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Underreported coal in statistics: A survey-based solid fuel consumption and emission inventory for the rural residential sector in China

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HIGHLIGHTS

- Solid fuel consumption rises with the increase in Heating Degree Days.
- A transition from biofuel to coal occurs with per capita income growth.
- Estimated coal consumption is 62% higher than that reported in official statistics.
- An improved emission inventory of the residential sector is built in China.
- Our work provides a new approach of obtaining data for other developing countries.

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ABSTRACT

Solid fuel consumption and associated emissions from residential use are highly uncertain due to a lack of reliable statistics. In this study, we estimate solid fuel consumption and emissions from the rural residential sector in China by using data collected from a new nationwide field survey. We conducted a field survey in 2010 which covered ~17,000 rural residential households in 183 counties in China, to obtain data for solid fuel consumption and use patterns. We then developed a Generalized Additive Model (GAM) to establish the relationship between solid fuel consumption and heating degree days (HDD), income, coal production, coal price, and vegetation coverage, respectively. The GAM was used to estimate solid fuel consumption in rural households in China at the county level. We estimated that, in 2010, 179.8Tg of coal were consumed in Chinese rural households for heating and cooking, which is 62% higher than that reported in official energy statistics. We found that large quantities of rural residential coal consumption in the North China Plain were underreported in energy statistics. For instance, estimated coal consumption in rural households in Hebei (one of most polluted provinces in China) was 20.8Tg in 2010, which is twice as high as government statistics indicate. In contrast, modeled national total consumption of crop residues (used as fuels) we found to be ~50% lower than reported data. Combining the underlying data from the survey, the GAM and emission factors from literature, we estimate emissions from China's rural residential sector in 2010 to be: 3.3Tg $PM_{2.5}$, 0.6Tg BC, 1.2Tg OC, 2.1Tg VOC, 2.3Tg SO_2, 0.4Tg NOx, 43.6Tg CO and 727.2Tg CO_2, contributing to 29%, 35%, 38% and 26% of national total $PM_{2.5}$, BC, OC, and CO emissions respectively. This work reveals that current emission inventories in China likely underestimate emissions from coal combustion in rural residential households due to missing coal consumption in official statistics, especially for the heavily polluted North China Plain (NCP) region. Per capita income appears to be the driving factor that results in the difference between surveyed data and official data. Residents

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with high income prefer commercial energy and have a higher per capita fuel consumption than lower income residents. Therefore, rural residential coal combustion may contribute even more to regional air pollution than the large contributions previously identified.

1. Introduction

In spite of rapid urbanization, almost one-half of the population in China in 2010 lived in rural areas. The majority of rural households in China rely on solid fuels (i.e., coal, wood, and crop residue) for cooking and heating which emit large quantities of a variety of air pollutants. Compared to its relatively small contribution to total energy consumption, solid fuel combustion in rural households in China emitted 33%, 42%, 73%, and 36% of total $PM_{2.5}$, BC, OC and CO respectively, in the year 2010 (Multi-resolution Emission Inventory for China (MEIC); www.meicmodel.org). High emissions from the rural residential sector cause adverse impacts on human health through exposure to indoor and outdoor air pollution [1–4]. According to estimates of the global burden of disease [5], exposures to indoor air pollution due to residential cooking and heating caused 1.47 million attributable deaths in China in 2012. On the other hand, exposure to outdoor pollution resulting from emissions from combustion of coal and biofuels in the residential sector in China caused ~177 thousand (95% CI: 160, 193) premature deaths in 2013, and contributed to 19% of total premature mortalities due to outdoor $PM_{2.5}$ pollution in China [6]. The contribution of residential emissions to $PM_{2.5}$ pollution is larger in winter due to increased fuel consumption for heating. Liu et al. [7] estimated that residential emissions contributed 35–40% of daily average surface $PM_{2.5}$ concentrations in the North China Plain region in winter. Combustion of residential solid fuels also has warming effects on climate due to high emissions of BC [8–10]. He et al. [11] carried out a measures-based economic analysis of low carbon investment opportunities in the residential sector in Chinese megacities to estimate the CO_2 emission mitigation.

Compared to other anthropogenic activities, quantifying emissions from solid fuel combustion in rural households is more challenging than quantifying emissions from other sectors owing to a large variation in fuel use patterns and emission characteristics [12–15]. Previous studies have identified the relationships between temperature and residential fuel choices, and between socioeconomic conditions and residential fuel choices. Socioeconomic conditions and temperature also have an impact on quantity of fuel used and spatial and the temporal distribution of rural energy consumption. Temperature is a direct indicator of heating demand and is found to affect residential fuel consumption [16]. Fuel choice is also impacted by various socioeconomic factors including household income, energy prices, fuel access, electrification, and level of education [17–21]. Chen et al. [22] stated that the proportion of households using gas to cook increased, whereas the proportion using solid fuels decreased as per capita income increased for rural households. The fraction of households using electricity to cook increased slightly as income increased in rural areas [20]. Laboratory and field measurements found that emissions from residential solid fuel combustion are highly varied by fuel quality, fuel and stove types [12,13,21,23,24]. Primary $PM_{2.5}$ emissions from raw coal burned in a traditional stove has been found to be higher than from briquettes burned in an improved stove by 2–4 orders of magnitude [25,26]. Hence the choice of fuels and stoves greatly impacts the levels of emissions.

In most current global, regional, and national emission inventories covering China, emissions are estimated by using activity rates from official energy statistics from the International Energy Agency (IEA) or the China Energy Statistical Yearbook (CESY) [27] and emission factors from various literature [13,14,28,29]. Specific issues associated with the residential sector in CESY were identified in previous studies. Zhang et al. [29] argued that briquettes are widely used in the Chinese residential sector, while the CESY reported only low briquette consumption. A recent study found that the survey-based residential coal combustion in rural NCP regions was higher than coal consumption reported in CESY by a factor of 3 [30], indicating that coal consumption from the residential sector might be largely underreported in government statistics. The reasons for these discrepancies remain unknown, but the residential sector has been recognized as the largest source of uncertainties in CO, VOC, BC, and OC emissions over China due to unreliable statistics and a lack of real-world emission factors [13–15,29]. Considering the potential large uncertainties in residential coal use statistics, Lu et al. [15] assigned 33% and 80% uncertainty (95%CI around the mean) for residential coal and biofuel consumption in China. This contributes substantially to overall uncertainties in total emission estimates.

Given the high uncertainties in official statistics and large variation in fuel use patterns in the residential sector, alternative approaches were developed to better represent real-world fuel consumption. Although still using total annual fuel consumption from CESY, Zhu et al. [16] developed a model approach to estimate the spatial and temporal variations of residential fuel consumption by considering the heating days (HD) and heating degree days (HDD) in various regions over China. Surveys of household residential energy are conducted in many developed countries and some developing countries and have become a fundamental source of energy data. For example, the US Energy Information Administration started to survey US households' energy use in 1978 [31]. Some similar surveys [29,30,32–34] were conducted in China. Survey data can provide useful information on fuel consumption and its relationship with natural and socioeconomic factors. Based on national survey data, Bonjour et al. [35] developed a multilevel model to derive global solid fuel use for household cooking. The model was used to estimate the disease burden due to household air pollution for the GBD2010. Both national [32,33,36] and regional surveys [29,30,34] over China have identified the relationship between regional solid fuel consumption with temperature and household income. Missing coal consumption in CESY has also been observed in other studies [30,32] and emission inventories for a few regions were subsequently revisited based on survey data [30]. However, these surveys only estimate provincial fuel consumption based on per capita fuel consumption. Researchers then multiply per capita fuel consumption by the total population. What's more, improved emission inventory at the provincial level incorporating survey-based information of solid fuel use in the rural residential sector in China has not been included in previous studies. The primary difference between this work and other emission inventories [29,37] is that our activity levels are derived from the survey data while the activity level of other emission inventories is derived from CESY data.

Our objective is to improve the understanding of energy consumption and emission data for the rural residential sector in China by using data collected from our nationwide survey. We conduct a first-hand field survey in China among 17,633 households located in 183 counties in 28 provinces. We first investigate the factors that affect fuel consumption in the rural residential sector—socioeconomic, vegetation coverage and HDD, then build a statistical model to predict fuel consumption with these variables. We next estimate the solid fuel consumption in China and use the statistical model to estimate the consumption in counties without survey data. Third, we improve the emission inventory of the residential sector with the updated solid fuel consumption and develop an emission factor database with specific for various stove devices at the provincial level.

The quantitative model of fuel consumption can be used to forecast future fuel demands of rural residential areas. The updated coal and fuel consumption data based on the field survey also provides realistic information that can be used to adjust the international statistics data from International Energy Agency (IEA) and Food and Agriculture Organization (FAO), which have been used extensively [38,39]. The results in this study can further provide valuable guidance to policy makers in other developing countries, which face similar issues of air pollution and CO_2 emission mitigation. Bhattacharyya [40] pointed out

Table 1
Emission factors of solid fuel combustion used in this study (Unit: g/kg).

Fuel type	Fuel sub-type	Stove type	OC	BC	$PM_{2.5}$	VOC	SO_2	NO_X	CO	CO_2
Raw coal	Bituminite	Traditional stove	4.2[12,15,19,22]	1.65[14,15,19,22]	9.3[1,2,14,22]	2.9[27,30]	14.2[a]	0.9[30]	144.0[14]	2300[14,23]
		Improved stove	0.8[1,4,5,6,20]	0.64[4,5,6,20]	5.8[1,4,6,18]	2.9[b]		0.7[3]	189.0[1,5]	2167[23]
		Kang	4.2[b]	1.65[b]	9.3[b]	2.9[b]		0.9[b]	144.0[b]	2050[14,23]
		Brazier	4.2[b]	1.65[b]	9.3[b]	2.9[b]		0.9[b]	144.0[b]	2300[b]
		Household boiler	0.8[13]	0.38[13]	5.8[c]	2.2[19]		4.0[21]	124.0[29]	2167[c]
	Anthracite	Traditional stove	2.2[7,12,15,19,22]	1.15[19,15,22]	6.5[2,22]	2.9[27,30]		0.9[30]	144.0[14]	2527[23]
		Improved stove	1.2[1,4,5,20]	0.45[1,4,5,7,20]	4.3[4,7,20]	2.9[b]	14.2[a]	0.6[3]	95.0[1,5]	2167[23]
		Kang	2.2[b]	1.15[b]	6.5[b]	2.9[b]		0.9[b]	144.0[b]	2527[b]
		Brazier	2.2[b]	1.15[b]	6.5[b]	2.9[b]		0.9[b]	144.0[b]	2527[b]
		Household boiler	0.8[13]	0.38[13]	4.3[c]	2.2[19]		4.0[21]	124.0[29]	2167[c]
Briquettes	Bituminite	Traditional stove	4.4[7,14,15,22]	0.15[14,15,25]	8.2[2,14,25]	0.7[27,30]		0.5[30]	35.0[14,30]	2013[14,30]
		Improved stove	0.9[1,4,20]	0.09[1,4,20]	6.5[1,4,20,7]	0.5[27,30]		0.1[26,30]	35.0[1,30]	431[14,30]
		Kang	4.4[b]	0.05[b]	8.2[b]	0.7[b]	12.0[a]	0.5[b]	35.0[b]	2013[b]
		Brazier	4.4[b]	0.07[b]	8.2[b]	0.7[b]		0.5[b]	35.0[b]	2013[b]
		Household boiler	0.8[13]	0.38[13]	2.1[13]	0.5[c]		0.1[c]	15.0[29]	431[c]
	Anthracite	Traditional stove	1.2[14,15,22]	0.06[14,15,25]	4.3[2,14,25]	0.7[27,30]		0.5[30]	30.3[14,29]	2013[14,30]
		Improved stove	0.6[1,4,6,20]	0.03[1,4,6,20]	2.2[1,4,6,20]	0.5[27,30]		0.1[26,30]	35.0[1,29]	1713[14]
		Kang	1.2[b]	0.06[b]	4.3[b]	0.7[b]	12.0[a]	0.5[b]	30.3[b]	2013[b]
		Brazier	1.2[b]	0.06[b]	4.3[b]	0.7[b]		0.5[b]	30.3[b]	2013[b]
		Household boiler	0.8[13]	0.38[13]	2.1[13]	0.5[c]		0.1[c]	15.0[29]	1713[c]
Wood		Traditional stove	1.7[10,17,24]	1.02[8,10,12,17]	3.7[2,14]	4.7[18,30]	0.03[30]	1.0[30]	65.0[12,26,30]	1576[11,18,23,27]
		Improved stove	1.5[6,8,12,17]	0.95[6,8,17]	3.5[14]	2.6[27,30]	0.01[30]	0.9[30,18]	81.0[18,30]	1112[18,29]
		Kang	1.7[b]	1.02[b]	3.7[14]	1.8[18]	0.03[b]	1.7[9]	39.6[18]	1568[18]
		Brazier	1.7[b]	1.02[b]	3.7[b]	4.7[b]	0.03[b]	1.0[b]	65.0[b]	1576[b]
		Household boiler	1.5[c]	0.95[c]	3.5[c]	1.6[c]	0.01[c]	0.9[c]	81.0[c]	1112[c]
Crop residues		Traditional stove	2.1[6,16,17]	0.75[6,16,17]	10.4[2,24,28]	7.3[18,30]	0.02[30]	1.1[30]	67.7[30]	1180[11,14,18,23,30]
		Improved stove	1.6[16,17]	0.86[14,17]	8.7[8]	6.6[27,30]	0.10[30]	0.6[30,18]	102.6[13,16,18,30]	1092[11,14]
		Kang	1.5[14]	1.35[14]	10.4[b]	8.4[18]	0.02[b]	1.3[18]	124.9[14]	1613[14]
		Brazier	2.1[b]	0.75[b]	10.4[b]	7.3[b]	0.02[b]	1.1[b]	65.8[b]	1097[b]
		Household boiler	1.6[c]	0.86[c]	8.7[c]	6.6[c]	0.10[c]	0.6[c]	102.6[c]	1098[c]

[1] Li et al. [52].
[2] Shen et al. [53].
[3] Zhang et al. [54].
[4] Chen et al. [55].
[5] Shen et al. [24].
[6] Shen et al. [56].
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[8] Shen et al. [51].
[9] Ozgen et al. [68].
[10] Wei et al. [24].
[11] Wei et al. [58].
[12] Shen et al. [49].
[13] Lei et al. [37].
[14] Shen et al. [48].
[15] Chen et al. [57].
[16] Roden et al. [62].
[17] Li et al. [59].
[18] Wang et al. [60].
[19] Zhang et al. [63].
[20] Zhi et al. [47].
[21] Zhang et al. [29].
[22] Chen et al. [46].
[23] IPCC [61].
[24] Roden et al. [64].
[25] Chen et al. [23].
[26] Ge et al. [65].
[27] Tsai et al. [66].
[28] Venkataraman et al. [67].
[29] Ge et al. [69].
[30] Zhang et al. [70].
[a] Emission factors based on sulfur content of coal.
[b] Assume emission factor is as same as traditional stove.
[c] Assume emission factor is as same as improved stove.

that rural households in India also rely on traditional fuel with high emissions. In India, 87% of rural households use firewood, 82% still use some amount of kerosene, 67% use electricity and 15% use LPG.

This paper is organized as follows. The model framework and methodologies used in this study are documented in Section 2. The modeling results and emission estimates are provided in Section 3. In Section 4, we discuss the uncertainty in our newly developed emission inventory and the implications of previously underestimated coal consumption. We compare our emission inventory with historic fuel consumption trends and offer suggestions for further study.

2. Methodology and data

We construct a generalized additive model (GAM) to estimate rural residential solid fuel consumption at the county level using first-hand data collected by a questionnaire survey in 2010. We then develop an atmospheric pollutant emission inventory for the rural residential sector in 2010 and compare the estimates with previous studies that were based on official statistics. Finally, we quantify the uncertainties associated with our emission estimates based on the statistical distribution of survey data within a Monte Carlo framework.

2.1. Field survey

To obtain fuel consumption rates, use patterns, and combustion technologies of solid fuels in rural areas over China, a household survey was conducted in 201 randomly selected counties (8% of total) covering 28 provinces except Shanghai, Tianjin, and Tibet. The survey was conducted in the winter of 2010. We implemented face-to-face interviews with household participants to complete 21,351 questionnaires. Due to missing data and information error, overall, a total of 17,633 valid questionnaires were collected in this work, national average return rate is 72%, the return rate of samples in province is given in Fig. S1 in the Supplement.

We collect data corresponding to four types of annual solid fuel consumption from the questionnaires, including raw coal, briquettes, wood, and crop residues. For the same fuel type burned in different types of combustion devices, emission factors can vary significantly due to differences in combustion efficiencies. To better understand how emission patterns are affected by combustion technology, in the survey we further investigate how much solid fuel was used in each type of combustion device. A sample of the questionnaire is provided in Fig. S2. We classify combustion devices in Chinese residential households into five types: traditional stoves, improved stoves, kangs, braziers, and residential boilers (see Fig. S3).

2.2. Modelling

We use the survey data with GAM [41] to estimate per capita coal and biofuel consumption at the county level. GAM is a semi-parametric approach which can predict non-linear responses to selected predictor variables [42,43].

Using GAM we test the effect of temperature and socioeconomic parameters on fuel consumption. Fuel consumption was determined by heating demands in winter, which was influenced by outdoor temperature. As income has increased, people have switched to cleaner fuel types. In addition, energy consumption is affected by energy production and energy price. Biofuel consumption is largely correlated with local vegetation coverage because biofuels are not commercially available and are directly collected by users. We fit the coal and biofuel models with the GAM function in the mgcv package in R [44].

$$F_{coal} \sim \alpha_0 + s(Income) + s(HDD) + s(Price) + s(Prduc) \quad (1)$$

$$F_{biofuel} \sim \beta_0 + s(Income) + s(HDD) + s(Cover) \quad (2)$$

where F_{coal} and $F_{biofuel}$ represent the per capita coal and biofuel consumption, respectively. α_0 and β_0 are the intercepts. s (.) is a spline smoothing function of the variable (per capita income (*Income*), *HDD*, coal price (*Price*), coal production (*Prduc*) and vegetation coverage (*Cover*)). Income data was derived from survey in 2010. Coal price and coal production at the provincial level were derived from China coal industry development statistical yearbook (CCSY) [45]. Vegetation coverage of China was derived from the Global Land Cover product retrieved from Landsat observations (https://landcover.usgs.gov/glc/).

HDD is a measurement designed to reflect the demand for energy needed to heat a building.

$$HDD = \sum_{i=1}^{n} (1 - rd)(T_{b1} - T_i) \quad (3)$$

where n is the days of a year; T_i is daily mean temperature; T_{b1} is the base temperature of Heating degree days, which is 18 °C, derived from the energy conservation design standard for heating buildings in China; rd equals 1 if the average daily temperature is higher than the base temperature, otherwise 0. We derived surface temperature from the global surface weather data set, China Meteorological Data Sharing Service System (http://cdc.cma.gov.cn).

The leave-one-out cross-validation (LOOCV) method is applied to evaluate the performance of the GAM. For counties with coal and biofuel consumption, one county is selected as the validation set and the remaining counties are employed as the training set. Predictions of the validation set are generated using the model obtained through fitting of the training set. This process is repeated N times, and then LOOCV R^2 values were computed. In addition, statistical indicators including the coefficient of determination (R^2), root-mean-square prediction error (RMSE) and the normalized mean prediction error (NME) are also used to evaluate the performance of model fitting and cross-validation and to test for potential model over-fitting.

2.3. Emission estimates

In this work, we collect fuel consumption data to develop an improved emission inventory of China's rural residential sector. The emission estimates are similar to a bottom-up emission inventory, which were described in detail by Zhang et al. [29]. The emission of a particular species is estimated by the following equation:

$$E_j = \sum_i \sum_j A_{i,j} \left[\sum_m X_{i,j,m} EF_{i,j,m} \right] \quad (4)$$

where i represents the province (municipality, autonomous region); j represents the fuel type (e.g., raw coal, briquette, wood and crop residues), m represents the combustion technology type (e.g., traditional stoves, improved stoves, kangs, braziers and household boilers); A is the activity rate, such as fuel consumption; X is the fraction of fuel for the residential sector by a specific technology, where$\sum X = 1$for each fuel type; and EF is the emission factor.

Many studies [23,46–51] that measured residential emission factors showed that there are several-fold differences in emission factors among various stove technologies burning the same fuel type, which illustrates the important role of stove type in improving the accuracy of emission inventories. In the previous study, fuel was simply assumed to be burned in only one or two stove types. In this study, we first adopted a sophisticated distribution of stove technologies among rural residential areas at the provincial level based on survey data and established a detailed emission factor database. Table 1 lists the geometric average emission factors that were collected from literature reports focusing on China [23,24,37,46–70].

Emission factors are developed using technology-based methodologies. We conducted a comprehensive review of the literature for emission factors from various stoves and fuel types used around China. Resulting mean EF values are presented in Table 1 for each stove type and fuel for the year 2010. We apply the latest emission factors in our study for two reasons. First, there are large differences in EF measurements among published papers. We collect as many EF as possible from the published literature to use in our study – both recent and older measurements. Thus, the uncertainty of geometric mean EF can be reduced. Second, the fuel types and stove types in use in 2010 are quite similar to those used in the past. As a result, the latest EF results can represent the characteristics of emissions in 2010. However, the emission factor of SO_2 varied among provinces due to variations in the quality and sulfur content of the fuel. Therefore an average SO_2 EF for all stoves is reported in Table 1 and was calculated as follows:

$$E_{SO2,j} = \sum_{i}\sum_{j}\sum_{m}(A_{i,j} \times SC_{i,j,m} \times SR_{i,j,m} \times R_{i,j,m}) \times 2 \quad (5)$$

where SC is the sulfur content of the fuel, and SR is the sulfur release ratio (%).

3. Results

3.1. Solid fuel use pattern from the survey

3.1.1. Per capita fuel use

Fig. 1 summarizes the per capita fuel consumption of the four fuel types obtained from the average survey data and the average HDD at the provincial level. The per capita fuel consumption notably drops with the decline in HDD, which demonstrates the strong correlation between fuel consumption and temperature. The total fraction of raw coal, briquette, wood and crop residues consumption is 29%, 18%, 37% and 16%, respectively, in China.

As shown in Fig. 1, the characteristics of fuel consumption in rural residential areas are different in northern and southern China. For example, coal consumption in northern China is dominated by raw coal. Conversely, it is dominated by briquettes in southern China. The need of abundant coal to meet heating demands in rural residential areas in northern China and the unaffordability of higher-priced briquettes are key factors contributing to heavy air pollution in the winter in northern China. Biofuel consumption is not significantly different in northern and southern China. Provinces that consume the most crop residues are the three northeastern provinces (i.e., Heilongjiang, Jilin and Liaoning) due to their high crop yields. Wood consumption in southern China is higher than that in northern China because of greater forest coverage and wood resources in southern provinces.

The per capita fuel consumption by province has a positive relationship with HDD (R^2 = 0.66). With the decline of HDD, the per capita fuel consumption decreases dramatically. Xinjiang has the highest per capita raw coal consumption due to three main reasons. First, Xinjiang is one of the largest coal-producing provinces in China, with approximately 100 million tons of coal produced in 2010 [67]. Therefore, coal, particularly raw coal, has a very low price locally. Second, most areas in Xinjiang have dramatic daily temperature swings because Xinjiang has a generally semi-arid or desert climate. Therefore, although Xinjiang has a lower HDD than northeastern provinces such as Heilongjiang and Jilin, it has a higher heating demand at night. Third, wood and crop residues are scarce because deserts accounts for large areas there. Therefore, raw coal consumption accounts for approximately 90% of the total per capita fuel consumption in Xinjiang province.

The survey data also shows the correlation between fuel consumption, income and HDD using the regression analysis. The per capita coal consumption and per capita biofuel consumption has a positive and negative correlation with per capita income ($p < 0.05$), respectively, as presented in Fig. S4. The per capita fuel consumption drops notably along with the decline in HDD, which demonstrate the correlation ($p < 0.05$) between fuel consumption and temperature, as shown in Fig. S5. The regression model performance is shown in Fig. S6. We compare the estimated per capita coal, biofuel and solid fuel (sum of coal and biofuel) consumption with the survey data. The estimator of the regression model is in good agreement with the survey data (R^2 = 0.77, 0.83 and 0.84 for coal, biofuel and solid fuel consumption, respectively). The normalized mean error (NME) values for coal, biofuel and solid fuel are less than 9%, implying high accuracy of the predicted fuel consumption.

3.1.2. Stove types

The marked variation in economic development and climate conditions over China result in technology choices varying significantly across provinces. Fig. 2 presents the proportions of five stove types applied for fuel consumption (i.e., coal, wood and crop residues) in 28 provinces. The data for Fig. 2 are directly from the survey sampling

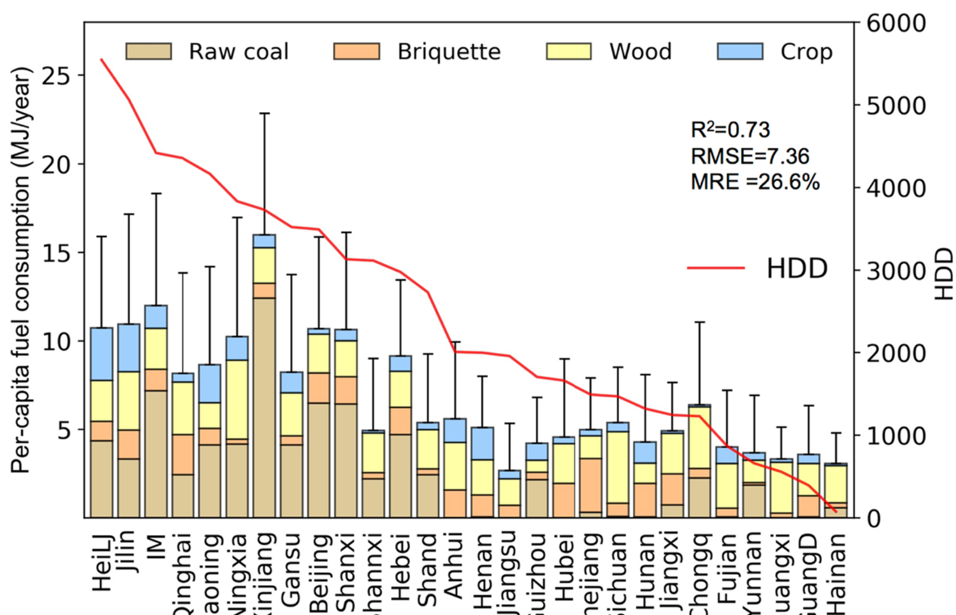

Fig. 1. Per capita fuel consumption by province and by solid fuel type in 2010. Data were obtained from original survey data. Provinces were ranked by Heating Degree Days (HDD).

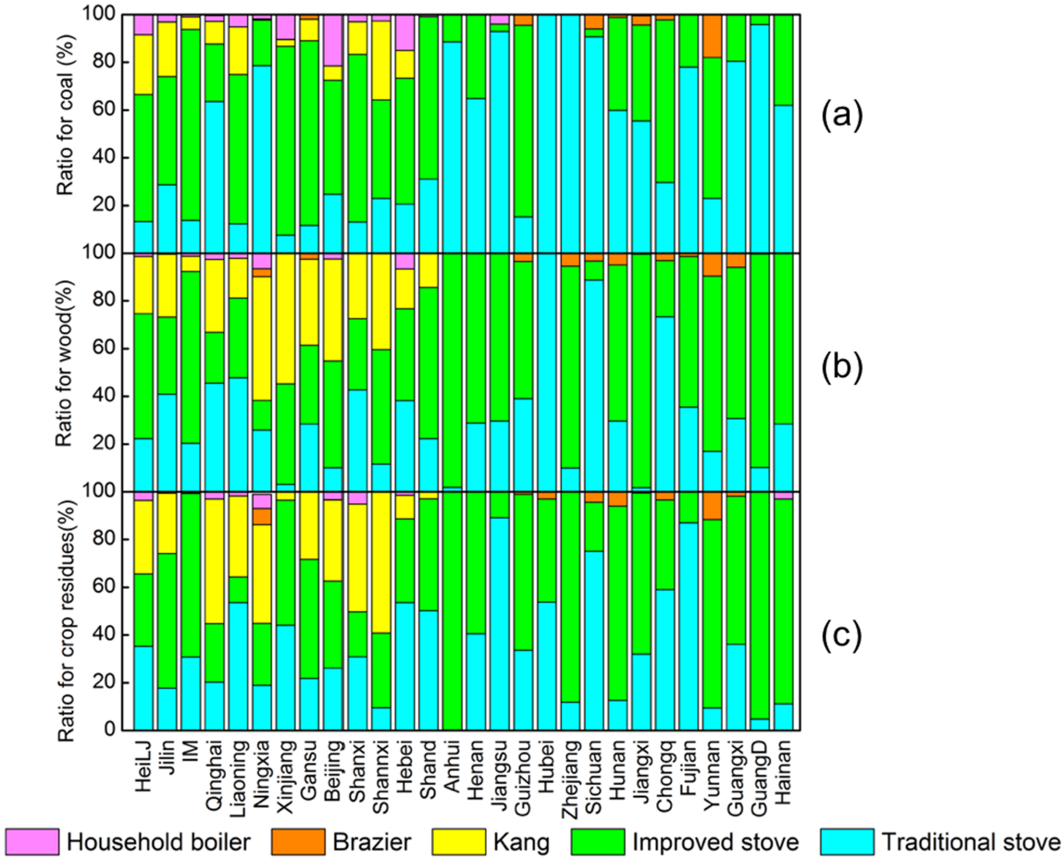

Fig. 2. Distribution of five stove types by province in 2010 for (a) coal, (b) wood and (c) crop residues.

data. Using the Huai River-Qin Mountain line as a dividing line between northern and southern China, we observe that the utilization of stove types differs significantly between northern and southern regions. For coal consumption, in northern China improved stoves are utilized most widely in northern China. In contrast, the most widely used stove types in southern China are traditional stoves. For crop residues and wood consumption, there is a high utilization proportion of kangs and household boilers in northern China. On national average, share of improved stoves ranks first, followed by traditional stoves, kangs, braziers and household boilers with ratios of 50%, 35%, 13%, 2%, 1%, respectively, for crop residue consumption and 52%, 37%, 7%, 3%, 1%, respectively, for wood consumption. In addition, we found that household boilers and kangs, are primarily used in northern China, while braziers are mostly used in southern China.

To further investigate the characteristics of regional stove types for fuel consumption (i.e., coal, crop residues and wood), we divide the entire country into seven geographical areas, as indicated in Fig. 3, corresponding to North China, Northeast China, East China, Central China, South China, Southwest China and Northwest China. The proportions of stove types for the various fuel differ significantly differ among regions. Improved stoves are the main stove for raw coal consumption throughout all regions. Improved stoves (58%) are most frequently used for briquette consumption in North China, whereas traditional stoves are the main stove type for briquette use in other regions.

Kangs (40%, 33%), improved stoves (36%, 36%) and traditional stoves (18%, 30%) are the primary stove types of wood consumption in Northwest and North China; however, traditional stoves (50%, 60% and 60%) are the main stove type in Northeast, Central and Southwest China, following by improved stoves. Conversely, improved stoves (77%, 70%) are the main stove type in East and South China, following by traditional stoves.

Kangs (46%) are the main stove type of crop residue consumption in Northwest China, following by improved stoves and traditional stoves. Improved stoves (37%, 39%) are the most frequently used in Northeast and North China, followed by traditional stoves and kangs. Traditional stoves (62%, 54%) are the main stove type in East and Southwest China, followed by improved stoves. Conversely, improved stoves (60%, 80%) are the main stove type in Central and South China, followed by traditional stoves.

3.2. Fuel consumption

Using the GAM, we estimate that coal and biofuel consumption in China's rural residential sector are 179.8 and 335.1Tg in 2010, respectively. We then split the coal and biofuel consumption into raw coal, briquettes, wood and crop residues, using the fractional information from the survey data. The estimated raw coal, briquette, wood and crop residues consumption are 92.9, 86.9, 177.1 and 159.0 Tg, respectively. Here, we use agricultural population [71] as rural population. The definition of agricultural population is defined as individuals who are dependent on agriculture, hunting, fishing, and forestry for their livelihood. The agriculture population includes the people who have access to biofuel and coal stoves. The people who have a rural hukou but migrate from rural to urban areas are not included in agricultural population. Fig. 4 shows the cross-validation results for the model. The R^2 values are 0.61 (Fig. 4a) and 0.50 (Fig. 4b) for per capita coal and biofuel consumption, respectively. The LOOCV RMSE of coal (0.121 Mg) is higher than biofuel (0.078 Mg), which may be attributed to the considerably higher per capita coal consumption.

The fuel consumption estimated in this work and that reported in the CESY [27] show a large difference. Table 2 summarizes the fuel consumption estimates using GAM and CESY. The estimated coal and biofuel consumption are 62% higher and 29% lower than that reported

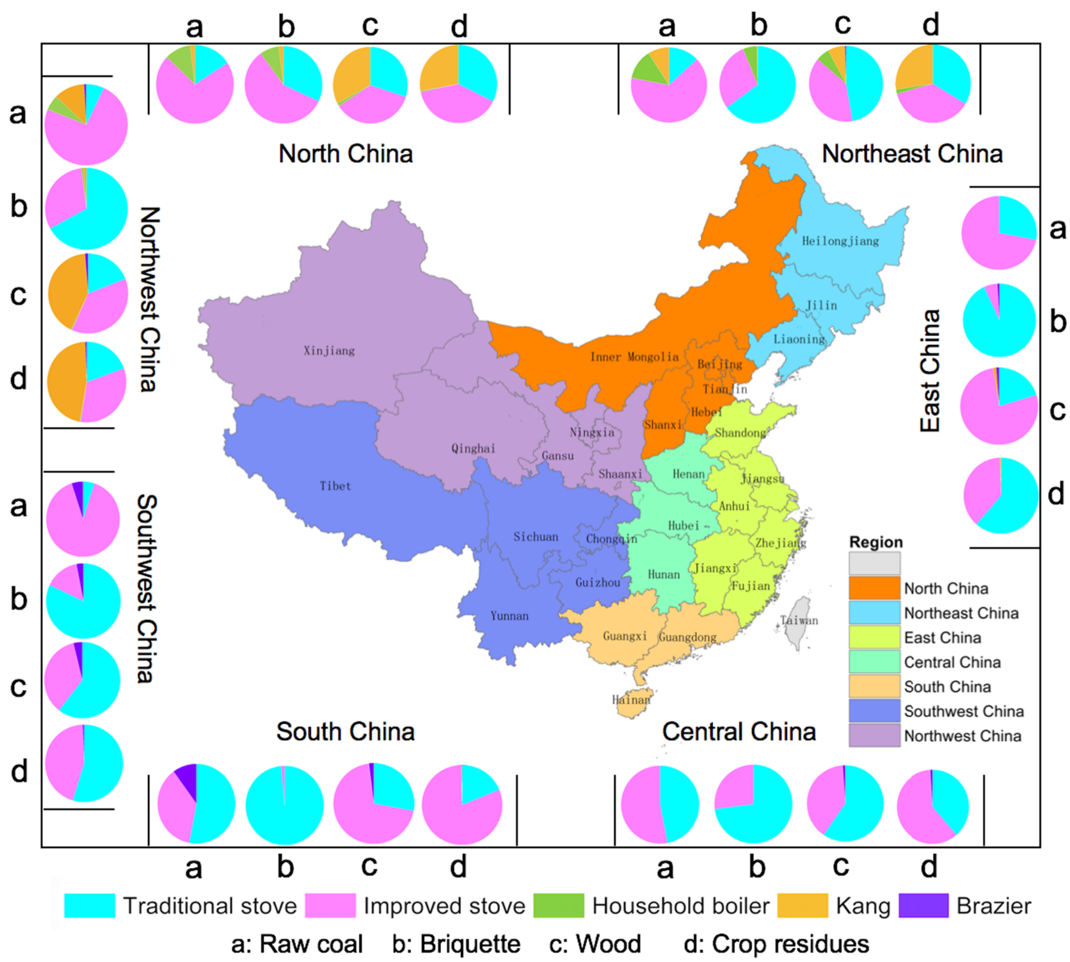

Fig. 3. Share of fuel consumption in each stove type in different regions of China.

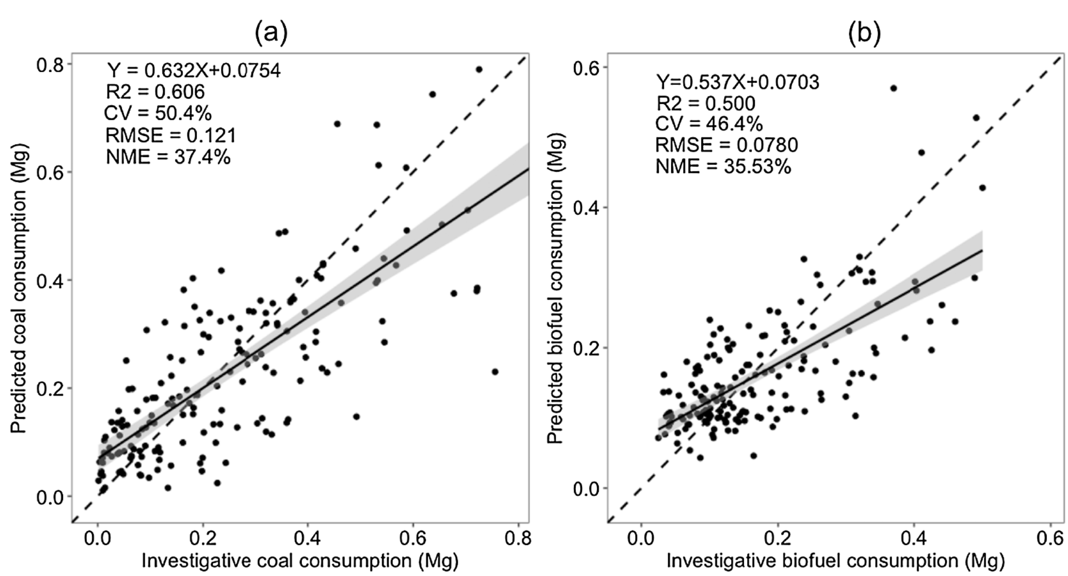

Fig. 4. Performance of full models assessed based on investigative fuel consumption and LOOCV predicted fuel consumption. Scatter plots of fuel consumption predicted based on LOOCV results for (a) coal, and (b) biofuel. The solid lines represent the regression lines, and the dashed lines represent the 1:1 lines. Grey shadow represents uncertainty of the fitted line.

Table 2
Comparison of solied fuel consumption in rural residential homes between GAM prediction in this study and the CESY data for the year 2010 (Unit: Tg).

Fuel type	GAM	CESY
Raw coal	92.1	97.2
Briquette	86.1	16.4
Wood	167.3	154.7
Crop Residues	164.6	320.8
Total	510.1	589.1

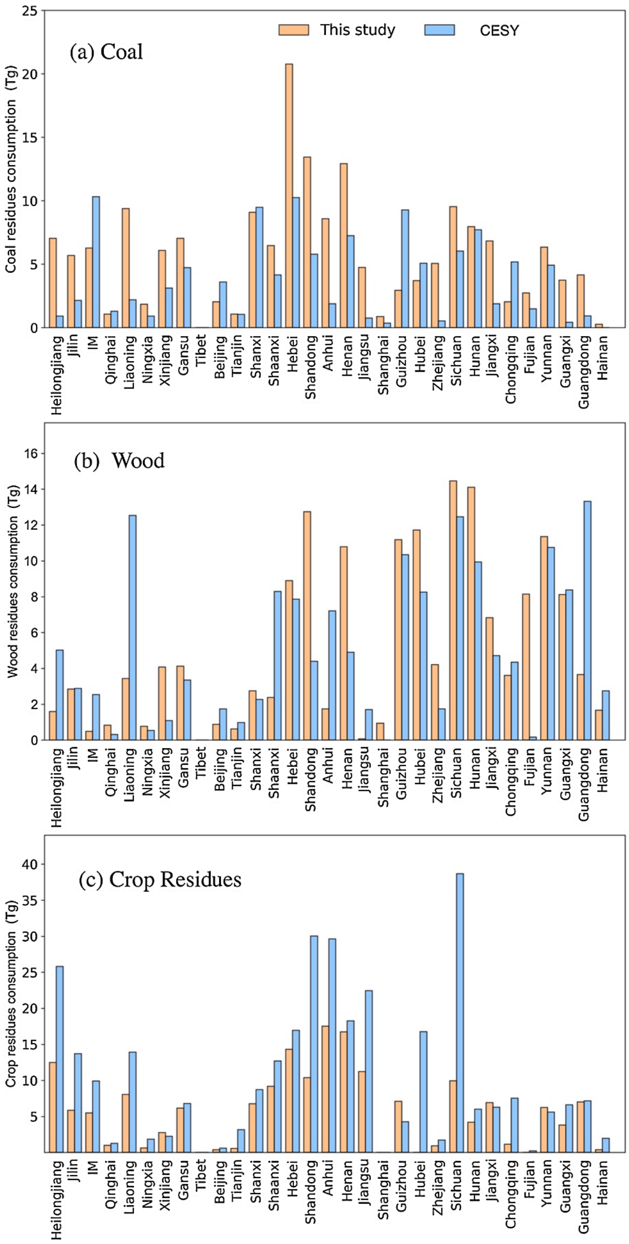

Fig. 5. Comparison of provincial fuel consumption between GAM prediction and the CESY data for the year 2010.

in the CESY in 2010, respectively. In most provinces, coal consumption estimated from the survey data is higher than those reported by the CESY, especially in the NCP regions, as illustrated in Fig. 5. Coal consumption in Hebei, Shandong and Henan provinces are highest with values of 20.8, 13.4 and 12.9 Tg, respectively. The estimated coal consumption in the three provinces are 2.0, 2.3 and 1.8 times higher than those reported in the CESY.

The highest biofuel consumption primarily occurs in the central and southern regions of China. The discrepancies of crop residue consumption estimated in this study and reported by the CESY are highest in Sichuan, Shandong and Heilongjiang provinces. The estimated results in the three provinces are 74%, 66%, and 52% lower than those reported in the CESY. Overestimates of biofuel consumption likely occurs in statistics because residents replaced traditional biofuel were replaced by more convenient commercial energy as income increased.

Some researches [72–81] have already found the high uncertainties and inconsistencies in Chinese coal use. The large discrepancy of coal consumption between the CESY and the survey-based estimates for the residential sector may be attributed to the following two reasons. First, coal used in rural areas may obtained from sources which are not included in statistics. Some local small coal mines and firms directly sell coal to residents. In 2009, 31% of coal (including raw coal and washed coal) was produced by small firms [72]. Coal productions from those small firms were not fully counted in official statistics, which results in an underestimates of real-world coal consumption in rural areas [73–75]. The estimated briquette consumption are 3.3 times higher than that reported in the CESY in 2010. The use of briquette was underestimated because a large portion of this material is homemade [76].

Second, the statistical approach by China’ s National Bureau of Statistics (NBS) on data collection, reporting and validation is not always consistent [77]. The NBS revised historial energy consumption data every five years based on the results from the National Economic Censues (NECs). Korsbakken et al. [78] pointed that the annual coal consumption in the statistics was revised up by 12–14% since 2005 according to National Economic Censues (NECs) [79]. Hong et al. [80] argued that the uncertainties of coal consumption in residential sector are up to 46.9%, respectively in 2012 by comparing different energy statistics, indicating that the inconsistency in statistics may substantially contribute to the uncertainties in coal consumption in residential sector.

We further evaluate the reliability of the estimated result by comparing it with the data from the survey conducted by Center for Science of Construction Energy Conservation (CSCEC) of Tsinghua University in 2006. The CSCEC survey covered 88 rural counties in 24 provinces in China [32]. The CSCEC survey revealed a similar difference as the comparison of the survey data with the CESY data, supporting our fuel consumption estimations. Cheng et al. [30], Duan et al. [33] and Zhi et al. [82] also showed that the actual amount of household coal combustion might be much higher than the statistical data indicated in CESY. However, the coal consumption in Tao et al. [83] are lower than the statistical data in CESY, as shown in Table 3.

3.3. Emissions

We develop a rural residential emission inventory with updated solid fuel consumption, stove type distribution and improved emission factor database in rural households. We build the emission inventory of rural residential solid fuel consumption using first-hand data obtained from a questionnaire survey in China in 2010 for the first time. We estimate the total emissions from solid fuel combustion in rural residential sector in the year 2010 as follows: 3.3Tg $PM_{2.5}$, 0.6Tg BC, 1.2Tg OC, 2.1Tg VOC, 2.3Tg SO_2, 0.4Tg NO_X, 43.6Tg CO and 727.2Tg CO_2. Crop residues significantly contribute to $PM_{2.5}$ and VOC emissions, which account for 48% and 56% of emissions. Coal is the main contributor to BC, OC, SO_2, CO and CO_2, which account for 49%, 52%, 99%, 38% and 41% of emissions.

Fig. 6 displays $PM_{2.5}$, BC, OC, VOC, SO_2 and NO_X emissions at the provincial level in China. Rural residential emissions are distributed unevenly throughout China. In 2010, the high level of $PM_{2.5}$, OC, VOC and SO_2 emissions are located in the NCP region and Sichuan Basin, especially in Hebei, Shandong and Henan province, which are three highest $PM_{2.5}$, BC, OC and NO_X emission provinces in China. The $PM_{2.5}$,

Table 3
Comparison of coal consumption and air pollutant emission estimates with other survey-based studies (Unit: Gg).

Region	References	Year	Coal consumption		Air pollutant emissions					
			Raw coal	Briquette	$PM_{2.5}$	BC	OC	VOC	SO_2	NO_X
China	This study	2010	92,100	86,100	3318.7	593.2	1221.2	2136.9	2273.3	446.6
	Yang et al. [32]	2006	91,220	101,210	/	/	/	/	/	/
	Duan et al. [33]	2012	241,700		/	/	/	/	/	/
	Tao et al. [83]	2012	78,000	18,000	2720	880	1400	/	1200	640
Beijing	This study	2010	1331	748	13.1	2.1	5	10.2	18.7	3.3
	Ru et al. [84]	2012	2013		17.1	3.8	7.4	/	3.7	4.1
	Cheng et al. [30]	2013	2054	216	37.6	10.5	15.4	16.5	53.2	7.8
	Zhi et al. [82]	2013	3340	348	46.4	11.2	18.6	11.6	69.7	8.3
	Cai et al. [85]	2015	2694		38.7	/	/	33.3	49.7	13
Tianjin	This study	2010	638	430	9.9	1.5	3.2	8.2	9.6	2.2
	Cheng et al. [30]	2013	2018	140	23.9	6.7	9.8	10.5	33.7	4.9
Hebei	This study	2010	14,150	5123	325.5	60.6	126.3	169.7	238.5	42.3
	Cheng et al. [30]	2013	31,035	1075	398.9	111.8	163.3	175.4	563.6	82.5

BC, OC and NO_X emissions are 325.5, 291.9 and 282.4Gg; 60.6, 25.4 and 63.3Gg; 126.3, 82.2 and 104.0Gg; 42.3, 27.7 and 35.5Gg, respectively, in Hebei, Henan and Shangdong province. For most air pollutants except for VOC, coal consumption is the major contribution, following by crop residues and wood consumption. Specifically, Hebei, Shangdong and Henan province have the highest share of coal in residential fuel consumptions, contributing to 58%, 50% and 46% of residential $PM_{2.5}$ emissions, respectively. Crop residues consumption is the second largest contribution to $PM_{2.5}$ emission, and accounts for 33%, 32% and 40% of residential $PM_{2.5}$ emissions, respectively. Wood consumption only contributes 10%, 18% and 13% of residential $PM_{2.5}$ emission, respectively. Crop residues consumption comprises a large portion of residential VOC emissions, approximately 74%, which is significantly higher than wood (17%) and coal (9%) consumption.

Table 3 summarized the comparison of our emission estimates with other survey-based estimates. Our 2010 national estimated $PM_{2.5}$ and SO_2 emissions are 22% and 90% higher than the 2013 survey-based emission estimate in Tao et al. [83], while our BC, OC and NO_X emissions are lower than their emission estimates. For Beijing, Tianjin and Hebei region (BTH), our estimated air pollutant emissions in Hebei are comparable with the emissions in Cheng et al. [30]. Our estimated air pollutants in Beijing are generally similar to the results in Ru et al. [84]. Estimated $PM_{2.5}$, BC, OC, SO_2 and NO_X emissions in Beijing and Tianjin in our study in 2010 are 20–40% of the emissions in 2013 in Zhi et al. [82], Cheng et al. [30] and Cai et al. [85] both of Zhi et al. [82] and Cheng et al. [30] only include emissions from coal consumption. This is because first, the estimated coal consumption in our study is lower than their results due to different sample size and composition, for example, the coal consumption in our study is 44% and 50% lower than the coal consumption of Beijing and Tianjin in Cheng et al. [30]; and second, residential emissions increased from 2010 to 2013 due to the growth of population, economy and solid fuel use in rural and suburb area in Beijing and Tianjin.

4. Discussion

4.1. Uncertainties and limitations

A Monte Carlo simulation is adopted to analyze the uncertainties of the emission estimates in this study. A true quantification of the uncertainty is difficult to obtain, and we often use the expert judgment from the IPCC in uncertainty estimates [61]. The input parameters of the activity levels, technology divisions and emission factors with the corresponding adequate measurement data and reported probability distributions are input into a Monte Carlo framework using the Crystal Ball software. A set of 10,000 runs are performed in this study as valid

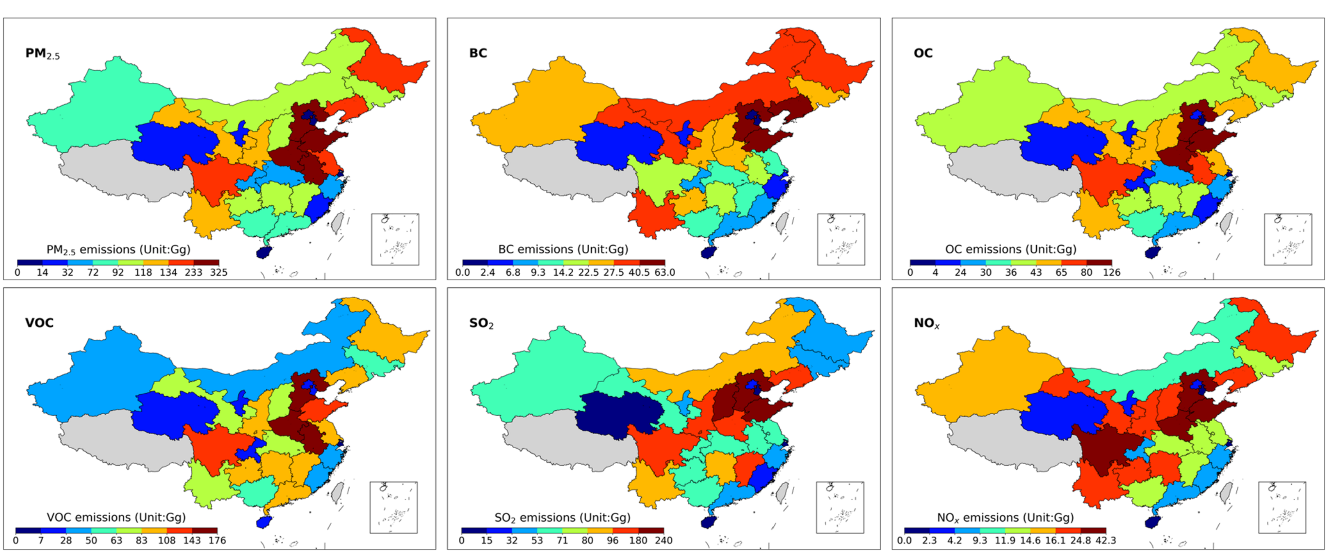

Fig. 6. Spatial distribution of air pollutant emissions for rural residential solid fuel consumption.

simulations to analyze the uncertainties. In this work, the term "uncertainty" refers to a 95% confidence interval (CI) about the mean estimate.

We apply a lognormal distribution for coal and biofuel usage according to the study by Lu et al. [15] and the IPCC [61]. The uncertainties of national coal, wood and crop residue consumption are 52%, 52% and 70% for the survey data, respectively, based on the relative error in the model. The technology distribution in each fuel/product are highly correlated. We assume to generate random variables of technology distribution. A similar approach as reported by Lu et al. [15] was adopted. For fuels/products with three or more divisions (of which the fractions are $X_1 - X_n$), we assume uniform distributions in the range of ± 0.3 about the mean for both the highest emitting (i.e., $[X_{high,\ mean} - 0.3, X_{high,\ mean} + 0.3]$) and lowest emitting technology (i.e., $[X_{low,\ mean} - 0.3, X_{low,\ mean} + 0.3]$) and simply determine the range of variation of the other technology fractions as $\pm (1 - X_{high} - X_{low} - \sum X_{other,mean})/(n - 2)$. A triangular distribution is assumed for emission factors for survey data.

The emission estimates reported in this study for China's rural residential sector are significantly improved due to our improved accuracy of activity level and detailed technology distributions. We use VOC, BC and OC as examples to estimate the uncertainty of emissions for each fuel type, as shown in Table 4. The average uncertainty ranges (expressed as the 95% CI around the central value) are estimated to be −53% to 88%, −64% to 126% and −59% to 114% for the total VOC, BC and OC emissions, respectively. The largest uncertainties in VOC, BC and OC emissions by fuel type are found for wood, followed by crop residues and coal. Compared with others studies, these results also demonstrate that our work reduces the inventory uncertainty to some extent. Lu et al. [15] reported that the entire uncertainties of residential areas for BC and OC are −62% to 155% and −58% to 119%, which are similar to the uncertainties found in this work. The uncertainties presented in Zhao et al. [14] are −47% to 259% and −54% to 148% for BC and OC, respectively, which are much higher than the uncertainties of −64% to 126% and −59% to 114% found in our work because our emission factors are taken from the latest domestic measurements based on detailed technology distributions.

This study also subjects to several limitations. First, the GAM developed in this work could be biased due to incomplete input of parameters. We test the correlations between predicted coal and biofuel consumption using GAM and investigative data, as shown in Fig. 7. We found that the survey-base data are lower than predicted results from GAM. However, good correlations between survey-based and model-predicted data indicate that the model performances are reasonable.

Second, due to the limited amount of survey data, the GAM was developed at national level in this work. The national GAM would bring the uncertainty for some provinces. On national level, our model explains 62% of variance in coal consumption and 54% of variance in biofuel consumption with three independent factors (e.g. per capita income, HDD, coal production). Other factors, such as the consumption of electricity, the accessibility of other clean energy (i.e. liquefied Petroleum Gas (LPG), nature gas), household fuel cooking habits, vary dramatically among the provinces. Households in relatively developed regions have a higher proportion of non-solid fuel consumption, using LPG or natural gas for cooking and electricity for heating in rural area [33], which induce the over-estimated coal consumption from our GAM as compared to the actual situation. For example, the estimated coal consumption in developed provinces such as Shanghai, Jiangsu, and Zhejiang are 1.49, 5.34 and 8.63 times higher than those reported by the CESY while small coal mines are strictly prohibited in these province [86]. Further studies with more detailed information (e.g. education level, age group) will provide a better understanding of driving factors of fuel consumption in the rural residential sector.

Third, this study estimates the provincial and national fuel consumption based on limited number of samples of counties in each province. However, some provinces have large differences of climatic conditions, economic development and lifestyles within the province. These differences induce the under-representation of the survey. Therefore, we should increase the samples in the future survey and consider the representation of sampling.

Forth, the replacement of current stove types in a rural area of China with second generation improved stoves increase with the rapid economic development. The characteristics of stove emissions would have change significantly in recent years due to the huge variance of emission factors among different stoves. Therefore, it is necessary to conduct supplementary questionnaires. We have conducted an additional survey in 2015 to verify the report and monitor the spatial and temporal change in fuel use pattern of rural residential sector.

4.2. Implications

Disparities in coal, wood and crop residue estimates in this study compared to the statistical yearbook data leads to different pollution emission profiles, are shown in Fig. 8. SO_2 is generated predominantly by coal because the emission factor of coal is higher than that of biofuel. For $PM_{2.5}$ and other secondary PM precursors, such as BC and VOC, the EFs of biofuel are higher than that of coal. Overall, the overestimation of biomass consumption and underestimation of coal consumption leads to an overestimation of air pollutant emissions. It appears that the energy transition from biofuels to coal has proceeded more quickly than the CESF data indicates.

Fig. 9 further compared $PM_{2.5}$ emission trend from rural residential solid-fuel consumption estimated from survey-based data and statistics. We used space-for-time method to obtain fuel consumption for the period 2000–2015 by using the GAM and annual per-capita income data. Space-for-time method based on the assumption that temporal dynamics in the community are autogenic and thus all sites had the same trajectory and endpoint. Here we extrapolate temporal trend based on the survey data on different sites [87]. Fig. 9(a) indicates that $PM_{2.5}$ emissions from coal consumption during 2000–2015 have a similar growth trend for both our results and the CESY, although they have a big difference in total quantity. The $PM_{2.5}$ emission based on the CESY shows a significant increase in 2005, then a slight decrease in 2006, and an increase starting again in 2008. In contrast, the change in the trend of $PM_{2.5}$ emissions from biofuel combustion is significantly different in Fig. 9(b). The trend of biofuel consumption has decreased steadily, while the consumption in the CESY increased until 2006, then started to decrease. In addition, $PM_{2.5}$ emissions based on CESY are several times higher than our results. Even though the $PM_{2.5}$ emissions due to higher coal consumption could offset a part of dramatic decline of $PM_{2.5}$ emission of overestimated biofuel consumption, the historical $PM_{2.5}$ emission trend is also much lower than what we suppose based on CESY.

The trend of emissions obtained in this study bears relatively high uncertainty. China's government has released a number of air pollution control policies to improve air quality [88–91]. These polices indeed impact the energy choice of rural populations. However, in this study, we only report the trend of total $PM_{2.5}$ emissions from solid fuel consumption of rural residents in China due to their income increase from

Table 4
Uncertainties of emission estimates for solid fuel combustion in China's rural residential sector in 2010. The ranges represent the 95% CI around the central estimates.

	VOC	BC	OC
Coal	−50% to 67%	−65% to 123%	−55% to 109%
Crop residues	−54% to 87%	−70% to 135%	−66% to 129%
Wood	−55% to 94%	−62% to 120%	−70% to 132%
Total	−53% to 88%	−64% to 126%	−59% to 114%

* The percentages in the parentheses indicate the 95% CI around the central estimation.

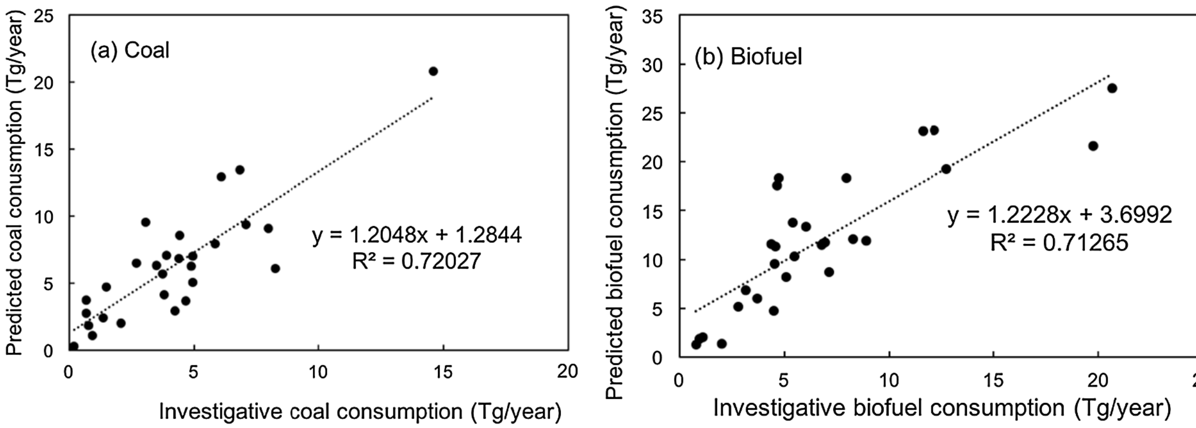

Fig. 7. Comparison of per capita fuel consumption between original survey data and GAM prediction for each province.

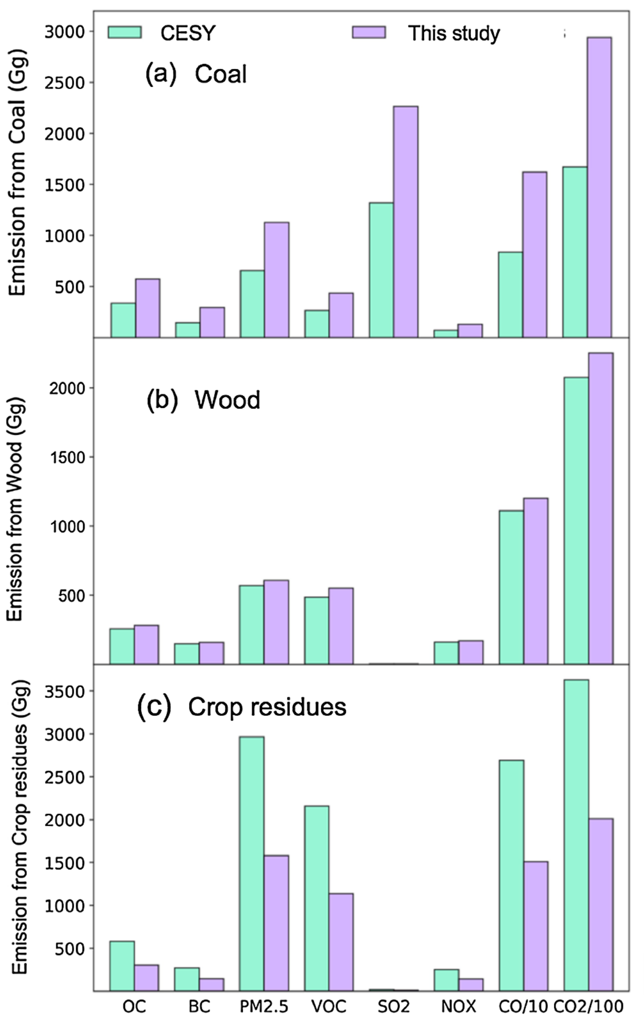

Fig. 8. Emissions from rural residential sector in China in 2010 estimated by using fuel consumption from GAM prediction and the CESY data.

2000 to 2015. We compare the characteristics of estimated emission trends between the GAM model statistical analysis of our survey data and the CESY data. The estimated emission results only represent emissions due to fuel consumption but not from other sources. More detailed and better information is required for future comprehensive assessment studies.

Our results have several important policy implications. First, our data and analysis demonstrate an overall picture to help policy-makers understand rural residential fuel consumption patterns including fuel types for cooking and heating and how they change with income. In the context of the accelerating economic development process, residential sector fuel demand is anticipated to increase continuously with an ongoing transition from biomass to coal stoves potentially followed by a later transition to cleaner fuels. Second, despite the rapid energy transition in China, solid fuel use is still a tough challenge for the future. Even though the Chinese government has launched a five year winter clean heating plan for 2017 to 2021, they bear the high cost of switching millions of households and thousands of businesses from coal to natural gas or electricity in northern China. However, the sustainability of the plan needs to be evaluated on a cost-benefit basis considering the shortage of natural gas resources and the cost of electricity. Another short-term possibility is to replace low efficiency traditional stoves by relatively clean coal stoves as a transitional alternative. Ultimately, a transition to renewably generated electricity will provide the largest co-benefits for reductions in air pollutants and carbon dioxide emissions. The biomass and coal stove emission information in our study provides an initial database to inform policy makers of the extent of solid fuel stove use and emissions. Third, although this research was based on data collected in China, the issue of air pollution and climate impacts of residential solid fuel is a worldwide phenomenon, especially in other developing countries. As a result, the general results and characteristics in this study could utilized by policy makers around the world.

5. Concluding remarks

Our study develops a 2010 emission inventory of rural residential solid fuel consumption. We develop a statistical model, for the first time, to extrapolate this inventory to other time periods based on per-capita income. The survey provides critical information to support energy and environmental decision making. Using the survey, we estimate the coal and biofuel consumption at the county level using a statistical model. We develop an improved emission inventory of the residential sector with updated solid fuel consumption in rural households and improved emission factor database in China at the provincial level. By comparing the estimated coal consumption in this work and that reported in the China Energy Statistical Yearbook (CESY), our survey analysis indicates a higher coal consumption and a lower biofuel consumption than found in the CESY. We quantify the additional coal consumption in China and discuss its implications.

In 2010, $PM_{2.5}$, BC, OC, VOC, SO_2, NOx, CO and CO_2 emissions from rural solid fuel combustion are estimated to be 3.3, 0.6, 1.2, 2.1, 2.3, 0.4, 43.6 and 727.2Tg, respectively. Compared with MEIC (www.meicmodel.org), SO_2 emission increase 70%, $PM_{2.5}$ and VOC emissions decrease 21% and 27%, respectively. This difference is owing to missing coal consumption and overestimated biofuel consumption from CESY.

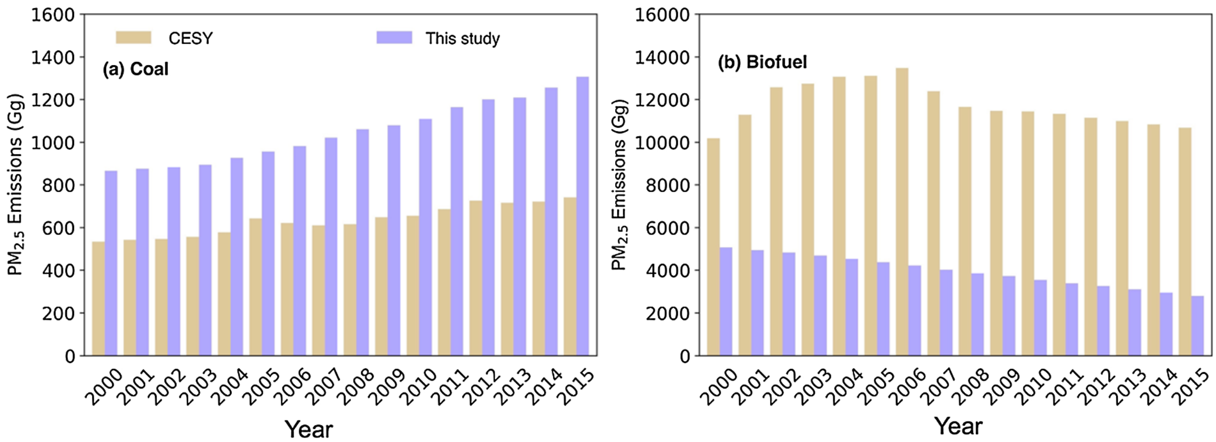

Fig. 9. Trends in primary $PM_{2.5}$ emission estimates by using fuel consumption from GAM predictions and CESY data.

The solid fuel use is affected by income level, HDD and other socioeconomic factors. The survey data shows solid fuel consumption rises with the increase in HDD because the higher heating demand in winter. Coal and biofuel consumption rises and drops with the increase in per capita income, respectively, because economic development would motivate the consumption of commercial fuel (e.g. switch from biofuel to coal). We estimate that coal and biofuel consumption in China's rural residential sector are 179.8 and 335.1Tg in 2010, accounting for 162% and 71%, respectively, of that reported in the CESY. In particular, the estimated coal consumption is much higher than statistics in North China Plain, for example, in Hebei province, coal consumption is 20.8Tg, which is about twice as high as the reported in CESY, which reveals the importance of rural coal in producing northern China's heavy winter haze. It also illustrates that the energy transition from biofuels to coal has proceeded more quickly than the CESY data indicates. We provide the emphasis on the missing coal in China's rural sector could help the government to implement effective measures and achieve its long-term goal of clean air.

Our study aims to improve the understanding of energy consumption and emission data in rural residential sector. As data is the basis for conducting research on energy studies and addressing policy and technologies for promoting sustainability, the results from our work will help designing effective emission mitigation policies for residential sector in China. In the meanwhile, uncertain statistics might be a common issue in developing countries such as India, our work could provide a new approach of obtaining reliable residential fuel consumption data for other developing countries.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2018.11.043.

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