

RESPONSE TO REVIEWERS' COMMENTS

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

Pankaj Sadavarte^{*a,c}, Maheswar Rupakheti^{*a}, Prakash V. Bhave^b, Kiran Shakya^b, Mark G. Lawrence^a

^aInstitute for Advanced Sustainability Studies (IASS), Berliner Str. 130, 14467 Potsdam, Germany

^bInternational Centre for Integrated Mountain Development (ICIMOD), Lalitpur, Nepal

^cNow at SRON Netherlands Institute for Space Research, Utrecht, The Netherlands

*Corresponding Authors: Pankaj Sadavarte (p.sadavarte@sron.nl) and Maheswar Rupakheti (Maheswar.rupakheti@iass-potsdam.de)

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 #1

- 1) A very useful, data rich, and rather well documented paper that deserves publication. However, in my view, it would benefit from shortening of the more general sections of the main text while more extensive and especially more focused discussion of results and comparison to other work.

Response: Thank you for a positive note on our study. The section (2.1) Activity rates and technology division, (2.2) Combustion technologies and (2.3) Emission factors are trimmed down to more concentrated information and additional details are moved to the Supplementary Information as section S1, S2, and S3, respectively. We have also provided a more extensive comparison of our emission estimates with five other available global and regional emissions data sets, and the results are discussed extensively.

- 2) One of the key issues is completeness of the inventory and consequently a decision about the content of the paper. The title indicates it is complete inventory, however, it focuses on anthropogenic and primary combustion sources. If it shall remain as such then the title should be modified and a clear statement about the content should be made already in the abstract.

Response: We agree with the reviewer that we have mixed technology-based emissions and open burning (and fugitive) emissions. Given the extensive nature of completing the open burning and fugitive emissions component, and in order to present the emissions for these two broad sectors more distinctly, we would like to split the manuscript into two parts, pending approval by the editor, as follows:

Nepal Emission Inventory - I: A high resolution bottom-up combustion and technology-based emissions inventory (NEEMI-Tech) for 2001-2016

Nepal Emission Inventory - II: A high resolution bottom-up open burning and fugitive emissions inventory (NEEMI-open) for 2001-2016

The title of the paper (part 1) has been modified accordingly. The abstract now mentions sectors, clearly highlighting that the current manuscript presents only combustion and technology-based emissions. All the sections and sub-sections on open burning emissions are now removed from part 1. We will prepare part 2 for publication as soon as possible.

A paragraph has been inserted clearly mentioning the scope of the study, sectors and pollutants on page 6 line 16 of the revised manuscript:

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).

- 3) Considering the sources that are currently covered (a table summarizing the coverage would be a great help)

Response: A Table with details like the source, pollutants, spatial and temporal coverage, and base year of the inventory is presented as “Table 1. Details about important features of NEpal Emission Inventory (NEEMI).”

- 4) I do not see why the N₂O and CH₄ is at all included since vast majority of emissions originate from sources NOT included in this work (agriculture, waste). Therefore, I'd suggest to remove these species from the inventory OR complete the dataset with agriculture (livestock, fertilizers, rice) and waste (use and refer to the results of the Das et al, 2018 paper).

Response: We had originally included N₂O and CH₄ emissions with the intention to estimate the burden of all the important pollutants arising from the combustion-based sources in Nepal. However, the referee is quite correct that for these two gases, the sources covered in this part of the database are very minor compared to their other sources, and we will save describing those major source of emissions until the second part is ready (having now split the complete study in two parts as explained above). The revised manuscript now contains only technology-based combustion emissions.

- 5) Few other comments about the source coverage; - For CO₂, it might be useful to specifically show the fossil fuel emissions vs biofuel emissions, possibly giving also a clear information about the assumptions about the non-sustainability of wood supply - it is mentioned but I have not found a clear explanation of assumptions. Since also the CO₂ from open biomass burning (agricultural residue) is included in the total it would be good to separate it from fossil fuel CO₂.

Response: The following analysis describing the difference in CO₂ emissions from biofuel and fossil fuel is added on page 21 line 7:

Broadly, fossil fuels and biofuels (firewood, agriculture residue, dungcakes and biogas) contribute 73 % and 27 %, respectively, to CO₂ emissions in 2011, in contrast to only 12 % (43 PJ) of the energy coming from fossil fuels, and 88 % (331 PJ) from biofuels, since fossil fuel combustion moves CO₂ from the long-term fossil reservoir into the atmosphere, while biofuels are mostly recycling of recent biomass (though they include some long-term removal of net biomass, which is small relative source to the atmosphere). Sectorally, the industry sector contributes 46 % of the combustion-based national CO₂ emissions, followed by residential (32 %) and transport (15 %), with small fractions from the commercial (4 %) and agricultural (mechanized farming) (3 %) sectors. Even though the residential activities are the main drivers of the national energy consumption, consuming 292 PJ of biofuels and 8 PJ of fossil energy, almost 92 % of the CO₂ emissions from biofuels are from recycled carbon, with the non-recycled fraction being about 10 % each from firewood, agricultural residue and 0 % dung cakes, according to Venkataraman et al. (2010). The CO₂ emissions from the industries are mostly driven by fossil fuel combustion (98 % fossil fuel and 2 % biofuel), especially coal use in the production of bricks (27 %) and process emissions (53 %) from cement manufacturing.

- 6) For NMVOC, according to my understanding the solvent use and losses from liquid fuel storage distribution and not included - it would be useful to add a few sentences about the potential contribution of those (it will be rather small I assume but still worth

mentioning for completeness and in the future these sources might be gaining in importance).

Response: Since we have now decided to include only combustion and technology-based emissions in part I, any fugitive emissions such as solvent use and evaporative loss will be provided in part-II. The following brief analysis on fugitive emissions of NMVOC is added on page 21 line 4:

The fugitives of NMVOC from storage tanks and service stations, and the transport and evaporative emissions from gasoline vehicles, which are expected to be a small fraction compared with combustion-related NMVOC emissions (though they might gain importance in the future) will be considered in detail in the second part of this study.

- 7) One potentially more important source that might be missing (?) are evaporative emissions from gasoline vehicles - I am not sure if the emission estimates include these in emission factors or not.

Response: See response in comment #6.

- 8) The authors mention the Das et al (2018) paper where emissions from waste burning are estimated; I'd suggest to include results of that paper here and quote that for this source emissions come from that paper as these are relevant for all air pollutant species and so the presented inventory would be more complete.

Response: As mentioned earlier in point 4, now we have split the NEEMI study in two parts as explained in detail on page 6 line 16. Please see the response to comment #2 to see the new paragraph inserted in the text.

- 9) Emissions of SO₂ from residential sector are typically not a major source and so it is the case in Nepal but considering the large role solid fuels play in the energy balance the contribution seems very small and I was wondering if the authors should not review the assumptions about the SO₂ emission factors used for biomass.

Response: Thank you for the suggestion. We have now revised the emission factors for SO₂ from firewood burning. Earlier, the SO₂ EF value of 0.08 g/kg from Habib et al. (2004) was used. Now, additional papers (Saud et al., 2011, Stockwell et al., 2015) were reviewed and a new EF has been used, which was obtained by averaging EFs from Habib et al. (2004), Saud et al. (2011) and Stockwell et al. (2015), i.e., $(0.08+0.26+0.499)/3 = 0.28$ g/kg. The change has been incorporated throughout the analysis and updated EFs can be seen in Table S1.

- 10) It is not clear if the non-exhaust emissions from transport (brake wear, tyre wear) are included or not.

Response: Non-exhaust emissions are not included. We inserted the following statement in the transport EF section on page 13 line 20:

Non-exhaust emissions such as brake wear and tire wear are not included in this study.

- 11) Comparison to other studies; obviously there is not a lot to compare to but I believe one could add few more sources, like the CMIP6 dataset (Hoesely et al., 2018) where annual estimates until 2014 were made and are available at sectoral level too, then also the EDGAR inventory (Crippa et al), and GAINS model work where the ECLIPSE project dataset is available (Klimont et al, 2017). The currently presented comparison provided in Fig 7 and one page of discussion comes short (in my view) of what could be discussed as the comparison could serve highlighting, for example key uncertainties or elements that are not well represented or out of date in the regional and global products.

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 discussing the comparison results:

The emissions were also compared with the global datasets of CMIP6, EDGARv4.3.2 and ECLIPSE V5a for the emission trends and year 2010. The objective behind developing the CMIP6 emissions was “to combine the global estimation framework with country-level inventories, to produce reproducible, consistent over space, time and species” (Hoesley et al., 2018). Following this, the CMIP6 inventory starts with fuel consumption at sector level from International Energy Agency (IEA) and the emission factors with an intention to scale their estimates by comparing along with regional emissions. For Nepal, the scaling was done with REAS 2.1, and we observe from Fig 7 that, the national estimates of NO_x, CO, NMVOC and SO₂ were found to be similar in both studies, while CH₄, BC, OC and CO₂ were not. One of the reasons for the disagreement in BC and OC was the default estimates from SPEW, while for CO₂ it can be inferred that their estimates are much closer to the NEEMI CO₂ emissions, including the non-renewability factor. The CH₄ emissions from CMIP6 are consistent and do not vary over the time, which is completely different than REAS 2.1 and NEEMI, where the increase can be attributed to an increase in fuel consumption over the one and half decade. At the sectoral level, the residential activities contribute 92-99 % to the national estimates of BC, OC, NMVOC, CH₄, CO and ~55-60 % for NO_x in CMIP6 and NEEMI inventories. A few disagreements between CMIP6 and NEEMI are observed in the NO_x emissions from the agriculture sector, due to inclusion of fertilizer application and manure management estimates in CMIP6, that are not covered in this part of the NEEMI inventory. Also, the SO₂ emissions from each sector vary a lot when compared to NEEMI bifurcations, showcasing the shortcomings due to the coarser resolution methodologies, that completely lacks minuscule details as present in the NEEMI inventory, like changes in the sulfur content of the fuel over the period of one and half decades, and the sulfur retention fraction in the ash content. In addition to this, CMIP6 considers only eight types of fuel, with no clear distinction in biomass such as firewood, agricultural residue and dungcakes.

Even EDGARv4.3.2 emissions are estimated using activity and production numbers from IEA and emission factors from EMEP/EEA guidebook (Crippa et al., 2018). One of the

core differences between global inventories of EDGARv4.3.2 and CMIP6 lies in the consideration of the level of detail and their integrity in each sector. For example, EDGAR covers 26 aggregated sources and 64 fuel types compared to 55 sources and 8 fuels in CMIP6 (Hoesley et al., 2018, Crippa et al., 2018, Janssens-Maenhout et al., 2017). At the national level, emissions of PM_{2.5}, BC, OC, NO_x, NMVOC and N₂O from NEEMI are higher than EDGAR by a factor 1.3-1.5, mainly due to differences in biomass consumption (especially consideration of space and water heating activities in the residential sector) and differences in the new field measured emission factors for traditional cookstoves and burning biomass (Stockwell et al., 2015). Also, differences arise due to the assumption of a 40 % superemitter fraction in on-road vehicles and use of technology specific emission factors throughout the inventory. The CO₂, CO and SO₂ emissions from NEEMI are lower than EDGAR by a factor of 0.7-0.9, due to the use of tier-II/III approaches in the methodologies and technology specific emission factors, while there is a good agreement for CH₄ emissions. Across sectors, the residential and commercial together contribute 90-97 % of the national estimate in EDGAR, which is consistent with NEEMI for all pollutants except CO₂, NO_x, CO and SO₂. These differences in emissions can be explained with the underlying assumptions in each activity, fuel consumption and emission factors.

The emissions from the GAINS-ECLIPSEv5a model was also compared for 2005, 2010 and 2015 for PM_{2.5}, BC, OC, NO_x, CO, NMVOC, CH₄ and SO₂. One of the first inferences that can be derived is, the decrease in GAINS model emissions by a factor of about 0.10 – 0.35 for the year 2015 with respect to 2010. Since there has been an increase in fuel use over the years, the GAINS model assumes a decrease in emission factors for PM_{2.5} by a factor 15 % globally during 2005-2010 due to improvements in combustion technologies for cookstoves in the Asia (Klimont et al., 2017). Under the ‘current legislation emission’ (CLE) scenarios it continues to improve further and the impact is visible due to higher penetration of ICS. A large variability is observed when the GAINS emissions are compared with NEEMI for the 2005-2010-2015 period. Still they are within an uncertainty ratio of 0.8 – 1.2 (GAINS/NEEMI) during 2005 and 2010 for PM_{2.5}, OC, NO_x, NMVOC, and CH₄. The BC, CO and SO₂ emissions from GAINS are a factor 1.5-3.0 higher than NEEMI, anticipating the difference in high emission factors. Overall, the residential sector is the dominant source, contributing to ~90 % of the national emissions, while the difference arises in NO_x and SO₂ emissions. The GAINS inventory estimates 50 % NO_x emissions from the transport sector, compared with 19 % from NEEMI. Inclusion of 20 % superemitter fleet fraction with a varying and high amplification factor up to 10 across different emission standard vehicles may be one of the reasons. In the case of SO₂, 43 % is emitted from industry and 53 % from residential, which is different from 61 % and 37 % in NEEMI, due to use of regional and technology specific emission factors and assumptions about sulfur retention in ash.

- 12) BC and OC emission factors for transport sources. While the Bond et al (2004) work certainly provides a great starting point the shares presented there referred submicron PM so one needs to carefully use those numbers (for transport where exhaust PM emissions

are primarily in submicron fraction this is probably fine). However, there has been a lot more work done assessing diesel carbonaceous emissions, including work in Asia and also how the BC share changes in vehicles with more advanced emission standards - something that seems to be ignored here; please review the possibility of using also some more recent studies and consider the extent to which for more recent vehicles the factors might be different.

Response: Emission factors for BC and OC are revised and updated from more recent work on diesel and gasoline vehicles. The description about BC and OC fraction is added on page 13 line 12:

The fractions of BC and OC were obtained by averaging respective fractions from chassis dynamometer test results by Kim Oanh et al. (2010), Wu et al. (2015), Zhang et al. (2015), Yang et al. (2019) and Jaiprakash et al. (2016). These studies reflect the regional characteristics of driving cycles and the road infrastructure, which plays an important role in tail pipe exhaust. Kim Oanh et al., (2010) made a vintage based measurements showing the degradation of emissions and resultant high fractions of EC and OC in the oldest category of vehicles. However, Wu et al., (2015) and Jaiprakash et al., (2016) emphasized the importance of driving speed (on non-highways, highways and in cities) on the EC and OC fraction from diesel vehicles.

13) It is not clear from the current text, if the data about the share of fuel used by vehicles complying with different Bharat standards is available and explicitly used or not.

Response: The share of fuel used by vehicles complying with different Bharat Standards is explicitly used and mentioned while estimating the SO₂ emissions during 2001-2016 on page 13, line 19:

SO₂ emissions were calculated using the sulfur content of BS-II/III/IV fuel imported from India, with no retention assumed.

14) There has been few more studies looking at high emitters and the implications for emissions. It might be useful to add few more lines of discussion and in the result section highlight the importance of this source for specific pollutants - even show this in the charts explicitly as it offers a good policy target.

Response: An analysis on superemitters is added in the manuscript on page 20 line 5:

A 40 % of the fleet is assumed to be superemitters or high emitters and they contribute to 53 % PM_{2.5}, 58 % BC and 44 % OC emissions from the transport sector. Their emission factors were derived by scaling the normal emission factors (Klimont et al., 2017). The scaling factor was derived from Klimont et al., (2017), who provided the global scaling factors for diesel and gasoline vehicles across different emission standard vehicles, and also based on the measurements of emission factors for PM (Subramanian et al., 2009) in developing countries. On an average, light duty diesel vehicles are scaled by a factor 5 to get a value of 8.1 g/kg and an average heavy duty diesel vehicles are scaled by a factor 2 to get a value of 13.3 g/kg for superemitter vehicles. Though, there is no clear

distinction and measured emission factors for a superemitter vehicle, many contemporary studies have derived it using statistical percentile (Subramanian et al., 2009, Ban-Weiss et al., 2009). If a policy to identify and remove the superemitters is enforced, that would reduce ~30 % of PM_{2.5}, BC and OC transport sector emissions, which can be considered as a good and immediate policy target.

- 15) Continuing on the above, but for stationary sources, the use of BC and OC shares of PM_{2.5} where the abatement technologies, like particulate filters, are not considered is problematic since application of such filters changes the size profile (not reducing emissions of all PM species equally). Even if such information is not available as yet, it should be mentioned and for power plants and industrial boilers the installation of such stack control technology will become reality sooner or later.

Response: We have added the following sentence on page 22 line 23:

The information on emission control measures used in the industries is not readily available. Given poor implementation of policies in Nepal on emission control measures, we expect that most of the industries are operated without proper emission control measures. However, the installation of stack emission control technology in the power plants and industrial boilers will become a reality sooner or later. This is likely to change the emission profile, such as shares of BC and OC in PM_{2.5}, and the size of particles emitted, which needs to be considered in future emission estimates.

- 16) The aviation sector - The authors state in line 23-24 on page 11 that it is not included but in several parts of the manuscript and also all energy graphs aviation is mentioned. It should be made consistent.

Response: We have completely removed the mention of aviation energy from the manuscript. The transport sector, henceforth, only consists of on-road and off-road vehicular energy and emissions.

- 17) On page 15, line 23 - one of the paper has 'way to high' emission factors....it would be good to add some more justification to why this study is excluded ...or maybe should not be mentioned at all if it is wrong.

Response: The phrase 'way to high' relating to the emission factors has been removed.

- 18) Section 3.1.1 mentions also burning of ag residues but i would not include this under 'national energy trend"

Response: Agricultural residue burning on fields is completely removed from this part of the inventory paper and is being considered in part-II, i.e., NEEMI-Open. Details are mentioned in page 6 line 16. Please see the new paragraph in the response to comment #2.