

Changing carbon content of Chinese coal and implications for emissions of CO₂

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ABSTRACT

The changing carbon content of coal consumed in China between 2002 and 2012 is quantified using information from the power sector. The carbon content decreased by 7.7% over this interval, the decrease particularly pronounced between 2007 and 2009. Inferences with respect to the changing carbon content of coal and the oxidation rate for its consumption, combined with the recent information on coal use in China, are employed to evaluate the trend in emissions of CO₂. Emissions are estimated to have increased by 158% between 2002 and 2012, from 3.9 Gt y⁻¹ to 9.2 Gt y⁻¹. Our estimated emissions for 2005 are notably consistent with data reported by China in its “Second National Communication” to the UN (NDRC, 2012) and significantly higher than the estimation published recently in Nature. The difference is attributed, among other factors, to the assumption of a constant carbon content of coal in the latter study. The results indicate that CO₂ emissions of China in 2005 reported by Second National Communication are more reliable to serve as the baseline for China’s future carbon commitments (e.g. those in Paris Agreement of the UNFCCC). Discrepancies between national and provincial statistics on coal production and consumption are investigated and attributed primarily to anomalous reporting on interprovincial trade in four heavily industrialized provinces.

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1. Introduction

As the world’s largest CO₂ emitter, China has committed to reduce its carbon intensity (emissions/GDP) by 60–65% by 2030

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relative to 2005, as part of its “Intended Nationally Determined Contribution” (INDC) under the 2015 Paris Agreement of the United Nations Framework Convention on Climate Change (UNFCCC) (NDRC, 2015). In recent years China has pursued a number of carbon control policies, including measures to improve its energy efficiency, strategies to expand non-fossil energy sources, and a national CO₂-trading scheme scheduled to begin in 2017. Implementation of China’s carbon reduction commitments and verification of their success will depend on accurate estimates of CO₂ emissions over the target years. An effective carbon “cap-and-trade” regime will require these estimates to be available on an annual basis in order to set the requisite caps.

Estimates of Chinese historical and current CO₂ emissions indicate wide disparities. A study by Liu et al. (2015b) argued that China’s official Second National Communication (SNC) to the UNFCCC (NDRC, 2012) overestimated China’s CO₂ emissions by 12%

in 2005, the critical base year for measuring China's carbon-intensity commitments. These conclusions drew high-profile coverage in international news media (Buckley, 2015; McGrath, 2015). Emission estimates from other prominent organizations differ, including reports from the Carbon Dioxide Information Analysis Center (CDIAC) (Boden et al., 2017), the PBL Netherlands Environmental Assessment Agency (Olivier et al., 2016), and the Global Carbon Project (GCP, 2017). The differences result from either or both of the two major factors involved in these estimates: "activity" levels, referring to all major uses of fossil fuels, and emission factors, which translate activity into levels of emitted CO₂. Reflecting China's heavy dependence on coal, the former is a function mainly of the quantity of coal consumed; the latter depends on the quality of this coal, identified most notably by its carbon content. The default values of emission factors range from 25.8tC/TJ for bituminous coal to 27.6tC/TJ for lignite according to IPCC.

Consistently sampled quantitative evidence of the time-varying carbon content of coal consumed in China's economy is lacking. Measurements of the quality of coal consumed in China are reported for individual years, but they differ in scopes of coverage, making comparisons and inferences for trends in carbon content problematic. Liu et al. (2015a) provided the first quantitative analysis of temporal changes in the quality of coal consumed in China's electric power sector from 1990 to 2010, expressed in terms of heating values and based on a combination of measurements for 2010 by the Ministry of Environmental Protection and temporal changes in the coal data reported from national energy statistics. They argued for a "remarkable" decline in the quality of coal consumed in the Chinese power sector between 2007 and 2010, inviting a more comprehensive analysis of the changing carbon content of coal used in the Chinese economy.

Statistics on Chinese coal consumption are also subject to large uncertainty. Official data have undergone major revisions every five years recently, including an adjustment in August 2015 that raised official estimates for total coal consumption by as much as 17% over recent years. In addition, national and aggregate provincial data for coal use in China differ by as much as 20% (NBS, 2002–2015), with reports from the latter consistently higher. Although this discrepancy has been recognized for more than a decade (Akimoto et al., 2006; Sinton, 2001), it has persisted. The source of the discrepancy has yet to be resolved definitively, although a number of possible explanations have been suggested. These include divergent accounting for consumption of coal produced by small and/or illegal mines (Guan et al., 2015; Sinton, 2001), double counting of energy involved in cross-provincial economic activities (Ma et al., 2014; Wang and Chandler, 2011), and institutional incentives to misreport coal used in specific sectors (Ma et al., 2014). As combustion of coal contributes more than 70% of the total CO₂ emissions in China, such problems result in significant uncertainty for the national CO₂ emissions.

To resolve the disagreements in both emission factors and coal statistics related to Chinese carbon accounting, we present here an analysis of both temporal changes in the carbon content of Chinese coal and new evidence relating to the source of the discrepancies in the coal consumption statistics. First, we derive a trend for the carbon content of coal used in the Chinese power sector that is independent of the problematic national coal data employed in other studies. Arguing that the quality of coal consumed in the power sector provides a conservative estimate for the quality of coal used economy-wide, we combine data on coal consumption and electricity production to argue for a significant decline in the carbon content of coal deployed in China between 2002 and 2012. Recognition of this trend allows us to reconcile Chinese official estimates for the carbon content of coal used in 2005 with

independent estimates based on surveys of the quality of coal reported for 2012. Second, we disaggregate and compare different statistical databases on coal production, consumption, and inter-provincial trade in order to explore reasons for the inconsistencies between national and summed provincial data. The discrepancies are attributed to anomalies in data from several highly industrialized provinces, consistent with suggestions of institutional incentives to misreport coal used in a number of industrial applications. Finally, we combine results inferred for the declining carbon content of coal with recently revised national energy statistics to develop a best estimate for the trend in China's CO₂ emissions over the period 2000–2012.

2. Methods

CO₂ emissions from coal consumption in China can be calculated as the product of the average carbon content of coal, the average oxidation rate, and a best estimate for aggregate coal consumption.

2.1. Calculation of annual average carbon content

Emissions of CO₂ from the power sector can be evaluated either on an energy or on a mass basis. We derive emissions here first on an energy basis, using this approach to infer the carbon content and the quantity of coal consumed.

On an energy basis, CO₂ emissions from the power sector, CO₂^{p1} (in tC), can be expressed as:

$$CO_2^{p1} = P \cdot \alpha \cdot h \cdot EF_e \quad (1)$$

Here, P defines the annual thermal power production (excluding the minor contribution fueled by natural gas); α is the national average coal consumption rate for power supplied by units larger than 6 MW, derived from the *China Energy Statistical Yearbook (CESY)* and expressed as tons of standard coal equivalent per megawatt-hour (t sce/MWh); h is the energy conversion factor for standard coal (GJ/t sce); and EF_e is the energy-based emission factor (tC/GJ). The estimate for annual thermal power production is based on instrumental metering and reported values are consistent across diverse statistical sources, specifically national and provincial data from the *CESY (NBS, 2002–2015)*. As indicated in the Supplementary Data, the national average coal consumption rate for power production declined steadily from 382 g/kWh in 2002 to 325 g/kWh in 2012, reflecting a notable improvement in combustion technology.

The power generated by gas-fired units in China represents a minor share of total thermal generation, 0.6% in 2005 rising to 2.8% in 2012. Estimates of annual power generation from gas-fired units are not reported in the *CESY* but are available for 2000 and 2005 (Zhu, 2008) and starting annually from 2008 in the *China Electric Power Yearbook (CEPY, 2008–2013)*. Estimates for gas-fired power generated in years for which data are lacking are calculated based on linear interpolation between the values for years for which the data are available. Electricity generated by oil-fired power units is negligible and is ignored. For each year, the gas-fired share is subtracted from the total thermal power generation before calculating CO₂ emissions from the coal-fired power sector.

On a mass basis, CO₂ emissions from the power sector, CO₂^{p2}, can be represented by:

$$CO_2^{p2} = E_c \cdot C_{ar} \cdot r \quad (2)$$

where E_c defines the quantity of raw coal used in the power sector (tons, t); C_{ar} is the corresponding average carbon content (tC/t

coal); and r is the oxidation rate, taken as 0.97 (Liu et al., 2015b). Assuming consistency in the different data inputs, CO_2^{p1} should equal CO_2^{p2} , and we can solve for C_{ar} , the average carbon content.

All of the data used in this calculation are presented in the Supplementary Data (with citations linking to the original sources). The analysis is based on the total consumption of coal in the power sector, including contributions from both domestic and foreign sources (i.e., imports). Note that raw coal accounts for more than 98% of the total coal consumed in the power sector (NBS, 2002–2015); the impact of coal washing on the results developed here is negligible.

2.2. Comparison of carbon content of steam coal and national average coal

Coal used in the power system is referred to as “steam coal”. The quality requirements for steam coal are weaker than those for coal used in other industries, such as chemical processing. The implication is that steam coal may have higher levels of volatile compounds, ash, and sulfur.

The quality of steam coal serves as a conservative indicator of the properties of all coal combusted nationally for the following reasons. It accounts for 50% of the total coal consumed in China and encompasses a wide range of coal types, including lignite, long-flame coal, non-caking coal, weakly caking coal, meager coal, and anthracite, using Chinese coal terminology (CIY, 2001–2012). Li and Jong (1993) conducted a comprehensive comparison of the quality of steam coal relative to national average coal reserves based on the national “Coal Type Resource Database”, which surveyed 33,500 coal samples (Chen, 1996). The distribution of “high heat” values (a standard coal quality metric) for steam coal is contrasted with values for all coal in Fig. 1. As indicated, steam coal covers the whole range of heating values, but the share of low quality coal is slightly higher in the power sector relative to the national average.

The average high heat value for steam coal is 33.48 MJ/kg, lower than the value for coal overall in China, 34.14 MJ/kg⁵. As the heat value is almost linearly correlated with carbon content, we may conclude that the carbon content of coal used in the power sector is in reasonable agreement, on average slightly lower, than the carbon content for all coal produced in China. This property allows us to use the quality of steam coal as a conservative indicator of the national average for coal overall.

2.3. Calculation of the coal oxidation rate

Liu et al. (2015b) calculated the average oxidation rate for Chinese coal weighted by the production of coal by type. Coal

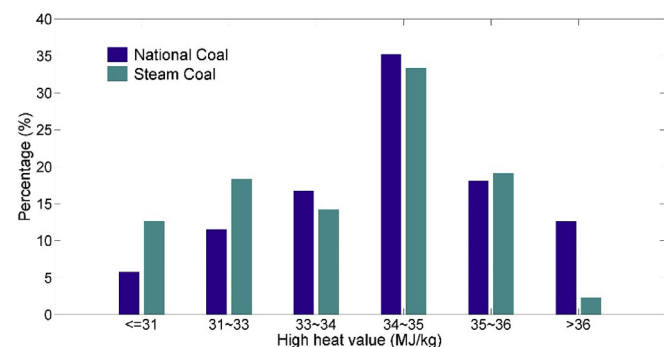


Fig. 1. High heat value distributions for Chinese coal reserves (data from McGrath (2015)).

oxidation rates however differ across sectors, which employ different combustion technologies. Most notably, the oxidation rate applicable for the power sector, which accounts for almost 50% of total Chinese coal consumption, is relatively high (~0.97) compared to values for other sectors (Liu et al., 2015b). It is important for this reason to apply a double-weighting approach in estimating the average oxidation rate, as follows:

$$\bar{r} = \sum_{i=1}^4 \left(PW_i \cdot \left(\sum_{j=1}^{n_i} SW_j \cdot r_{ij} \right) \right) \quad (4)$$

where \bar{r} is the double-weighted oxidation rate; i indicates coal type, classified in four categories; j defines the coal-consuming sector; n_i indicates the total number of sectors that use the i^{th} coal type; PW_i is the share of total coal production represented by the i^{th} coal type shown in the Supplementary Data 3.2; SW_j is the share of total coal consumption in sector j derived from the CESY, as summarized in the Supplementary Data 3.4; and r_{ij} is the average coal oxidation rate for the combination of the i^{th} coal type and j^{th} sector. In total nine coal-consuming sectors were included in the calculation, aggregating over 156 subsectors as indicated in the Supplementary Data 3.1 and 3.4. Since the sector shares for consumption change over time, \bar{r} was calculated for each year.

2.4. Calculation of activity levels

The amount of coal used in the Chinese economy can be traced from three different perspectives: production, consumption, and trade. The detailed channels of data collection are summarized in Fig. 2.

Production data are collected through two channels: the official statistical system, including both national and provincial statistical bureaus, and the coal industry association, which is entrusted by the State Administration of Coal Mine Safety to collect coal data from mines. The former data are summarized in the CESY, the latter in the *Coal Industry Yearbook* (CIY).

Coal consumption data are collected by official statistical bureaus at both provincial and national levels. (The coal industry association does collect some consumption data on the basis of coal contracts, but these data are considered very rough.) Due to the absence of a strict supervisory system to guarantee the accuracy of data collection and its reporting to higher-level agencies, the accuracy of the data can be influenced by data collectors and reporters in individual companies and in different levels of government, all of which are constrained by multiple regulations and laws during different periods.

Reflecting doubts about the reliability of coal consumption data for countries such as China, a number of researchers (Andres et al., 2012, 2014; Liu et al., 2015b) have suggested the use instead of “apparent consumption,” i.e., the total primary coal supply minus its non-energy use (mainly chemical processing by industry), data for which are expected to be more accurate. Apparent coal consumption is defined as the sum of indigenous production, net imports, and net changes in stocks, minus non-energy uses. The apparent consumption of coal was calculated using values reported at the national level for all of these quantities.

The national coal production and consumption data have been revised on three occasions, in 2005, 2010, and 2015, reflecting inputs from economic censuses targeting periodic visits to every enterprise in China (Ma et al., 2014; Wang and Chandler, 2011). The sequential revisions of indigenous coal production are summarized in Fig. 3. Coal production and consumption data for individual provinces, by contrast, are available for each year only in the provincial energy balance sheets. These data have not been subjected

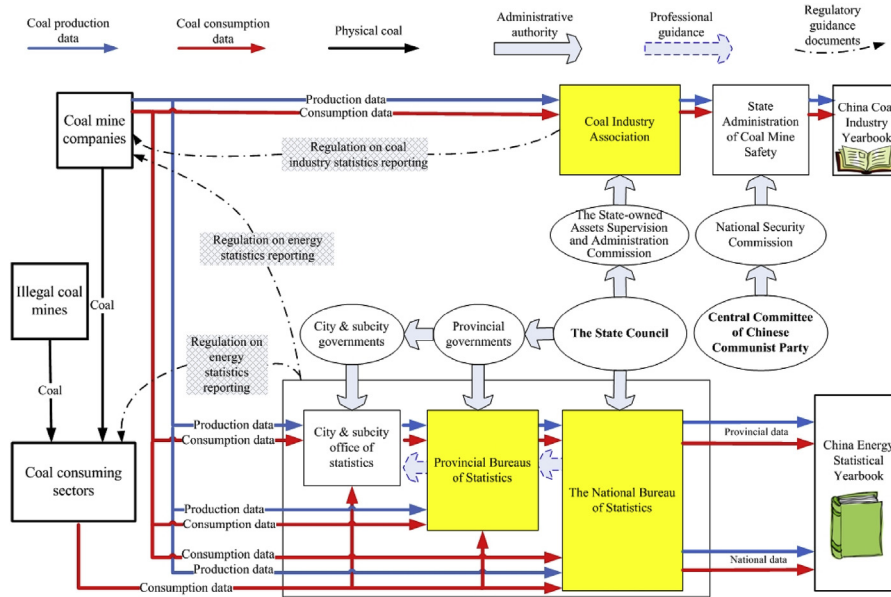


Fig. 2. Coal data collection channels in China.

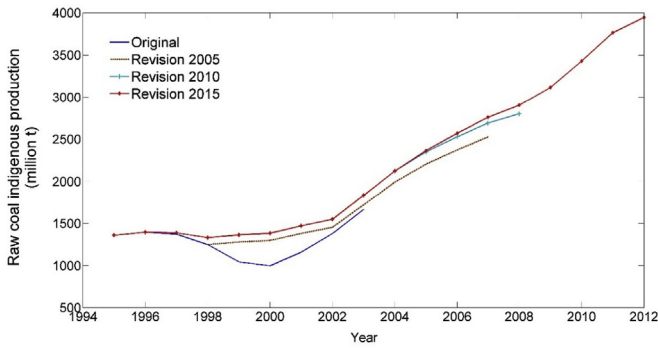


Fig. 3. Revision of indigenous raw coal production.

to subsequent revisions. Revised national energy statistics were published in *CESY 2014* in August 2015 (NBS, 2015), and are used here to calculate apparent consumption from 2002 to 2012.

3. Results

3.1. Declining carbon content of Chinese coal

Analysis of coal consumed in the power sector provides an independent estimate for the changing average carbon content of this quantity over time, as described in Methods. As indicated in Fig. 4,

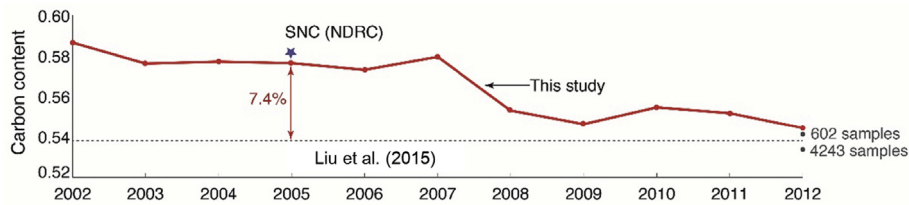


Fig. 4. The carbon content of coal used in China's power sector (2002–2012). The time-invariant estimate of coal carbon content used in Liu et al. (2015b) is derived from two sets of coal samples.

the analysis reveals a significant decline in the trend for the carbon content for coal employed in the power sector between 2002 and 2012.

For 2005, the important benchmark year of China's carbon commitments, the estimated carbon content of coal derived here is close (0.64% lower) to the estimate reported in China's SNC to the UNFCCC (NDRC, 2012) but significantly higher (7.4%) than the time-invariant value. However, our estimate for 2012, the year of the sampling of coal analyzed in Liu et al. (2015b), is similar to this value (1.4% higher). These results indicate that estimates of the carbon content of coal based on coal sampling for any particular year may be useful in estimating emissions of CO₂ for that year but could be seriously misleading.

The decline in carbon content was particularly pronounced between 2007 and 2009, consistent with conclusions reached by Liu et al. (2015a). In 2008, coal demand increased as a consequence of an unusually severe winter, which also disrupted coal transportation prompting local shortages. This led to a spike in coal prices and authorization by the Chinese government to reopen small mines, facilities responsible generally for production of lower-quality coal (NDRC, 2008).

Changes over time in the production of different coal types (Coal Industry Yearbook, 2000–2012) (CIY, 2001–2012) also support our conclusions for a decline in the carbon content of Chinese coal, as illustrated in Fig. 5. The share of coal with relatively low carbon content ($C_{ar} < 0.5$, represented by the top three coal types in the figure) increased from 29% in 2000 to 35% in 2011, reaching peak

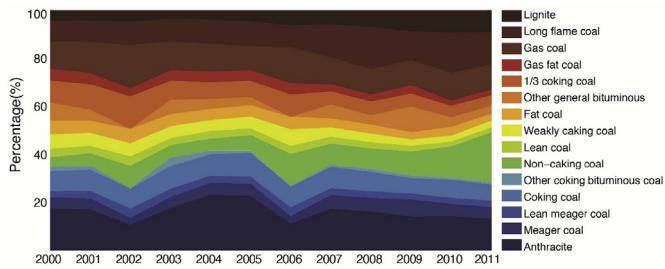


Fig. 5. The distribution of raw coal produced in China (2000–2011) based on Chinese coal type categories. Ranked by rising average carbon content from top to bottom. The color indicates corresponding coal types on the right. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

levels of 38% and 39% in 2008 and 2010, respectively.

3.2. Double-weighted oxidation rates of coal

The double-weighted averaging method for estimating coal oxidation rates (see Methods) results in values for \bar{r} varying between 0.946 and 0.950 over the period 2000–2012, as indicated in Table 1. The values inferred using this double weighting approach are consistently higher than those derived by weighting only by production, both with respect to the time-invariant result (0.92) applied across the time period by Liu et al. (2015b) as well as the values recalculated here for each year (Table 1). The double-weighted oxidation rate for the policy benchmark year 2005 (0.948) is consistent, on the other hand, with the oxidation rate for this year reported by the Chinese government (0.943) in its SNC to the UNFCCC (Teng and Zhu, 2015).

3.3. Chinese CO₂ emissions (2002–2012)

Results derived above for the time-varying carbon content of coal, the time-varying average oxidation rates of coal, and the revised official energy statistics released in August of 2015, were used to calculate Chinese CO₂ emissions from fossil energy use and cement manufacturing over the period 2002 to 2012. Results are displayed in Fig. 5a. Cumulative emissions of CO₂ over this time interval are about 9.72% higher than values calculated by Liu et al. (2015b), close however to results reported by CDIAC (Boden et al., 2017). Emissions inferred for 2012 are 12.6% higher than those reported by Liu et al. (2015b).

A comparison of CO₂ emissions from different analyses for the benchmark year 2005 is presented in Fig. 6b. The estimate in China's SNC (NDRC, 2012), on the right, includes emissions not only

from fossil fuel combustion and cement calcination, but also process emissions from other industries. Even as their results were compared to SNC, these sources add ~2.6% to total CO₂ emissions reported in the SNC for 2005 (NDRC, 2012). Results from the present analysis and the earlier study by Liu et al. (2015b) were adjusted to include these additional process emissions, indicated by addition of an asterisk in the label (“This study*” and “Liu et al., 2015*”). Accounting for this adjustment, emissions of CO₂ derived here for 2005 are 10.4% higher than the value given by Liu et al. (2015b) and 7.8% higher when their results are adjusted to allow for non-cement process emissions (Liu et al., 2015*). The present result is in satisfactory agreement (1.2% lower) than the value reported in China's SNC (NDRC, 2012).

Note that the newly revised official energy data imply slightly lower emissions for 2005 than the previous official data used by the SNC (NDRC, 2012) and Liu et al. (2015b). If SNC (NDRC, 2012) and Liu et al. (2015b) were updated to account for the new official energy data, the present result for 2005 would be in even closer agreement with that of SNC (about 0.8% lower) and the disagreement with Liu et al. (2015b) would be even larger (about 10.8% higher).

In addition, the first biennial update report on climate change from China has been released at the end of 2016 (NDRC, 2016). It reported that the CO₂ emission from energy activities in China in 2012 is 8.688 Gt including fugitive emissions from fossil fuel exploration processes; while the CO₂ emission from industry processes, including cement production, raw steel and synthesis ammonia departments, is 1.193 Gt. Adding up the CO₂ emissions both from energy activities and industry processes, the national reported CO₂ emissions is 9.881 Gt, 1.31% lower than 10.013 Gt from our study. To sum up, our results are in closer agreement with main estimations in the world (e.g., PBL, CDIAC and NDRC) in the year of 2012.

4. Discussion

4.1. Inconsistencies of provincial and national coal data

Inconsistencies in Chinese coal statistics have prompted debate about Chinese energy use and related carbon emissions (Akimoto et al., 2006; Guan et al., 2015; Ma et al., 2014; Sinton, 2001; Ma et al., 2014, 2014). As noted before, there are two official statistical channels, reporting data for both energy production and consumption. See section 2.4 and Fig. 2 for a diagram and discussion concerning this complex statistical system.

A problematic feature of these energy data is that the values for total coal production and consumption aggregated from the provincial datasets are consistently higher than the values reported in the national statistics (Akimoto et al., 2006; Guan et al., 2015;

Table 1
Production share of different coal types and average oxidation rates based on two different weighting methods.

Year	Anthracite (%)	Bituminous (%)	Coking (%)	Lignite (%)	Production weighted average oxidation rate (%)	Double weighted average oxidation rate (%)
2012 ^a	13.28	45.24	32.42	9.06	91.31	94.61
2011	13.28	45.24	32.42	9.06	91.31	94.62
2010	14.33	41.49	34.96	9.22	91.44	94.64
2009	14.14	42.49	34.55	8.82	91.41	94.69
2008	16.25	39.02	37.58	7.14	91.58	94.74
2007	17.41	37.97	38.82	5.80	91.66	94.77
2006	11.17	32.72	49.80	6.31	92.02	94.91
2005	22.64	30.41	42.42	4.54	91.91	94.79
2004	23.22	28.51	44.27	3.99	92.00	94.90
2003	17.60	30.05	48.71	3.64	92.09	94.91
2002	10.69	27.62	56.98	4.71	92.33	95.02

^a The coal fraction of 2012 are assumed to be the same as those of 2011, due to data unavailability.

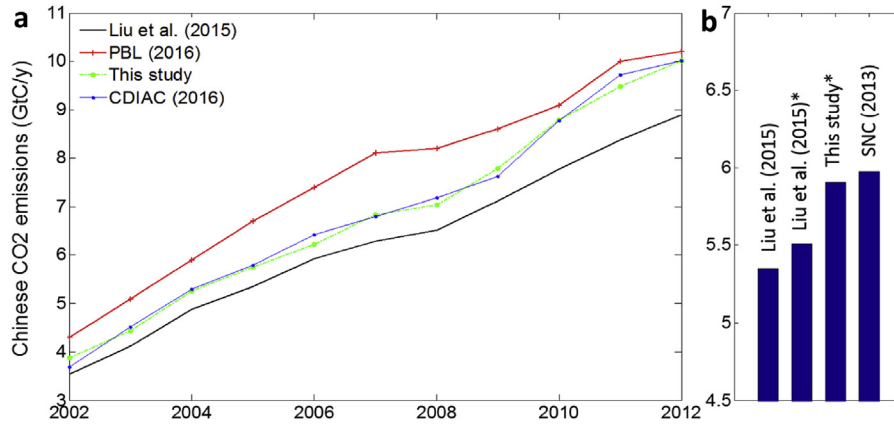


Fig. 6. Revised estimates of Chinese CO₂ emissions (2002–2012). **a**, CO₂ emissions from fossil fuel use and cement processes only. **b**, Total CO₂ emissions in 2005. “SNC,” “This study*,” and “Liu et al. (2015)*” include process emissions from all industries, not just cement.

Nielsen and Ho, 2007; Wang and Chandler, 2011; Zhao et al., 2012). The difference in terms of the total production of raw coal (in tons) amounted to 18% for 2005 prior to revision, corresponding to 390 Mt, mainly attributed to different statistical channels as summarized in Fig. 2. In Chinese coal statistics, production includes indigenous production from mining, net international imports, net interprovincial imports (in provincial datasets only), and changes in stockpiles. The discrepancy between national and aggregated provincial production can be decomposed into these categories. Only about 13 Mt of the 390 Mt inconsistency in 2005, or 3.4%, can be attributed to the difference in values between the two datasets for indigenous production. By contrast, 85.6% of the difference is associated with net interprovincial trade. While interprovincial coal imports and exports should balance nationally, integrated imports reported by the PBSs in fact exceeded exports by 336 Mt in 2005, as illustrated on the right of Fig. 7a.

A third, independent source of coal production data, collected by the coal industry association, is reported in the *Coal Industry Yearbook* (CIY, 2001–2012). Based on coal sales contracts, the net interprovincial imports from this dataset are shown by province for 2005 in Fig. 7b. The aggregate interprovincial trade imbalance in this dataset amounts to less than 30 million tons, suggesting that

interprovincial trade is recorded more accurately in the CIY database than in the PBS record.

The differences in net interprovincial trade on a province-by-province basis as reported in the two sources are displayed in Fig. 7c. Assuming that the CIY is more accurate, supported by its internal consistency, most of the coal trade imbalance reported in CESY can be attributed to anomalies in data for four provinces: Shandong (SD), Shaanxi (SAA), Jiangsu (JS), and Zhejiang (ZJ). That these provinces have proportionally large industrial sectors provides support for a proposed institutional mechanism for coal data manipulation. Decomposing discrepancies between aggregated provincial and national data for both GDP and raw coal consumption, Ma et al. (2014) identified the industrial sector as the primary source of the inconsistencies, and concluded that this results from incentives local leaders have to exaggerate local GDP in the form of coal-fired industrial production. The present analysis complements (Ma et al., 2014) in three respects: 1) by showing inconsistencies in coal production statistics consistent with those found in consumption data by Ma et al. (2014), additionally pinpointing interprovincial imports as the primary source of the coal production anomalies; 2) by identifying four industry-heavy provinces where data manipulation may have been concentrated; and 3) by

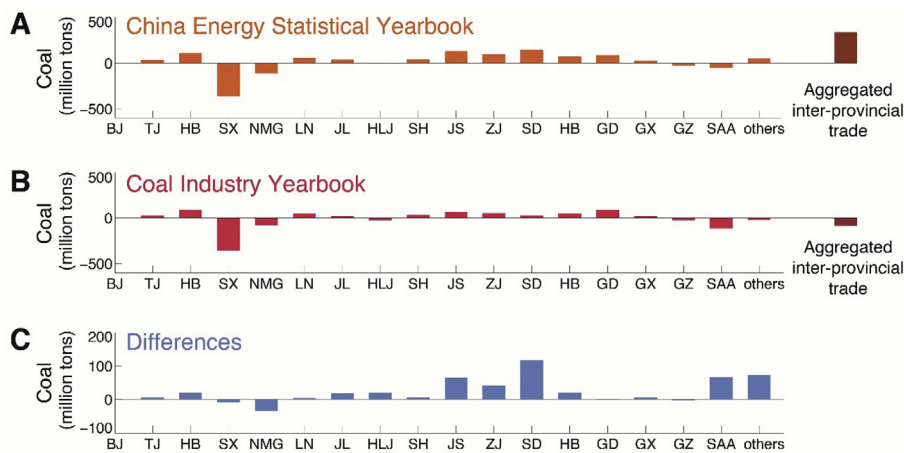


Fig. 7. Imbalances of net interprovincial imports of coal in 2005 (million tons), for key provinces and as a national aggregate. **(A)** As reported in NBS statistics (2002–2015). **(B)** As reported in coal industry statistics (CIY, 2001–2012). **(C)** Differences between the two datasets for key provinces. The abbreviations on the x axis represent respectively Beijing, Tianjin, Hebei, Shanxi, Inner Mongolia, Liaoning, Jilin, Heilongjiang, Shanghai, Jiangsu, Zhejiang, Shandong, Hubei, Guangdong, Guangxi, Guizhou and Shaanxi.

concurring that national energy data, after census-based revision, are likely to be more accurate than provincial data.

4.2. Uncertainties

Quantifying the uncertainty of CO₂ emissions can be inherently challenging for a variety of reasons (Marland, 2008; Marland et al., 2009), and is especially difficult if a country's underlying fossil energy use is itself poorly defined. This is the case for China, given the persistent and unresolved discrepancies in national energy statistics discussed above. Despite this, the uncertainty of China's CO₂ emissions is sometimes asserted with greater confidence than is warranted statistically, including by Liu et al. (2015b). Relatively rigorous quantification of the uncertainty in the carbon content of coal in China, however, is feasible.

While Gregg et al. (2008) suggest a 2-sigma uncertainty for Chinese emissions in 2005 “as high as 15%–20%,” they acknowledge that this reflects expert judgment based on limited evidence and that “it is, of course, not possible to independently evaluate the uncertainty of the Chinese data.” Liu et al. (2015b), by contrast, assert a precise and unqualified 2-sigma estimate of the uncertainty for 2013 of $\pm 7.3\%$ using methods that take account only of the residual scatter for the carbon content of two coal samples and the spread between national and provincial energy data. Zhao et al. (2012, 2013) sought to quantify the uncertainty in emissions with greater statistical rigor, applying Monte Carlo methods to coefficients of variation (CVs) and distributions for all parameters underlying emission factors and activity levels, compiled largely from the Chinese technical literature. This analysis suggested 95% confidence intervals for 2005 and 2010 of (–9%, +11%) and (–10%, +9%), respectively. However, these results were influenced by the use, lacking any alternative, of a generic value (10%) for the CV of industrial energy use recommended by IPCC for countries such as China (Zhao et al., 2012, 2013). It is now known that energy use in China's industrial sector is especially poorly understood (Ma et al., 2014), although it contributes centrally to China's CO₂ emission totals. Korsbakken et al. (2016) recognize the difficulty of quantifying the uncertainty of coal-derived Chinese energy use and suggest only “heuristic” error ranges, based on the magnitude of census-based revisions of official statistics. Given these conditions there may be little basis to adopt narrower estimates of Chinese CO₂ emission uncertainty than a $\pm 9\%$ –20% combined range of Zhao et al. (2012, 2013) and Gregg et al. (2008) until statistical anomalies are resolved sufficiently to strengthen underlying uncertainty assumptions about Chinese coal consumption, or until new forms of evidence, such as satellite-based retrievals of CO₂ levels over China, become available and can be analyzed appropriately.

As noted above, the differences between national and aggregated provincial coal production data have ranged as high as 20%. Calculating the annual trend of carbon content based on these data will be necessarily uncertain given the magnitude of the associated ambiguity. The approach adopted here focuses on the carbon content of coal consumed in the power sector. As discussed below, the major uncertainties embedded in this approach are associated with the data for coal consumed in this sector (t), the national average efficiency for coal-fired power generation (t sce/MWh), and the energy-based carbon content (t C/t coal). Other parameters, such as annual electricity production, are derived directly from data metered by power companies, and related uncertainties are considered inconsequential.

The difference between national and aggregated provincial data for coal consumed in the power sector is only about 2% (NBS, 2002–2015). The national average efficiency for coal-fired power generation is taken from the CESY (NBS, 2002–2015), noting that the value inferred from the database maintained by the Ministry of

Environment Protection was only 2% lower in 2010 (Liu et al., 2015a) than the value inferred for that year in the current analysis. The energy-based carbon content is relatively constant for different coal types, ranging from a low of 25.8 kg/GJ for bituminous and coking coal to values of 26.8 kg/GJ for anthracite, 26.2 kg/GJ for subbituminous, and 27.6 kg/GJ for lignite, according to the Intergovernmental Panel on Climate Change (IPCC). The arithmetic mean, median, and national averages weighted by the production shares for each coal type are 26.4, 26.2, and 26.2 kg/GJ, respectively. The largest deviation between the three values is thus less than 1%. Assuming that the uncertainty in the data for coal consumed in the power sector, the national average efficiency of coal-fired power generation, and the energy-based carbon content are consistent with the above (2%, 2%, and 1%, respectively), the overall 2-sigma uncertainty inferred for carbon content of steam coal amounts to 3%, calculated according to Marland and Rotty (1984). As the national average carbon content of coal is slightly lower than that used only in the power sector, the probability that the carbon content of Chinese coal in 2005 falls in the uncertainty range of Z. Liu et al. ($0.538 \pm 3\%$) is less than 0.4%. On the other hand, the carbon content for 2005 from the SNC and the result for 2012 from Liu et al. (2015b) are well within the uncertainty range of this analysis (see Fig. 3).

5. Conclusions

The carbon content of coal consumed in China decreased notably between 2002 and 2012, reflecting use of coal from lower quality sources. Information on the changing carbon content of coal combined with improved estimates of the coal oxidation rate and best estimates for the total coal consumption were used to evaluate China's CO₂ emissions, implying an increase in emissions by 158% for the time interval studied here. Emissions reported to the UN by China for the important base year of 2005 are consistent with results from the present analysis. Meanwhile, China's latest CO₂ emissions reported to the UN for the year 2012 are also consistent with our estimation. To sum up, with the changing carbon content, CO₂ emissions accounting shows highly consistency with results from national reports, which indicates the strengthened confidence from China's national reporting results. The present study also highlights that the main estimations for China's carbon emission in the world are much closer with each other in the year of 2012 rather than other years from 2002 to 2011.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at <https://doi.org/10.1016/j.jclepro.2018.05.128>.

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