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Analysis of the Gravity Movement and Decoupling State of China's CO_2 Emission Embodied in Fixed Capital Formation

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Abstract: Investment is an essential engine of economic growth and a major source of China's CO_2 emission. It is therefore crucial to explore the gravity movement and decoupling state of China's CO_2 emission embodied in fixed capital formation (FCF). This study aims to estimate China's CO_2 emissions embodied in various categories of FCF by using input–output tables. The gravity model and Shapley decomposition method are used to explore the gravity movement and regional contributions for China's CO_2 emissions embodied in FCF. Then, the Tapio decoupling model and logarithmic mean Divisia index (LMDI) method are combined to uncover the decoupling relationship between CO_2 emissions and economic growth embodied in FCF and the corresponding driving factors. The results show that China's CO_2 emissions embodied in FCF experienced a rapid increase during 2002–2012 and remained almost stable during 2012–2017. The gravity center for CO_2 emissions embodied in FCF moved toward northwest during 2002–2015, with the northwestern region and middle Yellow River region being the main engine regions. The relations between CO_2 emissions and added values embodied in various categories of FCF were weak decoupling during 2002–2017. Investment scale was the major factor inhibiting the decoupling, while embodied energy intensity was the major factor promoting the decoupling. Finally, several policy recommendations are proposed based on these findings.

Keywords: CO_2 emissions; fixed capital formation; gravity movement; decoupling state; China

1. Introduction

Climate change has become a global challenge during the last couple of decades. In order to address this issue, energy saving and emission reduction have been promoted globally [1]. Carbon dioxide

(CO_2) is one of the main greenhouse gases and occupies the largest part of the total greenhouse gas emission [2]. China has surpassed the United States as the world's largest CO_2 emitter since 2006 [3]. According to the International Energy Agency [4], China's CO_2 emissions increased from 3552 million tons (Mt) in 2002 to 9257 Mt in 2017, with an average annual growth rate of 6.6% [4]. China has initiated several mitigation policies and set up its own emission-reduction targets. In particular, China's rapid development focuses on supporting various manufacturing sectors, which is based upon consuming a large amount of fossil fuels. Therefore, it is critical to investigate the relationship between engines of economic growth and corresponding CO_2 emissions so that feasible and effective emission-reduction measures can be proposed.

Investment, consumption, and import–export trade are regarded as three engines of economic growth [5]. China's economic growth has heavily relied on investment for decades. The share of investment in gross domestic production (GDP) in China was maintained at 40–50% over 2002–2017 [6]. After the 2008 financial crisis, the Chinese government implemented special investment policies to rescue the market, such as the Four-Trillion RMB (Chinese currency, 1USD = 6.6 RMB) Investment Plan. Most investment funds were used to build up infrastructure and improve the life quality of the Chinese citizens. As a result, the accumulated capital, including newly formed capital and stock, provided the production capacities of goods and services in various economic sectors [7]. In terms of statistical indicators, the gross capital formation is comprised of fixed capital (excluding those disposed) and inventory change, namely fixed capital formation (FCF) and inventory increase [8]. FCF accounted for the vast majority, while inventory occupied less than 2% in China's gross capital formation over the past years [9,10]. Considering that the negative value of inventory implies the CO_2 emissions caused by capital formation in the previous period, and given the important role of FCF in gross capital formation, this study mainly focuses on the effect of FCF on the CO_2 emissions.

Academically, a number of studies have examined the CO_2 emissions embodied in China's various economic activities from the final demand-based perspective. Several studies pay attention to the trend of embodied CO_2 emission caused by household consumption. For instance, Zhang et al. [11] explored the indirect energy consumption and CO_2 emission from household consumption using the input–output method, and uncovered the influencing factors of the indirect CO_2 emission. Wu et al. [12] calculated the direct and indirect CO_2 emissions from household consumption at the provincial level in China and explored the interprovincial transfer of such CO_2 emissions. Similar studies have been performed by Wang et al. [13], Wiedenhofer et al. [14], and Li et al. [15]. Other studies pay attention to CO_2 emission embodied in international trade. For instance, Mi et al. [16] explored the patterns and driving forces of China's export-embodied CO_2 emission in the New Normal economy. Wu et al. [17] quantified the potential economic and CO_2 emission impacts of export restructuring under various export structure patterns and climate policies scenarios. Similar studies have also been performed by Liu et al. [18], Xu et al. [19], and Huang et al. [20]. In addition, several studies pay attention to CO_2 emission induced by investment, although studies on embodied CO_2 emissions in FCF are less sufficient. For instance, Li et al. [21] calculated China's provincial CO_2 emissions from investment demand and interprovincial transfer of CO_2 emission caused by investment demand. Gao et al. [8] measured China's CO_2 emissions embodied in FCF from 2007 to 2017. However, these existing studies do not investigate the CO_2 emissions driven by various categories of fixed capital formation in China. Syngros et al. [22] investigated the embodied CO_2 emissions in building construction and pointed out that this process constitutes a large part of global CO_2 emissions. In addition to construction, there are several other types of fixed capital formation which are also worth studying. Besides, in order to achieve the national and regional CO_2 emission reduction targets, it is critical to explore the dynamic variation trace of the gravity center of CO_2 emissions embodied in FCF, as well as the decoupling state between CO_2 emissions embodied in FCF and economic growth embodied in FCF.

To fill the above research gaps, this study aims to estimate the CO_2 emissions embodied in various sub-categories of FCF from economic sectors' perspectives in China's 30 provinces. FCF can be divided into tangible capital formation and intangible capital formation. Grouped by composition of funds, tangible capital formation can be divided into construction and installation, purchase of equipment and instruments, and others. Grouped by type of construction, tangible capital formation can be divided into new construction, expansion, and reconstruction and technical transformation. These kinds of FCF and the corresponding embodied CO_2 emissions in the years 2002, 2007, 2012, 2015, and 2017 will be accounted by using the input–output method. Then, the gravity theory will be applied to explore the gravity movement of CO_2 emissions embodied in FCF among different Chinese provinces during 2002–2015, and the Shapley decomposition method will be used to uncover regional contributions to the movement of the gravity center of CO_2 emissions embodied in FCF. In addition, the Tapio decoupling method and the logarithmic mean Divisia index (LMDI) method are combined to examine the decoupling state between CO_2 emissions embodied in FCF and economic growth embodied in FCF during 2002–2017, and uncover the driving forces of the decoupling relationship in China. Due to data unavailability, this study has limitations in estimating the CO_2 emissions embodied in FCF in different Chinese provinces in the year 2017, and thus is unable to examine the gravity center of CO_2 emissions embodied in FCF in the year 2017. Another limitation is the estimation of added value embodied in FCF in different provinces. The added values and taxation duty of some large companies are counted in such places where they are headquartered (like Shanghai and Beijing), although they may have business operations in many other provinces. This may have a marginal effect on the data accuracy of added value embodied in FCF in Chinese provinces.

The rest of this paper is structured as follows. Section 2 introduces research methods and data. Section 3 presents research results. Finally, Section 4 draws research conclusions and proposes several policy suggestions.

2. Materials and Methods

2.1. Gravity Theory and Shapley Decomposition Method

The gravity theory originally derived from the physical concept proposed by Isaac Newton. It was used to describe the mutual attraction between two objects [23]. Then, Jan Tinbergen introduced the gravity theory into economics research. This theory has been widely applied to study the geographic distributions of research objects in many fields, such as population [24], economic growth [25], land utilization [26], immigration [27], energy consumption [28], and CO_2 emission [29].

In this study, we use the gravity theory to explore the changes in the spatiotemporal centers of gravity for CO_2 emissions embodied in FCF in China. The gravity center of CO_2 emission embodied in FCF in year t is calculated as:

$$X^t = \frac{\sum_{i=1}^{n} M_i^t \times x_i}{\sum_{i=1}^{n} M_i^t} \quad (1)$$

$$Y^t = \frac{\sum_{i=1}^{n} M_i^t \times y_i}{\sum_{i=1}^{n} M_i^t} \quad (2)$$

where (x_i, y_i) represents the coordinate of the ith province, xi and yi respectively represent the longitude and latitude of the ith province, M_i^t represents the attribute value (CO_2 emission embodied in FCF) of the ith province in year t, n represents the total number of provinces, and X^t and Y^t represent the longitude and latitude of the gravity center for the attribute value in year t, respectively. The longitude and latitude coordinates are determined for each province, along with their corresponding attribute values.

Shapley decomposition method is combined with the gravity theory to uncover regional contributions to the gravity movement of CO_2 emissions embodied in FCF in China. To date, three decomposition methods have been developed for exploring the driving forces of gravity movement, including variance decomposition method, differential decomposition method, and Shapley decomposition method. Compared with variance decomposition method and differential decomposition method, Shapley decomposition method can incorporate both direct and indirect regional contributions and is more suitable for the target variable with obvious changes [30]. Moreover, Shapley decomposition method is regarded as a symmetric and perfect decomposition method [31]. Each variable is fully decomposed, and the impacts are completely allocated to each factor with no residuals [32]. Given these advantages, Shapley decomposition method is adopted in this study.

Assume a large region consists of n regions, set $K = \{1, 2, \ldots, k, \ldots, n\}$. The marginal contribution of region k to the gravity movement is defined as:

$$MC_{k,X} = \Delta X(K) - \Delta X(K \backslash \{k\}) \tag{3}$$

$$MC_{k,Y} = \Delta Y(K) - \Delta Y(K \backslash \{k\}) \tag{4}$$

where ΔX and ΔY represent the changes of longitude and latitude of the gravity center, respectively, and $MC_{k,X}$ and $MC_{k,Y}$ represent the marginal contributions of region k to the changes of longitude and latitude of gravity center, respectively.

Considering the order $\sigma = (\sigma_1, \sigma_2, \ldots, \sigma_n)$ of all regions and assuming region k at the rth position, then there is $\sigma = (\sigma_1, \sigma_2, \ldots, \sigma_{r-1}, \sigma_r = k, \ldots, \sigma_n)$. Defining the set of regions listed before region k as $Pre^k(\sigma) = (\sigma_1, \sigma_2, \ldots, \sigma_{r-1})$, then the marginal contribution of region k to the gravity movement is calculated as:

$$MC_{k,X}(\sigma) = \Delta X(Pre^k(\sigma) \cup \{k\}) - \Delta X(Pre^k(\sigma)) \tag{5}$$

$$MC_{k,Y}(\sigma) = \Delta Y(Pre^k(\sigma) \cup \{k\}) - \Delta Y(Pre^k(\sigma)) \tag{6}$$

To eliminate path dependence, we consider all permutation cases $\Pi(n)$, and then the Shapley contribution of region k to the gravity movement of CO_2 emissions embodied in FCF in China is calculated as:

$$CX_k = \frac{1}{n!} \sum_{\sigma \in \Pi(n)} MC_{k,X}(\sigma) = \frac{1}{n!} \sum_{\sigma \in \Pi(n)} [\Delta X(Pre^k(\sigma) \cup \{k\}) - \Delta X(Pre^k(\sigma))] \tag{7}$$

$$CY_k = \frac{1}{n!} \sum_{\sigma \in \Pi(n)} MC_{k,Y}(\sigma) = \frac{1}{n!} \sum_{\sigma \in \Pi(n)} [\Delta Y(Pre^k(\sigma) \cup \{k\}) - \Delta Y(Pre^k(\sigma))] \tag{8}$$

where CX_k and CY_k represent the Shapley decomposition results of the contributions of region k to the changes of longitude and latitude of the gravity center, respectively.

2.2. Decoupling Decomposition Model

Decoupling theory was introduced to the research field of energy and environment at the beginning of the 2000s [33]. To date, two main decoupling models have been proposed, i.e., the OECD decoupling model and Tapio decoupling model. Compared with the OECD decoupling model, the Tapio decoupling model offers a finer distinction of decoupling states and overcomes the high sensitivity in the choice of benchmark years [34]. Here, we choose the Tapio decoupling model to judge the decoupling state between CO_2 emissions embodied in FCF and added value embodied in FCF. The expression of the Tapio decoupling model is presented as below:

$$\theta = \frac{\Delta BC / BC_{t-1}}{\Delta EV / EV_{t-1}} = \frac{(BC_t - BC_{t-1}) / BC_{t-1}}{(EV_t - EV_{t-1}) / EV_{t-1}} \tag{9}$$

where subscript t refers to the target year, θ refers to the decoupling indicator, BC denotes CO_2 emissions embodied in FCF, and EV denotes added value embodied in FCF. According to the value of θ, the decoupling state can be classified into eight categories, as shown in Figure 1.

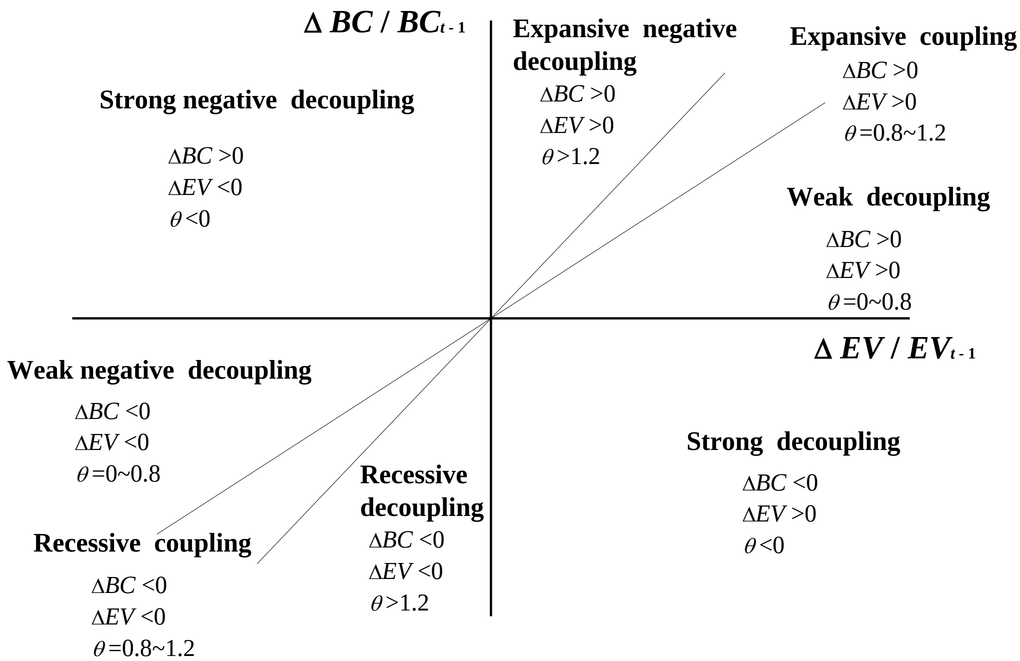

Figure 1. Classifications of decoupling states in the Tapio decoupling model.

Next, we use the LMDI method to decompose the change of CO_2 emissions embodied in FCF (ΔBC) into several drivers. The LMDI method has been recognized as the most popular method for the decomposition of energy consumption and environmental emissions. Based on the Kaya identity, CO_2 emission embodied in FCF can be disaggregated into the following factors:

$$BC = \sum_{r=1}^{s} BC_r = \sum_{r=1}^{s} \frac{BC_r}{BE_r} \times \frac{BE_r}{EV_r} \times \frac{EV_r}{I_r} \times I_r = \sum_{r=1}^{s} T_r \times S_r \times X_r \times I_r \tag{10}$$

where r refers to economic sectors, s refers to the total number of economic sectors, BE denotes energy consumption embodied in FCF, I denotes the amount of FCF, T denotes the embodied carbon intensity, S denotes the embodied energy intensity, and X denotes the embodied investment efficiency.

According to the rationale of LMDI, the change of CO_2 emissions embodied in FCF during the period $[t-1, t]$ can be decomposed into the following form:

$$\Delta BC = BC_t - BC_{t-1} = \Delta BC_T + \Delta BC_S + \Delta BC_X + \Delta BC_I \tag{11}$$

The determinants on the right hand of Equation (11) are calculated as follows:

$$\Delta BC_T = \sum_{i=1}^{n} \frac{BC_{i,t} - BC_{i,t-1}}{\ln BC_{i,t} - \ln BC_{i,t-1}} \ln(T_{i,t}/T_{i,t-1}) \tag{12}$$

$$\Delta BC_S = \sum_{i=1}^{n} \frac{BC_{i,t} - BC_{i,t-1}}{\ln BC_{i,t} - \ln BC_{i,t-1}} \ln(S_{i,t}/S_{i,t-1}) \tag{13}$$

$$\Delta BC_X = \sum_{i=1}^{n} \frac{BC_{i,t} - BC_{i,t-1}}{\ln BC_{i,t} - \ln BC_{i,t-1}} \ln(X_{i,t}/X_{i,t-1}) \tag{14}$$

$$\Delta BC_I = \sum_{i=1}^{n} \frac{BC_{i,t} - BC_{i,t-1}}{\ln BC_{i,t} - \ln BC_{i,t-1}} \ln(I_{i,t}/I_{i,t-1}) \tag{15}$$

Four effects of the changes of CO_2 emission embodied in FCF are entitled as embodied carbon intensity effect (ΔBC_T), embodied energy intensity effect (ΔBC_S), embodied investment efficiency effect (ΔBC_X), and investment scale effect (ΔBC_I).

Then, Equation (9) can be extended into the following decomposition form:

$$\begin{aligned}\theta &= \frac{\Delta BC/BC_{t-1}}{\Delta EV/EV_{t-1}} \\ &= \frac{\left(\Delta BC_T + \Delta BC_S + \Delta BC_X + \Delta BC_I\right)/BC_{t-1}}{\Delta EV/EV_{t-1}} \\ &= \frac{\Delta BC_T/BC_{t-1}}{\Delta EV/EV_{t-1}} + \frac{\Delta BC_S/BC_{t-1}}{\Delta EV/EV_{t-1}} + \frac{\Delta BC_X/BC_{t-1}}{\Delta EV/EV_{t-1}} + \frac{\Delta BC_I/BC_{t-1}}{\Delta EV/EV_{t-1}} \\ &= \theta_T + \theta_S + \theta_X + \theta_I\end{aligned} \quad (16)$$

Based on Equation (16), there are four decoupling sub-indicators ($\theta_{sub} = \theta_T, \theta_S, \theta_X, \theta_I$). Table 1 illustrates the classifications of effects from decoupling sub-indicators [35].

Table 1. Classifications of effects from decoupling sub-indicators.

ΔEV	θ_{sub}	Effects
$\Delta EV > 0$	$\theta_{sub} > 0$	Negative effect
	$\theta_{sub} < 0$	Positive effect
$\Delta EV < 0$	$\theta_{sub} > 0$	Positive effect
	$\theta_{sub} < 0$	Negative effect

2.3. Data Sources

Based on the data availability, we collect the Chinese input–output tables for the years 2002, 2007, 2012, 2015, and 2017. For the years 2002, 2007, 2012, and 2015, there are Multi-Regional Input-Output (MRIO) tables, of which the table for the year 2002 is derived from Li et al. [36], the tables for the years 2007 and 2012 are derived from Institute of Geographic Science and Natural Resources Research, CAS [9,10], and the table for 2015 is derived from the Carbon Dioxide Information Analysis Center [37]. For the year 2017, only the Single Region Input-Output (SRIO) table was issued, and thus we collect it from the National Bureau of Statistics of China [38]. The amounts of gross FCF are derived from the input–output tables. As for the amounts of sub-categories of FCF, the data are estimated according to the constitutions of fixed asset investment. The data for CO_2 emission, energy consumption, and added value embodied in FCF are estimated according to the process of MRIO and SRIO models in Gao et al. [8]. The data for FCF and added value embodied in FCF are deflated at 2010 prices.

Due to the data availability, we exclude Tibet, Hong Kong, Macao, and Taiwan in our analysis. According to the report by the Development Research Center of the State Council of China [39], China's 30 provinces could be classified into eight regions, as shown in Table A1. Since sectoral classifications of CO_2 emission inventory vary in MRIO and SRIO tables, we aggregated all the sectors into eight categories according to the Standard of Industrial Classification for National Economic Activities (GB/T 4754-2011) [38], including: Agriculture (ARG), mining and quarrying industry (MQI), manufacturing industry (MFI), electricity, gas, and water production, and supply (EGW), construction (CON), wholesale, retail trade and hotel (WRH), transportation, storage and post (TSP), and other service industries (OTH).

3. Results

3.1. Analysis of CO_2 Emission Embodied in FCF

Figure 2a shows that China's CO_2 emissions embodied in FCF increased from 1.388 billion tons (Bt) in 2002 to 2.431 Bt in 2007, followed by a sharp increase to 4.821 Bt in 2012 and 5.063 Bt in 2015, and finally decreased to 4.823 Bt in 2017. The share of CO_2 emissions embodied in FCF in the total CO_2 emission decreased from 39.5% in 2002 to 35.6% in 2007, followed by the increase to 50.7% in 2012 and

53.0% in 2015, and finally decreased to 48.9% in 2017. Figure 2b shows that among the two types of FCF, the amount of CO_2 emissions embodied in intangible capital formation is much smaller than that embodied in tangible capital formation. The CO_2 emission embodied in intangible capital formation sharply increased from 0.537 million tons (Mt) in 2002 to 33.225 Mt in 2012, and then decreased to 29.883 Mt in 2015, and increased to 48.267 Mt in 2017. The share of CO_2 emissions embodied in intangible capital formation in CO_2 emissions embodied in FCF increased from 0.04% in 2002 to 0.69% in 2012, followed by a decrease to 0.59% in 2015, and finally increased to 1% in 2017. Figure 2c shows that among the CO_2 emissions embodied in tangible capital formation grouped by compositions of funds, construction and installation played an important role, of which the embodied CO_2 emission continuously increased from 0.995 Bt in 2002 to 3.561 Bt in 2017. The CO_2 emissions embodied in the purchase of equipment and instruments is higher than that embodied in others. Both continuously increased over 2002–2012 and then decreased over 2012–2017. The CO_2 emissions embodied in the purchase of equipment and instruments increased from 0.187 Bt in 2002 to 1.020 Bt in 2012, and decreased to 0.935 Bt in 2017. The CO_2 emissions embodied in others increased from 0.205 Bt in 2002 to 0.754 Bt in 2012, and decreased to 0.279 Bt in 2017. Figure 2d shows that among the CO_2 emissions embodied in tangible capital formation grouped by the types of construction, new construction played a major role, and its embodied CO_2 emissions sharply increased from 0.801 Bt in 2002 to 3.656 Bt in 2015, and then decreased to 3.597 Bt in 2017. The CO_2 emissions embodied in expansion increased from 0.41 Bt in 2002 to 0.754 Bt in 2012, and then decreased to 0.531 Bt in 2017. The CO_2 emissions embodied in reconstruction and technical transformation increased from 0.176 Bt in 2002 to 0.739 Bt in 2015, and then decreased to 0.648 Bt in 2017. Obviously, the CO_2 emissions embodied in expansion was surpassed by the CO_2 emissions embodied in reconstruction and technical transformation in 2015 and 2017.

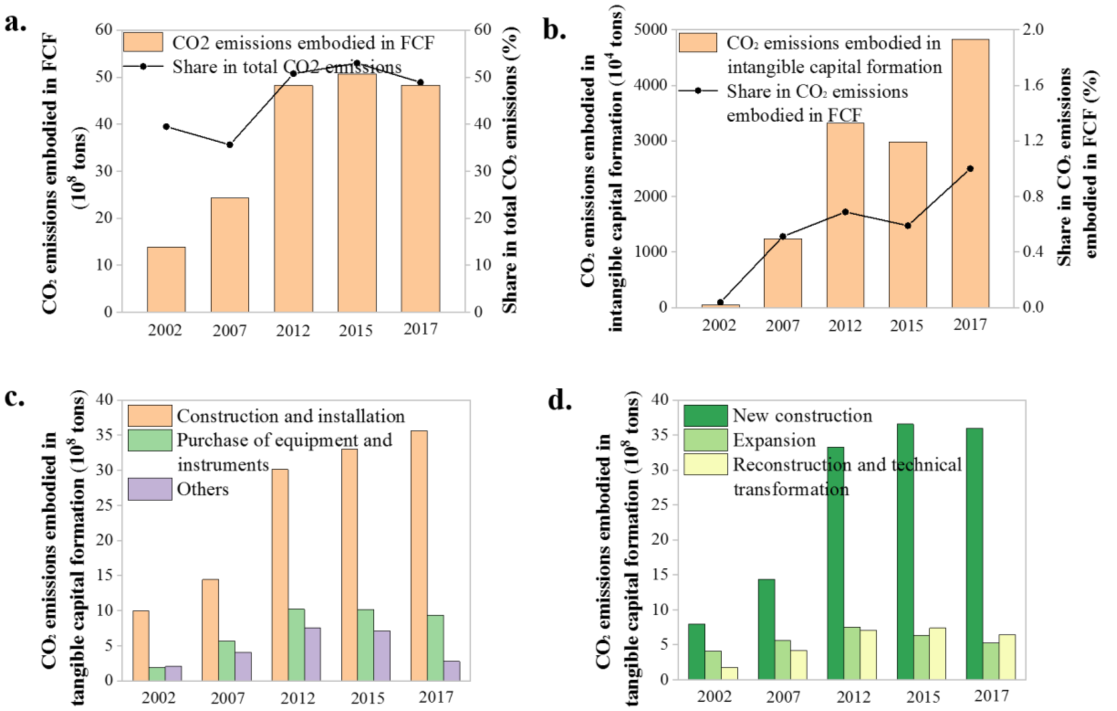

Figure 2. Trends of CO_2 emissions embodied in fixed capital formation (FCF) and its compositions in China.

Figure 3 shows sectoral flows of CO_2 emissions embodied in FCF from the supply side to the demand side. Among these sectors, ARG refers to the sector of farming, forestry, animal husbandry, and fishery products and services; MQI refers to the sector of coal mining and dressing, petroleum and natural gas extraction, metals mining and dressing, and nonmetal and other minerals mining and dressing; MFI refers to the sector of manufacture of foods, textiles, paper products, chemical materials and products, nonmetal mineral products, metal products, ordinary and special equipment, transportation equipment, electric equipment and machinery, etc.; EGW refers to the sector of production and supply of electric power, gas, steam, and hot water; CON refers to the sector of construction; WRH refers to the sector of wholesale, retail trade, catering services, and hotels; TSP refers to the sector of transportation, storage, post, and telecommunication; OTH refers to the sector of other service industries. From a supply-side perspective, MFI and EGW were two major sectors generating CO_2 emissions embodied in FCF, which totally occupied above 85 percent of CO_2 emissions embodied in FCF. The CO_2 emission embodied in MFI was larger than that in EGW in 2002, 2007, and 2017, but the situation was opposite in 2012 and 2015. Among other sectors, TSP and MQI generated relatively more CO_2 emission embodied in FCF, both of which accounted for 3–6% of the total CO_2 emissions embodied in FCF. They were followed by CON (1–2%), WRH (0.8–1.5%) and OTH (0.4–1.1%), while ARG had the least portion of CO_2 emissions embodied in FCF (0.3–0.9%). From a demand-side perspective, CON generated the largest part of CO_2 emissions embodied in FCF (60–80%), and such a proportion increased in recent years. The CO_2 emissions embodied in CON were mainly from MFI and EGW. MFI also generated a large amount of CO_2 emissions embodied in FCF (18–30%), which also mainly resulted from MFI and EGW. Among other sectors, OTH generated relatively more CO_2 emissions embodied in FCF, followed by ARG, TSP, and WRH, while EGW had the least amount of CO_2 emission embodied in FCF.

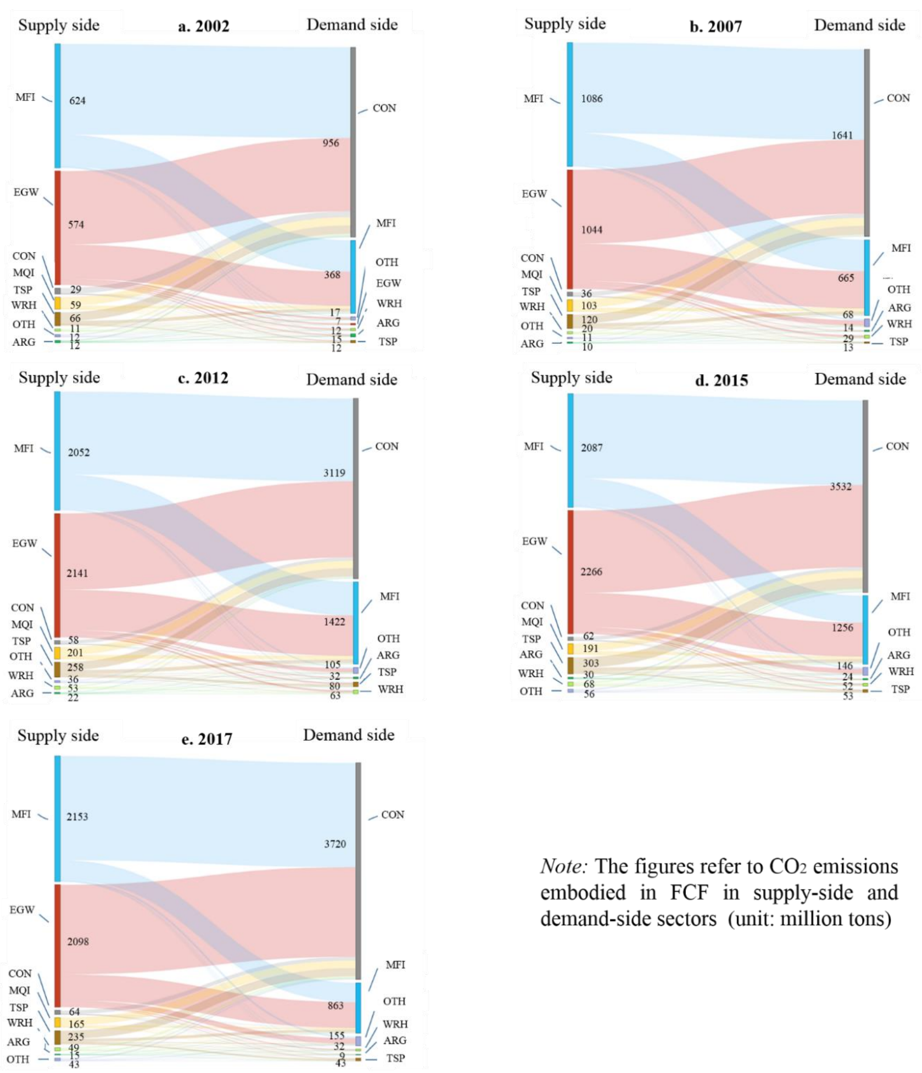

Figure 3. Flows of CO_2 emissions embodied in FCF among different sectors.

Further, Figure 4 shows the compositions of CO_2 emissions embodied in FCF in main sectors from both supply-side and demand-side perspectives. MFI and EGW were two major supply-side sectors, while CON and MFI were two major demand-side sectors generating CO_2 emissions embodied in FCF. From a supply-side perspective, the CO_2 emissions embodied in new construction occupied the largest proportion among three types of FCF grouped by different types of construction in MFI and EGW, which were above 50%, and the proportions gradually increased with time. CO_2 emissions embodied in expansion in MFI and EGW gradually decreased with time. CO_2 emissions embodied in reconstruction and technical transformation in MFI and EGW increased during 2002–2007, but decreased during 2007–2017. From a demand-side perspective, CO_2 emissions embodied in new construction played the most important role among the three types of FCF grouped by compositions of funds, of which the percentage increased with time in CON while presenting a volatile trend with time in MFI. CO_2 emissions embodied in expansion gradually decreased with time in CON, and they decreased from 2002 to 2015, but then increased from 2015 to 2017 in MFI. CO_2 emissions embodied in reconstruction and technical transformation firstly increased and then decreased in CON, while they gradually increased in MFI.

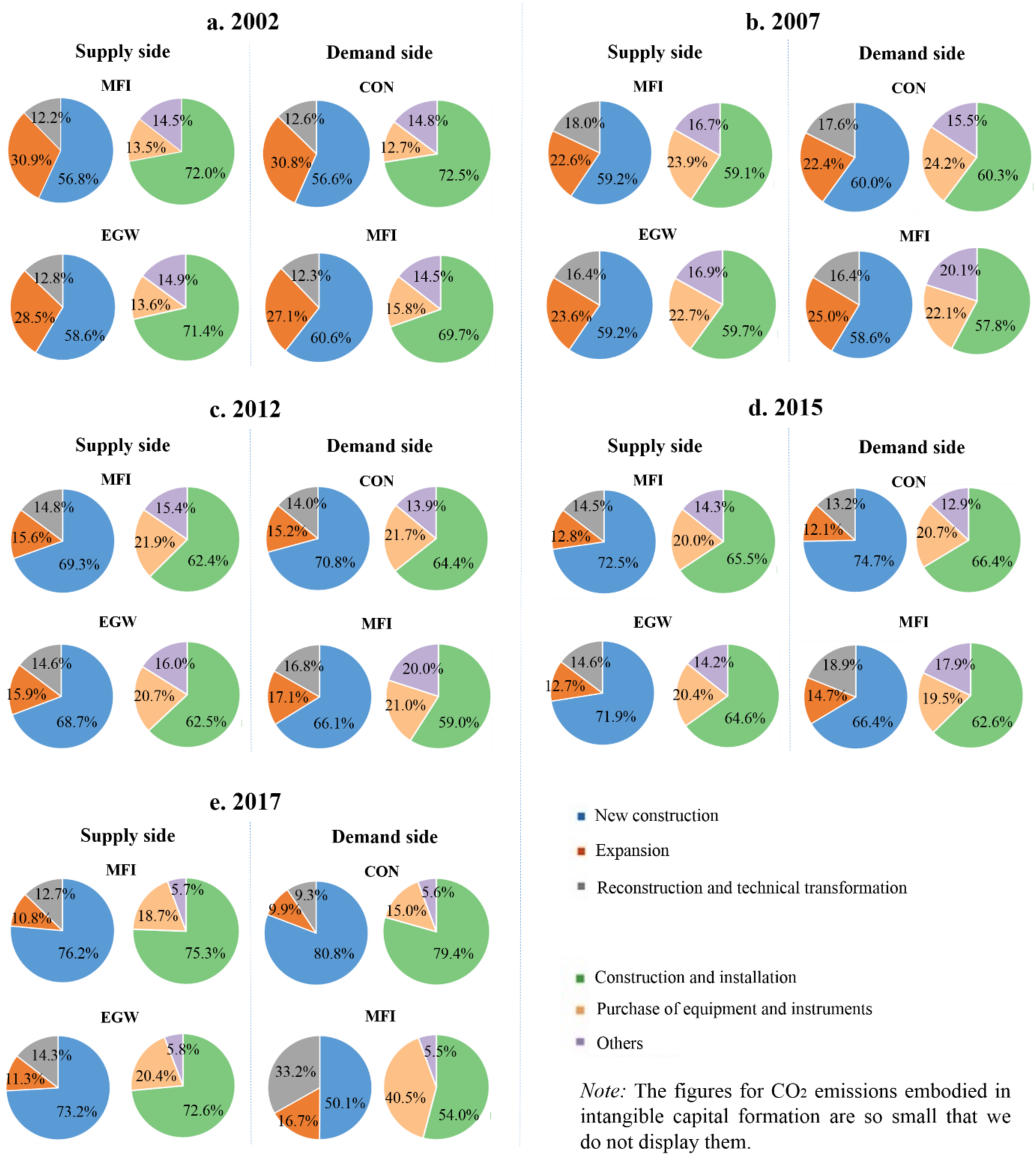

Figure 4. Compositions of CO_2 emissions embodied in FCF in main sectors from both supply-side and demand-side perspectives.

Regarding FCF grouped by compositions of funds, the CO_2 emissions embodied in construction and installation accounted for the largest part in the overall CO_2 emissions embodied in FCF, both in supply-side and demand-side sectors. From a supply-side perspective, the CO_2 emissions embodied in construction and installation decreased during 2002–2007, but increased during 2007–2017 in MFI and EGW. In contrast, the CO_2 emissions embodied in purchase of equipment and instruments and CO_2 emissions embodied in others increased during 2002–2007, but decreased during 2007–2017 in MFI and EGW. From a demand-side perspective, the CO_2 emissions embodied in construction and installation firstly decreased and then increased in CON, while they were more volatile in MFI. The CO_2 emissions embodied in the purchase of equipment and instruments firstly increased and then decreased in CON, while they were more volatile in MFI. The CO_2 emissions embodied in others firstly increased, and then decreased in CON and MFI.

The CO_2 emissions embodied in intangible capital formation were much smaller, and they mainly existed in MFI and EGW from a supply-side perspective, and in OTH from a demand-side perspective. The percentage of the CO_2 emissions embodied in intangible capital formation to the CO_2 emissions embodied in FCF in these sectors increased with time.

3.2. Analysis of Gravity Movement and Its Drivers

Figure 5 shows the movement of gravity centers for China's CO_2 emissions embodied in FCF during 2002–2015. Here, we do not consider the year 2017 since the provincial data of CO_2 emissions embodied in FCF are unable to be obtained due to the lack of an MRIO table for the year 2017. Over 2002–2015, the gravity center for CO_2 emissions embodied in FCF was situated in the region between 113.4 E and 114.5 E, and between 34.1 N and 34.4 N. The gravity center moved from 113.7 E and 34.1 N in 2002 to 114.5 E and 34.2 N in 2007, followed by the movement to 113.6 E and 34.4 N in 2012, and finally it moved to 113.4 E and 34.4 N in 2015. On the whole, the gravity center moved toward the northwest during 2002–2015.

The gravity center for CO_2 emissions embodied in intangible capital formation was situated in the region between 114.3 E and 116.4 E, and between 33.9 N and 40.0 N. The gravity center moved from 116.4 E and 39.9 N in 2002 to 115.6 E and 34.1 N in 2007, followed by the movement to 114.6 E and 34.0 N in 2012, and finally it moved to 114.3 E and 34.2 N in 2015. On the whole, the gravity center moved toward the southwest during 2002–2015. The shift degree of the gravity center of CO_2 emissions embodied in intangible capital formation was larger than that of CO_2 emissions embodied in FCF.

As for tangible capital formation grouped by compositions of funds, the gravity center for CO_2 emission embodied in construction and installation was situated in the region between 113.3 E and 114.7 E, and between 34.2 N and 34.4 N. The gravity center moved from 113.4 E and 34.3 N in 2002 to 114.6 E and 34.2 N in 2007, followed by the movement to 113.5 E and 34.3 N in 2012, and finally it moved to 113.3 E and 34.4 N in 2015. On the whole, the gravity center moved toward the northwest during 2002–2015. The gravity center for CO_2 emissions embodied in the purchase of equipment and instruments was situated in the region between 113.1 E and 114.4 E, and between 34.0 N and 35.0 N. The gravity center moved from 114.3 E and 34.0 N in 2002 to 113.9 E and 34.6 N in 2007, followed by the movement to 113.5 E and 34.9 N in 2012, and finally it moved to 113.2 E and 34.7 N in 2015. On the whole, the gravity center moved toward the northwest during 2002–2015. The gravity center for CO_2 emissions embodied in others was situated in the region between 114.2 E and 114.8 E, and between 33.3 N and 34.0 N. The gravity center moved from 114.5 E and 33.3 N in 2002 to 114.8 E and 33.7 N in 2007, followed by the movement to 114.5 E and 33.8 N in 2012, and finally it moved to 114.2 E and 34.0 N in 2015. On the whole, the gravity center moved toward the northwest during 2002–2015. The shift directions of the gravity centers of CO_2 emissions embodied in intangible capital formation, purchase of equipment and instruments, and others were the same with that of CO_2 emissions embodied in FCF.

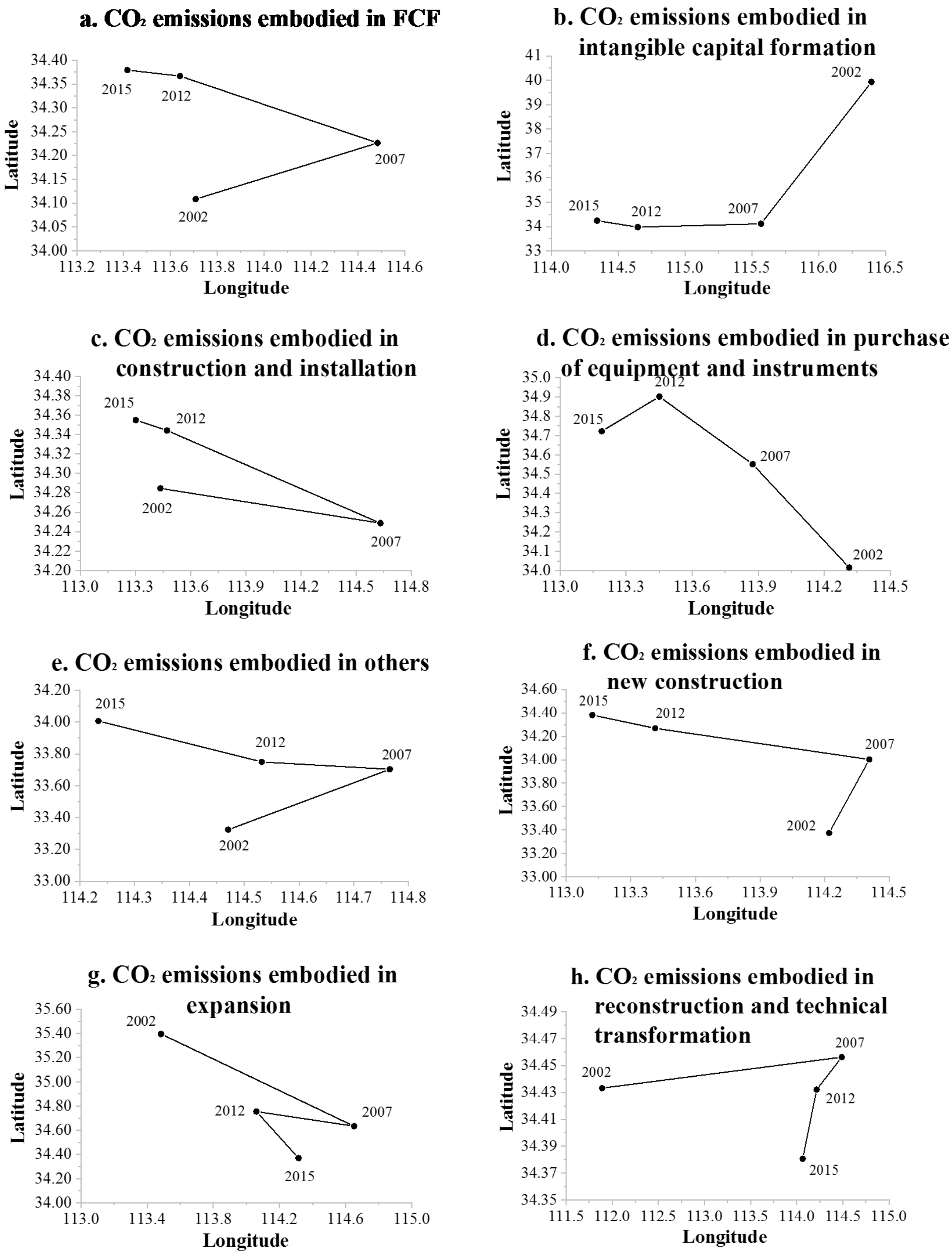

Figure 5. Gravity movements of China's CO_2 emissions embodied in FCF.

As for tangible capital formation grouped by types of construction, the gravity center for CO_2 emissions embodied in new construction was situated in the region between 113.1 E and 114.5 E, and between 33.3 N and 34.5 N. The gravity center moved from 114.2 E and 33.4 N in 2002 to 114.4 E and 34.0 N in 2007, followed by the movement to 113.4 E and 34.3 N in 2012, and finally it moved to 113.1 E and 34.4 N in 2015. On the whole, the gravity center moved toward the northwest during 2002–2015. The gravity center for CO_2 emissions embodied in expansion was situated in the region between 113.5 E and 114.7 E, and between 34.3 N and 35.4 N. The gravity center moved from 113.5 E and 35.4 N in 2002 to 114.7 E and 34.6 N in 2007, followed by the movement to 114.1 E and 34.8 N in 2012, and finally it moved to 114.3 E and 34.4 N in 2015. On the whole, the gravity center moved toward the southeast during 2002–2015. The gravity center for CO_2 emissions embodied in reconstruction and technical transformation was situated in the region between 111.9 E and 114.5 E, and between 34.3 N and 34.5 N. The gravity center moved from 111.9 E and 34.4 N in 2002 to 114.5 E and 34.5 N in 2007, followed by the movement to 114.2 E and 34.4 N in 2012, and finally it moved to 114.1 E and 34.4 N in 2015. On the whole, the gravity center moved toward the southeast during 2002–2015. The shift directions of the gravity centers of CO_2 emissions embodied in expansion as well as reconstruction and technical transformation were contrary to that of CO_2 emissions embodied in FCF.

Figure 6 further shows regional contributions to the movements of gravity centers for China's CO_2 emissions embodied in FCF. The region that drives the gravity movement along the gravity shift direction is named as an engine region, while the region that prevents the gravity movement along the gravity shift direction is called as an inverse engine region. During the period 2002–2015, the northwestern region and middle Yellow River region were the main engine regions for the gravity shift of CO_2 emissions embodied in FCF. Among other regions, the eastern coast and northern coast had essential effects on promoting the gravity shift to the west, while the eastern coast and southern coast exerted significant positive effects on the northward movement of the gravity center. On the contrary, the southwestern region and middle Yangtze River region were inverse engine regions both along the longitude and latitude.

Regarding the gravity movement of CO_2 emissions embodied in intangible capital formation, the southwestern region and southern coast were the main engine regions. Among other regions, the northwestern region had essential effects on promoting the gravity shift to the west, while the northern coast exerted significant positive effects on the southward movement of the gravity center. On the contrary, the northeastern region was the only inverse engine region both along the longitude and latitude.

The roles of eight regions in the movement of the gravity center for CO_2 emissions embodied in construction and installation were similar to those for CO_2 emissions embodied in FCF. With regard to CO_2 emissions embodied in the purchase of equipment and instruments, the northwestern region and southern coast were the top engine regions driving the gravity shift. The eastern coast and southwestern regions were small engines driving the gravity shift to the west. The Middle Yellow River and eastern coast had much smaller effects on the northward movement of the gravity center. On the contrary, the middle Yangtze River was the inverse engine region both along the longitude and latitude. With regard to CO_2 emissions embodied in others, the Middle Yellow River and the northwestern coast were the top engine regions driving the gravity shift. The eastern coast and northeastern region also had important effects on promoting the gravity shift to the west, while the eastern coast and southwestern region exerted significant positive effects on the northward movement of the gravity center. On the contrary, the southern coast was the only inverse engine region both along the longitude and latitude.

As for the gravity movement of CO_2 emissions embodied in new construction, the northwestern region was the major engine region. Among other regions, the eastern coast had essential effects on promoting the gravity shift to the west, while the middle Yellow River and the southern coast exerted significant positive effects on the northward movement of the gravity center. On the contrary, the northern coast and southwestern region were the main inverse engine regions both along the longitude and latitude. With regard to CO_2 emissions embodied in expansion, the southern coast was the top engine region driving the gravity shift. Besides, the eastern coast, and northwestern and southwestern regions, were essential engines driving the gravity shift to the east. With regard to CO_2 emissions embodied in reconstruction and technical transformation, the northwestern region was the top engine region driving the gravity shift. The southwestern region also had important effects on promoting the gravity shift to the east, while the southern coast exerted significant positive effects on the southward movement of the gravity center. On the contrary, the middle Yellow River region was the only inverse engine region both along the longitude and latitude.

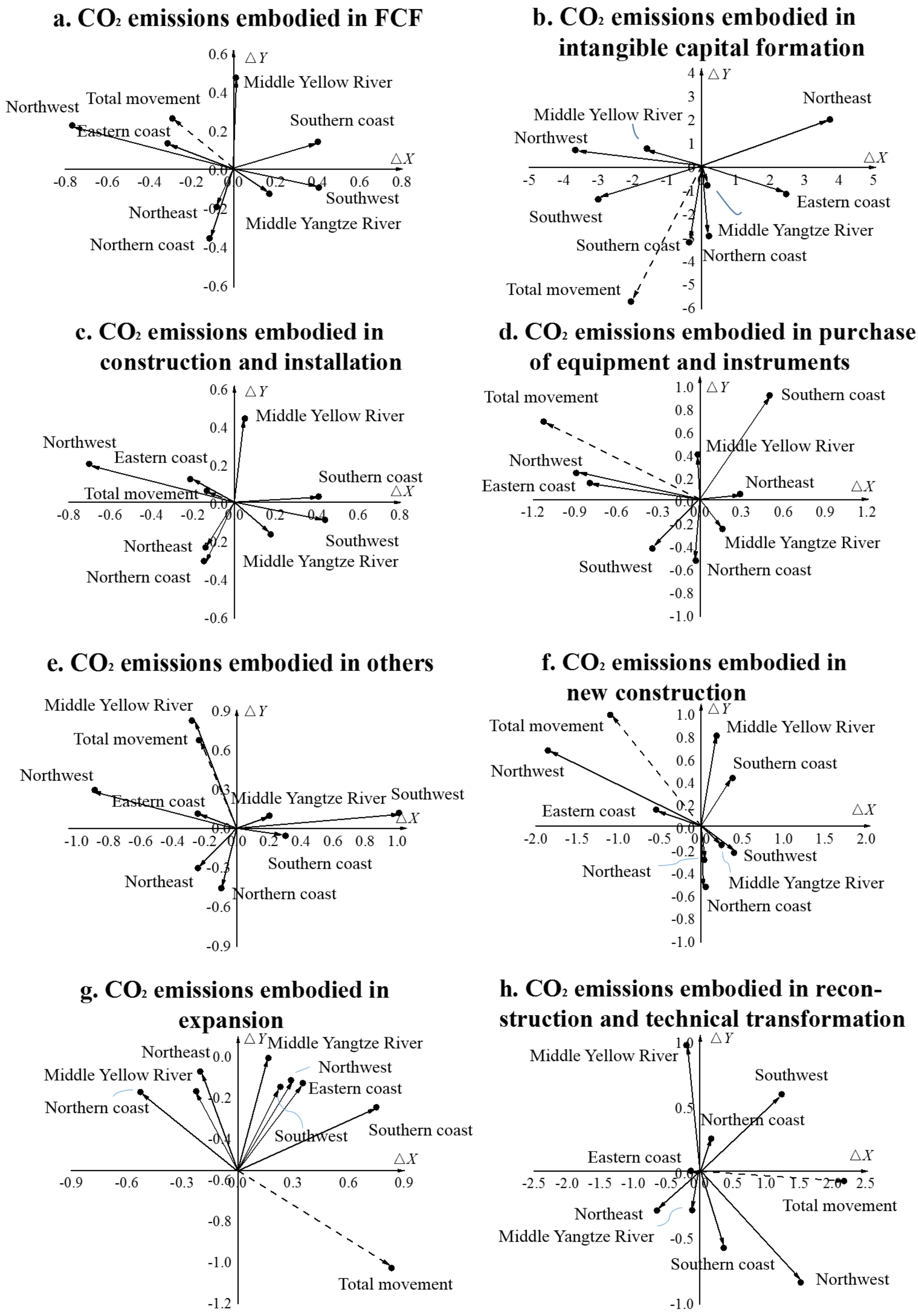

Figure 6. Regional contributions to the gravity movement of China's CO_2 emissions embodied in FCF during 2002–2015.

3.3. Analysis of Decoupling State and Its Drivers

Figure 7 illustrates the decoupling states between CO_2 emission embodied in FCF and added value embodied in FCF in China, as well as the driving forces behind them. It is clear that CO_2 emissions embodied in FCF had weak decoupling relation with added value embodied in FCF during 2002–2007, 2007–2012, 2012–2017, and the entire period of 2002–2017. Investment scale was the largest factor inhibiting the decoupling, while embodied energy intensity was the dominant driver promoting the decoupling during four sub-periods and the entire period. Embodied carbon intensity promoted the decoupling during 2002–2007, 2012–2017, and 2002–2017, while inhibiting the decoupling during 2007–2012. Embodied investment efficiency promoted the decoupling during 2012–2017, while inhibiting the decoupling during other periods. Such a phenomenon mainly resulted from the fact that China's FCF increased by about 7 times, while embodied energy intensity decreased by 55% during 2002–2017, with other factors having small changes.

The CO_2 emissions embodied in intangible capital formation had an expansive coupling relation with the embodied added value during 2002–2007, and then the relation turned to be a weak decoupling during 2007–2012, 2012–2017, and the entire period of 2002–2017. Investment scale and embodied energy intensity were the main driving forces for inhibiting and promoting the decoupling, respectively. Embodied carbon intensity inhibited the decoupling during 2002–2007, while it promoted the decoupling during other periods. Embodied investment efficiency promoted the decoupling during 2007–2012, while it inhibited the decoupling during other periods. As a whole, China's intangible capital formation increased by about 3 times, and embodied investment efficiency increased by 9.6% during 2002–2017, while embodied energy intensity and embodied carbon intensity decreased by 70.6% and 14.1%, respectively.

The CO_2 emissions embodied in construction and installation had weak decoupling relation with the embodied added value during all the periods. During 2002–2017, China's FCF of construction and installation increased by about 7 times, while the embodied energy intensity decreased by 52.8%; embodied carbon intensity decreased by 9.8%, while embodied investment efficiency increased by 6.1%. Therefore, investment scale became the main factor inhibiting the decoupling, while embodied energy intensity played the major role in promoting the decoupling. Two other factors, including embodied carbon intensity and embodied investment efficiency, had marginal effects on the decoupling.

The relation between CO_2 emission and added value embodied in purchase of equipment and instruments was expansive coupling during 2002–2007, weak decoupling during 2007–2012, and strong decoupling during 2012–2017. As a whole, it was a weak decoupling during 2002–2017. Investment scale was the major factor inhibiting the decoupling during all sub-periods and the whole period. Embodied carbon intensity was the main driving force for promoting the decoupling during 2002–2007, while embodied energy intensity was the main driver for promoting the decoupling during 2007–2012, 2012–2017, and the entire period 2002–2017. It is worth mentioning that the CO_2 emission embodied in the purchase of equipment and instruments decreased by 8.4% during 2012–2017, and embodied energy intensity, embodied investment efficiency, and embodied carbon intensity presented strong effects on promoting the emission reduction.

The relation between CO_2 emissions and added value embodied in others was weak decoupling during 2002–2007 and 2007–2012, recessive decoupling during 2012–2017, and weak decoupling during the entire period 2002–2017. In contrast to other sub-periods, the added value embodied in others decreased during 2012–2017. Investment scale was the major factor inhibiting the decoupling during 2002–2007, 2007–2012, and the entire period. However, it promoted the decoupling during 2012–2017 mainly because the FCF of others decreased by 52% in this period. Embodied energy intensity maintained the largest promotion effect on the decoupling during all periods. Embodied carbon intensity inhibited the decoupling during 2007–2012, but promoted the decoupling during other sub-periods. Embodied investment efficiency presented a small inhibitory effect on the decoupling during all periods. Over 2002–2017, the FCF of others increased by twofold, embodied energy intensity decreased by 55.6%, embodied carbon intensity decreased by 12.7%, and embodied investment efficiency increased by 15.1%.

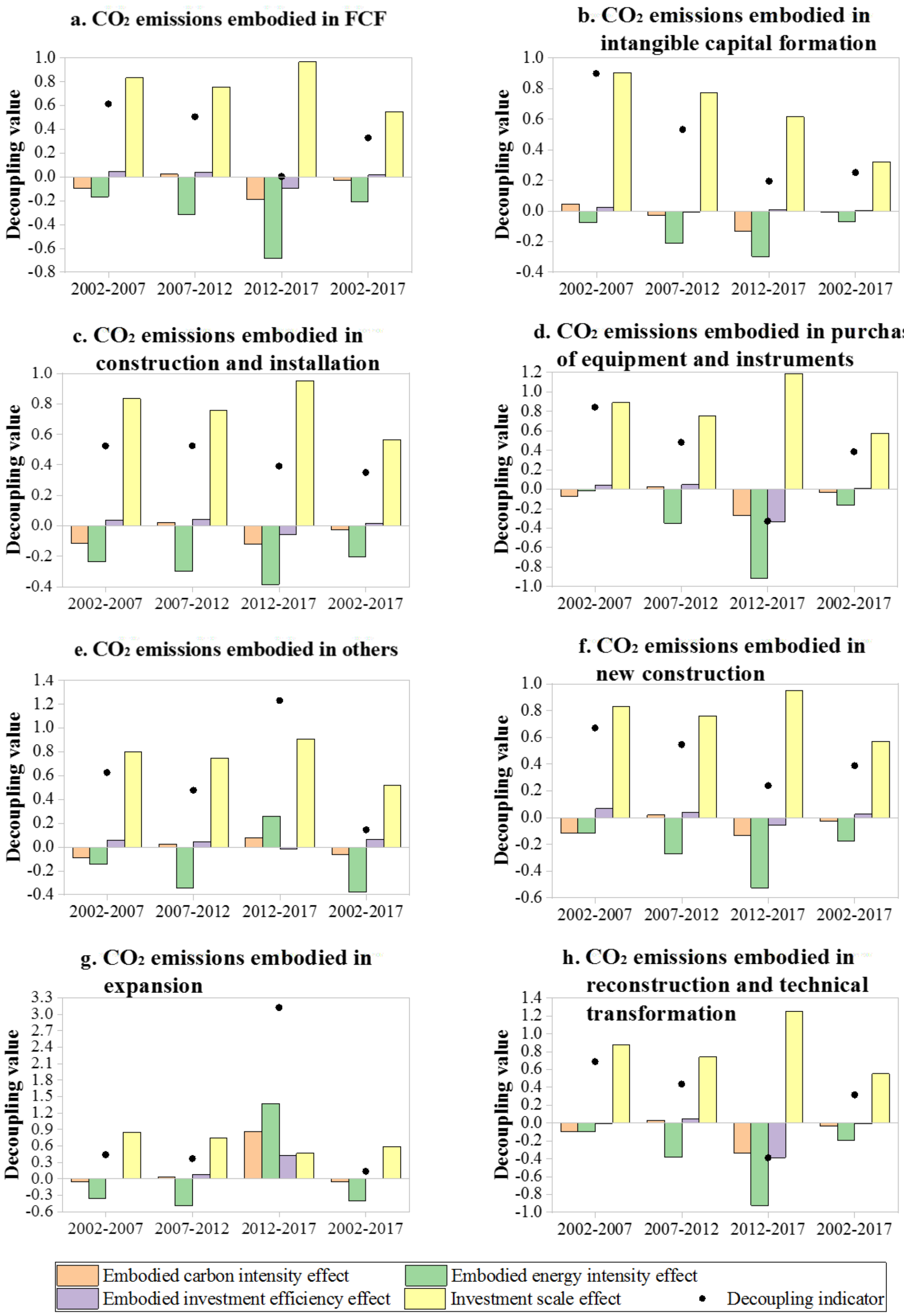

Figure 7. Decoupling states and driving forces of CO_2 emissions embodied in FCF and added value embodied in FCF.

The CO_2 emissions embodied in new construction had a weak decoupling relation with the embodied added value during all the periods. Investment scale was the major factor inhibiting the decoupling in all periods. Embodied carbon intensity was the key driver for promoting the decoupling during 2002–2007, while embodied energy intensity was the leading driver for promoting the decoupling during 2007–2012, 2012–2017, and the entire period. The effect of embodied investment efficiency on the decoupling was small. This is mainly because that, over the period of 2002–2017, the FCF of new construction increased by 8 times, which was the main promotion factor of embodied CO_2 emissions. In contrast, embodied energy intensity decreased by 50%, which was the main driver for the embodied CO_2 emissions reduction. Embodied carbon intensity and embodied investment efficiency had small variations, with a 10.7% reduction and 10.3% increase, respectively.

The relation between CO_2 emission and added value embodied in expansion was weak decoupling during 2002–2007, 2007–2012, and the entire period of 2002–2017, while presenting recessive decoupling during 2012–2017. In contrast to other sub-periods, the added value embodied in expansion decreased during 2012–2017. Investment scale was the main factor inhibiting the decoupling during all the periods except 2012–2017. Embodied energy intensity was the main factor promoting the decoupling during all the periods. During 2012–2017, all the four factors promoted the decoupling. During the entire period 2002–2017, the FCF and embodied investment efficiency of expansion increased by 220% and 1.3%, respectively, and embodied energy intensity and embodied carbon intensity decreased by 55.7% and 10.4%, respectively.

The relation between CO_2 emissions and added value embodied in reconstruction and technical transformation was strong decoupling during 2012–2017 and weak decoupling during 2002–2007, 2007–2012 and the entire period 2002–2017. Investment scale and embodied energy intensity were two major driving forces for inhibiting and promoting the decoupling, respectively. However, the effects of embodied carbon intensity and embodied investment efficiency on the decoupling were small. During the entire period of 2002–2017, the FCF of reconstruction and technical transformation increased by 8.9 times, embodied energy intensity decreased by 54.9%, embodied carbon intensity decreased by 14.5%, and the embodied investment efficiency decreased by 3.5%.

4. Conclusions and Policy Implications

With increasing attention on global climate change, it is crucial for China to reducing CO_2 emissions embodied in various economic activities. Although investment is an essential engine of economic growth, there is a lack of a detailed analysis on the CO_2 emissions embodied in various categories of FCF in China, as well as the related driving forces. Using the input–output tables for 2002, 2007, 2012, 2015m and 2017, this study estimates the CO_2 emissions embodied in various categories of FCF in China. The gravity model and the Shapley decomposition method are employed to explore the gravity movement of CO_2 emissions embodied in various categories of FCF among China's provinces, as well as regional contributions to the gravity movement. Finally, we combine the Tapio decoupling model and the LMDI method to investigate the decoupling relationship between CO_2 emissions embodied in FCF and the economic growth embodied in FCF and uncover the driving factors.

The results show that China's CO_2 emissions embodied in FCF had a rapid increase during 2002–2012 and remained almost flat during 2012–2017. The amount of CO_2 emissions embodied in intangible capital formation was much smaller than that embodied in tangible capital formation. On one hand, the CO_2 emissions embodied in construction and installation played a dominant role among tangible capital formation grouped by compositions of funds. On the other hand, the CO_2 emissions embodied in new construction played a dominant role among tangible capital formation grouped by types of construction. MFI and EGW were two major supply-side sectors generating more CO_2 emissions embodied in FCF, while CON and MFI were two major demand-side sectors.

Over 2002–2015, the gravity center for CO_2 emission embodied in FCF moved toward the northwest, with the northwestern region and middle Yellow River region being the main engine regions. The situations of CO_2 emissions embodied in construction and installation, new construction, and others were similar with that of CO_2 emissions embodied in FCF. The gravity center for CO_2 emissions embodied in intangible capital formation moved toward the southwest, with the southwestern region and southern coast being the main engine regions. The gravity center for CO_2 emissions embodied in the purchase of equipment and instruments moved toward the northwest, with the northwestern region and southern coast being the main engine regions. The gravity center for CO_2 emissions embodied in expansion moved toward the southeast, with the southern coast being the main engine region. The gravity center for CO_2 emissions embodied in reconstruction and technical transformation moved toward the southeast, with the northwestern region being the main engine region.

Over 2002–2017, the relations between CO_2 emissions and added value embodied in various categories of FCF were a weak decoupling. Investment scale was the major factor inhibiting the decoupling, while embodied energy intensity was the major factor promoting the decoupling during all sub-periods and the whole period. In contrast, embodied carbon intensity and embodied investment efficiency had marginal effects on the decoupling.

Several policy recommendations are proposed based upon the key findings of this study. First, the Chinese government should pay more attention on reducing its CO_2 emissions embodied in construction and installation, as well as new construction. As investment scale was the major driver for the increase of CO_2 emissions in these two projects, China should strengthen the macro-control on fixed capital formation so as to effectively restrain the excessively rapid growth of investment, especially for sectors of MFI, EGW, and CON. Embodied energy intensity largely promoted the decoupling of embodied CO_2 emission, but the effects from embodied carbon intensity and embodied investment efficiency were too small. Therefore, there is a great potential to optimize the carbon intensity and investment efficiency. Coal-type consumption has been playing the dominant role in the production activities due to China's energy endowment [40]. It is therefore necessary to develop low carbon energy sources, such as natural gas, hydropower, solar power, wind power, and geothermal power. For example, the local governments in Yellow River region could promote the application of photovoltaic solar panels on the roofs of local residential buildings due to the abundant solar energy resources in Yellow River region. Financial subsidies should be provided to those residents who have financial pressure to afford solar panels. The marketization reform of energy pricing mechanisms is also one effective incentive measure to optimize energy structure. [41,42]. Besides, the Chinese government should improve the investment efficiency and adjust the capital ratio of investment projects to introduce more environmentally friendly enterprises. All the enterprises should be encouraged to increase their green investment so that cleaner production technologies and energy efficient equipment could be introduced and applied.

Moreover, the northwestern region and middle Yellow River region were two major drivers of the gravity movement of CO_2 emissions embodied in FCF. The Chinese government should focus on reducing the CO_2 emissions in these two regions by optimizing the investment distribution among regions, as well as reducing energy intensity, optimizing energy structure, and improving investment efficiency. With regard to projects of construction and installation as well as new construction, their embodied CO_2 emissions in the northwestern region and middle Yellow River region should also be the focus of emission reduction. With regard to the purchase of equipment and instruments, the embodied CO_2 emissions in the northwestern region and southern coast should be the focus of emission reduction. With regard to project of expansion, the embodied CO_2 emission in the southern coast should be the focus of emission reduction. With regard to project of reconstruction and technical transformation, the embodied CO_2 emission in the northwestern region should be the focus of emission reduction. It is necessary for the local governments in the above regions to adopt effective measures and regulations to mitigate the CO_2 emissions embodied in corresponding FCF categories.

In general, this study can help decision-makers identify the key regions affecting the gravity movement of CO_2 emissions embodied in FCF, as well as the key factors affecting the decoupling effect between CO_2 emissions and added value embodied in FCF. Although this study focuses on China, policy implications from this study can provide valuable insights for other emerging countries facing similar challenges so that they can prepare their policies to mitigate the CO_2 emissions embodied in FCF.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Classification of China's 30 provinces into eight regions.

No.	Region	Province
1	Northeast	Liaoning, Jilin, Heilongjiang
2	Northern coast	Beijing, Tianjin, Hebei, Shandong
3	Eastern coast	Shanghai, Jiangsu, Zhejiang
4	Southern coast	Fujian, Guangdong, Hainan
5	Middle Yellow River	Shanxi, Inner Mongolia, Henan, Shaanxi
6	Middle Yangtze River	Jiangxi, Anhui, Hubei, Hunan
7	Southwest	Guangxi, Chongqing, Sichuan, Guizhou, Yunnan
8	Northwest	Gansu, Qinghai, Ningxia, Xinjiang

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