years; E_{ijt} is the total energy consumption for the type j energy source in Zone i over t years (KG or kW/h); cv_j is the reference coefficient for the type j energy source; and δ_j is the carbon emission coefficient for the type j energy source.

Based on the estimation of carbon dynamics for the natural and socio-economic systems, and in reference to the methods for calculating ecological footprint, a carbon emission measurement model has been created:

$$CF_{it} = (CE_{it}/NPP_r) \times 10^{-4}/H, \tag{2}$$

where NPP_r is the regional NPP value (G·C)/(m^2·a). Our previous research used the improved CASA model to simulate China's NPP values, and compared the results of our simulated Chinese NPP with other scholars to obtain scientific and reliable data (Wang et al., 2018b). CF_{it} is the carbon footprint (ha) in Zone i over t years. Our CF refers to the ecological footprint per unit area, and our unit area is 1 km^2. For example, a grid with a value of 50 ha means that the grid needs 50 ha of productive land to absorb the amount of carbon produced by this grid); CE_{it} is the total carbon emissions from energy use ((G·C)/a) in Zone i over t years; H is the total land area (km^2) in Zone i. The carbon footprint calculation flowchart is shown in Fig. 1.

3.2 Trend analysis approach

M-K (Manner-Kendall) trend analysis is a nonparametric test method (Mann, 1945; Kendall, 1990). It does not require the data series to be normally distributed. Many scholars in hydrology and meteorology use this method for academic research (Gocic and Trajkovic, 2013; Tosunoglu and Kisi, 2017; Nourani et al., 2018). The null hypothesis H0 shows the data series x_k ($k = 1,2,3...,n$) as a sample of n independent and identically distributed; whereas the

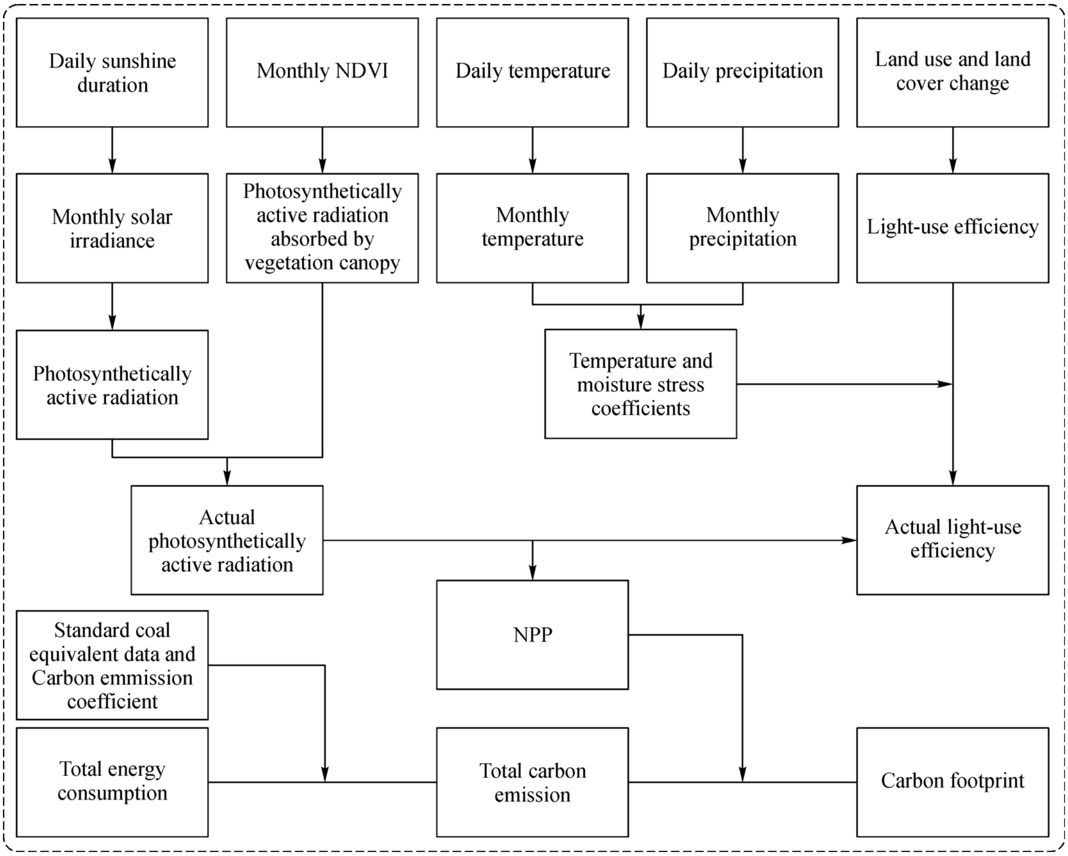


Fig. 1 Carbon footprint calculation flowchart.

alternative hypothesis H1 is that there has been an increasing or decreasing trend in the data series. The Mann-Kendall test statistics are calculated as follows:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \mathrm{sgn}(x_j - x_i), \tag{3}$$

where, x_j is the sequential data value, n is the length of the data set, and sgn is calculated as follows:

$$\mathrm{sgn}(x_j - x_i) = \begin{cases} 1 & \text{if } x_j > x_i, \\ 0 & \text{if } x_j = x_i, \\ -1 & \text{if } x_j < x_i, \end{cases} \tag{4}$$

According to Mann and Kendall, when $n \geqslant 8$, the test statistics S is normally distributed with the mean and variance as follows:

$$E(S) = 0, \tag{5}$$

$$VAR(S) = [n(n-1)(2n+5) - \sum_{i=1}^{m} t_i(t_i - 1)(2t_i + 5)]/18, \tag{6}$$

where t_i represents the number of ties for the ith value and m represents the number of tied data. The standardized test statistic Z is calculated using the following equation:

$$Z = \begin{cases} (S-1)/\sqrt{V(S)} & S > 0, \\ 0 & S = 0, \\ (S+1)/\sqrt{V(S)} & S < 0. \end{cases} \tag{7}$$

$|Z\alpha| = 1.65$, 1.96, and 2.58, which correspond to the critical values at the significance level $p = 0.1$, 0.05, and 0.01, respectively. If $|Z| > |Z\alpha|$, the null hypothesis H0 is rejected and $p = 0.05$ and 0.01 are considered in our research.

To analyze the trend of the time-series variable, we used the robust estimator for the amplitude of trend slopes:

$$\text{slope} = \text{Median}(x_j - x_i)/(j - i) \quad (1 \leqslant i < j \leqslant n), \tag{8}$$

where slope is the rate of change of the entire data series x_k ($k = 1,2,3...,n$). If it is positive, the series increases monotonically; otherwise, the series is monotonically decreased. Median represents the function that takes the median value.

3.3 Identification of ecological sustainability indicators

Regional ecological assessment is critical for the coordinated development of the regional economy and ecological civilization, as indicated from 1) the carbon perspective, 2) the carbon sustainability index proposed by Rattan Lal (2004), 3) the perspective of carbon efficiency, 4) the carbon eco-efficiency index proposed by Hu et al. (2016), 5) the perspective of environmental development, 6) the environmental deficit and environmental surplus indexes proposed by Fang (2014), 7) the perspective of carbon safety, 8) the carbon emission alerts proposed by Rong et al. (2016), 9) the perspective of carbon emission coupled with population, and 10) the concept of per-capita carbon emission proposed by XU et al. (2006) etc. Based on these previous researches, this paper estimates the ecological sustainability in this region using five indices: 1) carbon sustainability, 2) land-based carbon intensity, 3) income-based carbon intensity, 4) per-capita carbon use, and 5) carbon surplus ratio, coupled with land, economy, and population conditions.

The regional ecological sustainability index is an important index of overall progress toward environmental sustainability. Based on carbon emissions and carbon sequestration in the region, the carbon sustainability index proposed by Rattan Lal (2004) is calculated as

$$C_S = (C_T - C_E)/C_E, \tag{9}$$

where C_S is the sustainability index for carbon; C_T is the amount of carbon uptake characterized by NPP; and C_E represents carbon emission. When C_S is 0, the system is "carbon balanced." The higher the value of C_S, the more the carbon taken up by the system, the less the impact of greenhouse gas emissions on the environment, resulting in increased sustainability.

The land-based carbon intensity refers to the carbon footprint per unit of land area, calculated as (Hu et al., 2016):

$$\beta = C_E/H \times 10^{-8}, \tag{10}$$

where, β is the land-based carbon intensity ((T·C)/ha) and H represents the land area (km^2). The higher the value of β, the greater the carbon footprint produced by the system using the unit land area.

The income-based carbon intensity refers to the cost of carbon per dollar of income and is used to evaluate the carbon benefits of the ecosystem. The estimation formula is as follows (Hu et al., 2016):

$$L = C_E/I, \tag{11}$$

where L is the income-based carbon intensity ((G·C)/yuan) and I represents the GDP (yuan). A higher L indicates a higher carbon footprint per unit of economic gain.

Per-capita carbon used as the amount of carbon consumed per person indicates the societal demand for carbon. The estimation formula is as follows (Guoquan et al., 2006):

$$Q = C_E/p \times 10^{-6}, \tag{12}$$

where Q is per-capita carbon use ($(T \cdot C)$/person) and p is the population. The higher the value of Q, the higher the amount of carbon consumed and the greater the pressure on the ecosystem.

The carbon surplus ratio represents the percentage of land area with a carbon surplus in the total area of the region, with 100 as the limit. A carbon footprint above 100 indicates the carbon footprint emissions exceed 100 ha/km^2; in this case, the region is deemed in carbon deficit. Otherwise, the region has a carbon surplus. The carbon surplus ratio is calculated as (Fang, 2014):

$$A = C_S/H, \tag{13}$$

where A is the carbon surplus ratio, C_S the land area with a carbon surplus (km^2), and H the total area of the region (km^2).

4 Results and analysis

4.1 Spatial pattern characteristics in carbon footprint

Spatial analysis is important for identifying the spatial elements and hotspots. This research investigates the spatial patterns of carbon footprint from 2005 to 2017 in Fujian Province and identifies the hotspots. In view of these long-term time series measurements, the carbon footprint data for 2005, 2011, and 2017 are used in the analysis of spatial patterns. At the same time, we calculated the average carbon footprint of terrestrial ecosystems in nine prefecture-level regions in Fujian Province from 2005 to 2017, based on the spatial map.

In 2005, the carbon footprint of Fujian's terrestrial ecosystems was low (Fig. 2(a)). There was a noticeable difference, however, between the carbon footprint levels in the eastern and western areas of the province. Levels were less than 40 in the west; whereas the coastal areas exhibited much higher levels. In particular, economically developed areas, such as Fuzhou, Quanzhou, and Xiamen showed higher levels above 100 ha, indicating a carbon deficit in the coastal areas. Further analysis revealed that Fujian had 112078 km^2 of land in carbon surplus with 11922 km^2 in carbon deficit, showing a carbon surplus ratio above 90%.

In 2011, the overall carbon footprint of Fujian was higher than that in 2005, showing a difference between the north and the south (Fig. 2(b)). The difference between the carbon footprint levels in the eastern and western areas of the province increased in 2011, with the overall value lower than 60 ha in the west and remarkably exceeding 80 ha in the east. Fujian had 103234 km^2 of land in carbon surplus and 20766 km^2 of land in carbon deficit, with a carbon surplus ratio of 83.25%, marking a decrease from that in 2005. Most of the areas in carbon deficit were near cities.

In 2017, significant spatial characteristics were expressed as the difference between the east and the west (Fig. 2(c)). The carbon footprint of the western region has declined compared to 2011. However, highly-developed areas such as Fuzhou, Quanzhou, and Xiamen were in extreme carbon deficit with levels above 200 ha, suggesting high carbon balance pressures. Statistics show that Fujian's terrestrial ecosystems had 102925 km^2 of land in carbon surplus and 21075 km^2 of land in carbon deficit, with a carbon surplus ratio of 80.0%, equivalent to the 2011 level.

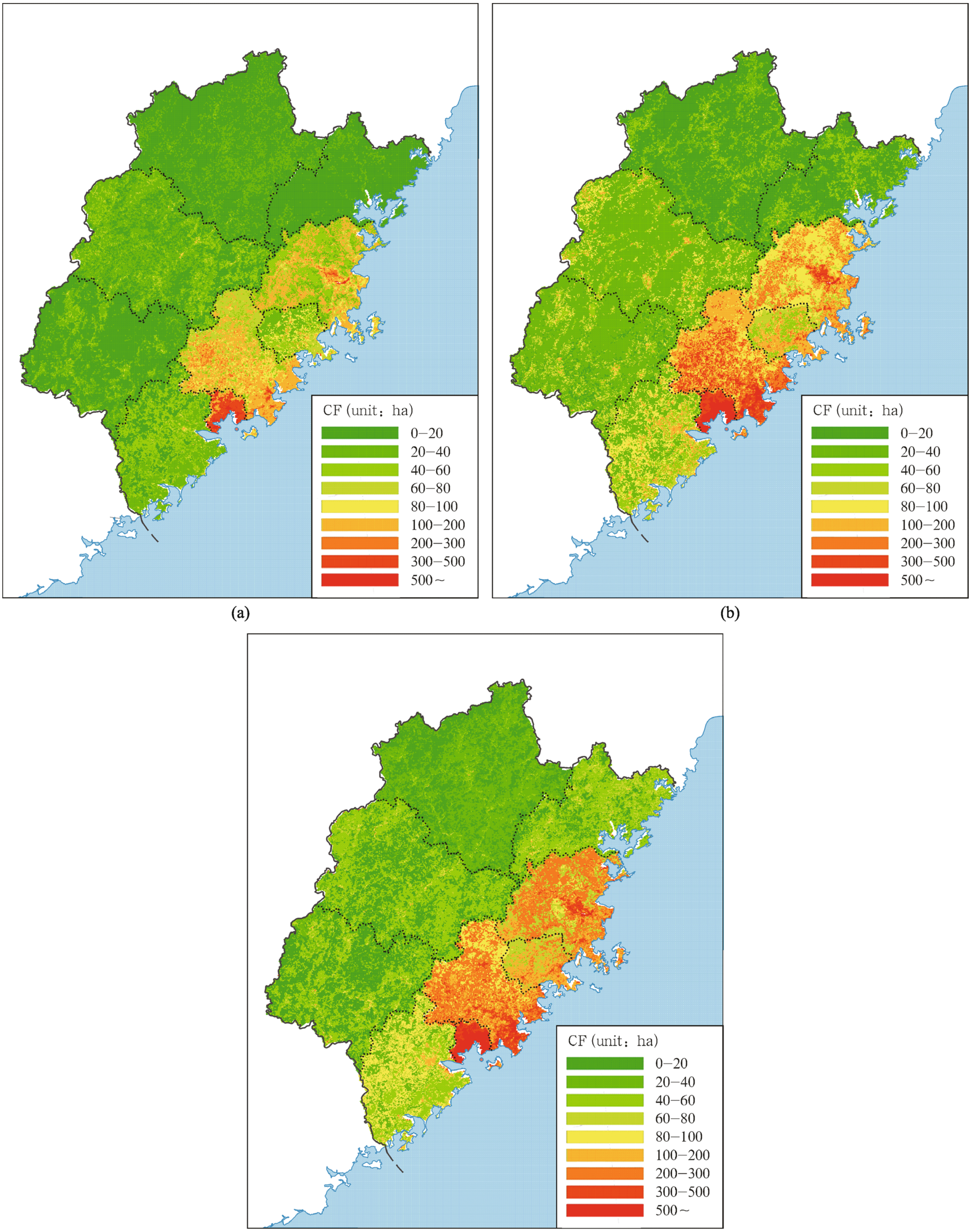
The carbon footprint of terrestrial ecosystems among the nine prefecture-level regions in Fujian Province is quite different (Fig. 3). Among them, the average carbon footprint of Xiamen Region in 2005–2017 was the highest, nearly 800, followed by Quanzhou, Fuzhou, and Putian, respectively. The developed economy and the small area of productive land may be one of the reasons for the high carbon footprint in Xiamen. The regions with a lower average footprint are Ningde, Nanping, Longyan, Sanming, and Zhangzhou. The analysis found that regions with a high carbon footprint are primarily located on the coast and with greater economic development, while regions with lower levels are located in the western region of Fujian Province, with relatively high forest coverage.

4.2 Trend variation characteristics in carbon footprint

Spatial trend analysis is an important method for measuring the intensity or magnitude of changes in spatial environmental elements. This research analyzes the spatial trends of Fujian's terrestrial ecosystems from 2005 to 2017 to identify areas with the most significant or remarkable changes. At the same time, in order to explore the trend of carbon footprint in Fujian Province since the 21st century, we measured the average carbon footprint from 2005–2017.

The interannual variations in the carbon footprint of Fujian's terrestrial ecosystems during 2005–2017 were complex and varied widely between regions (Fig. 4). There was an upward trend in Fujian Province, yet a decline was observed in western areas, with a high degree of fragmentation. As shown in spatial distribution maps of carbon footprint trends, the increase observed in western areas was less than 4 ha per year (less than 3 ha in the southwest); however, in most eastern areas, there was an annual increase of more than 4 ha. The value observed in Fujian, Quanzhou was above 10 ha, with a variance by as much as 20 ha in the annual carbon footprint in the Xiamen area. The significance map of interannual variations in the carbon footprint of Fujian indicates that the changes in carbon footprint in the northeast were extremely significant ($p < 0.01$) and less significant in the southwest. For Fuzhou, Quanzhou, and Xiamen, where carbon levels showed the most remarkable increases, interannual variations were extreme, indicating ecological deterioration at a significant scale.

There was a steady increase in the carbon footprint of terrestrial ecosystems in Fujian Province from 2005–2017 (Fig. 5). In 2005, the average level was less than 50,



(a) (b)

(c)

Fig. 2 Spatial patterns of carbon footprint in Fujian's terrestrial ecosystems. (a): 2005; (b): 2011; (c): 2017.

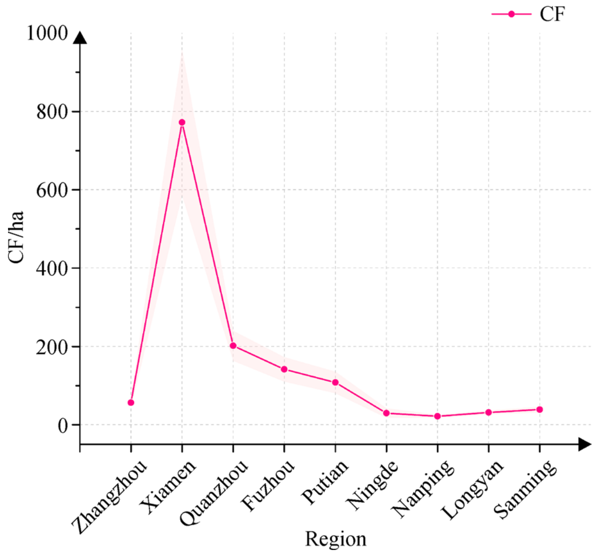


Fig. 3 Fujian city terrestrial ecosystem carbon footprint line chart. Note: uncertainty bounds (shaded area) reflected the anomalous range of the mean carbon footprint of terrestrial ecosystems in nine prefecture-level regions in Fujian Province.

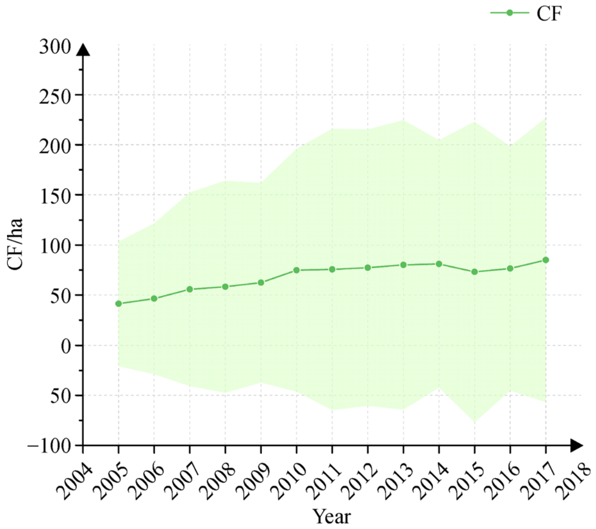


Fig. 5 Fujian Province terrestrial ecosystem carbon footprint annual average line chart. Note: uncertainty bounds (shaded area) reflected the anomalous range of carbon footprint mean values for the terrestrial ecosystems from 2005 to 2017.

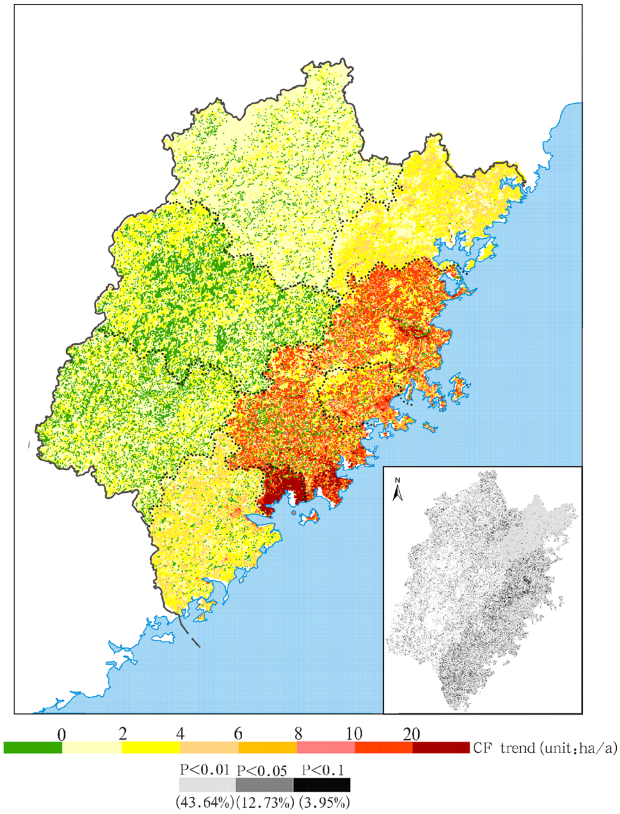


Fig. 4 Trends in carbon footprint of Fujian's terrestrial ecosystems during 2005-2017. Note: The sub graph is the significance level of the trend change, in which the light gray part is extremely significant ($p < 0.01$), the gray part is highly significant ($p < 0.05$), and the black part is significant ($p < 0.1$). The remainder did not pass the significance test.

whereas in 2017, levels reached a high of 85. The average annual growth rate was approximately 6.2%.

4.3 Index-based sustainability

Based on the analysis of spatial patterns and trends, this research examines ecological changes over a 13-year period, using the five ecological evaluation indexes (Table 1).

Sustainability index, land-based carbon intensity, income-based carbon intensity, per-capita carbon use, and carbon surplus ratios are shown in Table 1. Analysis shows a decline in carbon sustainability during 2005–2017 on a year-over-year basis. This value fell below 1 in 2010 and further decreased to 0.15 in 2017. Although the 2017 Fujian Sustainability Index was still above 0, it has fallen sharply compared to the 2005 level. Along with economic development and urbanization, the land-based carbon intensity increased from 3.24 (T·C)/ha in 2005 to 8.50 (T·C)/ha in 2017, with an annual growth rate of 8.37%. The lower the income-based carbon intensity, the lower the carbon footprint per unit of economic gain. Fujian's income-based carbon intensity decreased on a year-over-year basis to 32.06 (G·C)/yuan in 2017. Further analysis indicates a yearly increase in both carbon emissions and GDP values during 2005–2017, with the rise in carbon emissions slower than that in GDP, as shown in the annual decrease in carbon footprint per unit of economic gain. The uneconomical and unsustainable development model of Fujian Province led to unsustainable ecological results. The higher the per-capita carbon use, the higher the demand for carbon. Chen et al. (2015) categorized per-capita carbon use as low, moderate, high,

Table 1 Ecological sustainability indexes of Fujian Province during 2005–2017

Year	Sustainability index	Land-based carbon intensity /($T\cdot C\cdot ha^{-1}$)	Income carbon intensity /($G\cdot C\cdot yuan^{-1}$)	Per-capita carbon use /($T\cdot P^{-1}$)	Carbon surplus ratio /%
2005	2.12	3.24	59.93	1.11	90.39
2006	1.87	3.65	58.63	1.24	89.21
2007	1.36	4.29	57.60	1.45	87.57
2008	1.24	4.91	56.20	1.65	87.08
2009	1.08	5.24	52.42	1.75	85.69
2010	0.68	6.09	51.08	2.00	82.69
2011	0.76	6.12	42.08	2.00	83.25
2012	0.65	6.55	40.34	2.12	82.20
2013	0.60	7.01	39.03	2.25	80.78
2014	0.24	7.77	39.24	2.48	81.43
2015	0.39	7.48	35.01	2.36	83.84
2016	0.27	7.72	33.00	2.42	83.68
2017	0.15	8.50	32.06	2.64	83.00

and very high. This value consistently increased from 1.11 (T·C)/person in 2005 to 2.64 (T·C)/person in 2017, or from low to moderate, with an annual growth rate of 7.49%, which was much higher than both the population growth and GDP growth.

Carbon surplus ratio refers to the percentage of land area with the capacity to absorb local carbon emissions in the total area of the region. In 2005, Fujian's carbon surplus ratio was as high as 90.39%. However, with a rapid increase in population, this value has decreased annually, dropping to 80.78% in 2013. Subsequently, the carbon surplus ratio increased to over 83% by 2017. Taking into account previous research on sustainable development from the perspective of the ecological footprint, Fujian is still at a sustainable level as compared with the ecological footprint at a global scale (Wackernagel et al., 1999). Even so, ecological conditions continue to deteriorate. Although Fujian's carbon surplus ratio is at a relatively high level, in some economically developed areas such as Fuzhou, Quanzhou, and Xiamen, the amount of carbon dioxide emitted was far greater than the amount absorbed, posing a serious threat to the carbon balance of neighboring areas. In urban areas, ecosystems were faced with tough challenges.

5 Discussion

Carbon footprint is one of the important indicators for characterizing regional, ecological sustainability. Accurate assessments of the spatial hotspots of carbon footprint and trends are critical to achieve sustainable regional development.

In this study, the carbon footprint in Fujian Province during 2005–2017 was calculated by combining the relevant statistical data with the NPP simulated by the improved CASA model. The results were characterized from the grid scale. The carbon footprint spatial pattern and spatial change trend map with spatial resolution of 1 km × 1 km can identify the hotspots affected by severe change at micro levels. At the same time, economic, population, and land data are combined to construct indicators for evaluating regional, ecological sustainability.

We find that the carbon footprint of economically developed regions is high, with low levels observed in areas with high forest coverage. It is coincident, based on conclusions from other scholars, that the provinces with a large carbon footprint have higher levels of economic development (Shi et al., 2012). The analysis of the carbon intensity of earnings is consistent with a previous conclusion that Fujian's GDP growth rate is much faster than that of the carbon footprint (Xiu and Chen, 2015). At the same time, Fujian Province has increased its ecological pressure in recent years and is developing in an unsustainable direction as verified by some scholars (Ding and Yang, 2017).

The aim of this paper is to reveal the spatial distribution pattern of the carbon footprint in Fujian Province, explore its spatial hotspots and changing laws, and provide a reference for the sustainable development of the regional system of human and land relations. The method proposed in this study is based on the grid-scale method to estimate the regional carbon footprint with good operability and simulation results. This method is suitable for measuring regional carbon footprint at a macro level, to include county to national to global levels. However, the mechanism of carbon footprint changes is currently unclear. In the future, it will be necessary to reveal how different land use types affect the change of the carbon footprint, which will help people to rationally formulate corresponding policies to achieve sustainable development in both human populations and natural ecology.

6 Conclusions

Carbon footprint, as an important energy parameter and ecological indicator, reflects the changes in the ecological environment and the results of regional carbon budget management. Using an improved CASA model for NPP simulation and the IPCC methodologies for estimation of carbon emissions, this research focuses on spatial patterns, interannual variations, and ecological index-based analysis of the carbon footprint in Fujian Province during 2005–2017. This research draws the following conclusions.

In terms of spatial patterns, the carbon footprint in eastern regions was higher than in the western regions. Nanping, Sanming, and Longyan had a lower carbon footprint, while Fuzhou, Quanzhou, and Xiamen, with greater economic development, showed higher carbon levels.

There was an uptrend in the carbon footprint during this time period; slower in the western regions and faster in the east. Fuzhou, Quanzhou, and Xiamen had the highest rate of growth. Ecosystem sustainability is faced with tough challenges in these areas.

The assessment of five ecological indexes shows an ecologically unsustainable trend during this 13-year period. As a whole, Fujian's economic development is more about the rate of growth than improved quality of life, resulting in the lack of ecological sustainability. To move toward sustainable development, there must be an increase in industrial restructuring efforts, improvement in the quality of economic growth, and construction plans developed for an ecological civilization demonstration zone in Fujian Province.

These conclusions allow us to understand the variations in carbon footprint during the first 13 years of the 21st century at the macro level and can provide support for a grid-based model for estimating carbon footprint of the terrestrial ecosystems.

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