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Article

Temporal and Spatial Variations in Provincial CO_2 Emissions in China from 2005 to 2015 and Assessment of a Reduction Plan

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Abstract: This study calculated the provincial carbon dioxide (CO_2) emissions in China, analyzed the temporal and spatial variations in emissions, and determined the emission intensity from 2005 to 2015. The total emissions control was forecasted in 2015, and the reduction pressure of the 30 provinces in China was assessed based on historical emissions and the 12th five-year (2011–2015) reduction plan. Results indicate that CO_2 emissions eventually increased and gradually decreased from east to west, whereas the emission intensity ultimately decreased and gradually increased from south to north. By the end of 2015, the total control of provincial emissions will increase significantly compared to the 2010 level, whereas the emission intensity will decrease. The provinces in the North, East, and South Coast regions will maintain the highest emission levels. The provinces in the Southwest and Northwest regions will experience a rapid growth rate of emissions. However, the national emission reduction target will nearly be achieved if all provinces can implement reduction targets as planned. Pressure indices show that the South Coast and Northwest regions are confronted with a greater reduction pressure of emission intensity. Finally, policy implications are provided for CO_2 reductions in China.

Keywords: CO_2 emissions; total control; reduction pressure; regional differences; distribution

1. Introduction

The international community has reached a consensus that global warming poses a serious threat. Consequently, greenhouse gas reduction plans have been successively promulgated in the major developed and developing countries. China, as the largest developing country, announced its program to reduce future carbon dioxide (CO_2) emissions during the 15th International Climate Conference held in Copenhagen in 2009. Moreover, achieving a national reduction target of CO_2 emissions depends on how intra-national units implement their own reduction targets. Therefore, China announced its 12th five-year (2011–2015) plan to reduce emissions in 2012, which explicitly stipulated the reduction target for each provincial unit in mainland China. Both of these announcements emphasized the decrease of CO_2 emission intensity. The first target, which was announced in Copenhagen, stated that the emission intensity in 2020 should be reduced by 40%–45% compared with the 2005 level. The second target, which was announced in Beijing, stated that the emission intensity in 2015 should be reduced by 17% compared with the 2010 level. Moreover, a binding reduction target was assigned for all provincial units in the second target. Nevertheless, no clear total control target is set for the nation and individual provinces. The total control of CO_2 emissions should be calculated to have a more intuitive emissions reduction target. Understanding the amount of total control of CO_2 emissions is necessary for each province during the reduction period. This is the first issue discussed in this paper.

Calculating CO_2 emissions, one of the main greenhouse gasses, has been an increasing concern around the world in recent years. Research shows that the United States, China, the European Union, Japan, and India are considered as major emitters of CO_2 [1]. In 2006, China overtook the United States as the world's leading emitter of CO_2 [2]. Historical emissions provided the foundation for burden sharing of global CO_2 emissions responsibility in the future. Cumulative emissions [3] or per capita cumulative emissions [4] are adopted as the standard for burden sharing. The major emitters need to reduce emissions while maintaining economic development. As a result, the future emissions of these major emitters have become a research hotspot [5,6]. To calculate the CO_2 emissions of each province in the future, the emissions from previous years must be determined first. Many studies have reported on China's CO_2 emissions because China is the top emitting country in the world [2]. Energy consumption especially from fossil fuel combustion is considered to be the main source of CO_2 emissions. Carbon emissions from energy consumption usually account for more than 90% of the total carbon emissions [7]. Previous studies have used several calculation methods for the regional CO_2 emissions. Many of them examined CO_2 emissions from energy consumption instead of total regional emissions. For instance, Zhao [8] used a bottom-up inventory framework to calculate total annual CO_2 emissions based on detailed provincial economic and energy data. Liu [9] used energy consumption data to calculate China's regional and sectoral greenhouse gas emissions, including CO_2 emissions. Wang [10] used energy consumption data to calculate provincial CO_2 emissions from 1995 to 2011. Many examples used emissions from energy consumption in place of regional emissions, both at the national [11] and intra-national levels [12]. However, the manufacturing process of some industrial products also generates significant CO_2 emissions. The main raw material of the cement industry is calcium carbonate. The process of cement production emits large amounts of CO_2, along with calcium carbonate decomposition and coal combustion. Thus, some scholars began to consider CO_2 emissions from regional cement production. For instance, Xu [13] analyzed the changes in energy consumption and CO_2 emissions in China's cement industry based on the typical production process for clinker manufacturing. Kim and Worrell [14] analyzed carbon emissions from China's cement industry from 1980 to 1998. Ke [15] estimated CO_2 emissions from China's cement production from 2005 to 2009. Forests and green lands have the ability to absorb and store CO_2; This ability is called carbon sequestration [16]. From a regional perspective, carbon sequestration should be considered calculating total regional CO_2 emissions [17,18]. For instance, Fang [19] used a biomass method to estimate forest carbon stocks in five East Asian countries between the 1970s and 2000s. Guo [20] explored the spatial-temporal changes in forest biomass carbon stocks in China between 1977 and 2008. Most previous studies on carbon emissions in China considered only one aspect of the carbon emission accounting and focused on the national level. The regional total CO_2 emissions can be accurately calculated by considering all aspects of regional emission accounting.

Allocation results at the national level were found in many previous studies that investigated reduction targets or burden-sharing of CO_2 emissions. For instance, Wei [21] allocated permits of carbon emissions to 137 countries and regions on the basis of per-capita cumulative emissions. Chakravarty [22] presented a framework for allocating a global carbon reduction target among nations. Some studies began to allocate the national reduction target to the industrial [23] or sectoral levels. For instance, Chen [24] disaggregated China's national CO_2 mitigation burden at the sectoral level. Some scholars recently studied the reduction burden-sharing of the inner regions of China, and most of this research is based on the targets of Copenhagen [25,26]. Yi [27] developed a comprehensive index and constructed an intensity allocation model for inner China provinces on the basis of the Copenhagen reduction target. Few relevant studies have been conducted on the second China reduction target in the 12th five-year (FY) period because most previous studies have focused on the target in the national level [28,29]. The results of previous studies regarding China's intra-nation or provincial emission reduction targets often provide the future controlling intensity but lack total emission control. This type of result is not a straightforward target. Central and local governments operate with difficulty. China is currently developing based on its 12th Five-Year Plan (FYP), which includes the second reduction target of CO_2 emissions. Thus, the present work calculates a reduction plan, conducted from 2011 to 2015. A target to reduce emission intensity yields pressure. Research on this emission reduction pressure is extremely scarce, and providing results at the provincial level is difficult. Moreover, the provinces formulate development plans in detail, setting the speed of economic growth. The second point of interest to guarantee the specific speed is to identify the amount of pressure every province receives to control emissions. The final point to consider is whether the national reduction target can be achieved if each province completes its own reduction target.

This paper reports the intra-national provincial-level CO_2 emissions of China. First, a more accurate framework is used to calculate the provincial CO_2 emissions from 2005 to 2010. Then, the spatial-temporal variations of emissions and emission intensity are analyzed. Second, the total control of provincial and national CO_2 emissions in 2015 is calculated. Third, two new indices are designed to assess the pressure of reduction for each province. Conclusions and policy implications are provided in the last two sections.

2. Methodology

2.1. Calculation of Provincial CO_2 Emissions

The CO_2 emissions of a province are mainly derived from energy consumption and the process of cement production, as well as the process of removing CO_2 via sequestration by forests and green lands. The provincial carbon emissions calculating framework was used in this paper (Figure 1).

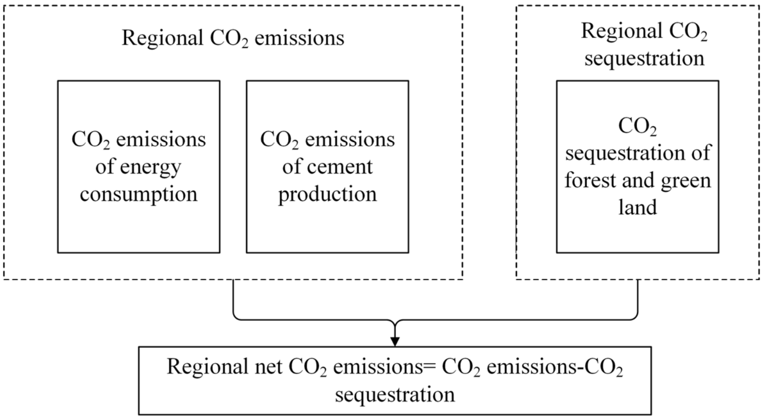


Figure 1. Regional net CO_2 emissions calculating framework.

Equation (1) was used to calculate the provincial CO_2 emissions:

$$C = C_e + C_c - S_f \tag{1}$$

where C is the total CO_2 emissions of a province (million tons, *M*t), C_e represents the CO_2 emissions from energy consumption (Mt), C_c represents the CO_2 emissions from the process of cement production (*M*t), and S_f is the CO_2 sequestration by forests and green lands (*M*t).

The guidelines of Intergovernmental Panel on Climate Change (IPCC) were adopted to calculate CO_2 emissions from energy consumption using the following equation [30,31]:

$$C_e = \sum_j \frac{E_j \times NCV \times EF_j \times O_j \times 44}{12} \tag{2}$$

where E_j is the amount of energy consumption j (tons or m^3 for natural gas), NCV is the net calorific value (kJ/(kcal×kg)), EF_j is the carbon emission factor of energy j (kg/GJ), and O_j is the carbon oxidation rate of energy j (default value is 1).

IPCC guidelines and Zhai's article [32,33] to calculate CO_2 emissions from cement production using the following equation:

$$C_c = q \times r \times e \tag{3}$$

where q is the amount of cement (*M*t), r is the proportion of clinker (%), and e is the CO_2 emission factor, which involves the three processes of decomposition of carbonate raw material, calcination of kiln dust, and decomposition of organic carbon in the calcined materials. The three processes have a total coefficient of 0.55 (tons per one ton).

Equation (4) was used to estimate the amount of CO_2 sequestration by forests and green lands [34]. Green lands refer to urban gardens and green spaces that are evergreen and have the absorption capacity of CO_2 such as forests:

$$S_f = \left(A_f + A_g\right) \times a_s \quad (4)$$

where A_f is the area of forests (hm^2), A_g is the area of green lands (hm^2), and a_s is the sequestration coefficient, for the sequestration amount per hectare per year. The carbon sequestration by Chinese forests has been estimated by many scientists. The sequestration amount per hectare per year is indirectly provided by these reports. Using the sequestration coefficient is inevitable in calculating the regional CO_2 absorption in a certain year by forests and green lands. A significant difference exists in the results of this sequestration coefficient (Table 1).

Table 1. Sequestration coefficient of forests in China.

Soures	Carbon Sequestration (t/hm^2/year)	Carbon Dioxide Sequstration (t/hm^2/year)
Ma and Wang [34]	0.61	2.24
Fang *et al*. [35]	0.53	1.93
Lai and Huang [36]	0.52	1.90
Zhou *et al*. [37]	0.50	1.83
Guo *et al*. [38]	0.39	1.42
Piao [39]	0.15	0.55

In the International Academic Symposium on Ecosystem Carbon Balance in 2005, Zhou precisely calculated, for the first time in the international academia, that each hectare of forests absorbed 0.5 tons of net carbon a year. That is, each hectare of forest a year can absorb 1.83 tons of CO_2. A total of 1.83 (tons per one hectare) was chosen as the calculation parameter of sequestration coefficient, which was also used in the article by Yu [40].

2.2. Forecasting Total Control of CO_2 Emissions

The emission intensity of CO_2 is usually defined as the unit of GDP emissions [29]. According to the definition of emission intensity, Equations (5–8) was used to forecast the future emissions of each province:

$$I_i = \frac{C_i}{GDP_i} \quad (5)$$

where I_i is the emission intensity (tons per 10,000 Chinese yuan, $t/10^4$ CNY) of province i, C_i is the CO_2 emissions (M_t) of province i, and GDP_i is the GDP of province i (CNY).

The total control of emissions in the target year is equal to the intensity in the target year multiplied by the GDP in the target year, which is expressed as follows:

$$C_i^t = I_i^t \times GDP_i^t \quad (6)$$

where C_i^t is the CO_2 emissions of province i in target year t, I_i^t is the emission intensity of province i in target year t, and GDP_i^t is the GDP of province i in target year t.

The emission intensity of the target year is calculated by the reduction plan, and the GDP of the target year is calculated by the economic growth setting as follows:

$$I_i^t = I_i^0 \times (1 - A_i) \tag{7}$$

$$GDP_i^t = GDP_i^0 \times (1 + G_i)^{t-0} \tag{8}$$

where 0 is the base year, t is the target year of forecasting, I_i^t is the emission intensity in the target year of province i, I_i^0 is the emission intensity in the base year of province i, G_i is the economic growth rate of province i (this value is generally fixed according to the annual economic development), and A_i is the intensity controlled target of province i in the 12th national reduction plan.

Given that the country is composed of provinces, the amount of national CO_2 emissions is equal to the sum of all provinces, as with the GDP. The national emission intensity of the target year can be calculated according to the definition of emission intensity. Unlike the base year national intensity, whether the national reduction target in this period can be achieved or not can be known. From the 12th FY from 2011 to 2015, according to the national reduction plan of China in this period, the base year is 2010, and the target year is 2015, which is expressed as follows:

$$I = \frac{\sum_i C_i}{\sum_i GDP_i} \tag{9}$$

$$GDP_i^t = GDP_i^0 \times (1 + G_i)^{t-0} \tag{10}$$

where I is the national intensity of CO_2 emissions, C_i is the CO_2 emissions of province i, GDP_i is the GDP of province i, F is the completion of the national reduction target (%), I^0 is the national base year intensity, I^t is the national target year intensity and A is the national reduction target of emission intensity in this period, which is 17%.

2.3. Assessment of Reduction Pressure

This study designed two indices to reflect the pressure of reduction for each province. One index is designed by forecasting future emissions based on historical emissions. The other one is based on the comparison of emissions over the same length of time; we choose 2010–2015 and 2005–2010.

2.3.1. Index of Forecasting Based on Historical Emissions

A logistic curve fit model of provincial CO_2 emissions is established based on the time sequence. The logistic equation is written as:

$$x_t = \frac{1}{c + ae^{bt}} \tag{11}$$

where x_t represents the CO_2 emissions of one province in year t, and a, b, and c are parameters of the logistic model. All of these parameters are estimated by statistical software Origin 9.0. Then, the index is designed as follows:

$$D_j = x_j^{2015} - C_j^{2015} \tag{12}$$

where D_j represents the pressure of province j (M_t), x_j^{2015} is the prediction value of CO_2 emissions of province j in 2015, and C_j^{2015} represents the emissions of total control by the reduction plan described in Section 2.2. A larger index corresponds to greater pressure.

2.3.2. Index of Same Length of Time

The ratio of the actual variation of CO_2 emissions in 2005–2010 and control variation in 2010–2015 is the index of reduction pressure. Expressed as a percentage to make the index more intuitive, the equation is written as follows:

$$P_j = \frac{\left(C_j^{2010} - C_j^{2005}\right)}{\left(C_j^{2015} - C_j^{2010}\right)} \times 100\% \tag{13}$$

where P_j represents the pressure of province j; C_j^{2005} and C_j^{2010} are the emissions of province j in years 2005 and 2010, respectively; and C_j^{2015} is the total control of emissions of province j by the reduction plan.

3. Study Area and Data

3.1. Study Area

Mainland China has 31 provincial-level administrative units, including 22 provinces, four municipalities (Beijing, Tianjin, Shanghai and Chongqing), and five autonomous regions (Guangxi, Ningxia, Tibet, Xinjiang, and Inner Mongolia). The study area comprises 30 provincial-level units of mainland China, except Tibet. In addition to missing related data, Tibet has China's lowest CO_2 emissions. The 30 units are referred to as provinces.

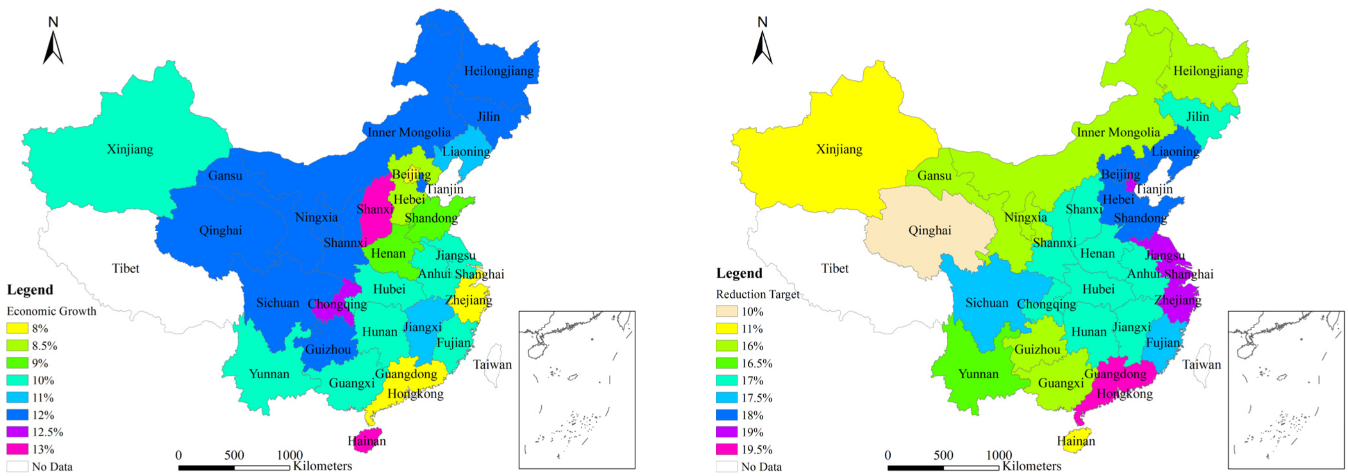
The provinces are divided into the following eight economic regions: (1) Northeast: Liaoning, Jilin, and Heilongjiang; (2) North Coast: Beijing, Tianjin, Hebei, and Shandong; (3) East Coast: Shanghai, Jiangsu, and Zhejiang; (4) South Coast: Fujian, Guangdong, and Hainan; (5) Middle Yellow River: Shaanxi; Shanxi, Henan, and Inner Mongolia; (6) Middle Yangtze River: Hubei, Hunan, Jiangxi, and Anhui; (7) Southwest China: Yunnan, Guizhou, Sichuan, Chongqing, and Guangxi; and (8) Northwest China: Gansu, Qinghai, Ningxia, and Xinjiang. This division is the latest regional classification officially provided by the Chinese government. The distribution of the eight regions is shown in Figure 2. For a long time, significant differences in the economic development levels have existed among the different regions of China because of the historic suffering and causal localization in districts. The North Coast, East Coast, and South Coast regions have higher levels of economic development, whereas the Northwest and Southwest regions are relatively backward.

3.2. Data sources and Description

Three aspects of data sources are involved in calculating the CO_2 emissions. The first aspect of energy consumption data and the net calorific values of each type of energy are obtained from the China Energy Statistic Yearbook [41–52]; the data include eight types of energy consumption in 30 provinces and each type of energy calorific value. The second aspect of cement production data is obtained from the China Statistical Yearbook [52–70]; The data included cement production in 30 provinces. The third aspect of forests and green lands data is obtained from the China Forestry

Statistical Yearbook [71–88]; The data include an area of forests and green lands in 30 provinces. The parameters in the IPCC guidelines of greenhouse gas emissions are used to calculate CO_2 emissions. The proportion of cement clinker from industry report in recent years is used. All parameters for calculating CO_2 emissions are not listed in this paper. Moreover, the data on economic development setting are obtained. The data are found in the 12th FYP of each province. There are expectations and control of future economic development (Figure 3). The annual GDP figures of 30 provinces are obtained from the China Statistical Yearbook [52–70] and converted into comparable prices with the 2010 figure. In the section on assessment of reduction pressure, the data on historical emissions of provinces from 1995 to 2012, which were calculated by the method of provincial CO_2 emissions, were used.

Figure 2. Eight-region division of the study area.



(**a**) (**b**)

Figure 3. Target setting in 30 provinces (**a**) China's economic growth target in 12th FYP. (**b**) China's CO_2 emission reduction target in 12th FYP.

Provinces with a traditionally high economic level, such as Beijing, Shanghai, Zhejiang, and Guangdong, set a relatively low growth economic speed. The central and western provinces generally lag behind those of eastern China because of uneven development of the regional economies. In Figure 3a, the high setting growth provinces are nearly all in central and western China. The data from China's 12th FY work programs were used to control greenhouse gas emissions. This work plan is the only existing intra-national reduction plan for CO_2 emissions in China. The country and each province have their own CO_2 emission reduction targets (Figure 3b). According to this plan, the national CO_2 emission intensity should decrease by 17% in 2015 compared with the 2010 level. This target is spread into 30 provinces and incorporated into the development planning of each province. Unlike the economic growth setting, provinces in the high economy level (for instance, Tianjin, Jiangsu, Shanghai, Zhejiang and Guangdong) are bonded with high reduction targets of emission intensity. The targets of the Middle Yellow River and Middle Yangtze River are consistent with the national target which has a rather low reduction target in the Northwest and Southwest regions. The reduction targets of Hainan, Xinjiang and Qinghai, as the lowest in all provinces, are significantly different.

4. Results and Discussion

4.1. Composition of Provincial CO_2 Emissions

The results of taking 2010 as an example to illustrate the composition of the three aspects in the calculation of provincial CO_2 emissions are shown in Figure 4. According to the results, energy consumption remains the main source of CO_2 emissions, accounting for more than 90% of CO_2 emissions in a province.

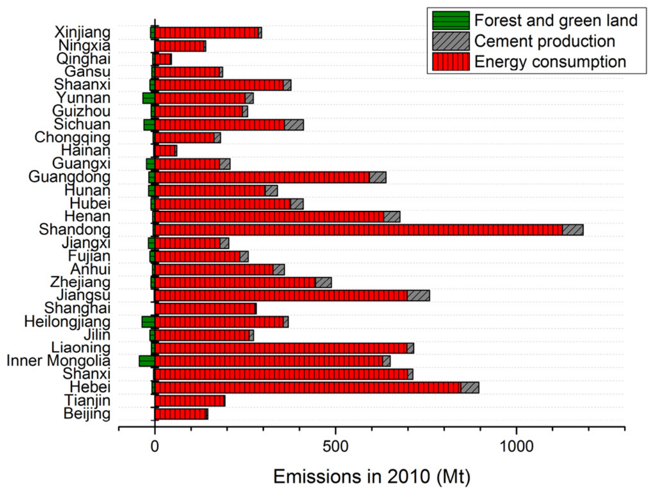


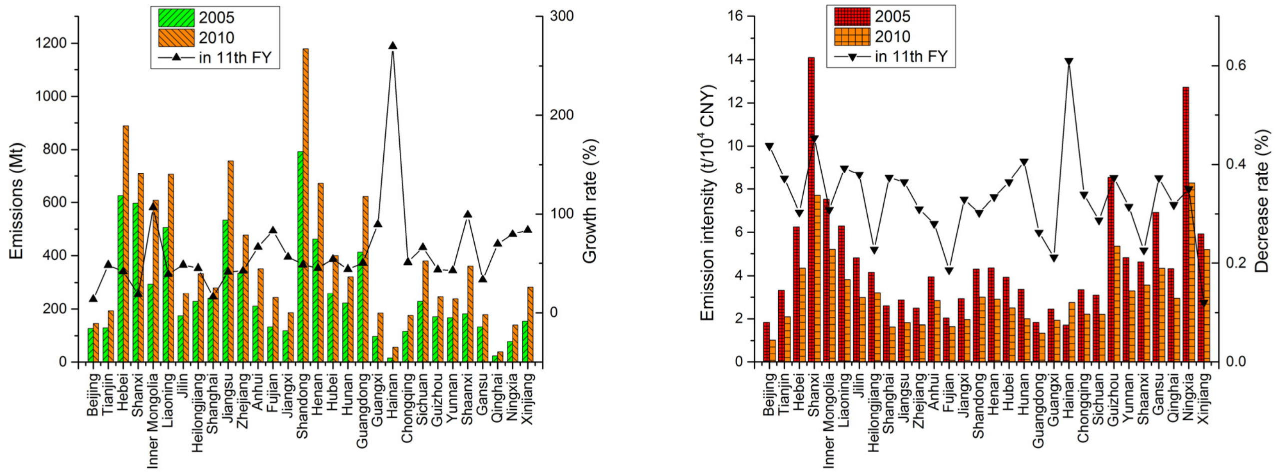
Figure 4. Three aspects of provincial CO_2 emissions.

The emissions from energy consumption are very close to the net provincial emissions. However, differences exist between the calculation results of regional emissions from pure energy consumption and the computing framework that is proposed by this paper. In some provinces, the emissions from cement production cannot be ignored. Figure 4 shows that, the amounts of emissions from cement production are evident in Hebei, Jiangsu, Shandong, Guangdong and Sichuan. In Guangxi, Sichuan, Shandong, Hunan, and Chongqing, the proportions of emissions from cement production are greater than

10%. According to the historical and statistical data, these provinces are the main cement producers in China. Although the amount of CO_2 sequestration is not obvious in most provinces, Inner Mongolia, Heilongjiang, Guangxi, Sichuan, and Yunnan are exceptions. The absorption by forests and green lands is also close to 10% of the emissions in 2010. Cement production and forests cannot be ignored to accurately calculate regional CO_2 emissions.

4.2. Temporal and Spatial Variations of Provincial CO_2 Emissions

The years 2005 and 2010 were chosen to analyze the variation in provincial CO_2 emissions. These two years represent the start and end years of China's 11th FYP. The data can better reflect the differences in CO_2 emissions over the past development stage. The temporal variation of CO_2 emissions is shown in Figure 5a. The temporal variation of emission intensity is shown in Figure 5b.



(**a**) (**b**)

Figure 5. Temporal variation in provincial CO_2 emission (**a**) Variation of emissions in 2005–2010; and (**b**) Variation of emission intensity in 2005–2010.

The national emissions were calculated by summing the emissions from each province. The national emissions are 7778.35 million tons (M_t) in 2005 and 11,623.04 Mt in 2010. The national growth rate of CO_2 emissions in this period is nearly 50%. The gap in CO_2 emissions is clear among the provinces. The maximal provincial emission is dozens of times higher than the minimal one. The province with minimal emissions in 2005 is Hainan. Qinghai is the province with minimal emissions in 2010. Shandong always has the highest emissions in these two years. Hainan had the fastest growth rate of emissions because it had a low emission base in 2005 and a requirement of economic development during this period. Beijing and Shanghai had the lowest growth rate because these two metropolises paid more attention to controlling carbon emissions. Between these two years, the CO_2 emissions of most provinces indicated significant growth, with growth rates of more than 60% or even close to 100%. The national emission intensity is 3.91 tons per 10,000 CNY (t/10^4 CNY) in 2005 and 2.66 t/10^4 CNY in 2010. The decrease rate of the national emission intensity is nearly 32%. The emission intensities at the national and provincial levels exhibited dramatic decreases in this period. Only Hainan's intensity increased, and its decrease rate is indicated in Figure 5b as a positive value for convenience. Shanxi and Ningxia have the highest emission intensities at 14.10 and 12.74 in 2005 and 7.71 and 8.28 in 2010, respectively. They also had the most significant decrease in emission intensity but still maintained the highest intensity in 2010 of mainland China. Between these two years, the emission intensity of 29 provinces obviously decreased. The decreases were from 20% to 40%.

The variation in spatial distribution is also obvious. The unified grouping rules of emissions and emission intensity were adapted to different provinces into four groups, reflecting variations in time and space. Each group differs by 200 Mt in emissions and 2 t/10^4 CNY in emission intensity. The distribution results are shown in Figures 6 and 7. The emissions of east China in 2005 and 2010 are the highest, decreasing gradually from east to west. The emissions of the provinces around Beijing, which belong to the North Coast region, are significantly higher than those of the other provinces. Moreover, Guangdong is one of the provinces where emissions are higher in 2005 and 2010. The emissions of the North Coast and Middle Yellow River regions are the highest according to the rule of the study area division in 2005 (Figure 6a). The previous two regions and East Coast are the highest in 2010 (Figure 6b). The CO_2 emissions of provinces in the North Coast region from 2005 to 2010 are becoming much higher than those of the other regions. This distribution of CO_2 emissions is more evident. Hebei and Shandong became the top two provinces with more than 800 Mt emissions. Other provinces, such as Xinjiang, Sichuan and Guizhou in the Southwest and Northwest regions, obviously increased their emissions during this period.

The emission intensity of northern China is the highest in both 2005 and 2010. Unlike emissions, the distribution of emission intensity rose from south to north in both 2005 and 2010. The provinces in the South Coast and East Coast regions have the lowest emission intensities. Although these provinces have high emissions, they also have high GDPs. A rule indicates that poor and backward provinces have higher emission intensities.

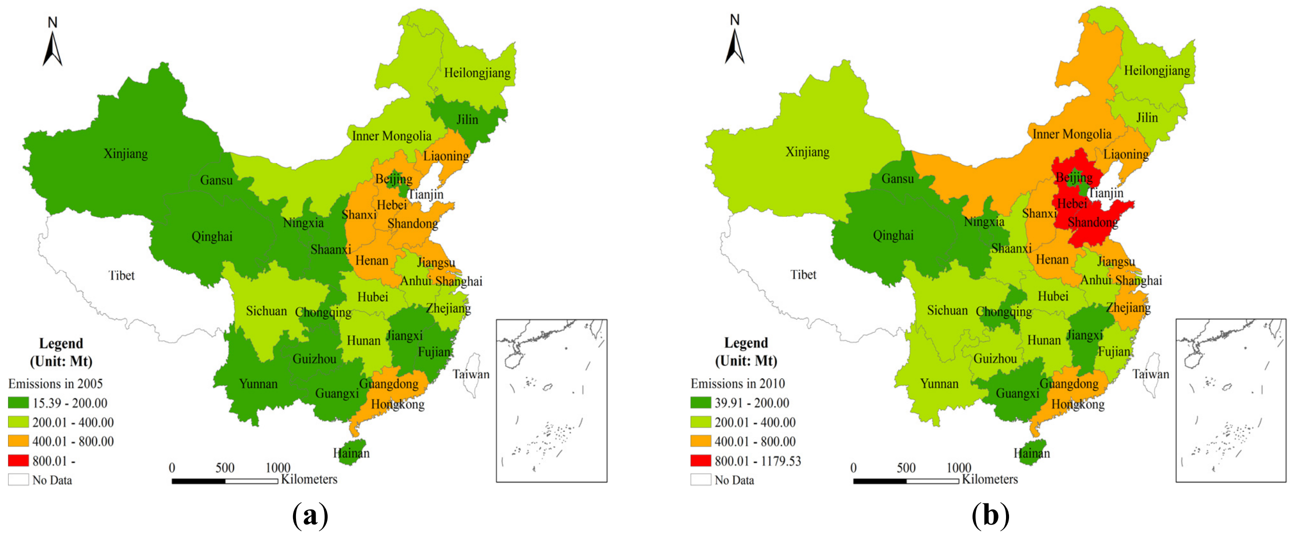
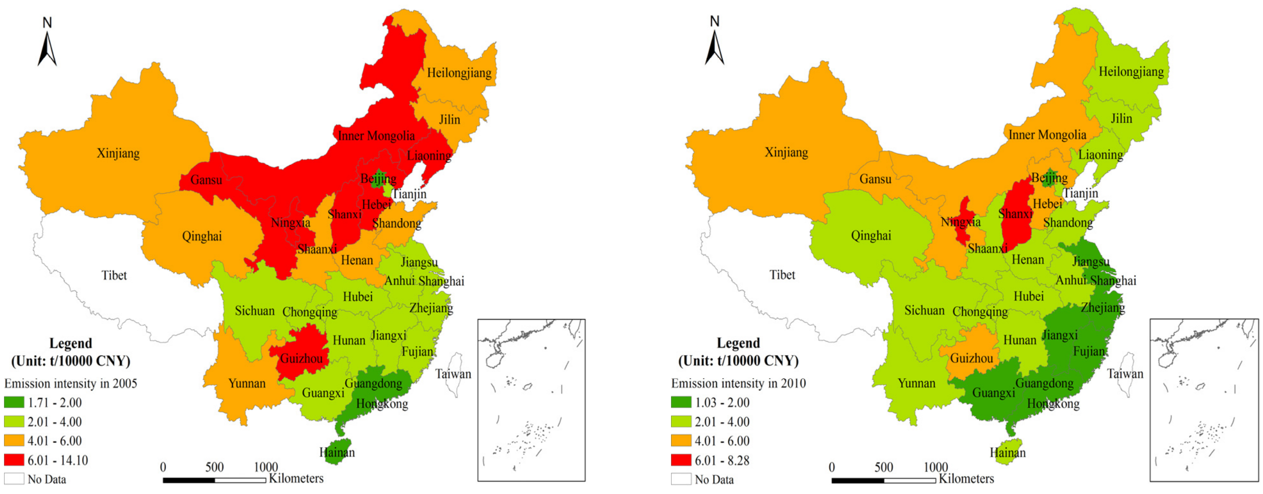


Figure 6. Provincial emission distribution (**a**) CO_2 emissions in 2005; and (**b**) CO_2 emissions in 2010.



(**a**) (**b**)

Figure 7. Provincial emission intensity distribution (**a**) Emission Intensity in 2005; and (**b**) Emission intensity in 2010.

The Northwest, Middle Yellow River and Southwest regions have the highest intensities of CO_2 emissions in 2005 (Figure 7a). The obviously high intensity in 2010 (Figure 7b) was distributed in the Northwest and Middle Yellow River regions. From 2005 to 2010, the intensity decreased for every province, except Hainan, mostly because of the rapid growth in GDP and the low level of energy utilization efficiency. The emissions in Hainan grew faster than its economic development. Shanxi and Ningxia in central mainland China are clearly the two provinces with the highest emission intensity. The overall spatial-temporal variation of CO_2 emissions in 2005 to 2010 can be summarized as follows: the emissions increased over time with a decreasing pattern from east to west, and the intensity decreased over time with a rising pattern from south to north.

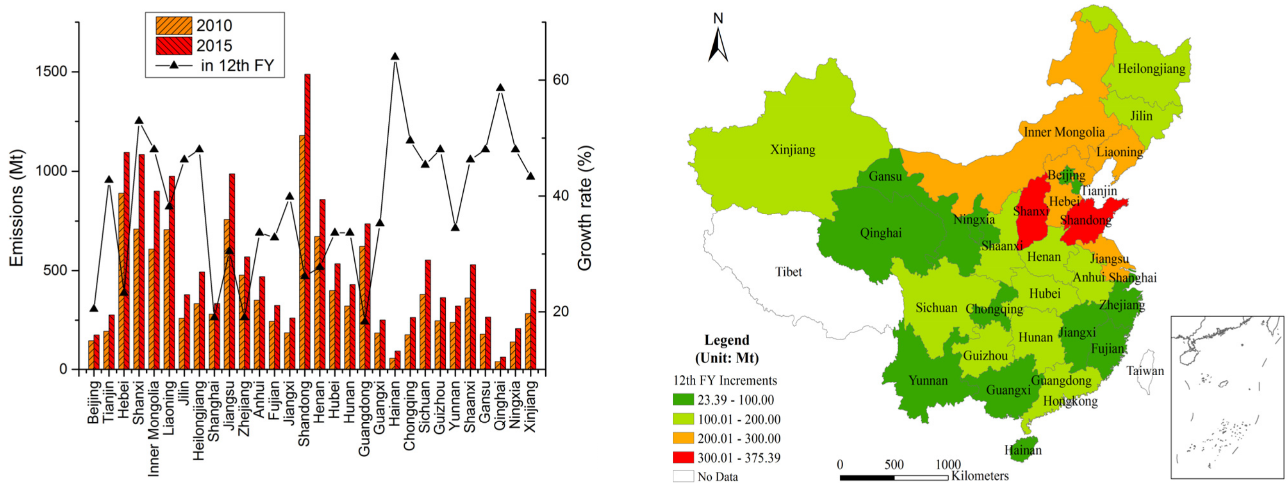
4.3. Total Control of Emissions in 2015

Based on the reduction plan in the 12th FY of China, 2015 was set as the target year and 2010 as the base year. According to the model of forecasting CO_2 emissions in Section 2.2, the total control in 2015 and increments during the 12th FY of CO_2 emissions were calculated. The results are presented in Table 2 which includes the total control target of CO_2 emissions in 2015. This target was compared with the emissions in 2010 (Figure 8a).

The CO_2 emissions of each province in 2015 are still increasing compared with those in 2010. The provinces that have high emissions in the base year still have high emissions in the target year. Shandong, Hebei, and Shanxi are the top three emitting provinces. They will emit more than 1000 M_t emissions in 2015. The increment distribution of CO_2 emissions in the 12th FY is shown in Figure 8b. The increments are different among the provinces. Shanxi accounts for the maximum at 375.39 Mt, and Qinghai accounts for the minimum at 23.39 M_t. All provinces, except Shanghai, have 20% or even more than 50% growth in the 12th FY. Beijing, Shanghai, Zhejiang, and Guangdong are slower growth provinces in terms of CO_2 emissions. The high economic development levels in these regions force them to pay more attention to controlling CO_2 emissions. They have gradually limited their dependence on fossil energy contour carbon energy. By contrast, Hainan, Qinghai, Shanxi and other poor western and central provinces need to maintain a high growth of emissions at the present stage. On the right side of Figure 8a, a higher growth rate from Chongqing to Ningxia is shown. Provinces in this range belong to the west China region, which lags behind in economic development.

Table 2. Provincial total control and increments of CO_2 emissions.

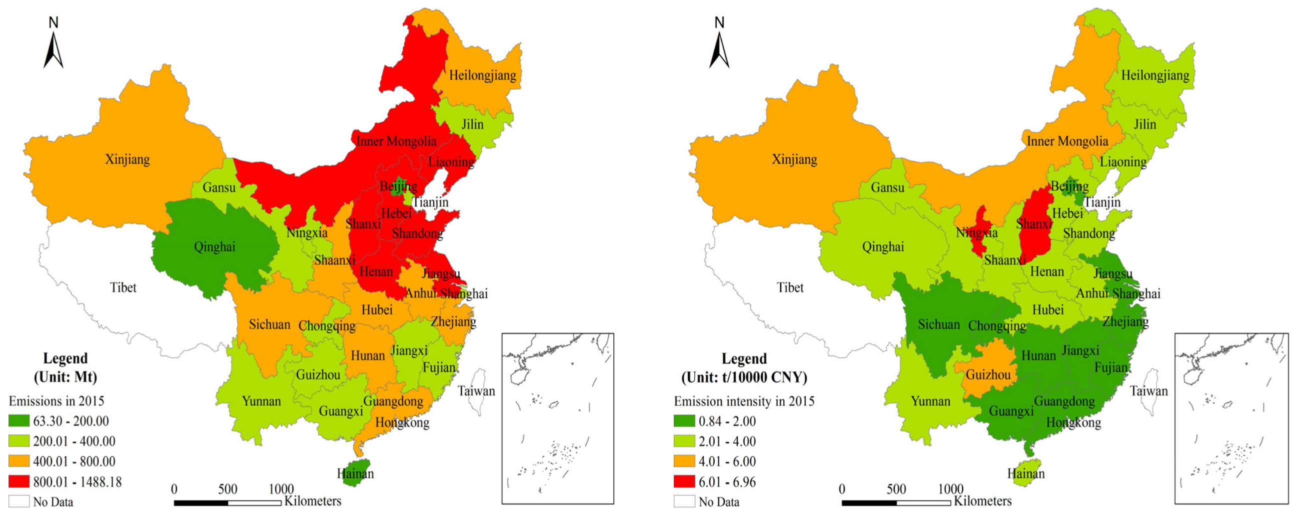
Province	Emissions in 2015 (M_t)	Increments in 12th FY (M_t)	Province	Emissions in 2015 (M_t)	Increments in 12th FY (M_t)
Beijing	175.15	29.78	Henan	857.87	186.11
Tianjin	276.22	82.72	Hubei	534.22	134.57
Hebei	1095.54	207.02	Hunan	429.94	108.30
Shanxi	1084.70	375.39	Guangdong	736.11	113.77
Inner Mongolia	899.53	291.89	Guangxi	250.35	65.29
Liaoning	975.60	269.54	Hainan	93.42	36.45
Jilin	379.06	119.92	Chongqing	263.46	87.31
Heilongjiang	493.52	160.14	Sichuan	552.87	172.61
Shanghai	333.79	53.33	Guizhou	364.85	118.39
Jiangsu	987.63	230.54	Yunnan	321.42	82.41
Zhejiang	568.46	90.82	Shaanxi	529.89	167.63
Anhui	469.95	118.38	Gansu	265.12	86.03
Fujian	324.31	80.22	Qinghai	63.30	23.39
Jiangxi	260.57	74.26	Ningxia	207.15	67.22
Shandong	1488.18	308.65	Xinjiang	405.60	122.63



(**a**) (**b**)

Figure 8. Provincial variation in CO_2 emission (**a**) Temporal variation of emissions in 2010–2015; and (**b**) Increments of emissions in 2010–2015.

CO_2 emissions and emission intensity were classified by the same group rules in Section 4.2 (Figure 9). The distribution of CO_2 emissions in 2015 is similar to 2010 and 2005 (Figure 9a). The overall distribution indicating that east China has higher emissions than west China has not changed. The North Coast and Middle Yellow River regions remain those with the highest emissions. The one obvious change is that the emissions of more provinces are over 800 Mt. The distribution of these high-emission provinces indicates that Beijing is a center of expansion. Moreover, Guangdong in the South Coast is now in the top emissions group. The Middle Yangtze River represents the region of higher growth in emissions for this period. Hubei, Hunan, and Anhui belong to this region. Many provinces in central and western China have significant emission growths, including Shanxi and Henan in Middle Yellow River and Sichuan and Xinjiang in western China. The emission intensities of all provinces have decreased because the reduction plan in this period focuses on decreasing the emission intensity. The distribution is high in the north and low in the south (Figure 9b). Although the emission intensity is expected to decrease significantly after the provinces execute their own reduction targets, previous high-intensity provinces still have higher emissions than the others. Ningxia, Xinjiang, Inner Mongolia, Guizhou, and Shanxi are the best representatives of the provinces and still belong to the higher groups with intensities. Conversely, Gansu and Hebei no longer belong to the higher groups with intensities of 4–6 t/10^4 CNY. The Northeast, North Coast, East Coast, South Coast, and Middle Yangtze River regions belong to the lower-intensity groups. Emissions and there intensity are predicted to show large changes in their time and space after the reduction plans.



(**a**) (**b**)

Figure 9. Provincial emissions and emission intensity distribution (**a**) CO_2 emissions in 2015; and (**b**) Emission intensity in 2015.

Based on the same assumptions described in Section 4.2, the national CO_2 emissions and emission intensity in 2015 can also be calculated. The results show that the national emissions are 15,687.76 M_t and intensity is 2.24 t/10^4 CNY. If fully in accordance with the national emission reduction target compared with the 2010 level, the national emission intensity needs to decrease to 2.21 t/10^4 CNY and the national emissions to 15,464.42 Mt. The national emissions increased by nearly 4000 Mt compared with the level in 2010. According to the definition of completion of the national reduction target, the end result is 92.95%. The national emission intensity decreased by 15.80%. This value is extremely close to achieving the national emission reduction plan.

4.4. Assessment of Reduction Pressure

The CO_2 emissions of every province were forecasted in 2015 using historical emission data from 1995 to 2012. These historical data on emissions were all calculated by the model described in Section 2.1. The forecasting values of 2015 and D index results are shown in Table 3.

Table 3. Forecasting emissions in 2015 and D index.

Province	Forecasting Value (M_t)	D Index (M_t)	Province	Forecasting Value (M_t)	D Index (M_t)
Beijing	140.29	−34.86	Henan	715.48	−142.39
Tianjin	272.91	−3.31	Hubei	533.75	−0.47
Hebei	1068.03	−27.52	Hunan	349.23	−80.71
Shanxi	762.57	−322.13	Guangdong	738.64	2.53
Inner Mongolia	917.59	18.06	Guangxi	394.00	143.65
Liaoning	830.40	−145.21	Hainan	79.65	−13.77
Jilin	323.14	−55.91	Chongqing	245.63	−17.83
Heilongjiang	404.04	−89.48	Sichuan	407.03	−145.84
Shanghai	295.52	−38.27	Guizhou	344.96	−19.89
Jiangsu	917.04	−70.59	Yunnan	258.07	−63.35
Zhejiang	507.38	−61.07	Shaanxi	557.72	27.83
Anhui	467.23	−2.72	Gansu	250.64	−14.49
Fujian	327.92	3.61	Qinghai	88.80	25.50
Jiangxi	227.08	−33.49	Ningxia	314.20	107.05
Shandong	1257.30	−230.88	Xinjiang	632.04	226.45

Logistic curves effectively describe the historical CO_2 emissions of each province. A difference exists between the forecasting value and total control value in 2015. According to the definition of index D, a positive value signifies that the total control emissions are less than the forecasted value, which indicates that total control is not adequate to normal development demand. A greater value D indicates greater pressure. Xinjiang, Guangxi, Ningxia, Qinghai, Shaanxi, Inner Mongolia, Fujian, and Guangdong are expected to have reduction pressure. These provinces are distributed in the Northwest and South Coast regions in mainland China. By comparing the provincial increments of CO_2 emissions in the 11th FY and 12th FY, the P index was calculated. A ratio of 50% was used as group rule for classification, and the P value was used to classify four groups. The distribution result is shown in Figure 10.

P value that is greater than 100% indicates that the control increments of emissions in the 12th FY are less than those at the 11th FY level. A greater P value corresponds to greater pressure to reduce emissions. The reduction plan in the 12th FY is difficult to produce. Zhejiang and Guangdong are in the first group of pressure, and they belong to the East Coast and South Coast regions, respectively. Hebei and Shandong in the North Coast region; Shaanxi, Henan and Inner Mongolia in the Middle Yellow River region; Hubei and Anhui in the Middle Yangtze River region; and Fujian and Hainan in the South Coast region are in the second group of pressure. The second group of pressure also includes Xinjiang and Guangxi, which belong to the Northwest and Southwest regions, respectively. The same groupings were found in the results of index D and P calculation. Xinjiang, Inner Mongolia, Shaanxi, Guangxi, Guangdong and Fujian have greater reduction pressures in the 12th FY. The South Coast and Northwest China regions have a greater reduction pressure of emission intensity.

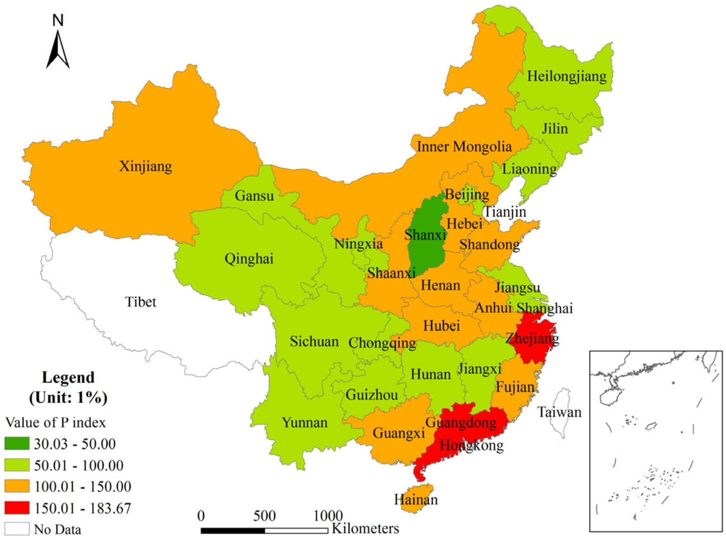


Figure 10. Distribution of P index.

The verification of the predictions is attempted based on the latest available data on provincial emissions in 2012. Provincial emission intensity is calculated in 2012 to estimate their completion of reduction plan compared with the level in 2010 (Table 4).

Table 4. Provincial completion of reduction plan in 2012 and incompletion before 2015.

Province	Completion in 2012	Incompletion before 2015	Province	Completion in 2012	Incompletion before 2015
Beijing	19.15%	−1.15%	Henan	14.92%	2.08%
Tianjin	16.63%	2.37%	Hubei	9.67%	7.33%
Hebei	6.47%	11.53%	Hunan	11.13%	5.87%
Shanxi	7.06%	9.94%	Guangdong	10.09%	9.41%
Inner Mongolia	−2.98%	18.98%	Guangxi	−11.01%	27.01%
Liaoning	9.78%	8.22%	Hainan	−2.34%	13.34%
Jilin	11.00%	6.00%	Chongqing	14.04%	2.96%
Heilongjiang	8.03%	7.97%	Sichuan	18.95%	−1.45%
Shanghai	12.70%	6.30%	Guizhou	4.11%	11.89%
Jiangsu	4.38%	14.62%	Yunnan	13.46%	3.04%
Zhejiang	12.69%	6.31%	Shaanxi	−0.22%	17.22%
Anhui	10.02%	6.98%	Gansu	3.99%	12.01%
Fujian	8.15%	9.35%	Qinghai	−17.48%	27.48%
Jiangxi	9.18%	7.82%	Ningxia	−13.72%	29.72%
Shandong	9.13%	8.87%	Xinjiang	−11.44%	22.44%

As of the end of 2012, Beijing and Sichuan had completed their reduction targets. Some provinces whose emission intensity reached a higher level than those in the 2010s are Qinghai, Ningxia, Xinjiang, Guangxi, Inner Mongolia, Hainan, and Shaanxi. Therefore, before the end of 2015, they faced great pressure to complete their reduction targets. Moreover, Fujian, Guangdong, Gansu, and Hebei had to decrease their emission intensity to nearly 10%. From 2013 to 2015, a greater reduction pressure is basically concentrated in the South Coast and Northwest China regions. These calculation results are consistent with those from the aforementioned two pressure indices.

5. Conclusions

A new computing framework was proposed to calculate provincial CO_2 emissions from 2005 to 2010 in China, and the composition of CO_2 emissions and spatial-temporal variations were analyzed. Then, China's 12th FY (2011–2015) reduction plan was then analyzed in depth, and the provincial total control of CO_2 emissions in 2015 was calculated. The pressure of reduction was finally assessed for every province. The main conclusions are presented as follows.

When calculating the provincial CO_2 emissions, energy consumption is the main source of China's provincial CO_2 emissions. However, emissions of cement production and absorption of forest and green land cannot be ignored. The overall spatial-temporal variations of CO_2 emissions in 2005–2010 reflected that emissions were increasing over time with a decreasing distribution from east to west, and intensity was decreasing over time with an increasing distribution from south to north. The North Coast and East Coast regions had high emissions, whereas the Middle Yellow River, Northwest, and Southwest regions had high emission intensities.

The total control of CO_2 emissions in 2015 was determined. After every province executed the 12th FY reduction plan to control CO_2 emissions, the CO_2 emissions of each province in target year 2015 is expected to exhibit a significant growth compared with the level in 2010. An increasing number of provinces will shift to the top emitting group. The Southwest and Northwest regions have higher emission growth rates although the amounts are still less than those in the North, East, and South Coast regions. In 2015, the overall distribution of provincial emissions and emission intensity will not change. The national emission intensity decreased by 15.80% when the provinces had reduced the emission intensity in accordance with the reduction plan. This value is extremely close to achieving the national emission reduction plan.

The reduction pressure on emission intensity was assessed when every province conducted its reduction target in the 12th FY. The provinces with greater pressure of reduction were chosen through two designed indices. The classifications by the indices provided the same results. They indicated that Xinjiang, Inner Mongolia, Shaanxi, Guangxi, Guangdong, and Fujian had greater reduction pressure in the 12th FY. The South Coast and Northwest regions had a greater reduction pressure on CO_2 emissions based on the division of provinces.

6. Policy Implications

According to the calculations and analysis conducted in the present study, the following superficial policy implications are presented to serve as references for decision makers to control CO_2 emissions in China. Several provinces are confronted with high pressures of CO_2 emission reduction during the 12th FY period. To solve this problem, the ratio of utilizing non-fossil or low-carbon energy should be improved. Some provinces with low economic levels have high pressure to reduce CO_2 emissions; for example, Xinjiang, Inner Mongolia, Shaanxi, and Guangxi have to propose more strategies of CO_2 emission reduction to guarantee economic development. Some provinces that have high economic levels but low CO_2 emission intensity (e.g., Beijing, Shanghai, and Guangdong) should pay more attention to optimizing the energy consumption structure, increasing the ratio of technology-intensive industries, and promoting the development of low-carbon industry. Some provinces such as Shanxi, Inner Mongolia, Xinxiang, Ningxia, and Guizhou have abundant fossil energy resources, and their economy is dependent on energy consumption. To enforce them to have the same targets as other provinces is inappropriate. CO_2 emission reduction targets should be set according to local conditions. Moreover, central and western China, which are lagging behind economically, should actively promote low carbon development, and accelerate transformation of economic development patterns, ensuring sustainable economic growth.

Most provinces of China are still in the industrialization stage; therefore, a faster speed of economic growth expectations inevitably leads to greater energy demand and CO_2 emissions. Economic development that is overheated or too fast in a short period can induce significant growth of energy-intensive industries and products and, consequently, the increase of emission intensity. Thus, to achieve the national CO_2 emission reduction target, all intra-regions, especially Shaanxi, Hainan, and Chongqing, should consider the national reduction target of CO_2 emission intensity more than setting the speed of economic development. Eventually, maintaining economic growth at an appropriate and stable level will decrease the CO_2 emission intensity. Thus, the national CO_2 emission reduction target could likely be realized. The CO_2 emissions of the country and provinces will continue to increase while the intensity reduction plan is executed. If the future reduction plan chooses to reduce total emissions, the national and provincial targets will be extremely difficult to achieve. Moreover, economic development will be significantly affected. A future reduction plan should gradually implement more stringent emission reduction policies.

The amount and structure of energy consumption are the critical influencing factors of regional CO_2 emissions. The optimization of energy utilization mode, improvement of energy utilization efficiency, and the development and application of new energy and renewable energy favor CO_2 emission reductions. The most important point of realizing a low-carbon economy is a reasonable adjustment of the energy structure (e.g., exploiting hydroelectricity, wind power, solar energy, and biomass energy in the future based on the protection of the natural environment).

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Author Contributions

Xuankai Deng drafted the paper and contributed to data collection and calculation; Yanhua Yu contributed to data analysis; Yanfang Liu conceived and designed the research.

Conflicts of Interest

The authors declare no conflict of interest.

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