

RESPONSE TO REVIEWERS' COMMENTS

Title: “Nepal Emission Inventory (NEEMI): A high resolution technology-based bottom-up emissions inventory for Nepal 2001-2016”

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We thank both referees for their constructive comments. The scientific and grammatical comments have been carefully considered and addressed through the changes detailed below. The comments from both referees have been broken down into points and subsequently answered. A point by point response is included indicating where changes appear in the revised manuscript along with the subsequent changes. The referee's comments appear in black and response to the comments follows immediately after in blue color.

Note:

1. All the changes in the revised manuscript are highlighted in blue color.
2. Line numbers indicated in this text refer to the revised manuscript.

ANONYMOUS REFEREE #2

- 1) General comments Overall, this is an interesting, well-researched piece of work and is worthy of publication. However, there is some confusion about the scope of the study. Although the abstract states that the study focuses on the energy-use sectors and agro-residue open-burning, Section 3.2 also includes estimates of agricultural CH₄ emissions from livestock (but not rice cultivation) although these estimates do not appear in any graphs or tables as far as I can see. This is rather confusing and perhaps CH₄ should be omitted altogether (as Referee #1 suggested). However, if CH₄ is to be included, then perhaps all other major anthropogenic CH₄ sources should be covered as well, including rice paddy, landfill waste, waste-water etc.

Response: Thank you for the positive note on our study and for the comment on open burning of agro-residue and CH₄ emission from agricultural sources. We have now split the manuscript into two parts, as mentioned in the response to comments by the reviewer no. 1: part 1 on technology-related emissions and part 2 on open burning and fugitive emissions. The above mentioned discrepancies are now rectified and subsequent changes are made in the abstract on page 2 line 6 and kept consistent throughout the manuscript.

We estimate emissions of aerosols, trace gases and greenhouse gases from five energy-use sectors of residential, industry, commercial, agriculture (only use of tractors, tillers,

pumps and threshers) and transport (on-road and off-road) for the period 2001–2016 (with 2011 as the base year), using bottom-up methodologies.

The scope of the study, sectors and pollutants are clearly mentioned on page 6 line 16:

Analyzing the following issues, it is important to conduct a systematic and comprehensive study of all energy sectors, agriculture sources and solid waste burning in Nepal from an emissions point of view, which has not yet been done, integrating the primary information on energy production and use, fuel combustion technologies and corresponding EFs. The Nepal emissions inventory study is divided into two parts; technology-based emissions (NEEMI-Tech) as part I, and open burning and fugitive emissions (NEEMI-Open) as part II. This paper discusses the development of a high resolution (1 km × 1 km, monthly) combustion and technology-based emission inventory from the residential, industrial, transport (on-road and off-road), and commercial sectors, as well as the agricultural sector (only technology-based emissions from use of tractors, tillers, pumps and threshers), while part-II encompasses emissions from open burning of municipal wastes, agricultural open field burning, and forest fires, along with fugitive emissions from waste, paddy fields, enteric fermentation and manure management. Part -II is under preparation for publication. In both parts, emissions of a total of ten species, where applicable, are estimated in this study, including greenhouse gases and short-lived climate-forcing pollutants (SLCPs).

- 2) Also, if the study were to be expanded to include non-combustion agricultural activities, then adding ammonia (NH₃) (e.g. from livestock manure management and application of N-fertilizers) to the list of inventoried pollutants would also add value. This is because NH₃ is a very important precursor (in addition to NO_x and SO₂) of secondary inorganic aerosol, and so would need to be included if the inventory results were ever to be used as input to subsequent atmospheric chemistry transport modelling.

Response: We agree with the reviewer that NH₃ and SO₂ are important species for secondary inorganic formation. Now, since we have split the manuscript into two parts, NH₃ emissions from agriculture will be discussed in part 2 of the study as mentioned on page 6 line 16 (see the inserted paragraph in the response to comment # 1)

- 3) I also agree with Referee #1 that comparisons of the results with other inventory initiatives that cover Nepal, especially EDGAR and GAINS-Eclipse, would enhance this study.

Response: Thank you for pointing to several global and regional inventories. We have now compared NEEMI-Tech emissions with technology-based emissions from the EDGAR, CMIP6, ECLIPSE-GAINS, REAS and MIX HTAP emission inventories. The comparisons are now included in Figure 7 and a new text has been inserted in the manuscript page 24 line 26:

The emissions were also compared... about sulfur retention in ash.

- 4) Specific comments Scope of study. On page 22 (lines 1 and 2) it states that ‘For analysis and comparison purposes, only the combustion based emissions from energy sources are considered, leaving out fugitive emissions from livestock management.’ So this begs the question: What about open-burning of crop residues – were these included?

Response: The above confusing sentence has been deleted. Now, the scope of the study, sectors and pollutants are clearly specified in the manuscript on page 6 line 16. No emissions from agricultural residue burning (open field) are included in the revised manuscript.

- 5) Residential open burning. Not clear what is meant by residential ‘open burning emissions of wood and residues’ on line 20 of Page 2, ‘heating outside’ on lines 17-18 of page 8 and ‘Space heating, Open burning’ in Table S2. If this is just burning of biomass in open fires indoors this should be clarified. The term ‘open burning’ suggest to me that the fires are located outside the house (in the open) which seems a strange way to heat a house.

Response: The inconsistency in describing the activity has been corrected and made consistent on the above mentioned lines. For example,

- (i) ‘open burning emissions of wood and residues’ is changed to ‘*space heating*’, on page 2 line 19
- (ii) ‘heating outside’ is expressed in a more convincing way to ‘*space heating outdoors means, where people gather around an open fire to keep themselves and the immediate vicinity from cold by burning firewood, agricultural residue and dungcakes.*’ On page 8 line 19
- (iii) ‘Space heating, Open burning’ is changed to ‘*Space heating, burning fuel (indoor and outdoor)*’ in SI Table S1

- 6) Page 5, line 6: Does the 15-fold increase in vehicle registrations over 2 decades equate to an actual 15-fold increase in vehicle numbers – or just better enforcement of registration rules?

Response: The 15–fold increase in vehicle registrations over 2 decades roughly equate to a 15-fold increase in vehicle numbers because there was no vehicle retirement policy in place until only recently, i.e., until March 2017 (e.g, phasing out private transport vehicles older than 20 years). This resulted in virtually all registered vehicles running on the streets. However, in order to account for retiring vehicles and reflect more realistic situation we have used the vehicle survival functions to estimate the number of vehicles in service. We have reframed the sentence on page 5 line 8 as:

Moreover, the rapid urbanization has led to an increase in vehicle numbers by about 15-fold over the last two decades, unfortunately increasing the demand for petroleum fuels (DoTM, 2016).

- 7) Line 16: Should this be ‘IPCC Tier 1’ or ‘EMEP/EEA Tier 1’ or both?

Response: On page 5 line 19: TIER-I replaced with ‘IPCC Tier 1’ or ‘EMEP/EEA Tier 1’

- 8) Kerosene lamps. Little distinction is made between kerosene wick lamps and kerosene hurricane lamps – (although ‘kerosene lanterns’ are referred to once on page 22, line 9, which I assume equates to hurricane lamps?). In Table S2, for BC, only the emission factor (EF) for wick lamps (90 g/kg) is given, from Lam et al (2012), although that paper (Table S5) estimates 20% of kerosene used for lighting in this region is likely to be in hurricane lamps (EF for BC is 9 g/kg). Do the authors therefore assume no hurricane lamp use for their calculations? Also, in Table S2, Lam et al (2012) is given as the source of the N₂O and SO₂ EFs, but these do not exist in that paper (as far as I can see) and the OC EF of 0.52 g/kg in Table S2 compares with the average of 0.4 g/kg for wick lamps given in Lam et al. Please could the authors correct and/or explain the derivation of their EFs for kerosene-fuelled lighting.

Response: The assumption about kerosene lamps is revised here. Due to a lack of studies on the definite number of types of lamps, it is assumed that 50 % of the population relies on wick lamps and rest on kerosene lanterns. Therefore, a sample weighted average of the kerosene wick and hurricane lamp emission factors are considered (wherever possible) and revised accordingly:

Lam et al., (2012)

$$\text{CO}_2 - (7*2770 + 3*3080)/(7+3) = 2863 \text{ g/kg}$$

$$\text{CO} - (7*11 + 3*3)/(7+3) = 8.6 \text{ g/kg}$$

$$\text{BC} - (7*90+3*9)/(7+3) = 65.70 \text{ g/kg}$$

$$\text{OC} - (7*0.4+3*0.5)/(7+3) = 0.43 \text{ g/kg}$$

$$\text{PM}_{2.5} - (7*93+3*13)/(7+3) = 69 \text{ g/kg}$$

Zhang et al., (2000)

$$\text{SO}_2 - (0.033+0.011)/2 = 0.022 \text{ g/kg}$$

Smith et al., (2000)

$$\text{NMVOC} - (14.86+19.2)/2 = 17.03 \text{ g/kg}$$

$$\text{CH}_4 - (0.288+1.071)/2 = 0.68 \text{ g/kg}$$

$$\text{N}_2\text{O} - (0.079+0.102)/2 = 0.091 \text{ g/kg}$$

- 9) Brick kilns: Page 13, line 2: It would be nice to know how many of the 557 FCBTKs had the zig-zag firing technology, and also how many VSBK there were.

Response: Following sentence added on page 10 line 28:

The zig-zag firing technique is a relatively new development in Nepal. It has only been used in the brick kilns in the Kathmandu Valley, which were rebuilt after 2015 Earthquake in Nepal. Kilns outside the Kathmandu Valley are slowly adopting the zig-zag technique. An in-house survey of 82 brick factories in 2014 in the Kathmandu Valley showed that only 22 FCBTK (~25%) had zig-zag firing compared to straight ones. This fraction may be extrapolated at a national level to understand the number of zig-zag firing brick kilns in Nepal. A thorough study is indeed required to furnish the actual numbers.

10) Technical corrections Page 2, line 14: ‘Tons’ is not an SI unit – presumably this should be ‘tonnes’. Then Gg is used thereafter. Consistency in use of units required – suggest using Gg throughout (or Tg for CO₂ and CO).

Response: Units throughout the manuscript are made consistent. Fuel quantities are specified in tonnes/million tonnes and all emissions are reported in Tg and Gg.

11) Page 4, line 21: Should ‘intake’ be ‘exposure’? Line 22: children (not childrens’)

Response: Suggested changes incorporated on page 4 line 21 and line 22.

12) Page 6, line 6: ‘arising’ not ‘arousing’. Line 16, Delete ‘-forcing’ as SLCPs stand for ‘short-lived climate pollutants’.

Response: Suggested changes incorporated on page 6 line 11 and line 28.

13) Page 9, line 7: Replace ‘rest’ with ‘the remaining’. Line 8, ‘LPI’ and ‘SMI’ should have been defined earlier in this paragraph. Line 26: Insert ‘data on’ between ‘provided’ and ‘how’.

Response: Suggested changes incorporated on page 9 line 1.

14) Page 11, line 22: Should be ‘we intend’ not ‘we tend’.

Response: Sentence about aviation which had ‘we tend’ was deleted.

15) Page 13, line 19: Who is the personal (not personnel) communication from?

Response: By personal communication, we refer to a brief study by Dr. Prakash Bhawe, one of the co-authors, who along with a Master’s student from a local university, as a part of the thesis performed a random check on several vehicles’ exhaust before and after servicing the vehicles in the Kathmandu Valley. One of the key findings highlighted the higher percentage of the super-emitters in Nepal (rather than the assumed 20%) due to poor maintenance of the vehicle and road infrastructure.

16) Page 17, line 7: Replace ‘they’ with ‘there’.

Response: Sentence has been modified on page 14 line 26.

17) Page 19, line 2: Replace ‘small increase in’ with ‘slightly higher level of’. Line 6, Replace ‘increase’ with ‘difference’. Line 8, insert ‘being’ at start of line.

Response: Suggested changes are incorporated on page 16 line 22, line 28 and page 17 line 1.

18) Page 21, line 18: Replace ‘spike in 2016 energy’ with ‘large increase in 2016 energy use’.

Response: Suggested changes are incorporated on page 19 line 11.

- 19) Page 24, line 1: For ‘aerosols’ the %SO₂ is included in the list yet NO_x is also an important precursor of secondary inorganic aerosol – why not include this too? If NH₃ were to be added to the inventory (see general comments), this would also need to be added for the same reason.

Response: The NO_x emissions are classified under ozone precursors since NO_x plays a vital role in ozone chemistry, like VOCs and CO, and hence is explained in the succeeding paragraph page 23 line 4, although NH₃ and NO_x are associated with secondary inorganic aerosols as well.

- 20) Page 24, line 2: High OC emissions are referred to as shown in Fig 6 – but CO is in that fig, not OC. Has there been a mix-up over OC versus CO?

Response: Although this may at first be confusing, there is not a mix-up between OC and CO. Rather, Fig 6, cited on page 22 line 15 highlights the top six combustion technologies for PM_{2.5}, BC, NO_x and CO emissions. Since the top six combustion technologies for OC closely resemble those for PM_{2.5}, the additional sub-plot for OC is not shown here. Instead the emphasis is laid on the other distinct sources. A figure showing OC, SO₂, NMVOC, CH₄, CO₂ and N₂O is appended in the supplementary information as Fig S9.

- 21) Page 22, line 19: The text includes the 2011 emission estimate for CO and then on page 23, lines 5 & 6, emissions of CO₂, CH₄ and N₂O. Why were these not included in Figure 5(a) or perhaps in a separate table?

Response: CO, CO₂, CH₄ and N₂O emissions are now included in Figure 5(a).

- 22) Page 25, lines 19 & 20: Values given here for all species apart from SO₂ are slightly different from those given in Table 5.

Response: Table 5 was checked carefully again and the values match with the ratio mentioned on page 24 line 2.

- 23) Page 27, lines 23& 24: Need to rephrase this – I don’t think diesel gen-sets were changed to zig-zag firing!

Response: Thank you for catching this. We have rephrased the sentence as follows on page 28 line 13:

There was a major change in two main polluting sources during 2016, (i) straight firing brick kilns in the Kathmandu Valley were changed to the zig-zag firing technology when they were rebuilt after the 2015 earthquake and (ii) diesel generator sets were phased out due to improvements in load shedding hours since 2016.

- 24) Figure 9: Make clear this graph is for 2011.

Response: ‘Monthly distribution for 2011’ is now mentioned for Figure 9

- 25) Table 6: Make clear that these values are emission ratios (KTM/NPL).

Response: Emission ratios are now mentioned in the heading of the table:

Table 4. Comparison of total and sectoral emission ratios for the Kathmandu Valley and Nepal for 2011.

- 26) Table S3: Footnote ‘e’ refers to the liquid fuel combustion in industry having a 22.5% sulfur retention. But liquid fuels leave no ash and so there should be zero sulfur retention in ash – so this must be wrong. If this footnote should have applied to coal use in industry, then again 22.5% looks wrong as USEPA’s AP42 (5th edition, Section 1.1.3.2) implies only 5% retention-in-ash for bituminous coal (the type of coal used in Nepal). Please explain.

Response: The Footnote ‘e’ in Table S2 has been simplified and corrected. Liquid and gaseous fuels had no sulfur retention in the ash. It is now clearly mentioned in the footnote.

^eSO₂ based on the sulfur content of the fuel. For liquid and gases fuels, there is no sulfur retention in the ash.

For bituminous coal, 5% retention is assumed as noted in the USEPA’s AP42 (5th edition, Table 1.1-3), similarly corrected in Table S2.

^aCoal Combustion emission factors, from the USEPA’s AP42, Table 1.1-3, Table 1.1-11, Table 1.1-19. SO₂ is based on the sulfur content of the fuel. For coal, 5% sulfur retention is assumed from the AP42 document, Table 1.1-3