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 ($2\sigma=\pm 7.3$ 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}), which the 10% higher growth rate is consistent with satellite observations of NO_x[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.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

Figures (uploaded separately

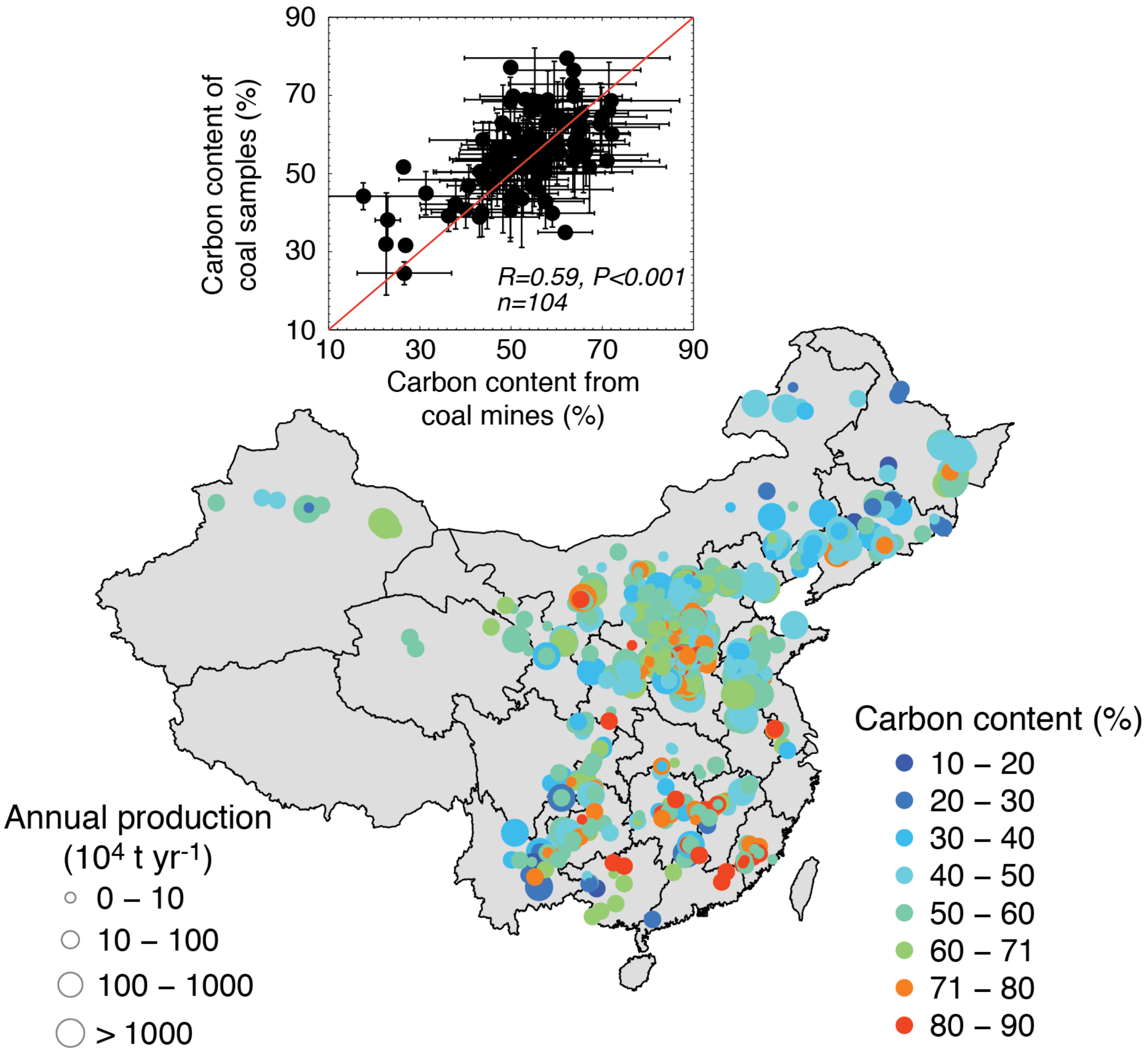

Figure 1 | Total carbon content and production of coal mines. The inset shows the comparison between carbon content from 602 coal samples and 4243 coal mines (R=0.59, P<0.001, n=104). Each dot in the inset indicates the average of carbon content from 602 coal samples and 4243 coal mines in the same 1 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.

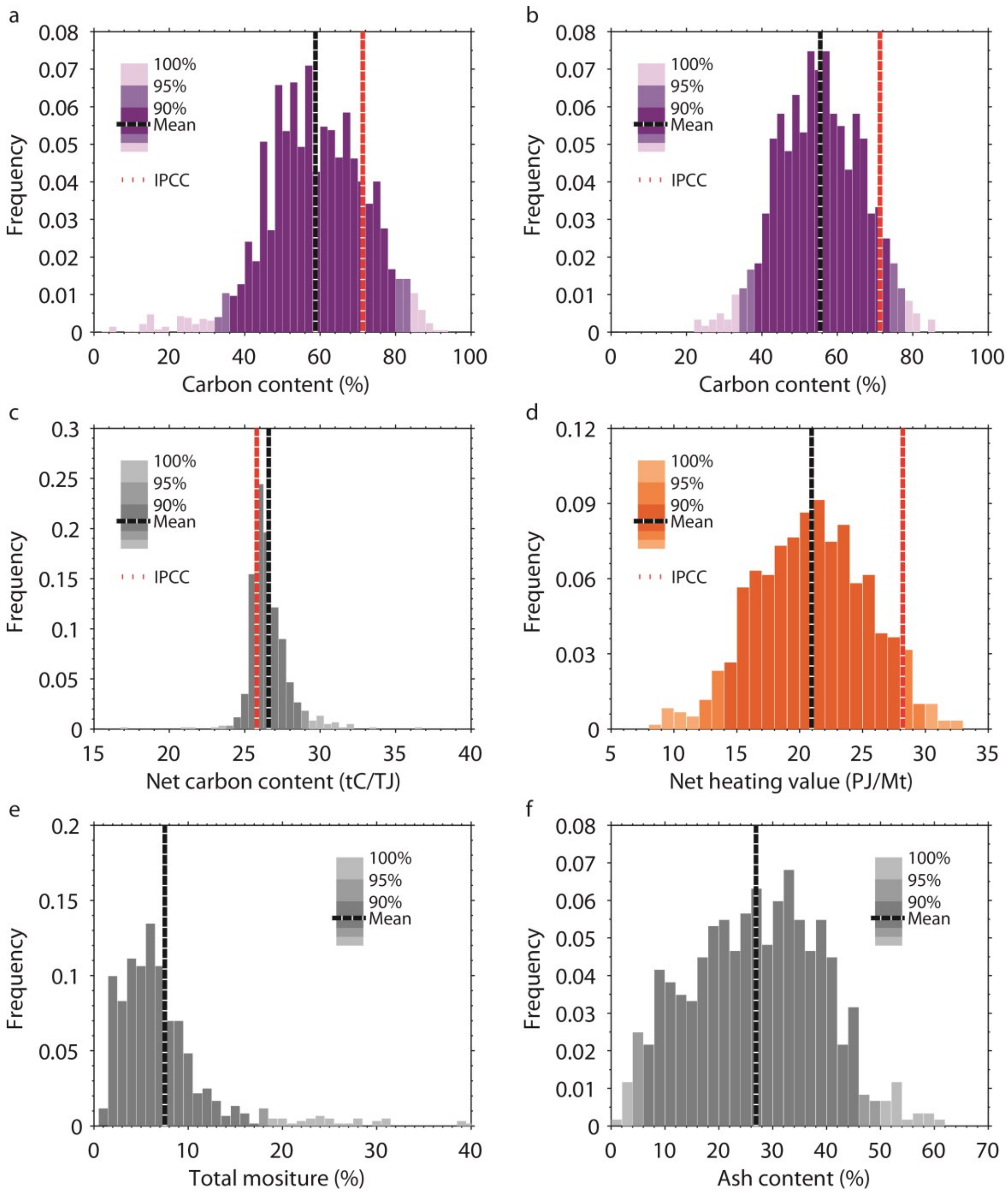

Figure 2 | Histograms of Chinese coal properties. Total carbon content of 4243 coal mines (**a**) and 602 coal samples (**b**). Dashed lines show mean, and shading indicates 90% and 95% intervals. **c** and **d**, show net carbon content (**c**) and net heating values of the 602 coal samples, respectively. 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.

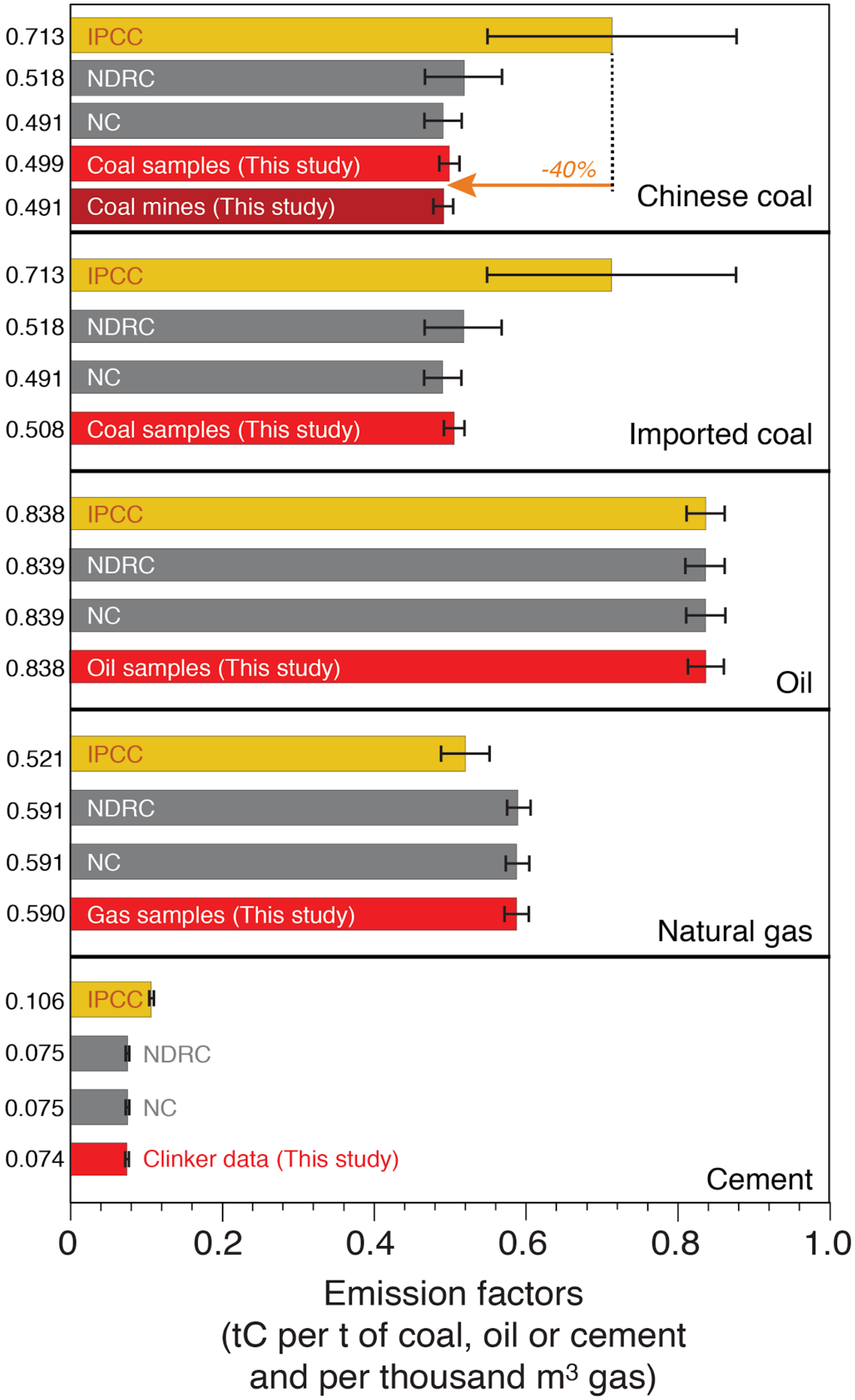

Figure 3 | Comparison of emission factors. (in 2012).

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

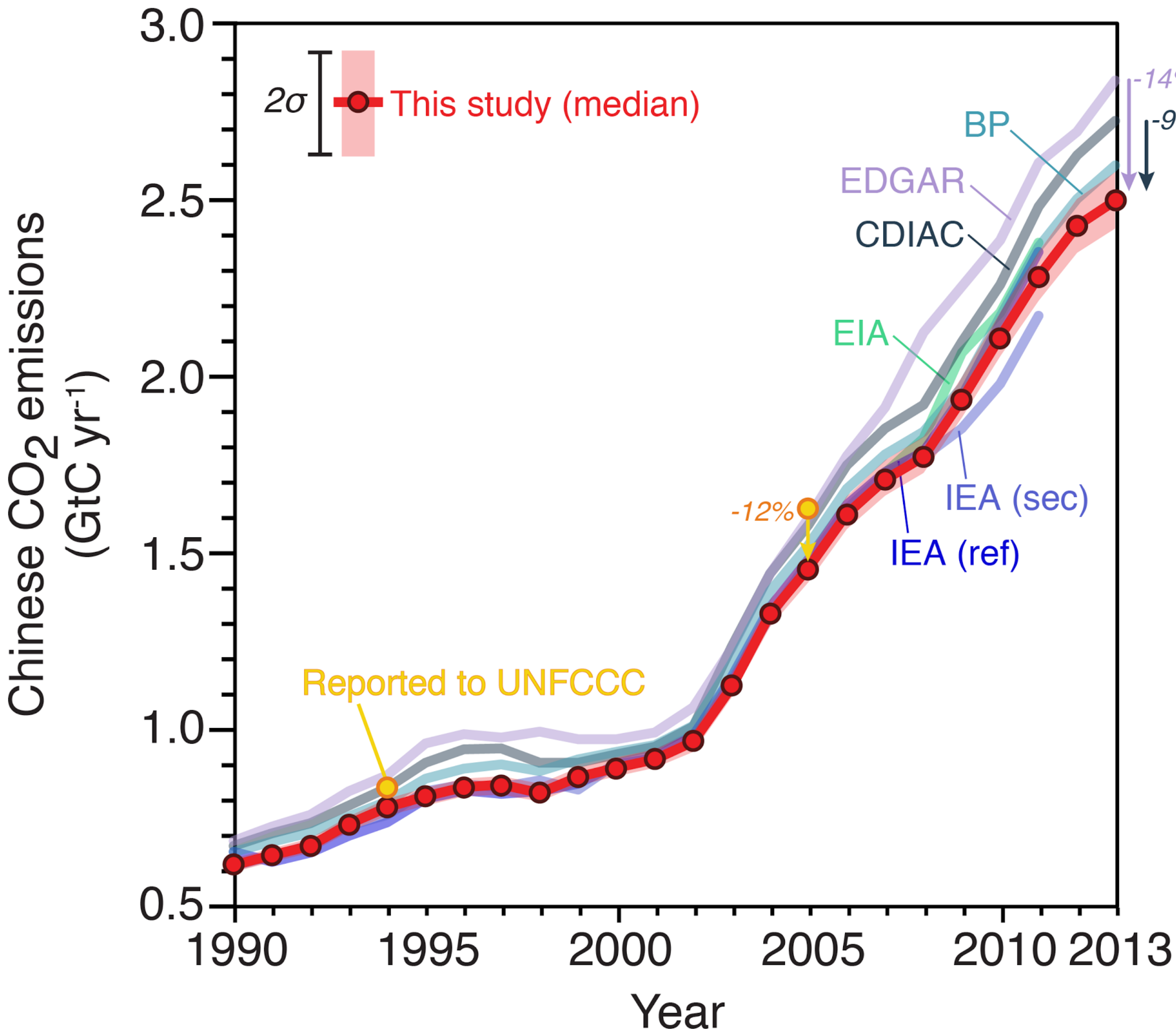

Figure 4 | Estimates of Chinese CO_2 emissions 1990-2013. Total carbon emissions from combustion of fossil fuels and manufacture of cement in China from different sources (IEA, EIA and BP estimates do not include the emission from cement production). The yellow dots are the numbers China reported to 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.