Reduced carbon emission estimates from fossil fuel combustion and cement production in China

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Abstract:

Nearly three-quarters of the growth in global carbon emission from burning of fossil fuels and cement production between 2010 and 2012 occurred in China[1,2]. Yet estimates of Chinese emissions remain subject to large uncertainty; inventories of China's total fossil fuel carbon emissions in 2008 varied by 0.3 GtC, or 15 per cent[1,3-5]. The primary sources of this uncertainty are conflicting estimates of energy consumption and emission factors, yet none of these estimates are based upon actual measurements of Chinese emission factors. Here, we re-evaluate China's carbon emissions using updated and harmonized energy consumption and clinker production data and two new and comprehensive sets of measured emission factors for Chinese coal. We find that total energy consumption in China was 10 per cent higher in 2000-2012 than the value reported by China's national statistics[6], that emission factors for Chinese coal are on average 40 per cent lower than the default values recommended by the Intergovernmental Panel on Climate Change-IPCC[7] and that emissions from China's cement production are 45 per cent less than recent estimates[1,4]. Altogether, our revised estimate of China's CO_2 emissions from fossil fuel combustion and cement production is 2.49 GtC ($2\sigma=\pm7.3$ per cent) in 2013, which is 14 per cent lower than the emissions reported by other prominent inventories[1,4,8]. Over the full period 2000 to 2013, our revised estimates are 2.9 GtC less than previous estimates of China's cumulative carbon emissions[1,4]. Our findings suggest that overestimation of China's emissions in 2000-2013 may be larger than China's estimated total forest sink in 1990-2007 (2.66 GtC)[9] or China's land carbon sink in 2000-2009 (2.6 GtC) [10] and implies additional 25-70 per cent quota[11] in the cumulative future emissions that can be emitted by China under a 2C warming target relative to the preindustrial era.

Reports of national carbon emissions [7,12-15] are based on activity data (i.e., amounts of fuels burned) and emission factors (i.e. amount of carbon oxidized per unit of fuel consumed), with these factors estimated as the product of the net carbon content (i.e. tons carbon per joule), net heating value (i.e. joules per ton coal), total carbon content (i.e. tons carbon per ton coal) and oxidation rate (i.e. carbon oxidized per carbon content, see Methods). The uncertainty of China's emissions estimates is typically reported as ±5 to ±10%[4,14,16], but this range is somewhat arbitrary because neither the activity data nor the accuracy of emission factors is well known. For instance, national activity data is substantially different from the sum of provincial activity data[17], and the emissions factors used are not based on up-to-date measurements of the fuels actually being burned in China, of which the quality and mix are known to vary widely from year to year, especially for coal[18]. Indeed, using different official sources of activity data and emissions factors can result in estimated emissions that vary by up to 40% in a given year (see Methods).

Here, we present revised estimates of Chinese carbon emissions from burning of fossil fuels and cement production during the period 1950-2013 using independently assessed activity data and two sets of comprehensive new measurements of emission factors. Results suggest that Chinese CO_2 emissions have been substantially overestimated in recent years; 14% less than the estimates by EDGAR 4.2 (EDGAR being adopted by IPCC as the emission baseline) in 2013 and 12% less than the latest inventory China reported to the UNFCCC (in 2005). The difference is due primarily to the emission factors used to estimate emissions from coal combustion; our measurements indicate that the factors applicable to Chinese coal are in average about 40% lower than the defaults values recommended by the IPCC [7,15]and used by previous emissions inventories[1,4,19].

In re-evaluating Chinese energy consumption, we adopt the "apparent consumption" approach[14,16], which does not depend upon energy consumption data (which previous studies have shown to be not very reliable[17,20]). Instead, apparent energy consumption is calculated from a mass balance of domestic fuel production, international trade, international fueling, and changes in stocks which data are less subject to "adjustment" by reporting bodies and accounting errors related to either energy consumed during the fuel processing or assumptions about the mix of fuel types (especially coal) being used by individual consumers. Further, this approach allows imported and domestically-produced fuels to be tracked separately so that appropriate emission factors can be applied to these fuels (See Methods).

Apparent consumption of coal, oil and natural gas in China in 2013 was 3.84 Gt, 401.16 Mt, and 131.30 Gm^3, respectively. Between 1997 and 2012, we estimate that cumulative energy consumption was 10% greater than the national statistics and 4% lower than provincial statistics (Extended Data Figure 3). In addition, our results indicate a higher annual growth rate of energy consumption than national statistics between 2000 and 2010 (9.9% yr-1 instead of 8.8% yr-1); the high growth rate is consistent with satellite observations of NOx [21,22], although NOx to fuel emission factors change with time as well.

Given the large fraction of CO_2 emissions from coal combustion (80% between 2000 and 2013), estimates of total emissions are heavily dependent on the emission factors used to assess coal emissions. Thus, we re-evaluate each of the variables that determine these emission factors. The mean total carbon content of raw coal samples from 4,243 state-owned Chinese coal mines (which 4,243 mines represent 36% of Chinese coal production in 2011[23]; Fig. 1) is 58.45% (Fig 2a), and the production-weighted total carbon content is 53.34%.

These results straddle the result of an independent set of 602 coal samples from the 100 largest coal-mining areas in China (which areas represent 99% of Chinese coal production in 2011[23]; Fig. 1) reveal a similarly low mean carbon content of 55.48% (Fig. 2b), and a production-weighted mean total carbon content of 54.21%. The net carbon content of these same samples is 26.59 tC TJ^{-1}, or 26.32 tC TJ^{-1} if weighted by production (Fig. 2c), and their net heating value is 20.95 PJ Mt^{-1}, or 20.6 PJ Mt^{-1} if weighted by production (Fig. 2d). Although the measured net carbon content of these samples is within 2% of the IPCC default value (25.8 tC TJ^{-1}), the heating value from these coal samples (20.95 PJ Mt^{-1}) is significantly less than either the IPCC default value of 28.2PJ Mt^{-1} or the mean value of US coal of 26.81PJ Mt^{-1} [24]. The lower heating value of Chinese coal reflects its generally low quality and high ash content (Fig. 2e and Fig. 2f). For example, the average ash content of our 602 coal samples was 26.91% compared to the average ash content of US coal, 14.08%[24], but consistent with recent studies[25].

Finally, we assessed the oxidation rate (carbon oxidized per carbon content) of the fossil fuels consumed by 15 major industry sectors in China with 135 different combustion technologies (See Supplementary Data) as analyzed by the National Development and Reform Commission (NDRC) in 2008[26]. We calculate a production-weighted average oxidation rate for coal of 92%, somewhat lower than the IPCC default value of 98%, but generally consistent with China-specific values reported by the NDRC (94%)[26], China's National Communication (NC) that reported to UNFCCC (92%)[8], and Peters et al., 2006 (in average 93%)[27]. Our estimates of the oxidation values of oil and natural gas in China (98% and 99%, respectively) are each within 1% of the IPCC default value.

Combining our revised estimates of carbon content, heating value, and oxidation value, we derive new emission factors for coal, natural gas, and oil burned in China. The revised emission factors are different than IPCC defaults by -40%, +13%, and -1%, respectively (Fig. 3). In turn applying these lower emission factors to our revised estimates of energy consumption, our best estimate of Chinese carbon emissions from fossil fuel combustion in 2013 is 2.33 GtC using the carbon content of 4243 coal mine samples and 2.31 GtC if the carbon content of 602 coal samples is used. Based on the residual scatter of carbon contents from these independent sets of coal samples (Fig. 1), the associated 2σ uncertainty related to coal carbon content is on the order of 3%. Additional uncertainty on Chinese emissions is provided by varying estimates of coal consumed, by ±10% as evidenced by the range between national and provincial activity data[15]. Combining these two numbers gives the 7.3% uncertainty range of Chinese fossil fuel carbon dioxide emissions.

We also used clinker production data[28] to re-calculate CO_2 emissions from cement production (which accounts for roughly 7%-9% of China's total annual emissions in recent years[4]). This direct method avoids use of default clinker-to-cement ratios (e.g., 75% and 95% in IPCC Guidelines[7,12]), and results in emissions estimates that are 32%-45% lower than previous estimates (0.17 Gt C yr^{-1} in 2012 compared to 0.30 reported by the CDIAC and 0.24 by EDGAR; Extended Data Fig. 5). The clinker-to-cement ratio calculated by clinker production is 58%, or ~23% lower than the latest IPCC default values. The new, lower estimated cement emissions are consistent with factory-level investigations[29] and several other recent studies[30,31].

Together, our revised estimates of fossil fuel and cement emissions in 2013 is 2.49 GtC (2σ = ±7.3%), the new estimates (1.46 GtC in 2005) is 12% less than the latest inventories China reported to the UNFCCC (1.63 GtC in 2005, 2σ = ±8) and 14% less than the estimates by EDGARv4.2 (2.84 GtC in 2013, 2σ = ±10%) (Fig. 4). By t-test, our revised estimates of fossil fuel and cement emissions during 2000-2013 is in generally lower (at 90% level) than estimates by EDGAR (P=0.016) and CDIAC (P=0.077).

Our new estimate represents a progression for improving estimate of annual global carbon emissions, reducing the global emissions in 2013 by 0.35 GtC, an amount larger than the reported increase in global emissions between 2012 and 2013 [32]. A systematic reduction of fossil fuel and cement emissions of 0.35 GtC translates into a 15% smaller land sink, when this term is calculated as a residual between anthropogenic carbon emissions, atmosphere carbon growth and the ocean carbon sink[32], and is two times of the estimated carbon sink in China's forests (0.18 $GtCy^{-1}$) [9]. Thus it implies a significant revision of the global carbon budget[32]. Over the full period 2000 to 2013, the downward revision of cumulative emissions in China by 2.9 GtC (13%) is larger than the cumulative forest sink in 1990-2007 (2.66 GtC)[9] or China's land carbon sink in 2000-2009 (2.6GtC) **[10]**. Depending upon how the remaining quota of cumulative future carbon emissions is shared among nations, a correction of China's current annual emissions by 10% suggests a 25% (Inertia basis) or 70% (Blended basis) difference in the cumulative future emissions that can be emitted by China under a 2°C warming target[11]. Evaluating progress toward national commitments to reduce CO_2 emissions depends upon improving the accuracy of annual emissions estimates and reducing related uncertainties.

[1796 words including abstract]

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Supplementary Information is available in the online version of the paper

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Author Contributions: Z.L. and D.G. designed the paper. Z.L. conceived the research. Z.L. provided the data of 4,243 coal mines. W.W. and J.B. provided the measurement data of 602 coal samples. S.D., J.B. Q.Z, R.J.A, and T.B provided the reference data. Z.L., D.G, S.D., P.C., S.P., J.L., H.Z.,C.H., Y.L. and Q.Z. performed the analysis. S.D., S.P., Z.L., H.Z. and K.F. drew the figures. All authors contributed to writing the paper.

Online Content Methods, along with any additional Extended Data display items and Source Data, are available in the online version of the paper; references unique to these sections appear only in the online paper

Main Figures (files uploaded separately)

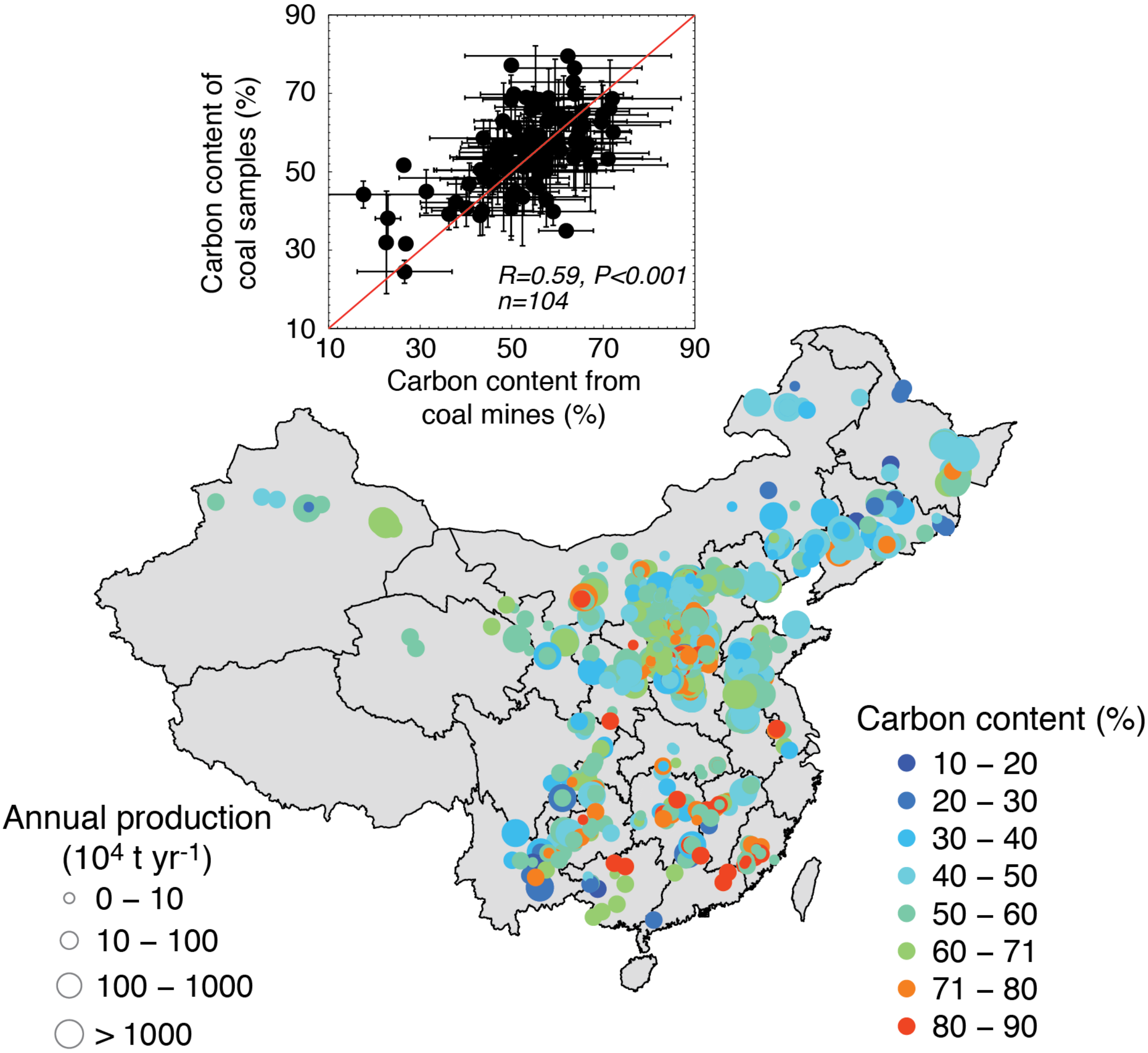

Figure 1 | Total carbon content and production of coal mines. The inset shows the comparison between carbon content from 602 coal samples and 4243 coal mines (R=0.59, P<0.001, n=104). Each dot in the inset indicates the average of carbon content from 602 coal samples and 4243 coal mines in the same 1 degree by 1 degree grid. The nearly one-to-one correlation indicates that samples and mines capture the same spatial variability of coal carbon content across China.

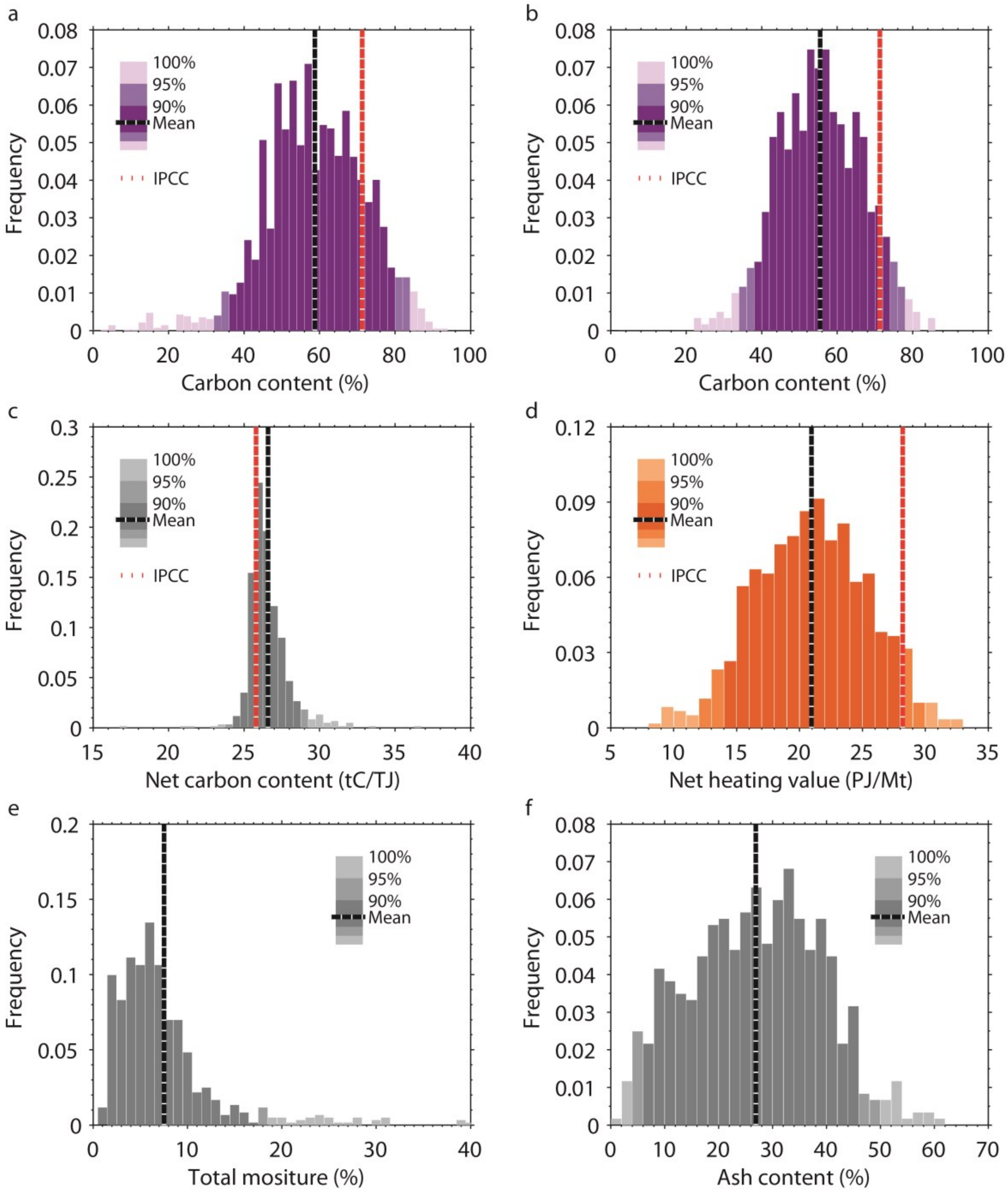

Figure 2 | Histograms of Chinese coal properties. Total carbon content of 4243 coal mines (**a**) and 602 coal samples (**b**). Dashed lines show mean, and shading indicates 90% and 95% intervals. **c** and **d**, show net carbon content (**c**) and net heating values of the 602 coal samples, respectively. Carbon content for coal mines (**a**) and samples (**b**) are significant lower than IPCC value, which is mainly because of the lower heating values, v, of China's coal (**d**), net carbon content is close to the IPCC value (**c**). Total moisture (**e**) and ash content (**f**) further proved the low quality of China's coal, which is in general with high ash content but low carbon content.

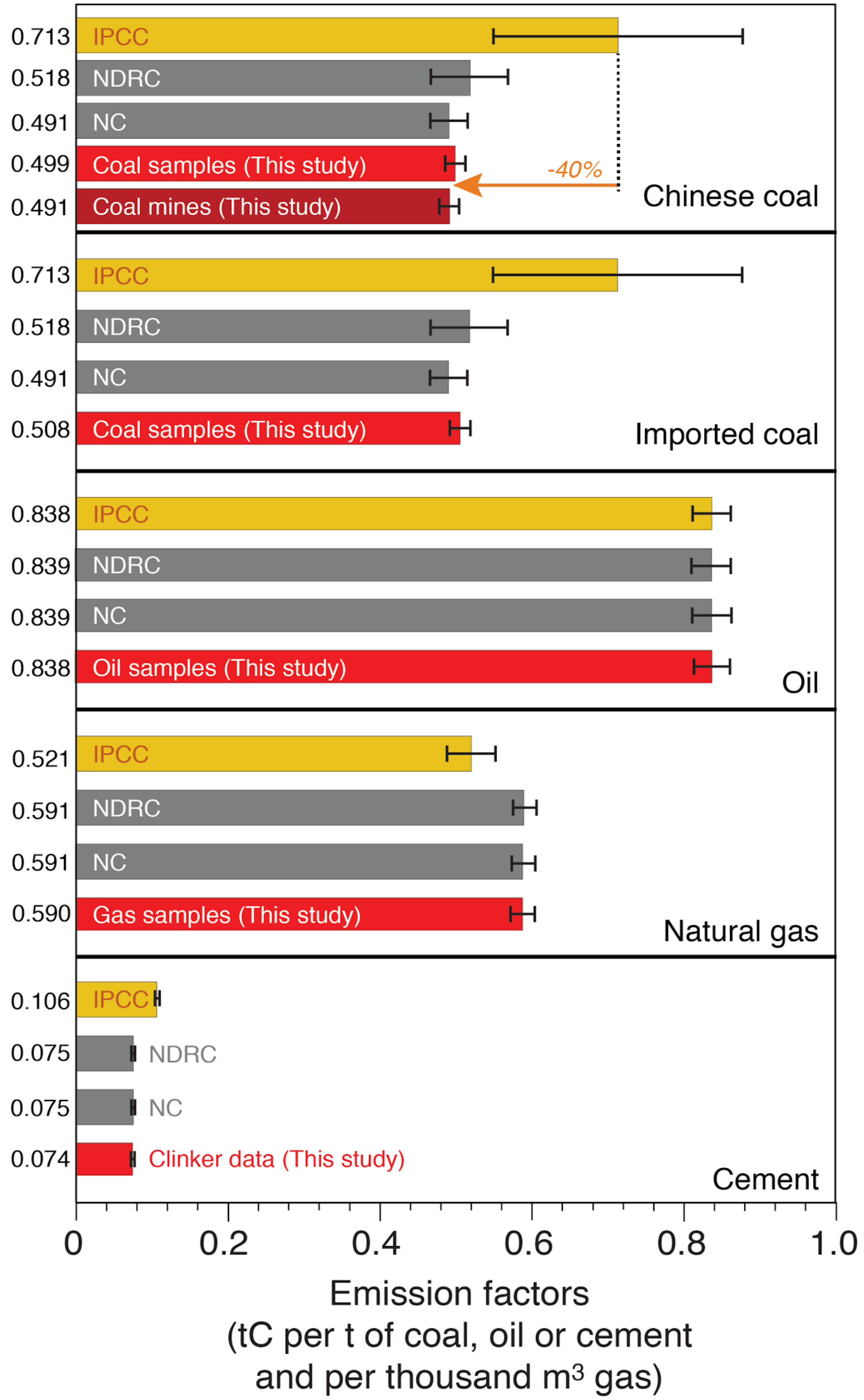

Figure 3 | Comparison of emission factors. (in 2012).

IPCC: default value from IPCC guidelines for national emission inventories (1996, 2006).

NDRC: value reported by National Development and Reform Commission (NDRC) in 2008[26]

NC: China's National Communication (NC) that reported to UNFCCC (2012 for value in 2005)[8]

All error bars are 2σ errors

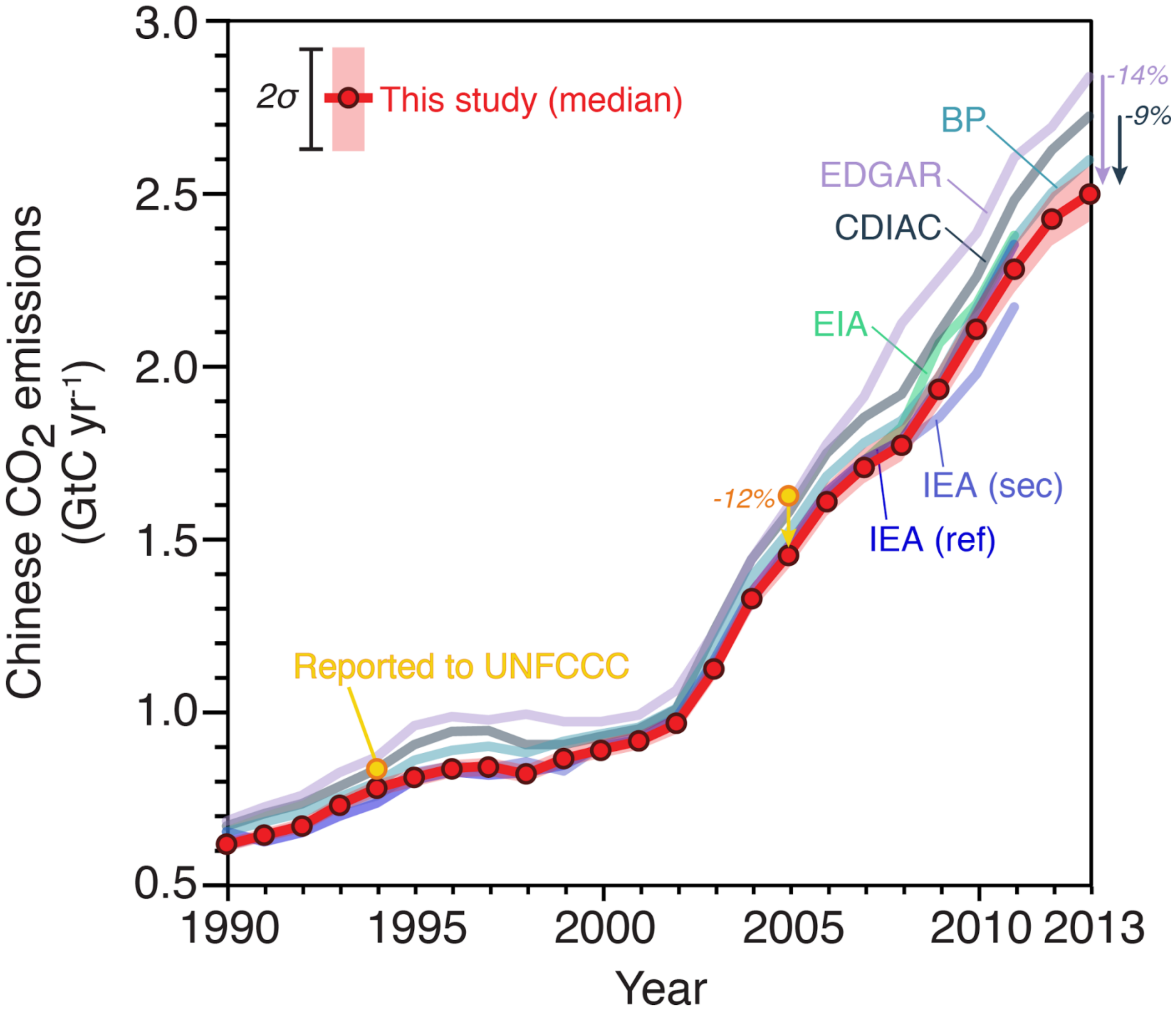

Figure 4 | Estimates of Chinese CO_2 emissions 1990-2013. Total carbon emissions from combustion of fossil fuels and manufacture of cement in China from different sources (IEA, EIA and BP estimates do not include the emission from cement production). The yellow dots are the numbers China reported to UNFCCC in year 1994 and 2005. The red-shaded area indicates the 95% uncertainty range of carbon emissions calculated by this study, assuming the emission factors during the period 1990-2013 are the same as those determined in the 2012 in this study.

Methods

1 Calculation of carbon emissions from fossil fuel combustion and cement production

Carbon emissions are calculated by using activity data, which are expressed as the amount of fossil fuels in physical units used during a production processes (activity data $_{clinker}$ is the amount of clinker produced) multiplied by the respective emission factor (*EF*).

$$\text{Emission} = \text{activity data} \times \text{emission factor } (EF) \quad (1)$$

Emissions from cement manufacturing are estimated as:

$$Emission_{cement} = \text{activity data}_{\ clinker} \times EF_{clinker} \quad (2)$$

If data on sectorial and fuel-specific activity data and *EF* are available, total emission can be calculated by:

$$\text{Emission} = \sum\sum\sum(Activity\ data_{i,j,k} \times EF_{i,j,k}) \quad (3)$$

Where *i* is an index for fuel types, *j* for sectors, and *k* for technology type. Activity data is measured in physical units (tons of fuel expressed as t fuel).

EF can be further separated into net heating value of each fuel *v*, the energy obtained per unit of fuel (TJ per t fuel), carbon content *c* (t C TJ^{-1} fuel) and oxidization rate *o* the fraction (in %) of fuel oxidized during combustion and emitted to the atmosphere. The value of *v, c* and *o* are specific for fuel type, sector and technology.

$$\text{Emission} = \sum\sum\sum(Activity\ data_{i,j,k} \times v_{i,j,k} \times c_{i,j,k} \times o_{i,j,k}) \quad (4)$$

For the coal extracted in China (e.g., for the 4,243 coal mines analyzed in this study) net heating *v* and carbon content *c* values are not directly available, and a more straightforward emission estimate for coal emissions can be obtained using the mass carbon content (C_{ar} in t C per t fuel) of fuels defined by $C_{ar} = c \times v$ so that the total emission can be calculated as:

$$\text{Emission} = \sum\sum\sum(Activity\ data_{i,j,k} \times Car_{i,j,k} \times o_{i,j,k}) \quad (5)$$

Apparent energy consumption calculation. The activity data can be directly extracted as the final energy consumption from energy statistics, or estimated based on the mass balance of energy, the so-called apparent energy consumption estimation:

$$\text{Apparent energy consumption} = \text{domestic production} + \text{imports} - \text{exports} +/- \text{change in stocks} - \text{non energy use of fuels} \quad (6)$$

Calculation of carbon emission from cement production. The carbon emission from cement production is due to the production of clinker, which is the major component of cement. When clinker is produced from raw materials, the calcination process of calcium carbonate ($CaCO_3$) and cement kiln dust (CKD) releases CO_2:

$$CaCO_3 \rightarrow CaO + CO_2$$

The amount of emission can be calculated from the molar masses of CaO (55.68 g $mole^{-1}$) and carbon (12 g $mole^{-1}$) and the proportion of their masses in clinker production. Furthermore, the emission associated with CKD that is not recycled to the kiln is calculated using the CKD correction factor, CF_{cdk}.

Carbon emission from cement production can be calculated by clinker emission factor (EF_{clinker}) and clinker production.

$$\text{Emission}_{\text{Cement}} = \text{Activity data}_{\text{Clinker}} \times \text{EF}_{\text{clinker}} \quad (7)$$

$$\text{EF}_{\text{clinker}} = \text{EF CaO} \times (1 + \text{CF}_{\text{cdk}}) \quad (8)$$

$$\text{EF CaO}_{\text{clinker}} = \text{Fraction CaO} \times (12/55.68) = \text{Fraction CaO} \times 0.2155 \quad (9)$$

Fraction CaO is the mass proportion of CaO per unit clinker (in %).

EF $\text{CaO}_{\text{clinker}}$ is the mass of total carbon emission released as CaO per unit of clinker (unit: t C per t clinker).

CF_{cdk} is the CKD correction factor (in %).

EF_{clinker} is the mass of total carbon emission per unit of clinker (t C per t clinker)

Clinker is the major component of cement. However, data on clinker production is less widely reported than that of cement production. When the data of clinker production is not available, the clinker-to-cement ratio "$R_{\textit{clinker-cement}}$" (in %) can be used for estimating the cement emission factor (EF_{cement}) and further estimate the emission based on cement production.

$$\text{R}_{\text{clinker-cement}} = \text{activity data}_{\text{clinker}} / \text{ activity data}_{cement} \quad (10)$$

$$EF_{cement} = R_{cement\text{-}clinker} \times EF_{clinker} \quad (11)$$

$$Emission_{Cement} = EF_{cement} \times M_{Cement} \quad (12)$$

The IPCC default Fraction CaO (clinker) is 64.6%, and the Fraction CaO (cement) is 63.5%; thus, the IPCC default $EF_{clinker}$ is 0.1384 (t C per t clinker). In the IPCC 1996 guideline, the clinker-to-cement ratio is 95%, which assumes that most cement is Portland cement and that the corresponding default EF_{cement} is 0.1360 (t C per t clinker). In the IPCC 2006 guideline, the clinker-to-cement ratio is 75% when no direct clinker production data are available, and the corresponding default EF_{cement} is 0.1065 (t C per t clinker). In this study, the clinker-to-cement ratio is calculated using clinker production statistics and cement production statistics. The cement production and clinker production statistics are listed in the SI.

It should be noted that the non-energy use of fossil fuels and other industrial process such as ammonia production, lime production and steel production will also produce carbon emissions. To keep consistent with the scope of international dataset we are comparing, those emissions are not included in this study. Based on previous study the total emission of these non-energy fuel use and industry processes was equivalent to 1.2% of China's emissions from fossil combustion in 2008[1].

2 The uncertainty range of China's emission estimates

We conduct analysis to show the uncertainty range of China's emission estimates based on emission factors (*EF*) reported in the literature. We collected 12 sets of *EF* data for fossil fuel combustion from the six following official sources: IPCC (1996, 2006)[2,3], China National Development and Reform Commission (NDRC)[4], UN Statistics (UN)[5], China National Communication on Climate Change (NC)[6], China National Bureau of Statistics (NBS)[7] and Multi-resolution Emission Inventory for China (MEIC)[8]. There are 3 sets of *EF* in the NDRC data, corresponding to 3 tiers of fuel classifications, 4 sets in NC and 2 sets in UN. We combined these 12 sets of *EF* with 2 sets of energy statistics derived from national and provincial data[7,9]. This yielded 24 possible inventories for China's carbon emissions of fossil fuel combustion for 1997-2012 (Extended Data Table 1). The underlying data used in the commonly used datasets (IEA, CDIAC, BP, EDGAR) is either listed in this data assembly (NBS and IPCC) or not publically available.

The mean value of 24 possible inventories is 2,490 MtC in 2012, and the standard deviation is 372 MtC (15%), the detailed data is listed in the Extended Data Table 1. The 2σ standard deviation range suggested by 24 possible inventories is 30%, which is larger than the reported range of 10% by current emission datasets such as EDGAR.

A Monte Carlo (Extended Data Fig.1) approach was adopted to assess the distribution range of the emissions by assuming that all reported *EF* values have the same probability (values have been randomly selected with equal probabilities and calculated for 100,000 times). The mean value of the 24 members' ensemble is 2.43 Gt C in 2012 (95% confidence interval is +20%, -11% and max-min range of +27%, -15%). The uncertainty is attributed to the activity data (about 40% of total uncertainty) and *EF* (60%). The variability of *EF* for coal dominates the total uncertainty (55% for total uncertainty and 90% for the uncertainty by *EF*), whereas the *EF* for other fuels are more comparable (Extended Data Fig. 2). Different *EF* values for coal mainly reflect variation in v and hence C_{ar} ($C_{ar} = v \times c$) values, whereas the variation of c and o are comparatively smaller (less than 10%).

The distribution range of the emissions was listed in Extended Data Fig. 1.

We assumed the equal possibility for various *EF* when conducting the Monte Carlo analysis, this will expand the uncertainty range. However, both the standard deviation of 24 possible inventories and the Monte Carlo analysis show the significant uncertainty range, implying the considerable system error of the emission estimates by using reported *EF*, thus it is critical to perform the emission estimates based on measurement based *EF*.

3 Apparent consumption calculation

We adopted the "Apparent Consumption" approach[10,11] to re-calculate China's energy consumption. The apparent energy consumption is the mass balance of fuels produced domestically for energy production, trade, international fuelling and change in stocks:

Apparent energy consumption= domestic production + imports – exports +/– change in stocks – non energy use of fuels

The calculated apparent energy consumption is usually different than the reported energy consumption in China. For example, our re-calculated energy consumption is higher (17% for coal, 2% for oil and 3% for gas) than the national reported energy consumption for 2013.

We believe the resulting estimates of energy consumption to be more accurate than both national and provincial energy statistics, because:

1) National energy statistics may be biased[12,13] because of under-reported fuel use in boilers from small factories and workshops[12-14]. In addition, the adjustment of national statistics by the Chinese government has been discussed in the literature[12,15-17].

2) Provincial energy statistics are also not reliable because the significant inconsistencies in provincial aggregated final-consumption energy statistics. When comparing energy consumption with total available energy supply (production plus imports and changes in stocks) in provincial statistics for 2012, coal and oil show differences of 0.25 Gt coal and 81 Mt oil[7], respectively. In addition, after removing international trade, the amount of exported and imported coal within all provinces should be equal to each other, whereas, in fact, we found an unexplained mismatch of 0.37 Gt coal in provincial aggregated energy statistics, equal to 21% of total domestically traded coal.

3) The apparent energy consumption is based on production and trade statistics. Chinese data of fuel production and trade statistics are more reliable and consistent than data of final energy consumption. After

many years of policy to reduce or close private coal mines, 97% of the coal production in China (3.40 Gt coal in 2011) is from government-owned companies (including central and local governments) that keep good records of the mass of coal extracted[18,19]. This reliability is supported by the fact that national and provincial statistics of coal production differed by only 10% in 2012[7] , while the same sources reported coal consumption that differed by 37% (3.19 Gt for national data vs. 4.36 Gt for provincial data). Moreover, coal production and trade data is consistently released earlier than coal consumption data, suggesting that the production data is the original data and therefore less prone to "adjustment" for political or other proposes. Finally, trade data has also been monitored internationally, the numbers can be verified by different nations.

4) Compared with the final energy consumption approach that involves 20 kinds of primary and secondary energy products, the apparent consumption approach is much simpler: it considers only three primary fuel types (raw coal, crude oil and natural gas) in order to avoid accounting errors due to energy consumed during the fuel processing (e.g., mass loss in coal washing and coking).

5) The apparent energy consumption approach using energy production data, which avoids having to deal with uncertain estimations of the mix of different coal types used by each final consumption category. When considering the variation of EF for different fuel types and sectors, analysis of the sources of uncertainty is more complex. It is difficult to assess specific coal-burning EF for a myriad of small consumers, and to scale these data up to the national level. Large energy consumers such as power plants continuously mix coal from different sources, which also makes it very difficult to assess national consumption-weighted average EF (weighted by share of different kinds and quality of coal consumed) from a consumption point of view. In contrast, production data can provide the national production-weighted average EF, and thus the national consumption-weighted average EF can be calculated by excluding the coal used for exports, non-energy use and stock changes.

6) The apparent consumption approach allows us to track imported and domestically produced fuels, so that a different EF can be applied.

Between 1997 and 2012, the calculated apparent energy consumption was 10% greater (14% for 2012) than the one reported in national statistics and 4% lower than provincial statistics (Extended Data Fig. 3). The growth rate of apparent energy consumption is consistent with the growth rate of industrial productions (Extended Data Fig. 2).

4 Sample measurements

4.1 Sample selection

China's coal resources are mainly concentrated in 100 major coal mine areas from 24 coal mine bases, and there are about 4,000 stable coal mines among these 100 coal mine areas that record coal production. The location of coal sampling is consistent with the distribution of coal mines (Extended Data Figure 6).

By collecting the coal samples, following principles are adopted:

a) The sampling spot is based on coal seams under production in one coal mine district, because the properties of coal from within a coal seam are almost the same. It is guaranteed that at least one sample is collected from each coal seam in one coal mine district.

b) Every coal mine area is sampled, so the 602 samples are across 100 mine areas that cover the majority of the nation's coal production.

c) There are at least 3 samples for each coal mine with a production is over 5 million tons.

d) In the same coal mine district, coal mines with high production are selected preferentially.

e) For the sampling within a location, if the samples are collected from a coal pile, they should be collected from at least 3 different coal piles. If the samples are collected from conveyor belt, they should be collected 3 times with several hour intervals from each other. All these three-times collected samples are merged together and considered as one sample data point (in total 602 sample data points) for further analysis. All samples are stored in sealed plastic bags for further analysis.

4.2 Sample analysis

For the sample measurements, we measured the air dry moisture, total moisture, net heating value, and the ash, carbon, hydrogen, nitrogen and total sulfur content. Carbon, hydrogen, nitrogen and total sulfur are determined by combustion using an Elementar elemental analyzer. Coal samples are weighed into a tin capsule and burned in a tube furnace at 1350°C. Carbon dioxide, water, nitrogen dioxide and sulfur oxide are released from the samples and measured by a TCD (Thermal conductive detector). Two parallel samples were tested together each time. The analysis is performed based on ISO standard:

Measurements process (ISO 18283:2006 Hard coal and coke -- Manual sampling)

Air dry moisture (ISO 11722: 2013-Solid mineral fuels- hard coal -determination of moisture in the general analysis test sample by drying in nitrogen).

The total moisture (ISO 589: 2008- Hard coal - Determination of total moisture).

Carbon, hydrogen and nitrogen contents: (ISO 625:1996 Solid mineral fuels -Determination of carbon and hydrogen- Liebig method; ISO 29541:2010 Solid mineral fuels -Determination of total carbon, hydrogen and nitrogen content -Instrumental method).

Ash content and volatile matter: (ISO 11722:2013, Solid mineral fuels- Hard coal- Determination of moisture in the general analysis test sample by drying in nitrogen; ISO 1171:1997 Solid mineral fuels-Determination of ash; and ISO 562:2010 Hard coal and coke-Determination of volatile matter).

The net calorific value (ISO 1928:2009, Solid mineral fuels- Determination of gross calorific value by the bomb calorimetric method and calculation of net calorific value).

Total sulfur contents: (ISO 334:2013 Solid mineral fuels -Determination of total sulfur -Eschka method)

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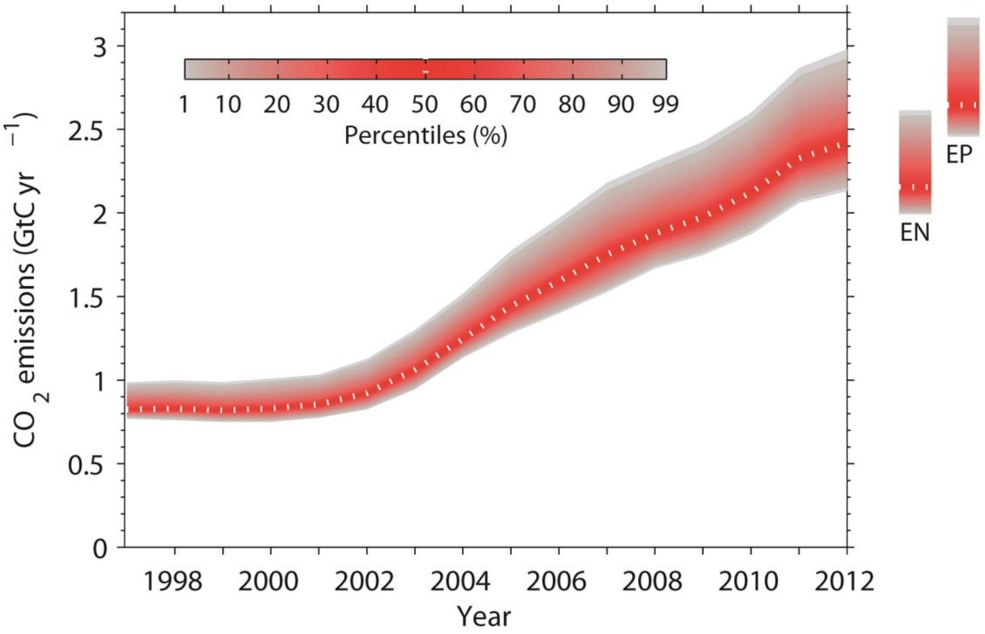
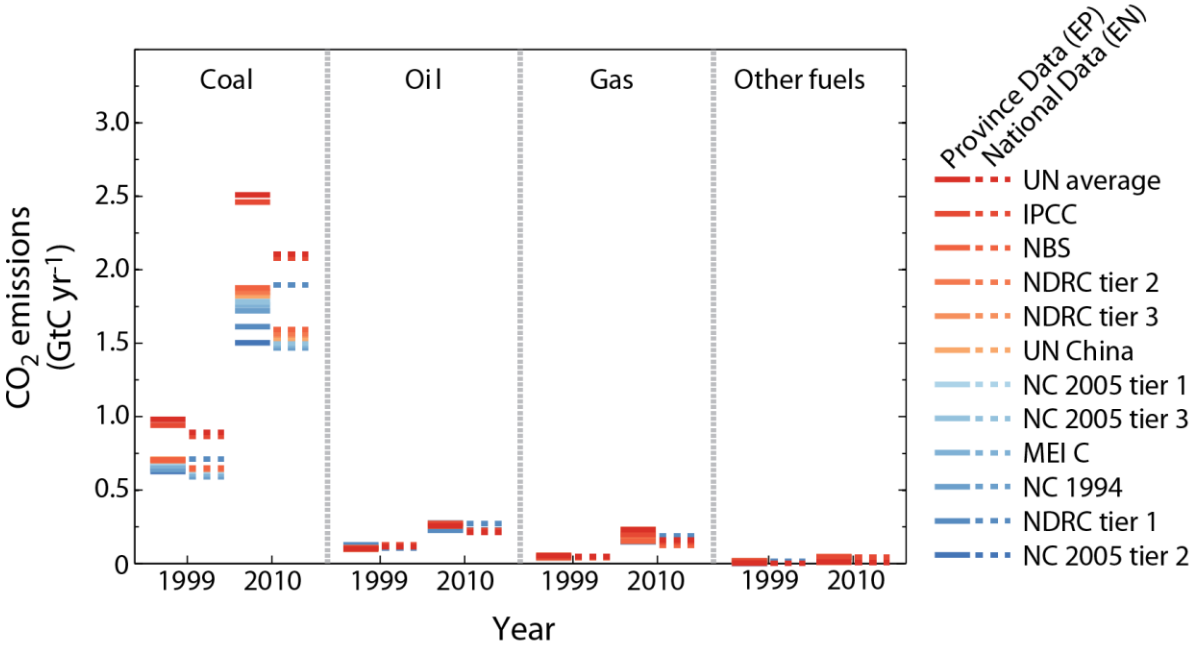
Extended Data Table

Extended Data Table 1 24 inventories of fossil fuel combustion based on reported emission factors (IPCC, MEIC, UN, NBS, NC, NDRC) and fuel inventories (EN, EP) in China, Unit Mt C.

Extended Data Figures

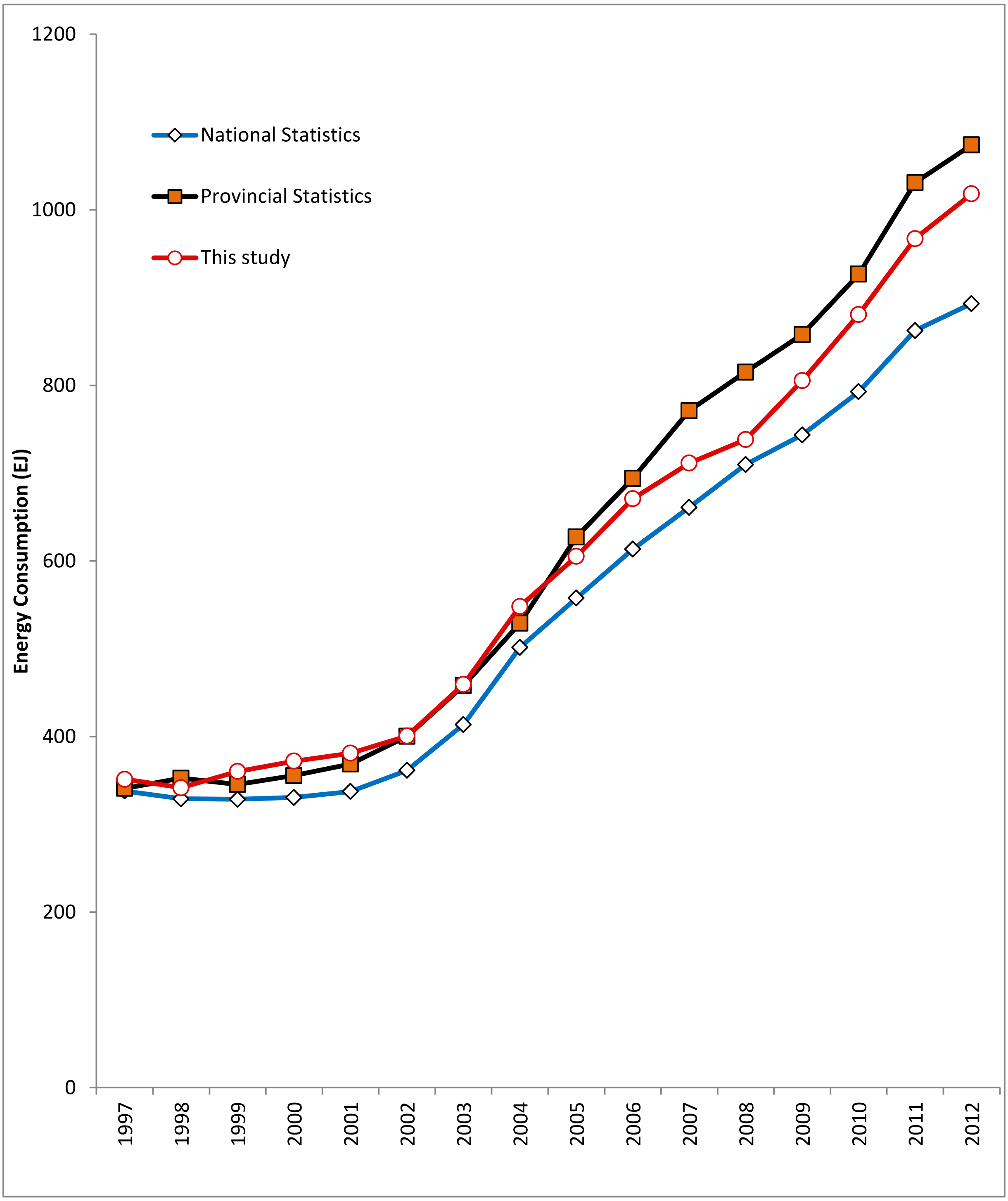


Extended Data Figure 1. Uncertainty distribution of Chinese CO_2 emissions 1997-2012. Monte Carlo simulations of the Chinese carbon emissions based on a blended activity data set where national and provincial data are assigned equal probabilities (n=100,000). Chinese carbon emissions based on national energy activity data (EN) and provincial activity energy data (EP) in 2012 are shown on the right bar.

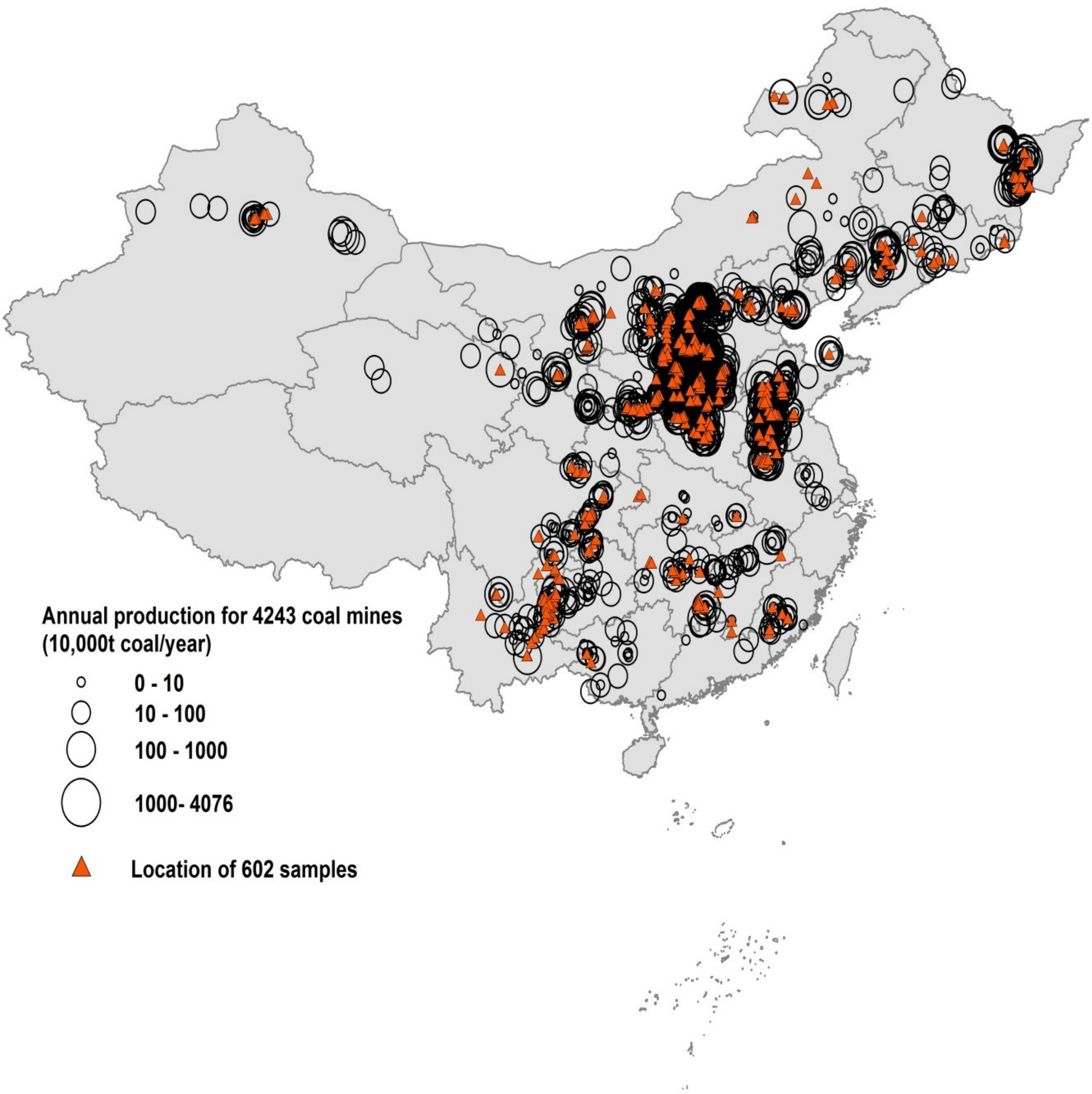


Extended Data Figure 2. Carbon emissions (Gt C yr^{-1}) from fossil fuel combustion based on different data sources

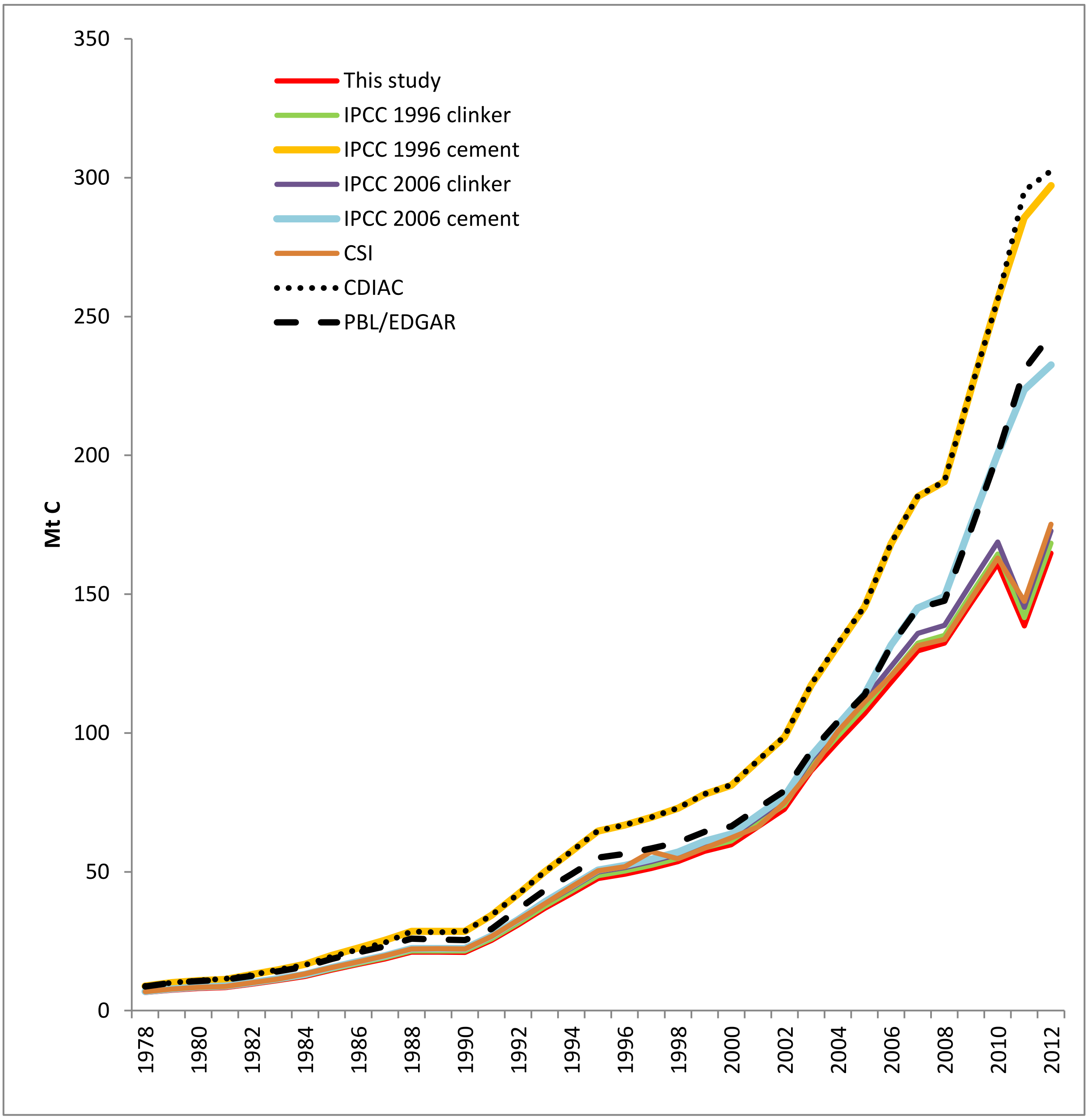
Figure 2. Carbon emissions (Gt C yr^{-1}) from fossil fuel combustion based on 12 reported emission factors (from 6 sources: IPCC, MEIC, UN, NBS, NC, NDRC) and 2 sets of activity data (EP: Aggregated Provincial statistics of energy consumption, EN: national statistics of energy consumption) in China during two periods 1997-2001 and 2008-2012. Years on the horizontal axis indicate the central year of a 5-year period. In general, the total uncertainty can be mainly attributed to the different estimates of emissions from coal consumption.



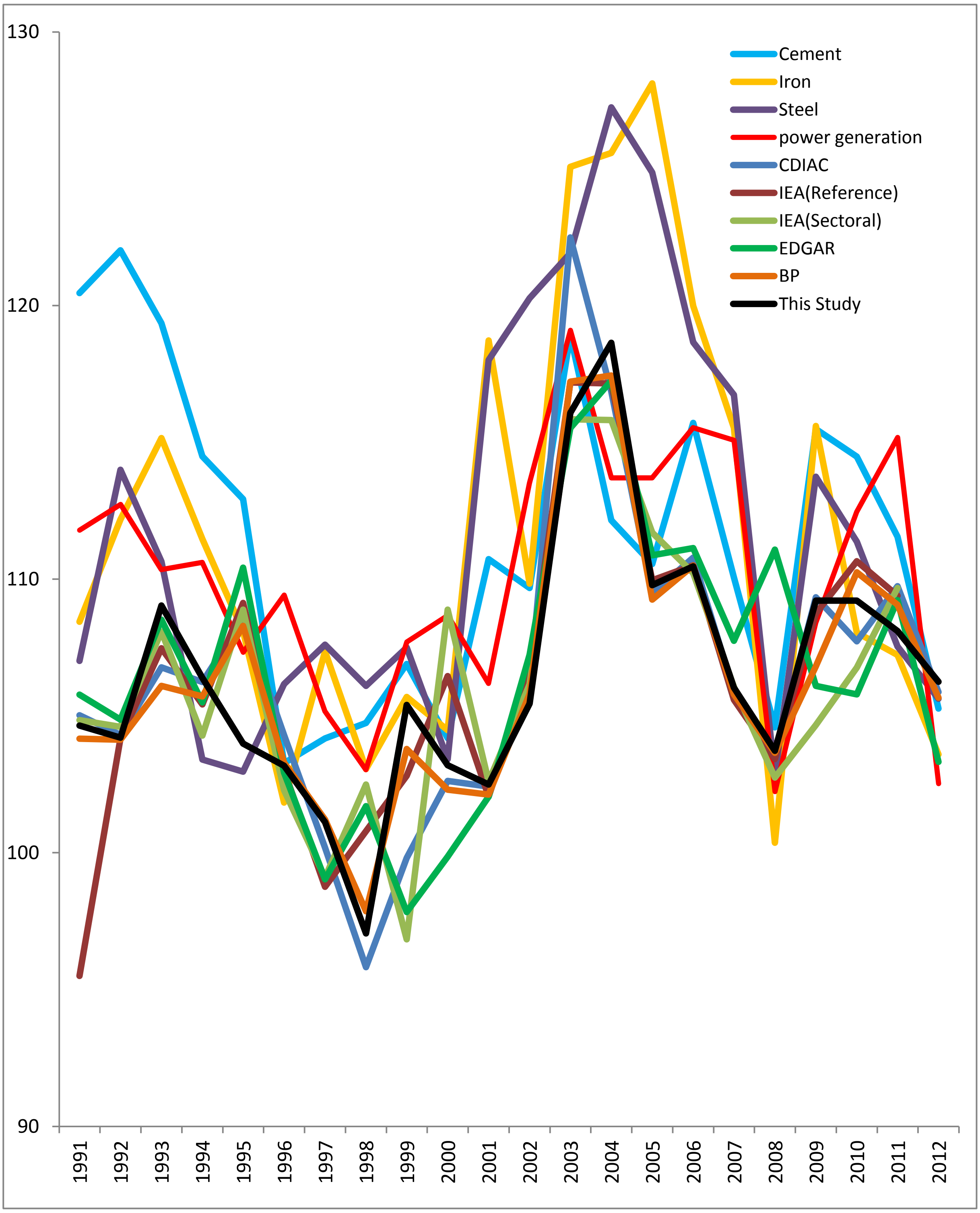
Extended Data Figure 3. Total fossil fuel energy consumption (in PJ) based upon national statistics, provincial statistics and own calculations in this study



Extended Data Figure 4. Location of 4243 coal mines (with annual production) and 602 coal samples. The coal samples and mines are consistent with spatial distribution.



Extended Data Figure 5. Emission estimates of China's cement production emissions by different sources



Extended Data Figure 6. Growth rate of carbon emissions (based upon BP, EGDAR, IEA and own calculations in this study) and industrial products (production of cement, iron, steel and power generation). The emission trends calculated in this study are consistent with the trends of industrial production