Responses to Anonymous Reviewer #1

"Inventory of anthropogenic methane emissions in Mainland China from 1980 to 2010". 2016-04-13

As the authors rightly point out, there are large discrepancies in existing bottom-up inventories of anthropogenic methane emissions for China and there is scope to improve these using more detailed information on a sector level from both international and national sources. In general, I find this paper a thorough contribution in this genre, which adds to existing inventories by the extensive use of data from national Chinese sources, thereby allowing in several sources to go beyond the use of default IPCC emission factors.

**[Response]** Thanks for your careful review and valuable comments.

I have, however, some concerns on the emission estimations at the sector level, which I would like addressed by the authors. I list them below by sector.

Livestock:

The estimations of $CH_4$ emissions follow standard IPCC methodology, which may explain why emissions fall within a close range of other inventories in Figure 2. I find it somewhat problematic that no adjustment has been made for the use of farm anaerobic digesters in China. I am also surprised that there would be no information available on this when China is since long a world leader on small-scale bio-digesters. I do understand that there is limited information on the number of digesters only digesting manure, since this is not very common. To get reasonable energy efficiency of the digestion, the manure needs to be mixed with at least 20 percent other organic material e.g., straw, food residuals, crop residues. Hence, you would need to look for the number of farm biogas installations that co-digest manure with other organic residues and make assumptions on the fraction of the feedstock that is manure. On p. 15 row 24 you mention that "35 million bio- digesters have been built for $CH_4$ utilization between 1996 and 2010 and capture annually 15 bcm biogas." If the methane content of the biogas is 60%, then it means that 9 bcm $CH_4$ (or about 6 Tg $CH_4$) is captured and utilized annually. Although only some fraction of this can be referred to as methane emissions reduced compared to the practice of not treating manure in digesters, it is still likely to be a significant fraction out of the about 10 Tg $CH_4$ estimated to be released from livestock according to Figure 2. As China is one of few countries with a widespread use of rural small-scale digesters, I find it problematic not at all accounting for this effect on methane emissions.

**[Response]** We agree that some of the biogas recuperation could reduce our estimate of $CH_4$ emissions from manure management. The annual output of biogas data is available from 1996 to 2010 (Feng et al., 2012). The number of household bio-digesters increased from 4 million in the early 1980s to 6 million in 1996. If the number of bio-digesters and the annual output of biogas linearly increased from the early of 1980s to 1996, then the annual output of biogas captured increased from 0.4 Tg

$CH_4$/yr in 1980 to 6.2 Tg $CH_4$/yr in 2010 (Figure R1), assuming 60% $CH_4$ in the biogas. However, because the fraction of manure in the mixed organic raw material (mostly mixed with manure and crop residues, or mixed municipal waste) is not clear, several scenarios are needed to estimate how much $CH_4$ emissions from manure management is mitigated by bio-digesters. The $CH_4$ production from manure is about 40% of $CH_4$ production of crop residues in 2012 (Yin, 2015, PhD thesis), and it is assumed that 10%, 15% and 25% of the biogas are low, medium, and high mitigation scenarios for $CH_4$ emissions from manure management, respectively. The biogas reduced $CH_4$ emissions from manure management by 0.1 [0.0-0.1] Tg $CH_4$/yr in 1980 and by 0.9 [0.6-1.6] Tg $CH_4$/yr in 2010. Compared to the $CH_4$ emissions from manure management without biogas mitigation in 2010 (2.3 Tg $CH_4$/yr), the biogas reduced ~40% [27%-68%] of $CH_4$ emissions from manure management in 2010. We added this updated $CH_4$ emissions from livestock with biogas accounted in the revised version.

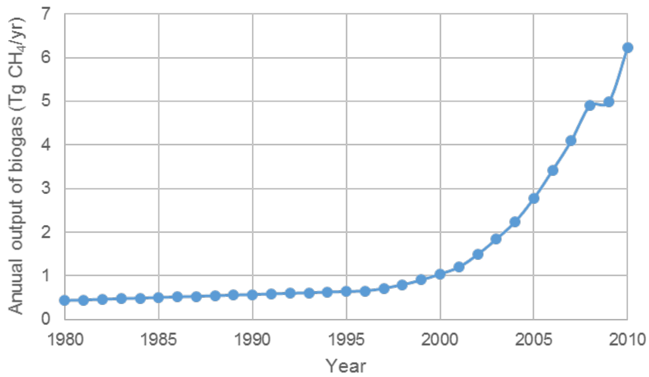


Figure R1. The annual output of biogas (Tg $CH_4$/yr) from 1980 to 2010. The biogas data is assumed a linear increase from 1980 to 1996. The biogas data from 1996 to 2010 is available from Feng et al. (2012).

Rice cultivation:

The estimation of methane emissions from rice cultivation in China based on Yan et al. 2013 is in my opinion state-of-the-art.

Biomass and biofuel burning:

The estimation of methane from this sector draws on information from several national studies and appears robust. I would however like to know how these estimates compare with existing estimates from satellite images of biomass burning e.g., from GFED. To what extent are the estimates consistent/inconsistent?

**[Response]** We distinguished crops residues used as biofuels in the houses from those burnt in open fields in our inventory. The emissions from fire detected by satellites only include to some extent (detection of small agricultural fires being problematic) the biomass burnt in open fields. In the latest GFED4.1 products, the average $CH_4$ emissions including agricultural fires in China during the period 1997-2010 is 0.09 [0.04-0.18] Tg $CH_4$/yr (http://www.globalfiredata.org/data.html; van der Werf et al., 2010). Our estimation of the average $CH_4$ emissions from crop residues burnt in open fields during the same period is 0.28 [0.05-0.51] Tg $CH_4$/yr, which is higher than that derived from GFED4.1. But considering the uncertainty of distinguishing agricultural fire and wild fire in GFED4.1 products and the poor detection of small fires using burned area from space, our estimates are close to the total $CH_4$ emissions including both wild fire and agricultural fire (0.22 Tg $CH_4$/yr).

Because the changes in biomass burning in open fields is unknown, the fraction of biomass burnt in open fields to total crop residues is assumed to keep constant from 1980 to 2010 in our inventory. The $CH_4$ emissions from biomass burning in open fields in our inventory is increasing with crop residues from 1997 to 2010, but GFED4.1 based on burned area data with fixed emission factors for agricultural fires shows no trend of $CH_4$ emissions. This indicates that the fraction of crop residues burnt in the open fields should be changing in the past two decades, which cause further uncertainty in our inventory. We added this comparison and discussion in the revised version (Page 13, line 11-15).

Coal exploitation:

For this sector, the authors have access to extensive information about depths of coal mines in different provinces as well as the extent of surface mining as opposed to the more common underground mining. This is among the most comprehensive estimates of methane emissions from coal mining in China that I have seen. I have only one question and that is if the authors have been able to assess the prevalence of pre-mining degasification and if the effect of an increasing use of this in China (which is happening according to GMI) in the last decade has been taken into consideration? Is this part of the increased utilization of $CH_4$ from mines that the authors discuss?

**[Response]** Yes, the pre-mining degasification is considered as one way of utilization in our inventory. The increased utilization of $CH_4$ from coal bed methane (CBM) and coal mine methane (CMM) is accounted by the increasing utilization fraction in our study, which increased by 4% in the last decade (from 5.2% in 2000 to 9.2% in 2010). It is assumed the utilization linearly increases from 1980 to 2010 in our inventory. In the CDM/JI pipeline database (http://www.cdmpipeline.org/overview.htm), the registered and validated projects of CBM and CMM in China started from 2004 and increased strongly in 2007/2008. The total reduction of $CH_4$ emissions by CBM and CMM in China derived from CDM/JI pipeline database is ~0.3 Tg $CH_4$/yr in 2006 and ~0.9 Tg $CH_4$/yr in 2010, which is close to our estimates of increased $CH_4$ recovery in 2006 (0.4 Tg $CH_4$/yr) and 2010 (0.8 Tg $CH_4$/yr). We added the discussion about the utilization of CBM and CMM in the revised version (Page 14, line 15-19).

Oil and natural gas systems:

I find the emission estimations of this sector the weakest point of the paper and I would like the authors to revise the emission estimations for this sector. The authors claim they are using default emission factors from IPCC (2006), but as shown in the Table below, the emission factor used for oil production is only 15% of the very low end of the IPCC default factor for oil production. For natural gas, the emission factor used is close to the very low end of the IPCC default range. I also include for comparison the corresponding emission factors used by the USA and Canada for their reporting to the UNFCCC. Just like the US and Canada, China's oil and natural gas fields are mostly on-shore and therefore likely to have relatively high emissions from unintended leakage (i.e., fugitive emissions from leakage that are not due to venting of associated petroleum gas (APG)). Moreover, NOAA estimates from satellite images of gas flares that China flares between 2 and 3 bcm of gas annually over the period

1994 to 2010. Most of this gas can be referred to flaring of associated gas primarily from oil production. Although there is not much methane being released from the flaring of associate gas as such, the flaring indicates that there is most likely also venting going on. E.g., for the Canadian province of Alberta, Johnson and Coderre (2011) estimate from measurements that out of total APG generated from conventional oil wells, 97% is recovered for reinjection or utilization, 2.1% is flared and 0.8% is vented. If we would assume similar circumstances for oil production in China as for conventional oil wells in Canada, it would mean that between 0.76 and 1.1 bcm APG is vented annually from Chinese oil production. If we assume the methane content of APG to be 85% and use the conversion factor 0.7178 kg $CH_4$/m3 $CH_4$, then China would be venting somewhere between 460 and 670 kt $CH_4$ annually from oil production (which is ten times higher than the authors' estimate for 1990, see Table 1). Adding emissions of unintended leakage would increase this number even further. Similar questions can be raised for the emission factor that the authors is using for gas production, transmission and distribution. It seems unreasonably low. Preferable emissions should be estimated separately for gas production, long-distance gas transmission and distribution networks.

Table 1: Methane emission factors for oil and gas systems. Note the emissions factors used in the reviewed paper for China of 0.36 kg/t for oil and 2.77 g/m3 for gas have been converted to kt $CH_4$/PJ to facilitate the comparison.

| | | China Reviewed paper | IPCC (2006) vol.2 Tables 4.2.4 and 4.2.5 | USA | | | Canada | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | NIR (2015) | UNFCCC (2014) | | NIR (2015) | | |
| | | 1990 | Range of default efs kt $CH_4$/PJ produced | 1990 | 2000 | 2010 | 1990 | 2000 | 2010 |
| Oil production (EIA, 2015) | PJ | 6280 | | 16428 | 13003 | 12244 | | | |
| $CH_4$ from oil systems | kt $CH_4$ | 54 | | 1260 | 1496 | 1406.52 | | | |
| Ef oil systems | kt $CH_4$/PJ | 0.009 | Vented associated gas: 0.056-0.39<br>Flaring associated gas: 0.0001-0.001<br>Unintended leakage: 0-0.11<br>Oil refinery: 0.0006-0.0015<br>**Sum oil systems: 0.057-0.502** | 0.077 | 0.115 | 0.115 | 0.25 (conventional oil)<br>0.07-0.13 (unconv. oil) | | |
| Natural gas production (EIA, 2015) | PJ | 617 | | 19335 | 20744 | 23007 | | | |
| $CH_4$ from natural gas systems | kt $CH_4$ | 40 | | 7164 | 7459 | 6412.76 | | | |
| Ef gas systems | kt $CH_4$/PJ | 0.065 | Vented associated gas: 0<br>Flaring associated gas: 0.000005-0.00005<br>Unintended leakage: 0.01-0.66<br>Gas transmission & storage: 0.004-0.13<br>Gas distribution networks: 0.024-0.30<br>**Sum gas systems: 0.038-1.09** | 0.371 | 0.360 | 0.279 | 0.15-0.16 (gas production) | | |

Finally, on p.9 row 15, authors mention that the province attribution of emissions from oil and gas systems has been done using GDP. There must surely be information available on the geographical distribution of oil and gas production in China. In particular for oil production, almost all emissions are released during extraction and GDP is not likely to be a good measure for the geographical attribution of these emissions.

**[Response]** Thank you for carefully checking fugitive emissions from oil and natural gas systems. Compared the default EFs of IPCC (2006) and EFs in Schwietzke et al. (2014a, 2014b), the EFs in the previous version have smaller value. Considering the "realistic" EFs in USA, Canada and other countries from UNFCCC (2014) and Schwietzke et al. (2014a, 2014b) suggested by the reviewer, in the revised version, we adopted the EFs in Schwietzke et al. (2014a, 2014b) for fugitive emissions from oil and natural gas systems. For fugitive emissions from oil systems, the average EF is 0.077 kt $CH_4$/PJ (2.9 kg $CH_4$/$m^3$ oil), and the low and high boundary of EF are 0.058 kt $CH_4$/PJ (2.2 kg $CH_4$/$m^3$ oil) and 0.190 kt $CH_4$/PJ (7.2 kg $CH_4$/$m^3$ oil), respectively (see Table 1 in Schwietzke et al., 2014a). These values of EF are consistent with the EFs in the table listed by the reviewer. The fugitive $CH_4$ emissions from oil systems increase from 0.36 [0.27-0.98] Tg $CH_4$/yr in 1980 to 0.68 [0.52-1.86] Tg $CH_4$/yr in 2010.

For fugitive emissions from gas systems, the fugitive emissions rates (FER) of natural gas is decreasing from 1980 to 2011 (Schwietzke et al., 2014b). In China, we adopted the FER linearly decreases from 4.6% (0.81 kt $CH_4$/PJ) in 1980 to 2.0% (0.35 kt $CH_4$/PJ) in 2010. This medium FER is close to the EF in 2010 in the above table. The low and scenario of FER in China decreases from 3.9% in 1980 to 1.8% in 2010, and the high scenario of FER in China decreases from 5.7% in 1980 to 4.9% in 2010. The fugitive $CH_4$ emissions from gas systems increase from 0.45 [0.38-0.56] Tg $CH_4$/yr in 1980 to 1.27 [1.14-3.11] Tg $CH_4$/yr in 2010.

We agree that GDP is not likely to be a good proxy for the geographical attribution of fugitive emissions from oil and gas systems. In the revised version, we applied the spatial distribution of EDGARv42 grid maps with spatial resolution of 0.1 degree by 0.1 degree, scaled by the total emissions from oil and gas systems in each province (Schwietzke et al., 2014a). The population density, oil and gas production sites, and other proxies for transportation routes are considered in EDGARv42 grid maps for $CH_4$ fugitive emissions from oil and gas systems. Thus, the spatial distributions of $CH_4$ fugitive emissions from oil and gas systems in the revised version include the geographical distribution of oil and gas production in China (Figure 3), which has better geographical distribution than the GDP proxy in the previous version. With all these changes, we think to have deeply revised the emissions from this sector as requested by the reviewer.

Fossil fuels combustion:

Use of default IPCC emission factors, which seems appropriate.

Landfills:

Use of FOD method, which is the recommended IPCC method. The levelling off of emissions from landfills towards the end of the period (visible in Figure 2) is explained by an increase in composting and incineration. Estimates seem consistent across mentioned studies.

Wastewater:

Estimates emissions from both domestic and industrial sources. No additional comments.

**References**

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