

CO₂ emissions from cement industry in China: A bottom-up estimation from factory to regional and national levels

YANG Yan^{1,2,3}, *WANG Limao¹, CAO Zhi^{1,2}, MOU Chufu^{1,2}, SHEN Lei¹,
ZHAO Jianan¹, FANG Yebing^{1,2}

1. Institute of Geographic Sciences and Natural Resources Research, CAS, Beijing 100101, China;

2. University of Chinese Academy of Sciences, Beijing 100049, China;

3. The CAE Center for Strategic Studies, Chinese Academy of Engineering, Beijing 100088, China

Abstract: Much attention is being given to estimating cement-related CO₂ emissions in China. However, scant explicit and systematical exploration is being done on regional and national CO₂ emission volumes. The aim of this work is therefore to provide an improved bottom-up spatial-integration system, relevant to CO₂ emissions at factory level, to allow a more accurate estimation of the CO₂ emissions from cement production. Based on this system, the sampling data of cement production lines were integrated as regional- and national-level information. The integration results showed that each ton of clinker produced 883 kg CO₂, of which the process, fuel, and electricity emissions accounted for 58.70%, 35.97%, and 5.33%, respectively. The volume of CO₂ emissions from clinker and cement production reached 1202 Mt and 1284 Mt, respectively, in 2013. A discrepancy was identified between the clinker emission factors relevant to the two main production processes (i.e., the new suspension preheating and pre-calcining kiln (NSP) and the vertical shaft kiln (VSK)), probably relevant to the energy efficiency of the two technologies. An analysis of the spatial characteristics indicated that the spatial distribution of the clinker emission factors mainly corresponded to that of the NSP process. The discrepancy of spatial pattern largely complied with the economic and population distribution pattern of China. The study could fill the knowledge gaps and provide role players with a useful spatial integration system that should facilitate the accurate estimation of carbon and corresponding regional mitigation strategies in China.

Keywords: China; cement industry; CO₂ emissions; bottom-up estimation; spatial integration

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Author: Yang Yan (1984–), PhD, specialized in resource industrial economics. E-mail: yycasw13@163.com

***Corresponding author:** Wang Limao (1962–), Professor, specialized in energy economics and climate change policy. E-mail: lmwang@igsnr.ac.cn

1 Introduction

The core issue of sustainable economic and society development nowadays is how to coordinate development of carbon emissions and economy (Wang *et al.*, 2014). Since the cement production industry is one of the largest waste emitters, it has a significant detrimental effect on environment, especially when CO₂ amounts to 99.2% of the related emissions (Chen *et al.*, 2015). The high-speed growth of Chinese economy and the concomitant accelerated rate of urbanization have brought about the consumption of large quantities of cement. Consequently, anthropogenic carbon emissions from cement producing in China contribute nearly half of the global volume of emissions related to this industry. Over the past three decades, China has been the largest cement producer in the world (Ke *et al.*, 2013), with 2414 million metric ton (Mt) in 2013 (CIIN, 2014a), which accounted for 59.16% of the global cement production (USGS, 2014). In view of the above-mentioned data, the conflicting pressures of global climate change and domestic industrial structure adjustment make it clear that the cement industry plays a significant role in domestic carbon mitigation efforts in China. Accordingly, academia has been giving much attention to the topic of CO₂ emissions relevant to the Chinese cement industry (Ke *et al.*, 2012, 2013; Xu *et al.*, 2012, 2014; Wang *et al.*, 2014; Shen *et al.*, 2015; Cao *et al.*, 2016a, 2016b).

Accurate estimation of CO₂ emissions is a key prerequisite to the implementation of carbon reduction in cement industry. Various useful studies have conducted on the estimation of cement-related CO₂ emissions in China. Most studies focused on calculation methods for the micro-level cement-related CO₂ emission factors, uncertainties, and major determinants of emissions (Ke *et al.*, 2013; Gao *et al.*, 2015; Wei *et al.*, 2012; Shen *et al.*, 2014). Others considered the macro-level cement-related CO₂ emission inventories based on default factors (Cui and Liu, 2008; Lei *et al.*, 2011). However, less explicit and systematical advancement has so far been seen in macro-level estimation of cement CO₂ emissions at factory-, regional- and national-level integration based on extensive samples. China Building Materials Academy conducted a survey on 13 Chinese representative cement plants, using the integration method of arithmetic average, revealed the CO₂ emission characteristics of domestic 2500–6000 t/d clinker production lines (Wang L X *et al.*, 2010). The carbon special research group from Chinese Academy of Sciences exploited a two-stage random sampling and proposed a bottom-up factory-level weighted average method (Wei *et al.*, 2013, 2014; Shen *et al.*, 2014). We note that there remain two main limitations in the simple random method in the previous work:

- The simple random method could not provide accurate estimation of mean and variance for sampled regions;
- The simple random method could not provide accurate inference for unsampled regions.

To fill these gaps, we establish an improved three-level bottom-up carbon spatial-integration system taking advantage of sandwich estimation approach, which is one of the widely used sampling estimation in the field of environmental and social research (Wang *et al.*, 2002, 2013; Liu, 2015). Bringing the prior knowledge (i.e., the key influencers on the space distribution of carbon emission factors in cement industry, such as cement-with-limestone quality, coal quality, technical level, investment level, and electricity emission factors for regional power grids) into the calculation process of spatial statistical inference, this paper

aims to provide a more accurate estimation for cement CO₂ emissions on regional and national level. In the bottom-up spatial-integration system, we categorize the cement production technologies as the NSP process and the VSK process. The spatial heterogeneity of cement CO₂ emissions is incorporated into the estimation as well. In addition, this paper conducts a comparative analysis for the CO₂ emission intensity of the NSP process and the VSK process. The spatial characteristics of CO₂ emissions related to Chinese cement industry are presented. The results of this paper offer a benchmarking of CO₂ emission factors for cement industry, which can facilitate the stakeholders and policy makers to comprehend the CO₂ emissions of the Chinese cement industry and formulate macro mitigation strategies (Chuai *et al.*, 2012).

2 CO₂ emissions and their major determinants from the cement industry

The cement production process consists of three main stages (Shen *et al.*, 2014): kiln feed preparation, clinker production, and cement manufacturing, excluding mining and quarrying. During these stages, CO₂ is emitted mainly directly from the combustion of fossil fuels and the calcination of calcium carbonate (CSI, 2011). An indirect amount of CO₂ derives from the consumption of electricity, generated by combusting fossil fuels (CSI, 2011). Approximately 90% of CO₂ emissions from the cement production process are direct emissions, whereas the remaining 10% originate from the transportation of raw materials and other production processes (Mikulčić *et al.*, 2013).

This information can be clearly expressed with the following equation:

$$\begin{aligned} \text{Total CO}_2 \text{ emissions} &= \text{CO}_2 \text{ emissions}_{\text{direct}} + \text{CO}_2 \text{ emissions}_{\text{indirect}} \\ &= (\text{CO}_2 \text{ emissions}_{\text{calcination process}} + \text{emissions}_{\text{fuel combustion}}) + \text{emissions}_{\text{electricity consumption}} \end{aligned} \quad (1)$$

CO₂ emissions from calcination process can be defined as “process emissions” (Ke *et al.*, 2013), which contain CO₂ from chemical reactions between raw materials (mainly calcium carbonate), CO₂ from CKD (cement kiln dust), and CO₂ from organic carbon (CSI, 2011; Ke *et al.*, 2013; Wang *et al.*, 2013; Shen *et al.*, 2014). The process emissions are determined by the raw meal consumed, the carbonate source content in the raw meal, various alternative materials (Rattanashotinunt *et al.*, 2013), and the quality of the clinker (Liu and Li, 2010; Gao *et al.*, 2015).

CO₂ emissions from fuel combustion can be defined as “fuel emissions” (Gao *et al.*, 2015) or “combustion emissions” (Shen *et al.*, 2014), which contain CO₂ from coal, petroleum coke, liquid/solid waste fuels, natural gas, and other new waste streams (CSI, 2011; Shen *et al.*, 2014). The fuel emissions are determined by the fuel intensity (Ali *et al.*, 2011), the TC (total carbon) content in the fossil fuels, and the carbon oxidation factors (Tu, 2003), as well as the alternative fuels (Aranda *et al.*, 2013; Rovira *et al.*, 2010).

CO₂ emissions from electricity consumption can be defined as “electricity emissions” (Shen *et al.*, 2014) or “indirect emissions”, which contain CO₂ from motors, the fans and blowers used for whirling a kiln, drying, heating, and the grinding of materials, feeds, or clinkers (CSI, 2011; Shen *et al.*, 2014). The electricity emissions are determined by the amount of electricity consumed and the electricity emission factors.

Our previous overview in this section, relevant to the differences in CO₂ emissions and their determinants in the cement industry, has indicated major factors that affect the spatial disparities of the CO₂ emissions. Accordingly, in our study on spatial integration, utilizing this prior knowledge is the significant basis of the value estimation and inference in the research area. Therefore, this is considered as the key element of the sandwich estimation of the NSP clinker emission factors presented in section 3.3.2.

3 Data and methods

3.1 Data

The data for this paper were obtained from the Strategic Priority Research Program, namely *Emissions from Cement Production*, of the Chinese Academy of Sciences (XDA 0510400). Using spatially stratified sampling, our research group had completed a large-scale sampling survey of cement production lines in 24 provinces in China, up to October 2015. The sampling survey includes 191 NSP process production lines, 75 VSK process production lines,

and 94 special cement and/or grinding lines, amounting to a total of 360 production lines and 1870 samples. The focus of our analysis is on two major whole- production processes, namely, NSP and VSK (Figure 1), whereas the production of special cement is not considered because of its negligible production amount.

During the large-scale sampling survey, we obtained the input data mainly from a field survey on production lines for the period 2011–2015. Furthermore, we obtained socioeconomic data, cement industry data, and geological data. Table 1 shows the micro & macro data sources for this paper.

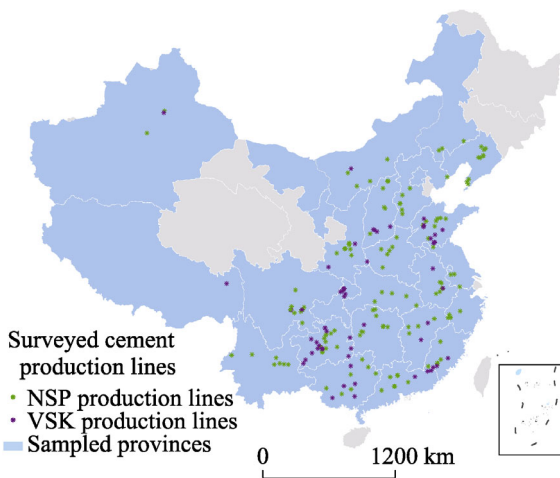


Figure 1 Locations of the surveyed cement production lines¹

3.2 Integration system for the bottom-up estimation of CO₂ emissions

In this section, we establish a spatial integration system for the production- line CO₂ emissions of the cement industry in China (Figure 2). This integrated system is an improvement of the work following the IPCC tier three (IPCC, 2006) and the bottom-up factory-level sampling method (BFSM) (Shen *et al.*, 2014), and includes three progressive levels. We are required to sequentially integrate the three progressive levels.

The factory level is the first level of integration. Our main task is to calculate all the CO₂

¹Note: for the object of study in this paper, Figure 1 shows the two major whole-production lines, including 191 NSP process production lines and 75 VSK process production lines. Each line contains 5–7 samples; meanwhile, some sampling enterprise contains 2–3 sampling production lines at different scales (in the same geographical location).

Table 1 The micro and macro data sources for this paper

| Data types | Data indexes | Data sources |
|------------------------------------|--|--|
| Production data from cement plants | The production-line scale of enterprises; Annual clinker and cement production | Field survey |
| | Annual consumption of coal; Annual consumption of electricity (including waste-heat power deduction) | Field survey |
| | Weighted-average lower heating value (LHV) of coal; Coal fuel- moisture content | Field survey |
| | Full chemical composition and individual proportion of raw meal/coal/ clinker (annual average); Each material ratio in raw meal (annual average) | Field survey |
| Socioeconomic data | GDP per capita | China Statistical Yearbook (2014) |
| Cement industry data | Technical level; Investment level; Scale level, Profit level; Total clinker output; Total cement output | China Cement Almanac (2012–2014); China Industry Information Network (2014a, 2014b, 2014c) |
| Geological data | Partitions of cement-with-limestone reserves and quality | The Information Center of the MLR (Ministry of Land and Resources of the PRC); CBMA (China Building Materials Academy) |
| | Partitions of coal quality | The Institute of Coal Chemistry, Chinese Academy of Sciences; Chen, 2009 |

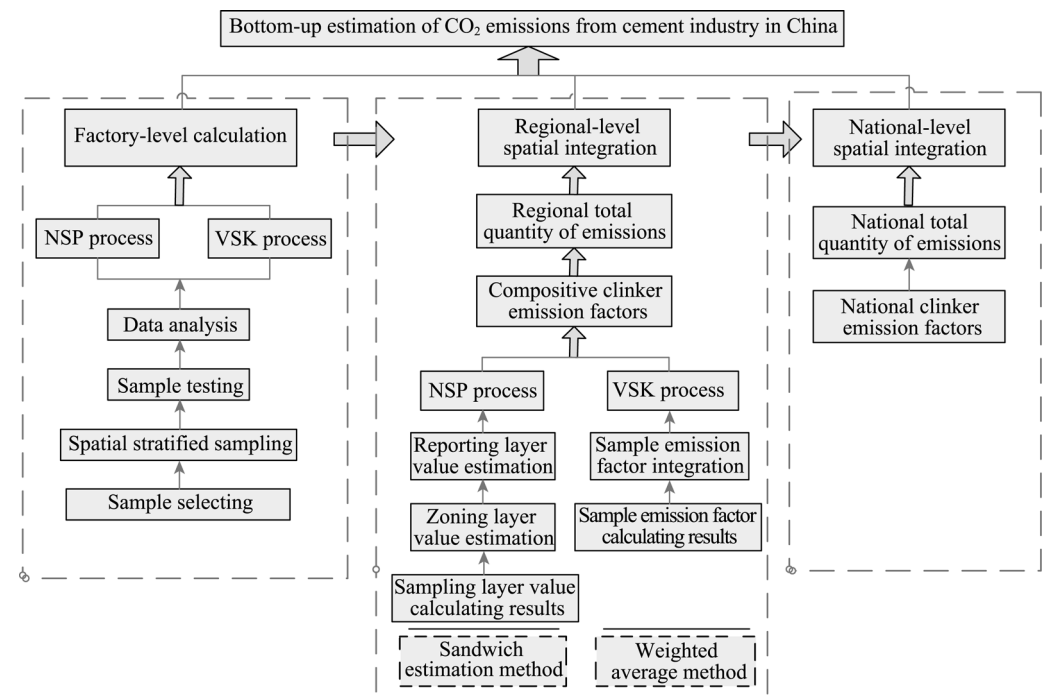


Figure 2 The framework of bottom-up CO₂ emission spatial-integration system

emission factors related to the production lines, based on the samples from the 24 provinces in China. However, before we can proceed to the calculations, substantial basic work is needed, which includes sample selecting, spatial stratified sampling, sample testing, and

production line data analyzing (including the data relevant to the two main kilns of the NSP and the VSK processes). The sample data processing results are represented in Table 2.

Table 2 Sample data processing results for this paper

| Process types | Units of clinker emission sources | Number (valid samples) | Max | Min | Difference | Average | Mean square deviation |
|---------------|-----------------------------------|------------------------|------|------|------------|---------|-----------------------|
| | | | kg/t | kg/t | kg/t | kg/t | |
| NSP process | Process emissions | 164 | 556 | 478 | 78.83 | 520 | 14.28 |
| | Fuel emissions | 162 | 391 | 261 | 129.24 | 312 | 26.51 |
| | Electricity emissions | 161 | 98 | 14 | 83.28 | 46 | 20.73 |
| VSK process | Process emissions | 64 | 529 | 392 | 137.52 | 501 | 20.76 |
| | Fuel emissions | 59 | 548 | 286 | 262.73 | 351 | 60.18 |
| | Electricity emissions | 63 | 114 | 37 | 76.32 | 59 | 15.79 |

After obtaining the three major emission factors relevant to all the production lines, we sequentially conduct the regional-level and national-level spatial integration to estimate the average clinker CO₂ emission factors and the total quantity of CO₂ emissions, respectively. As regards the second level, the task at the regional-level spatial integration can be divided into three parts. They are, the regional-level spatial integration related to the NSP clinker emission factors, the VSK clinker emission factors, and the total quantity of clinker & cement emissions. Relevant to the third level, the national-level spatial integration can be divided into two parts, namely, the national-level spatial integration related to the clinker emission factors and the total quantity of clinker & cement emissions.

Based on energy efficiency, the current production of cement in China includes mainly two typical types of technology processes (CIIN, 2014b, 2014c; CCA, 2014; China Cement, 2015), which are the NSP and the VSK processes (Ke *et al.*, 2013). Besides, it is well known that CO₂ emissions derive primarily from the clinker manufacturing because of the characteristics of the cement production process, as well as the major determinants of carbon emissions within the process. Therefore, in this paper, the focus is on the clinker production process in relation to the spatial integration of emission factors (Gao *et al.*, 2015).

3.3 The implementation of the spatial integration system

3.3.1 Level one: factory-level calculation

(1) CO₂ emission factors from calcination process:

The process emissions include those from carbonate calcination and non-carbonate calcination (CBMA, 2011; Shen *et al.*, 2014). The calculation formulae can be expressed as follows:

$$P_{pro} = P_{rc} + P_{ro} \quad (2)$$

$$P_{rc} = R_{\text{carbonate calcination in raw meal}} + R_{\text{flue gas dust in kiln-head}} + R_{\text{bypass dust}} \quad (3)$$

$$P_{ro} = r_a \cdot R_o \cdot \frac{44}{12} \quad (4)$$

where P_{pro} represents the process CO₂ emission factors (t CO₂/t clinker); P_{rc} represents the CO₂ emission factors from carbonate calcination (t CO₂/t clinker), which include three types

of sources (Formula (3), Table 3); P_{ro} represents the CO₂ emission factors from non-carbonate calcination (mainly from the combustion of organic carbon) (t CO₂/t clinker); R_o presents the carbon content in the raw meal (%); $\frac{44}{12}$ is the CO₂ content in the carbon.

Table 3 Descriptions of indicators for the CO₂ emission factors from carbonate calcination

| Indicators and their calculating methods | Explanations |
|---|---|
| $R_{carbonate\ calcination\ in\ raw\ meal} = Ra_{co_2} \times r_a \times 1000$ $Ra_{co_2} = \sum \left(Rca_i \times r_i \times \frac{44}{56} + Rmg_i \times r_i \times \frac{44}{40} \right) (i = 1, 2, 3, \dots)$ $r_a = \frac{1 - C_{cl} \times A_c}{1 - R_l}$ | Ra_{co_2} is the CO ₂ content in the raw meal (%); r_a is the raw meal-to-clinker ratio (t/t clinker); Rca_i and Rmg_i are respectively the calcium carbonate and magnesium carbonate content in the raw material i (%); r_i is the share of the raw material i in the raw meal (%); 44/56 and 44/40 are respectively the CO ₂ content in calcium carbonate and magnesium carbonate; C_{cl} is the coal consumption (dry) for producing a unit of clinker (t/t clinker); A_c is the ash content of coal (%); R_l is the loss on ignition of the raw meal (%). |
| $R_{flue\ gas\ dust\ in\ kiln-head} = \frac{R_{carbonate\ calcination\ in\ raw\ meal} \cdot U_e}{1000}$ | U_e is the amount of flue gas dust emissions per ton clinker in the cement kiln-head (kg/t clinker). |
| $R_{bypass\ dust} = \frac{Q_d \cdot B_e}{1000}$ $B_e = R_{carbonate\ calcination\ in\ raw\ meal} \cdot \left(1 - \frac{R_b}{R_l} \right)$ | Q_d is the quantity of bypass dust per ton of clinker production (kg/t clinker); B_e is the CO ₂ emissions from the bypass dust in producing a unit of clinker (kg/t clinker); R_b is loss on ignition of the bypass dust (%). |

Sources: Gao *et al.* (2014); CBMA (2011); Shen *et al.* (2014)

(2) CO₂ emission factors from fuel combustion:

As regards the fuel emissions, we take into account the fuel consumption and the corresponding CO₂ emission factors (CBMA, 2011) (Formula (5)).

$$P_f = C_f \times EF_f \quad (5)$$

where C_f is the fossil fuel consumption relevant to per ton of clinker production (kg ce/t clinker), and EF_f is the CO₂ emission factors from fossil fuel combustion (kg CO₂/kg ce).

(3) CO₂ emission factors from electricity consumption:

As regards the electricity emissions, we use the amount of electricity consumed and the electricity emission factors relevant to the regional power grids in China (Shen *et al.*, 2014) (Formula (6)).

$$P_e = C_e \times EF_e \quad (6)$$

where C_e is the electricity consumption from a unit of clinker production (kWh/t clinker), and EF_e is the regional electricity emission factors (kg CO₂/kWh).

Based on the above calculation methods, the CO₂ emission factors from clinker production (P_{cl} , kg CO₂/t clinker) can be expressed using the following formula:

$$P_{cl} = P_{pro} + P_f + P_e \quad (7)$$

3.3.2 Level two: regional-level spatial integration

(1) Regional-level spatial integration of NSP clinker emission factors:

In 2013, the Portland cement clinker production employing the NSP process increased to approximately 1195 Mt, accounting for 87.7% of the total Portland cement clinker production in China (CIIN, 2014a, 2014b). Therefore, our major regional integration approach for

clinker emission factors is reflected in the NSP kiln samples (Figure 3). To achieve a more accurate estimation, we use the sandwich estimation method to integrate the factory-level process emission factors, fuel emission factors, and electricity emission factors, respectively. The summary of the aforementioned three parts represent the regional mean values of the NSP clinker emission factors.

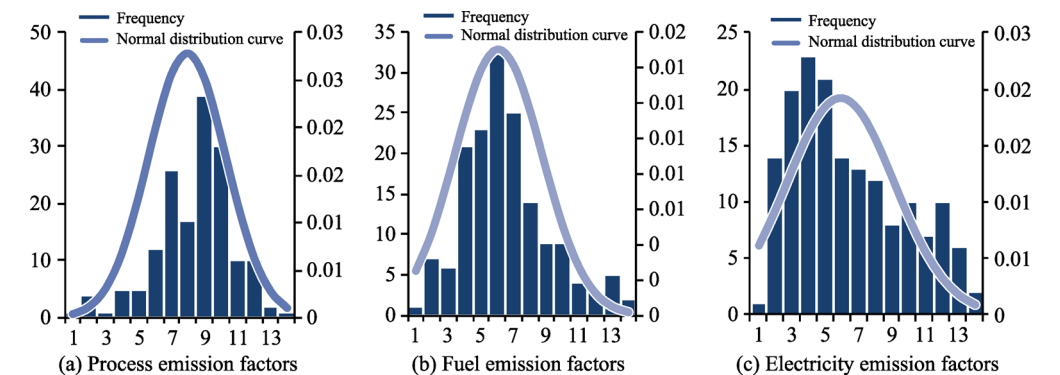


Figure 3 The probability distribution of NSP sample data

The sandwich spatial estimation model, put forward by Wang *et al.* (2002; 2009; 2013), is an effective design-based approach to spatial sampling and statistical inference for multi-unit reporting on stratified heterogeneous surfaces.

By introducing a “knowledge layer” (i.e., “zoning layer”) (Wang *et al.*, 2002; 2010a), the model breaks away from the traditional sampling and statistic strategy. Fully considering the spatial heterogeneity characteristics of a surveyed object, this model separates the reporting unit from the surveying unit. Moreover, it can indirectly convert the information obtained from limited samples to the randomly distributed multiple reporting units, by means of the optimized knowledge layer. Thus, it achieves the goal of using a small amount of samples to make a statistical inference on multiple reporting units. Just the features and advantages of “small sample amount, multiple reporting units, high estimation precision”, make it have a

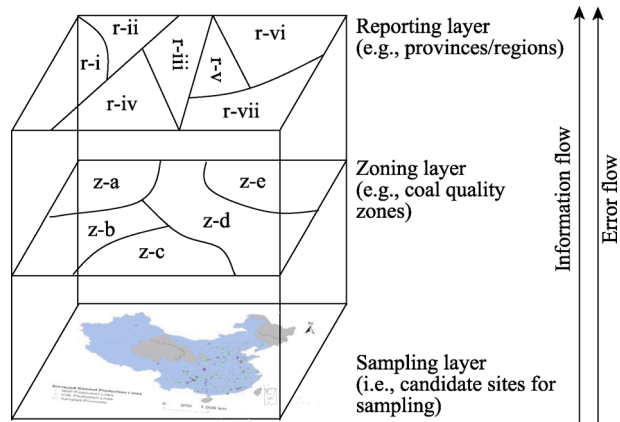


Figure 4 The conceptual model of sandwich estimation (Wang *et al.*, 2013)

high application value in the relevant fields, such as regional economics, industrial economics, and public services (Wang *et al.*, 2009; Liu, 2015). It is defined as “sandwich estimation” mainly owing to its three-layer structure (Figure 4), i.e., three layers above the bottom layer, which consist of a sampling layer, a zoning layer, and a reporting layer. Overlaid, the structure indicates the information, mean, and error flow from the sampling layer to the zoning layer and finally to the reporting layer (Wang *et al.*,

2013).

The sampling layer represents the sample units, e.g., the cement manufacturing plants for the sampling. The zoning layer above the sampling layer, also called the knowledge layer, implies surface classification, dividing the study area into several subareas that are spatially homogeneous (constant mean), e.g., partitions of technical/investment level. Prior knowledge about the variability of real surface can be used either to reduce the sample size for a given level of estimate precision, or to improve the precision of the estimate (Wang *et al.*, 2002; 2010a; 2013). The reporting layer above the zoning layer consists of spatial reporting units, which can be administrative units of provinces, cities, counties, postal zones, or the census units of a region (Wang *et al.*, 2002; 2013). This paper defines the reporting units as the 31-province administrative units, 15-region geographical units, and 7-region geographical units (Chuai *et al.*, 2012), to achieve more accurate mean estimation from microscopic points to mesoscopic regions, and finally to macroscopic regions² (see Tables 7-9).

In this paper, we choose the sandwich estimation method for the NSP CO₂ emission factor regional-level spatial integration, is based on the considering as follows:

(1) The simple random method cannot bring researchers' prior knowledge on surveying object (e.g., variation function, influencing factors, space zoning characteristics, etc.) into the calculation process.

(2) The results of Moran's I indicate a weak space correlation of sample points. In this case, it is difficult to obtain satisfactory results by means of statistical methods based on spatial correlation assumption.

(3) The previous studies show factors such as cement-with-limestone quality, coal quality, technical level, investment level, and electricity emission factors for regional power grids, have a significant effect on the space distribution of carbon emission factors. According to the principle of sandwich model, we can achieve the aim to bring the prior knowledge (i.e., these key influencers) into calculation process. As a result, the accuracy of statistical inference can be significantly improved.

Furthermore, stratifying can improve the sampling efficiency, according to the stratified sampling theory. As long as the stratifying reflects the spatial heterogeneity characteristics of surveying object, sampling efficiency would be improved, even if the stratification was very rough. Hence, different from those methods like the Kriging model, the sandwich method does not require users to acquire adequate theoretical knowledge. Researchers can achieve the model application in a short time.

How can we use the sandwich model to achieve a reasonable average statistical inference for the NSP clinker emission factors in China? This is the focal problem we are going to solve, on the basis of the already understanding of CO₂ emission sources and their main influencing factors in cement production, as well as the given samples. This problem can be resolved through the following four steps:

Step 1: Selection of zoning layers (knowledge layers)

The quality of the estimation at the reporting layer depends critically on constructing good zoning (Li *et al.*, 2008). According to the main sources of evidence for zone construc-

² Note: There exists uneven distribution of samples in the 31 provinces. We merge the units containing the same parameters to ensure each unit has samples, for more accurate estimation. Then we obtain the 15-region geographical units. This paper takes the authoritative 7-major geographical units as the final regional-level reporting layer.

tion proposed by Wang *et al.* (2010a), understanding and utilizing of the “prior knowledge” of CO₂ emissions from the cement industry can effectively and efficiently aid in selecting and optimally configuring the zoning layers. In view of this, relevant to the three main sections of CO₂ emissions in cement production process and the individual determinants (see section 2), we consider three kinds of zoning layers (Figure 5).

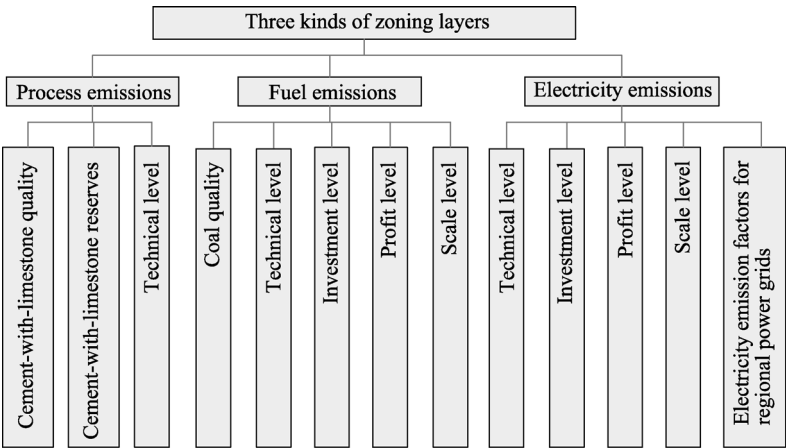


Figure 5 Three kinds of zoning layers (knowledge layers)

Step 2: Exploratory analysis of data

The aim of this step is to determine the applicability of the sampling data calculations with the sandwich model. The spatial correlation is a key judgment standard (Wang *et al.*, 2002; 2013). In this paper, the exploratory results show very weak correlation for the overall spatial correlation (Moran’s I: 0.189 (process emissions), 0.246 (fuel emissions), 0.191 (electricity emissions)), but a relatively high correlation for the local spatial correlation (Figure 6), which imply sandwich model is suitable.

Step 3: Fusion of multiple prior knowledge layers

It is necessary to perform fusion of the multiple prior knowledge layers to measure the representative extent (or explanatory power) of these preliminary selected zoning layers for the research area. In this paper, we use the power of determinant (PD) value from the factor detector (within the four geographic detector tools in Wang *et al.* (2010b)), to determine the knowledge layers (zoning layers) we could bring into the sandwich model. Tables 4 – 6 show the fusion results of multiple prior knowledge layers.

Step 4: Realization of the sandwich estimation

After completion of the abovementioned three steps, this step is done to realize the sandwich estimation by parallelization processing (computing). We use the *Sandwich Spatial Estimation Software* (<http://www.sssampling.org/sandwich/>) to realize the regional-level mean and variance estimation of the NSP clinker emission factors.

(2) Regional-level spatial integration of VSK clinker emission factors:

As regards the VSK process, because of its extremely small proportion of production in the current cement industry of China, as well as our concerns on sample quality, we employ the weighted average method to obtain a relatively accurate estimation result. The regional

VSK clinker emission factors are the integrated values that can be acquired by the estimated means under the three scale layers of the VSK clinker-production lines, multiplying the weights of each scale layer as follows (Formula 8):

$$\bar{y}_i = \sum_{h=1}^3 W_h \bar{y}_h = \frac{1}{N_i} \sum_{h=1}^3 N_h \bar{y}_h \quad (8)$$

where \bar{y}_i denotes the mean values of the VSK clinker CO₂ emission factors in the i -th region; N denotes the total VSK clinker-production lines; N_i is the total VSK clinker-production lines in the i -th region; The weight of the scale layers is indicated by W_h , denoting the mass of the VSK clinker production from three different scale layers of production lines (> 500 t/d, 300–500 t/d, < 300 t/d) contributing to the total regional VSK clinker production; N_h is the total VSK clinker-production lines of the i -th scale layer.

Based on the above integration work, we obtain the regional-level clinker-emission factors for the two process types. Using the respective regional NSP and VSK clinker emission factors, multiplied by the respective regional NSP and VSK clinker output proportion, we finally obtain the synthesized regional-level clinker emission factors, which are the weighted values from the NSP and the VSK processes.

(3) Regional-level spatial integration of total quantity of clinker and cement emissions:

For the clinker emissions, this means the regional integrated clinker emission factors multiplied by the regional clinker output. For the cement emissions, this refers to the regional integrated emission factors related to the consumption of grinding power, multiplying the regional cement output, added to the regional integrated total quantity of clinker emissions. Here, the regional inte-

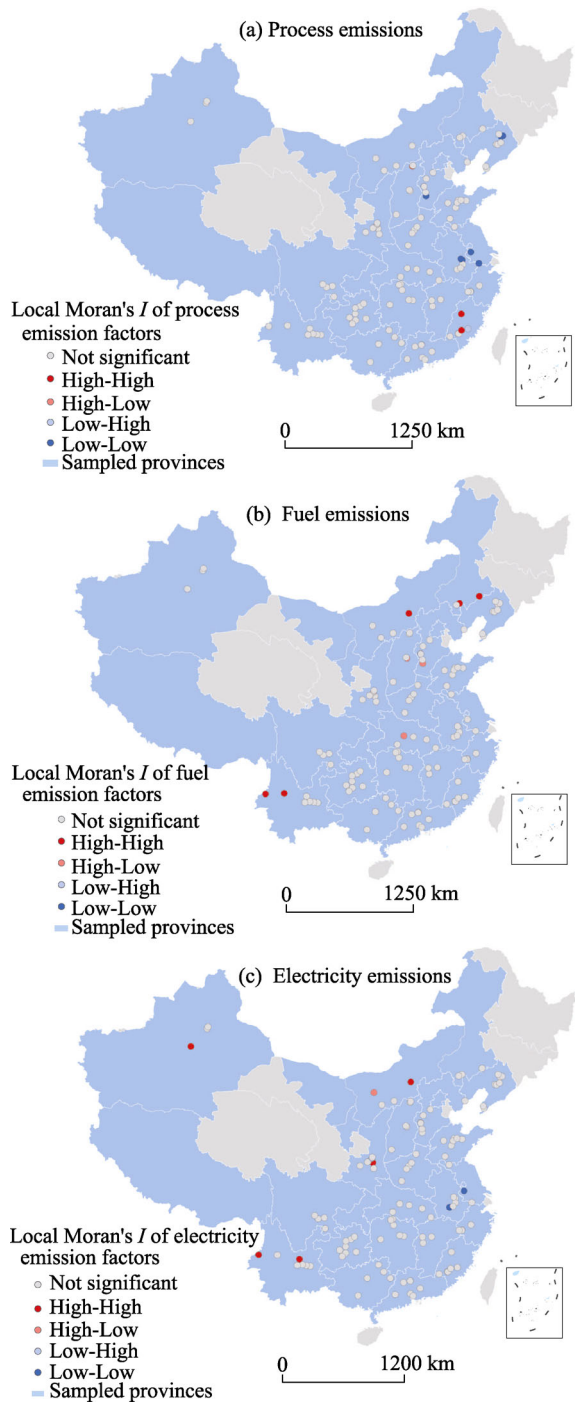


Figure 6 Local Moran's I of the NSP clinker emission factors

grated total quantity of clinker emissions. Here, the regional inte-

grated emission factors related to the consumption of grinding power are the weighted values of these respective regional NSP and VSK grinding-power-consumption emission factors, multiplied by the respective regional clinker proportion.

Table 4 PD values of the prior knowledge layers of process emissions

| Knowledge layer | Cement-with-limestone quality | Cement-with-limestone reserves | Technical level | Fusion knowledge layer |
|------------------|-------------------------------|--------------------------------|-----------------|------------------------|
| Power value (PD) | 0.045 | 0.013 | 0.027 | 0.142 |

Table 5 PD values of the prior knowledge layers of fuel emissions

| Knowledge layer | Coal quality | Technical level | Investment level | Profit level | Scale level | Fusion knowledge layer |
|------------------|--------------|-----------------|------------------|--------------|-------------|------------------------|
| Power value (PD) | 0.182 | 0.109 | 0.038 | 0.063 | 0.095 | 0.279 |

Table 6 PD values of the prior knowledge layers of electricity emissions

| Knowledge layer | Technical level | Investment level | Profit level | Scale level | Electricity emission factors for regional power grids | Fusion knowledge layer |
|------------------|-----------------|------------------|--------------|-------------|---|------------------------|
| Power value (PD) | 0.042 | 0.077 | 0.129 | 0.153 | 0.192 | 0.331 |

Note: PD represents the influence of each knowledge layer on the survey data.

3.3.3 Level three: national-level spatial integration

In this section, the national average CO₂ emission factors and the total CO₂ emissions are estimated by considering the weight of the clinker and cement production of each region.

(1) National-level spatial integration of clinker emission factors:

The national clinker emission factors can be acquired by the integrated values of regional clinker emission factors, multiplying the weights of the regional production lines (Formula 9), as follows:

$$\bar{y}_{National} = \sum_{i=1}^7 W_i \bar{y}_i = \frac{1}{N} \sum_{i=1}^7 N_i \bar{y}_i \tag{9}$$

where $\bar{y}_{National}$ represents the mean values of the national clinker CO₂ emission factors; N denotes the total clinker-production lines; N_i denotes the total clinker-production lines in the i -th region; W_i is the weight of the regional production lines, denoting the mass of the regional clinker production contributing to the total national clinker production.

(2) National-level total quantity of clinker and cement emissions:

We use the aggregation values of the regional integrated total quantity of clinker emissions and cement emissions, respectively.

4 Results analysis and discussion

4.1 Spatial integration results of sandwich estimation of NSP clinker emission factors

The estimation results of the regional-level NSP clinker emission factors (by 31 provinces, 15 regions, and 7 regions) obtained with the above methods are listed in Tables 7–9.

Tables 7–9 present the mean values and standard deviation values of three main emission sources from NSP clinker production in the 31-province administrative units, the 15-region

geographical units, and the authoritative 7-region geographical units. The above three tables achieve an increasingly accurate mean estimation from microscopic points to mesoscopic regions, and finally to macroscopic regions.

Table 7 The 31-province integration results of the sandwich estimation of the NSP clinker emission factors (kg CO₂/t clinker)

| Regions | Process emission factors | | Fuel emission factors | | Electricity emission factors | |
|----------------|--------------------------|--------------------|-----------------------|--------------------|------------------------------|--------------------|
| | Mean | Standard deviation | Mean | Standard deviation | Mean | Standard deviation |
| Xinjiang | 525 | 22.34 | 346 | 23.55 | 79 | 9.30 |
| Heilongjiang | 516 | 20.65 | 304 | 22.70 | 39 | 14.47 |
| Jilin | 516 | 20.65 | 294 | 44.59 | 39 | 14.47 |
| Hebei | 520 | 16.83 | 312 | 44.18 | 39 | 14.33 |
| Beijing | 520 | 22.34 | 243 | 22.70 | 60 | 22.44 |
| Tianjing | 520 | 22.34 | 294 | 25.09 | 53 | 25.83 |
| Liaoning | 516 | 20.65 | 296 | 22.70 | 60 | 22.44 |
| Ningxia | 527 | 27.11 | 313 | 36.33 | 55 | 20.47 |
| Shandong | 520 | 20.65 | 307 | 25.30 | 46 | 16.04 |
| Shaanxi | 524 | 14.08 | 313 | 36.33 | 54 | 25.83 |
| Shanxi | 527 | 27.98 | 309 | 35.82 | 58 | 22.12 |
| Qinghai | 528 | 28.39 | 305 | 36.33 | 49 | 21.41 |
| Gansu | 527 | 21.81 | 313 | 36.33 | 55 | 23.51 |
| Henan | 520 | 16.67 | 312 | 24.62 | 47 | 18.52 |
| Jiangsu | 516 | 20.28 | 276 | 23.25 | 30 | 13.08 |
| Tibet | 528 | 28.39 | 311 | 40.42 | 55 | 24.07 |
| Anhui | 519 | 13.88 | 312 | 24.36 | 30 | 12.89 |
| Chongqing | 520 | 19.63 | 303 | 51.50 | 55 | 20.72 |
| Hubei | 518 | 16.77 | 305 | 36.33 | 54 | 20.89 |
| Sichuan | 522 | 13.69 | 304 | 51.33 | 53 | 25.11 |
| Jiangxi | 525 | 13. 50 | 305 | 35.82 | 38 | 7.60 |
| Guizhou | 515 | 21.23 | 311 | 38.95 | 44 | 20.11 |
| Hunan | 518 | 16.77 | 305 | 36.33 | 55 | 23.46 |
| Yunnan | 520 | 16.99 | 321 | 40.42 | 55 | 24.07 |
| Guangxi | 524 | 14.08 | 315 | 40.42 | 48 | 24.07 |
| Shanghai | 520 | 22.34 | 253 | 25.09 | 47 | 18.88 |
| Hainan | 520 | 16.99 | 311 | 40.42 | 49 | 21.41 |
| Zhejiang | 520 | 16.99 | 266 | 23.67 | 30 | 13.08 |
| Fujian | 528 | 16.33 | 302 | 5.10 | 34 | 15.07 |
| Guangdong | 524 | 14.08 | 305 | 36.33 | 37 | 7.93 |
| Inner Mongolia | 520 | 22.34 | 305 | 36.33 | 60 | 22.44 |

Besides, we note a disproportion of the three major parts of emission factors among these regions, which results in a range of 51.69 kg CO₂/t clinker between the maximum (i.e., Northwest China) and the minimum (i.e., Northeast China) emission-intensive regions for

clinker emissions. However, regional gaps relevant to the three parts of the emission sources are mainly embodied in the fuel and the electricity emission factors, which, respectively, show a large mean range of 20.23 kg CO₂/t clinker and 29.59 kg CO₂/t clinker.

Table 8 The 15-region integration results of the sandwich estimation of the NSP clinker emission factors (kg CO₂/t clinker)

| Regions | Process emission factors | | Fuel emission factors | | Electricity emission factors | |
|--|--------------------------|--------------------|-----------------------|--------------------|------------------------------|--------------------|
| | Mean | Standard deviation | Mean | Standard deviation | Mean | Standard deviation |
| Xinjiang | 526 | 4.94 | 338 | 0.72 | 83 | 8.67 |
| Northeast China and eastern Inner Mongoria | 514 | 12.97 | 305 | 12.41 | 47 | 13.08 |
| Beijing, Tianjing, Hebei | 519 | 10.10 | 299 | 15.98 | 42 | 13.83 |
| Shandong | 520 | 14.14 | 306 | 15.25 | 46 | 15.28 |
| Shaanxi | 521 | 11.69 | 314 | 28.41 | 55 | 24.18 |
| Shanxi and central Inner Mongoria | 527 | 13.13 | 314 | 28.41 | 55 | 20.17 |
| Gansu, Ningxia, and western Inner Mongoria | 526 | 6.88 | 314 | 28.41 | 50 | 13.45 |
| Henan, Anhui | 518 | 8.98 | 312 | 28.68 | 41 | 11.51 |
| Shanghai, Zhejiang, and Jiangsu | 524 | 9.67 | 304 | 18.01 | 29 | 6.73 |
| Tibet, Qinghai | 528 | 20.55 | 316 | 21.78 | 46 | 14.83 |
| Sichuan, Chongqing | 519 | 9.58 | 304 | 18.18 | 54 | 18.89 |
| Guizhou | 515 | 14.71 | 321 | 28.56 | 44 | 17.98 |
| Yunnan | 518 | 15.33 | 321 | 29.66 | 52 | 21.17 |
| Fujian | 527 | 14.52 | 303 | 9.13 | 34 | 15.54 |
| Guangdong, Guangxi, and Hainan | 519 | 12.73 | 316 | 21.06 | 42 | 8.43 |
| Hunan, Hubei, and Jiangxi | 518 | 9.28 | 314 | 28.41 | 46 | 10.88 |

Table 9 The 7-region integration results of the sandwich estimation of the NSP clinker emission factors (kg CO₂/t clinker)

| Regions | Process emission factors | | Fuel emission factors | | Electricity emission factors | |
|-----------------|--------------------------|--------------------|-----------------------|--------------------|------------------------------|--------------------|
| | Mean | Standard deviation | Mean | Standard deviation | Mean | Standard deviation |
| Northeast China | 512 | 15.74 | 303 | 13.79 | 46 | 12.61 |
| Northern China | 523 | 7.16 | 307 | 16.91 | 49 | 12.94 |
| Eastern China | 522 | 8.51 | 306 | 10.10 | 35 | 6.37 |
| Central China | 518 | 9.86 | 313 | 21.47 | 48 | 9.44 |
| Southern China | 519 | 12.72 | 316 | 21.01 | 42 | 8.48 |
| Southwest China | 518 | 8.10 | 314 | 18.48 | 51 | 12.96 |
| Northwest China | 525 | 5.23 | 324 | 16.64 | 64 | 8.48 |

4.2 Spatial integration results of the comprehensive CO₂ emissions

Based on the integrated estimation results of the CO₂ factors, from the NSP and the VSK

clinker production lines, respectively, we finally obtained the regional and national CO₂ emission factors and the total quantity of CO₂ emissions according to the above integration systems (Table 10).

Table 10 The preliminary CO₂ emission spatial integration results for Chinese cement industry

| Regions | Portland clinker out- put (2013) | Cement output (2013) | Process emission factors | Fuel emission factors | Electricity emission factors | Clinker emission factors | Grinding emission factors | Clinker emissions (2013) | Cement emissions (2013) |
|--------------------|--|----------------------------|--------------------------------|-----------------------------|------------------------------------|--------------------------------|---------------------------------|--------------------------------|-------------------------------|
| | Mt | Mt | kg CO ₂ /t | kg CO ₂ /t | kg CO ₂ /t | kg CO ₂ /t | kg CO ₂ /t | Mt CO ₂ | Mt CO ₂ |
| Northeast China | 78 | 145 | 511 | 309 | 47 | 867 | 40 | 68 | 73 |
| Northern China | 126 | 259 | 521 | 314 | 50 | 885 | 38 | 112 | 122 |
| Eastern China | 369 | 674 | 521 | 310 | 36 | 867 | 25 | 320 | 337 |
| Central China | 242 | 483 | 515 | 313 | 50 | 877 | 34 | 213 | 229 |
| Southern China | 159 | 261 | 519 | 322 | 42 | 883 | 35 | 140 | 150 |
| Southwest China | 247 | 375 | 515 | 324 | 51 | 890 | 36 | 220 | 233 |
| Northwest China | 140 | 217 | 523 | 336 | 67 | 925 | 49 | 129 | 140 |
| National NSP | 1195 | — | 520 | 313 | 45 | 879 | 34 | — | — |
| National Shaft | 167 | — | 503 | 348 | 60 | 912 | 36 | — | — |
| National Composite | 1362 | 2414 | 518 | 318 | 47 | 883 | 34 | 1202 | 1284 |

Table 10 indicates that the current national average value of emission factors from clinker production is 883 kg CO₂/t clinker. The process, fuel, and electricity emission factors, as three parts of the national average value, are 518 kg CO₂/t clinker, 318 kg CO₂/t clinker, and 47 kg CO₂/t clinker, which respectively have a proportion of 58.70%, 35.97%, and 5.33%. The process emissions and the fuel emissions constitute the two main sources of clinker carbon emissions, indicating that in future these two emission sources should be the focus areas for carbon emission reduction relevant to cement industry of China.

Based on clinker and cement output in China in 2013, the national total emissions from clinker and cement production reached 1202 Mt and 1284 Mt, respectively.

4.3 Comparative analysis of CO₂ emissions

4.3.1 Comparative analysis based on process types

A comparison of the two main production processes (Table 11) indicates that the current average value of the NSP clinker emission factors (879 kg CO₂/t clinker) is lower than that of the VSK (912 kg CO₂/t clinker). This discrepancy is mainly reflected in the process and the fuel emission factors. As regards the process emission factors, those of the NSP are 16.93

Table 11 Comparison of two main process types in Chinese cement industry

| Process types | | Process emission factors | Fuel emission factors | Electricity emission factors | Clinker emission factors |
|---|--|-----------------------------|--------------------------|---------------------------------|-----------------------------|
| NSP process | Emission factors (kg CO ₂ /t clinker) | 520 | 313 | 45 | 879 |
| | Proportion in clinker emissions (%) | 59.20 | 35.65 | 5.15 | 59.20 |
| VSK process | Emission factors (kg CO ₂ /t clinker) | 503 | 348 | 60 | 912 |
| | Proportion in clinker emissions (%) | 55.22 | 38.18 | 6.60 | 55.22 |
| Gaps of the two (kg CO ₂ /t clinker) | | −16.93 | 34.72 | 14.97 | 32.76 |

kg higher compared with those of the VSK. As regards the fuel and the electricity emission factors, those of the VSK are 34.72 kg higher and 14.97 kg higher, respectively, compared with those of the NSP.

4.3.2 Comparative analysis based on spatial distribution

Carbon emissions primarily depend on the volume of output and emission factors (Gao *et al.*, 2015). In exploring the spatial disparity related to the spatial distribution of emission factors (Figure 7), we note that the clinker emission factors show a trend of gradually increasing from the east coast to the west inland area (sorting: Northwest China > Southwest China > Northern China > Southern China > Central China > Northeast China > Eastern China). Among the seven major geographical regions, East China (including Zhejiang, Jiangsu, Anhui, and other areas) and Northwest China (including Tibet, Xinjiang, Gansu, and other areas) represent, respectively, the minimum and the maximum emission-intensity regions for clinker emissions, reaching a mean range of 57.7 (867–925) kg CO₂/t clinker. Furthermore, the minimum-maximum emission intensity ranges for three types of clinker emission sources are 11.51 kg CO₂/t clinker (the process emission factors), 25.30 kg CO₂/t clinker (the fuel emission factors) and 30.87 kg CO₂/t clinker (the electricity emission factors), respectively. These spatial distribution characteristics relevant to clinker emission factors correspond with those of the NSP in Section 4.2 (despite subtle differences).

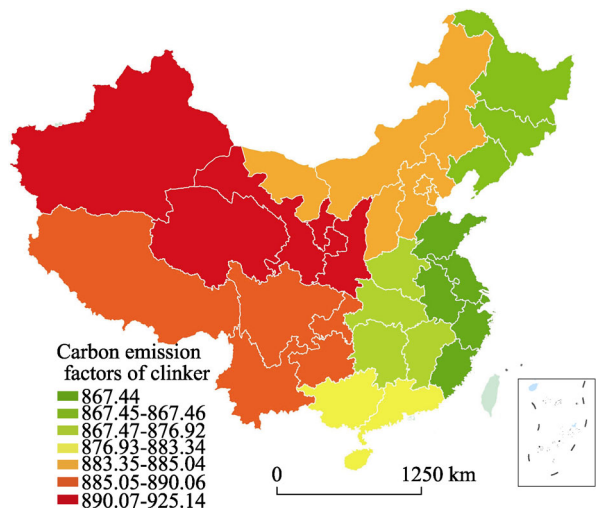


Figure 7 The spatial distribution of integrated carbon emission factors of clinker in regional China (kg CO₂/t clinker)

We explore the regional discrepancy of the total quantity of emissions from cement industry (Figure 8), finding that the spatial distribution pattern of the total carbon emissions is notably different from that of clinker-related carbon emission factors. The sorting of total carbon emissions from clinker and cement production shows the same characteristics: Eastern China > Southwest China > Central China > Southern China > Northwest China > Northern China > Northeast China in 2013. Obviously, although the spatial pattern of absolute carbon emissions is a comprehensive result, mainly determined by emission factors and clinker/cement output (Gao *et al.*, 2015), the clinker/cement output is the main contributing factor (Table 10).

4.4 Discussion

The comparative results of two typical process types verify that the NSP process is more advanced than the VSK process in terms of energy efficiency (Shen *et al.*, 2014; Ke *et al.*, 2013). It is evident that compared with the VSK process, the NSP process has higher thermal efficiency, less fuel consumption, a better limestone resources ratio, and higher dust collection efficiency rates. To reduce CO₂ emission intensity, the NSP process is superior to

the VSK process because of its technical advantages.

In perspective of spatial distribution, the CO₂ emission factors shows an almost opposite pattern to the absolute CO₂ emissions. The integration results of three emission sources indicate that energy-related emission factors are the principal influential contributors for the regional discrepancy of synthesized emission factors. Generally, energy efficiency in eastern region is better than that of other regions, which means the previous region pays more attention to energy efficiency than other regions. The process-related emission factors exert a rather small impact on the spatial disparity of the synthesized clinker emission factors because of the similar quality in cement-use limestone. Unlike emission factors, the spatial pattern of absolute CO₂ emissions show an almost opposite tendency. The absolute CO₂ emissions are largely determined by clinker/cement output, and thus comply with economic and population distribution pattern of China. The economic-intensive regions are cement consumption-intensive regions leading to higher CO₂ emissions (Cai *et al.*, 2015).

This is because cement is the primary component of construction and is largely consumed and produced locally (Shen *et al.*, 2014). The economic hotspot regions are large cement consumers (Cai *et al.*, 2015) that offset the advantage of emission factors in these regions.

The implicit purpose of the accurate estimation of CO₂ emissions is to achieve an optimized carbon reduction in cement industry. The results of this work have actually established a significant prerequisite basis for our next assessment study on the implementing effect of regional CO₂ mitigation strategies. The improved bottom-up spatial-integration system proposed in this paper and the introduction of the sandwich method (which has improved the accuracy of mean estimation, compared to the simple random method, see Table 12) will allow an accurate evaluation of carbon mitigation effects through technology upgrading (from VSK process to NSP process) in Chinese cement industry. However, this study is still preliminary with some limitations remaining. In view of estimation precision, our studies on the regional-level spatial integration for clinker CO₂ were confined to the

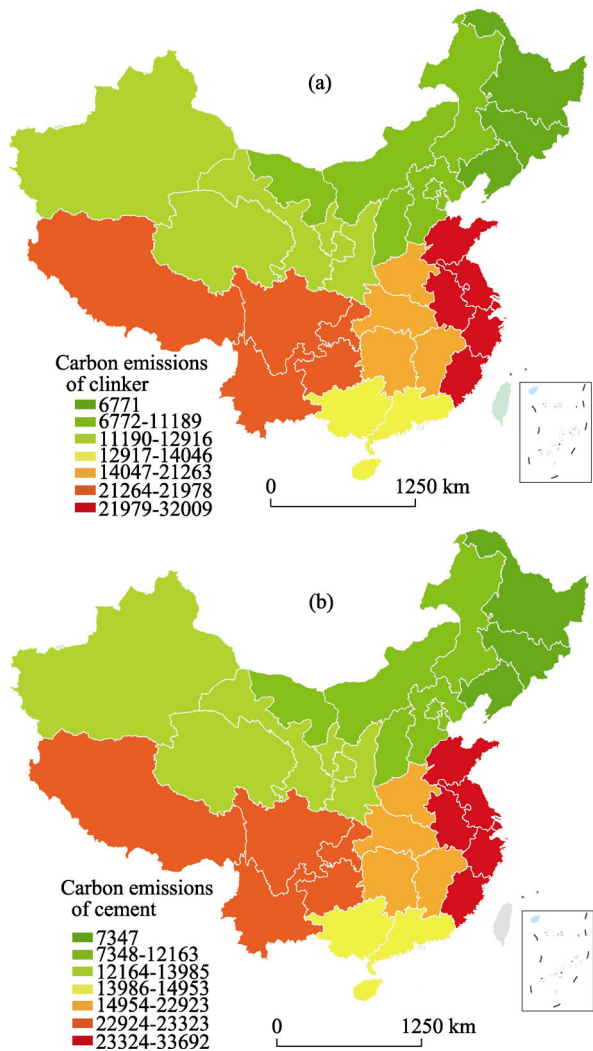


Figure 8 Carbon emissions of clinker and carbon emissions of cement in regional China in 2013 (10,000 t CO₂)

Table 12 Comparison of standard deviation results from methods of sandwich and simple random

| Regions | Standard deviation | | | | | |
|-----------------|--------------------------|---------------|-----------------------|---------------|------------------------------|---------------|
| | Process emission factors | | Fuel emission factors | | Electricity emission factors | |
| | Sandwich | Simple random | Sandwich | Simple random | Sandwich | Simple random |
| Northeast China | 15.74 | 17.52 | 13.79 | 18.72 | 12.61 | 15.75 |
| Northern China | 7.16 | 14.45 | 16.91 | 33.59 | 12.94 | 22.76 |
| Eastern China | 8.51 | 16.78 | 10.10 | 21.32 | 6.37 | 16.88 |
| Central China | 9.86 | 11.58 | 21.47 | 22.22 | 9.44 | 18.24 |
| Southern China | 12.72 | 7.22 | 21.01 | 17.35 | 8.48 | 16.07 |
| Southwest China | 8.10 | 14.29 | 18.48 | 32.08 | 12.96 | 21.88 |
| Northwest China | 5.23 | 12.11 | 16.64 | 18.01 | 8.48 | 25.09 |

NSP process. As regards the VSK process, because of its extremely small proportion of production and our sample quality concerns, we used the weighted average method in this study. In further studies, we aim to improve the integration approach, based on supplementary information and data from further investigation, in order to obtain a more accurate estimation result. Our work draws some key conclusions in Section 5, which provide stakeholders and policy makers with a useful reference work to facilitate the formulation of regional policies for carbon mitigation in China.

5 Conclusions

This paper constructed an improved bottom-up factory-level CO₂ emission spatial integration system, with the aim of obtaining a more accurate estimation of CO₂ emissions relevant to the cement industry in China. Mainly using the spatial integration approaches of the sandwich estimation, supplemented by the weighted average, the authors conducted empirical research on the mass sampling-survey data carried out by the carbon-based research group of the Chinese Academy of Sciences. We reached the following conclusions:

(1) The total emissions from clinker and cement production in China reached 1202 Mt and 1285 Mt, respectively, in 2013. Additionally, the individual contributions of the process (58.70%), fuel (35.97%), and electricity (5.33%) emissions per ton clinker produced imply that the process emissions and the fuel emissions remain the key aspects for the future reduction of carbon emissions in the cement industry of China.

(2) Clinker emission factors from the NSP kiln production process (879 kg CO₂/t clinker) are significantly lower than those from the VSK process (912 kg CO₂/t clinker). The gaps are mainly reflected in the process emissions and the fuel emissions, indicating the remarkable abatement effect brought about by the upgrading of technology.

(3) Spatial disparity exploration indicates that the spatial distribution of clinker emission factors corresponds to that of the NSP. The clinker emissions of NSP, thereupon, can be regarded as the representative of the current overall domestic clinker emissions. In addition, the clinker emission factors and total CO₂ emissions show a divergent pattern. This divergence, from another sense, reflects the regional disparity of economic and population distribution pattern in China.

(4) It is crucial that stakeholders and policy makers address this major environmental

concern relevant to cement industry. Several countermeasures combining the macro-industry levels and micro-plant levels should be taken to achieve carbon mitigation in China's cement industry, such as industry upgrading, energy efficiency improvement, and alternative materials and fuels.

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