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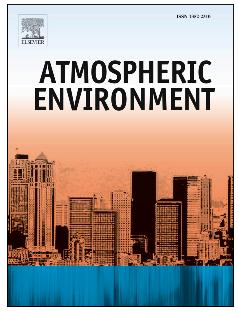

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Adrian Leip, Ute Skiba, Alex Vermeulen, Rona L. Thompson

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A complete rethink is needed on how greenhouse gas emissions are quantified for national reporting

Adrian Leip[1*], Ute Skiba[2], Alex Vermeulen[3], Rona L. Thompson[4]

1. European Commission, Joint Research Centre, Ispra (VA), Italy

2. Centre for Ecology and Hydrology (CEH), Penicuik EH26 0QB, UK

3. ICOS ERIC, Carbon Portal at Lund University, Lund, Sweden

4. Norsk Institutt for Luftforskning (NILU), Kjeller, Norway

e-mail: adrian.leip@jrc.ec.europa.eu

A complete rethink is needed on how greenhouse gas emissions are quantified for national reporting

Adrian Leip[1*], Ute Skiba[2], Alex Vermeulen[3], Rona L. Thompson[4]

The 2015 Conference of the Parties (COP21) in Paris has for the first time agreed that both developed and developing countries need to reduce greenhouse gas (GHG) emissions to maintain a global average temperature 'well below' 2ºC and aim to limit the increase to less than 1.5ºC above pre-industrial temperatures. This requires more ambitious emission reduction targets and an increased level of cooperation and transparency between countries. With the start of the second Kyoto Commitment period in 2013, and the 2015 Paris Agreement, it is, therefore, timely to reconsider how GHG emissions are determined and verified.

The policy agenda is currently centred on GHG emission estimates from bottom-up inventories (see box 1a). This includes annual national reporting of GHG emissions (e.g. to the United Nations Framework Convention on Climate Change (UNFCCC) and defining emission reduction targets. However, bottom-up emission estimates rely on highly uncertain and, in some cases, sparse input data and poorly characterized emission factors.

In order to enhance accuracy, cost-efficiency and transparency of the process to assess progress towards the national emissions reduction targets, we call for a rethink of the current reliance on 'bottom-up' inventories for reporting national and global anthropogenic GHG emissions.

Climate scientists employ atmospheric observations (in the so-called 'top-down' approach, see box 1b) to assess and verify national bottom-up emission inventories of non-CO_2 GHGs, principally nitrous oxide (N_2O) and methane (CH_4). Top-down approaches use atmospheric concentration (or mole fraction) measurements in conjunction with models of atmospheric transport (i.e. atmospheric inversions) to provide a mass balance constraint on the total emissions. For CO_2, the net flux between the atmosphere and the Earth's surface (land biosphere and ocean) amount to approximately half of the global anthropogenic emission and thus also need to be accounted for. It is currently a burning research question, how to accurately discern anthropogenic emissions versus land biosphere and ocean fluxes using top-down constraints, and a number of additional atmospheric tracers to achieve this have been proposed (e.g. ^{14}C, CO, and O_2). With present knowledge, it is pertinent that top-down approaches are incorporated in national reporting and policy for non-CO_2 GHGs and, in the future when the methods are fully developed, also for CO_2.

The use of top-down approaches is particularly relevant for CH_4 and N_2O (the second and third most important GHGs after CO_2, respectively). Both gases are predominately of microbial origin and, therefore, characterized by high spatial and temporal variability. This makes it very challenging to parameterize and up-scale their emissions to regional or national totals. Employing top-down approaches to quantify emissions of these GHGs can provide a cost-effective strategy for assessing reduction targets and would deliver several benefits by: (i) focusing on climate relevant data, i.e., the concentration of radiative forcers in the atmosphere, (ii) overcoming the problem of limited accuracy in bottom-up estimates, (iii) better integration of national estimates into a global framework, making emission estimates more transparent and independently verifiable, and (iv) providing a framework to focus investigations on emission hotspots using bottom-up methods.

If maximum accuracy of GHG emissions (i.e., across all source categories) and emission trends are the most important goals for international climate policy, then top-down approaches offer numerous advantages over bottom-up ones. Namely, by frequently measuring atmospheric GHG concentrations, a physical constraint on total emissions and emission trends can be provided; and, by resolving the atmospheric transport using models, constrained emission estimates can be reported regionally. Thereby problems of sparse and unreliable activity data, poorly characterized emission factors, and unaccounted-for emissions are avoided. Furthermore, by measuring concentration changes with time, the effect of mitigation can be more directly related to radiative forcing and thus to the expected global warming. Atmospheric observation networks will also serve to alert the policy maker of changing biogenic emissions in response to changing climate or unexpected disturbances.

While top-down approaches are better suited to detect the success or failure of countries and regions to reduce GHG emissions, they cannot give indications where future mitigation policies will be most effective. Therefore, it will be important for countries to supplement top-down data with targeted sophisticated bottom-up measurement and model approaches for hotspot sources and regions. It will not be necessary to improve existing basic inventories over the entire territory and for all sectors and any resulting financial savings should be channelled into improving the inventory for hotspots and optimizing mitigation.

We, therefore, suggest a paradigm shift from bottom-up to top-down approaches for emission estimation as a basis for policy, whilst maintaining bottom-up approaches in the role of planning mitigation strategies and for providing future emission scenarios. Tier 1 bottom-up estimates would also be used as prior information for top-down emission quantification. Furthermore, top-down estimates could be validated in meso-scale studies in which the inversions are performed for a given region with high observation density and the results compared to flux measurements (e.g. Eddy Covariance) or a flux data product (see Fig. 1).

The top-down approach requires spatially and temporally dense observation networks, complemented by future satellites missions. This includes existing surface measurement networks, such as those emerging in Europe, North America and now also in Asia. Satellite observations of GHGs are currently available for CH_4 and CO_2. Current projects such as those promoted by the Copernicus Atmosphere Monitoring Service (CAMS[1]) and the Integrated Carbon Observation System (ICOS[2]) demonstrate the feasibility of the approach. In Europe, where the density of atmospheric observation sites is relatively high, and where the natural sources of N_2O are nearly negligible, inverse models are already capable of providing good estimates of the total anthropogenic N_2O emissions for individual countries[1–3]. Furthermore, inverse models were able to detect regional trends in emissions such as for N_2O in Asia[4]. And inverse models have been able to constrain emissions of CH_4 in China, where the inventories were found to significantly overestimate emissions in the 2000s[5,6], or in the U.S. corn belt finding an underestimation of N_2O emissions if estimated with IPCC approaches[7]. Complications in detecting trends in anthropogenic emissions arise, however, when the natural emissions are changing as a response to climate forcing. Developing methods to discriminate different emission sources is a continuing area of research and include multiple tracer approaches, e.g., for CH_4 stable isotopes (^{13}C and D) can help discriminate microbial and fossil fuel sources[8].

Considerable effort, however, is still needed to further develop and integrate surface networks, with emphasis on tropical and southern hemisphere countries[9]. Clearly, a shift in emphasis to top-down approaches will require significant investment to improve the capacity and capability of atmospheric measurements and modelling. We calculate that for 500

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[1] http://atmosphere.copernicus.eu

[2] https://www.icos-ri.eu

stations globally, which would provide a good in-situ network sufficient to resolve most countries, an investment of about $500M would be required over the next 20 years. For comparison, in the UK a programme to improve the GHG inventory for agriculture required investment of about $20M, thereof $10M for specific measurements of N_2O emissions at different scales (Luke Spadavecchia, personal communication, Feb. 2016). The development of Tier 2 and Tier 3 methodologies[10] has shown that the cost of developing high-quality national bottom-up methodologies is substantial.

It is paramount that atmospheric concentration measurements and inversion modelling results will be internationally freely available. This not only will guarantee high quality (and lower uncertainty) of the emission estimates, but also allow countries that are not able to run their own inverse models to delegate the reporting of their national emissions to other countries or (international) research institutes. Therefore, such a paradigm shift will allow all countries to assess their progress towards their target, without the need to build their own national emission inventory, whilst at the same time providing highest possible transparency. Quality assessment and control would need to be carried-out: (i) on the in-situ measurements and (ii) by model inter-comparisons. This would be a significant simplification compared to the review system currently in place at the UNFCCC.

Our suggested approach for science and policy-relevant emissions estimates is summarized as follows (see Figure 1):

- Develop GHG emission estimates, spatially and temporally resolved, from inversions using atmospheric concentration measurements. These will be informed by prior flux estimates provided by global Tier 1 GHG emission inventories or from national data, if available. A (global) network of atmospheric observation sites provides high accuracy and frequency concentration data for use in inverse models yielding national-scale optimized emissions, which will be the appropriate data to be submitted to e.g. the UNFCCC.

- Use Tier 2 and Tier 3 bottom-up inventories for hot-spot areas and source categories for future emission scenarios, and to inform and monitor climate change mitigation policies.
- Cross-check regional inversion-based emission estimates using meso-scale inversions (resolution of ~10 km^2, nested in a larger regional inversion system) with flux measurements (e.g. from Eddy Covariance and chambers) to “close the gap” between top-down estimates and bottom-up ones based on field-scale flux measurements (see Fig. 1).

Our suggestion to move to top-down-based GHG emission estimates is motivated by the fact that for the assessment of compliance with emission reduction targets, anthropogenic emission trends need to be determined at the highest possible accuracy. Detailed knowledge of emissions from individual source categories is not required for this purpose. However, a profound understanding of processes and interactions is still needed to identify the most suitable and cost-effective mitigation approaches at national and sub-national scales.

References

1. Bergamaschi, P. *et al.* Top-down estimates of European CH_4 and N_2O emissions based on four different inverse models. *Atmos. Chem. Phys.* **15,** 715–736 (2015).
2. Miller, S. M. *et al.* Regional sources of nitrous oxide over the United States: Seasonal variation and spatial distribution. *J. Geophys. Res. Atmos.* **117,** (2012).
3. Ganesan, A. L. *et al.* Quantifying methane and nitrous oxide emissions from the UK and Ireland using a national-scale monitoring network. *Atmos. Chem. Phys.* **15,** 6393–6406 (2015).
4. Thompson, R. L. *et al.* Nitrous oxide emissions 1999 to 2009 from a global atmospheric inversion. *Atmos. Chem. Phys.* **14,** 1801–1817 (2014).
5. Bergamaschi, P. *et al.* Atmospheric CH 4 in the first decade of the 21st century: Inverse modeling analysis using SCIAMACHY satellite retrievals and NOAA surface measurements. *J. Geophys. Res. Atmos.* **118,** 7350–7369 (2013).
6. Thompson, R. L. *et al.* Methane emissions in East Asia for 2000-2011 estimated using an atmospheric Bayesian inversion. *J. Geophys. Res. Atmos.* **120,** 4352–4369 (2015).
7. Chen, Z. *et al.* Partitioning N2O emissions within the U.S. Corn Belt using an inverse modeling approach. *Global Biogeochem. Cycles* **30,** 1192–1205 (2016).
8. Dlugokencky, E. J., Nisbet, E. G., Fisher, R. & Lowry, D. Global atmospheric methane: budget, changes and dangers. *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.* **369,** 2058–2072 (2011).
9. Wells, K. C. *et al.* Simulation of atmospheric N2O with GEOS-Chem and its adjoint: Evaluation of observational constraints. *Geosci. Model Dev.* **8,** 3179–3198 (2015).
10. Del Grosso, S. J., Ogle, S. M., Parton, W. J. & Breidt, F. J. Estimating uncertainty in N2O emissions from U.S. cropland soils. *Global Biogeochem. Cycles* **24,** 1–12 (2010).
11. Leip, A. Quantitative quality assessment of the greenhouse gas inventory for agriculture in Europe. *Clim. Change* **103,** 245–261 (2010).
12. Leip, A. *et al.* Estimation of N2O fluxes at the regional scale: data, models, challenges. *Curr. Opin. Environ. Sustain.* **3,** 328–338 (2011).

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Author Contributions

AL conceived the idea for this manuscript, all authors contributed equally to the development of the proposal and to the writing of the manuscript.

Figure Legend

Figure 1: Schematic showing how a GHG emission assessment system could be designed. (a) Prior flux estimates provided by global Tier 1 GHG emission inventories or from national data, if available. (b) A (global) network of atmospheric observations for use in inverse models yielding national-scale optimized emissions, which will be submitted to e.g. the UNFCCC. (c and d) Validation of the results using nested meso-scale inversions (resolution of ~10 km^2), which will be compared to flux measurements (e.g. Eddy Covariance and chambers). Meso-scale experiments could also be employed in emission hot-spots to test mitigation strategies and could help with the verification of process-based models. Improvements to bottom-up estimates will be used to revise the GHG emission inventories.

Box 1: Explanation of a) bottom-up and b) top-down methods for estimating GHG emissions

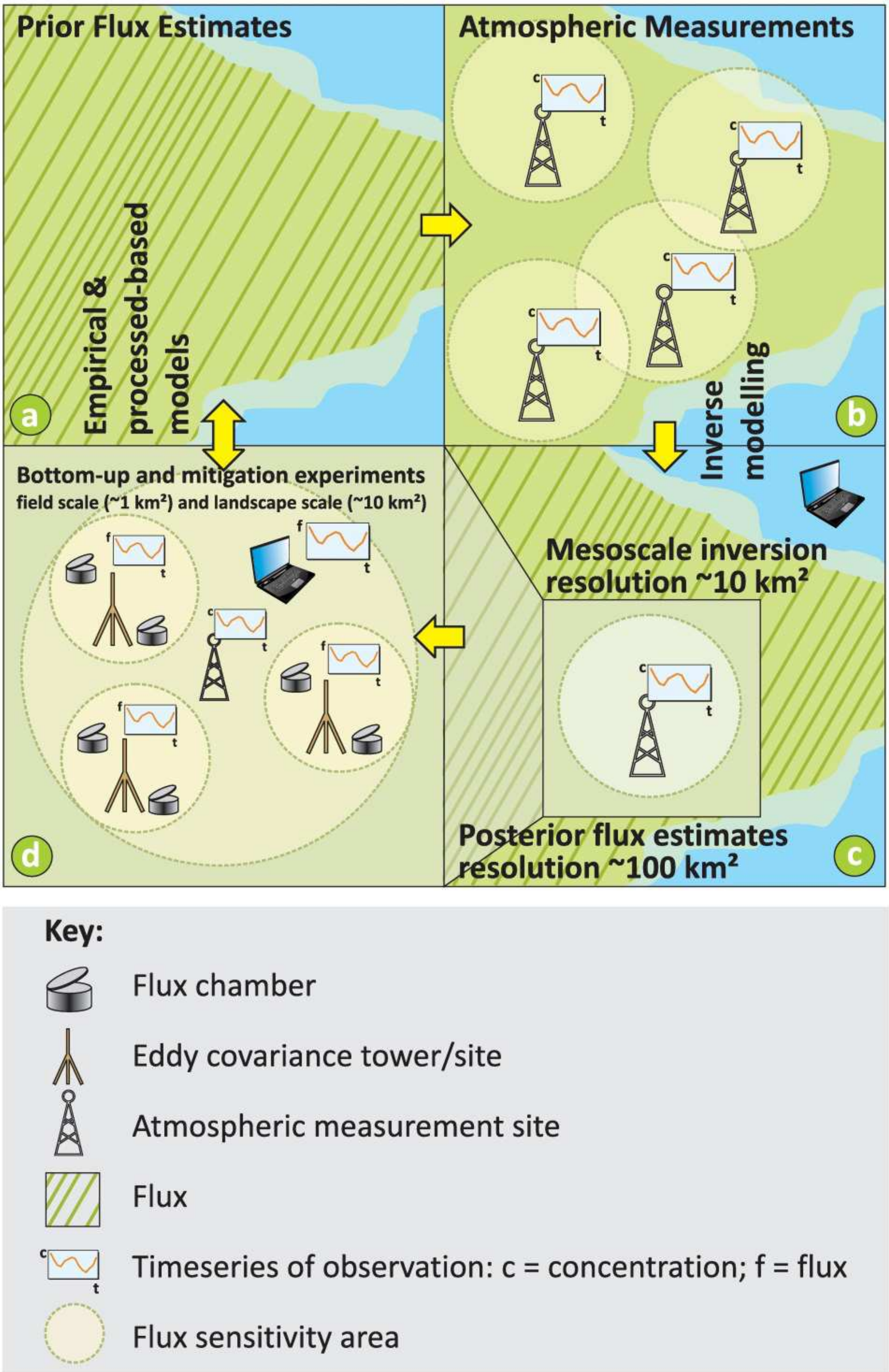
a) Bottom-up methods

In its simplest form bottom-up emission inventories are the mandatory annual GHG emissions reporting for all signatory countries of the UNFCCC declaration to reduce national GHG emissions. The main GHGs (CO_2, CH_4, N_2O and CFCs) from all anthropogenic sectors: energy, industry, solvent and other product use, agriculture, land use, land-use change and forestry, and waste, need to be reported. To standardize this process, the expert panel of the Intergovernmental Panel for Climate Change (IPCC) has developed guidelines on how to calculate emissions using a three-tier approach (http://www.ipcc-nggip.iges.or.jp/public/2006gl/). These guidelines reflect the current state-of-the-art for estimating anthropogenic emissions. The most commonly used Tier 1 approach employs universally applicable emission factors (EFs), Tier 2 employs country specific EF's, or simple regression equations, and Tier 3 employs process-based models. Tier 2 and 3 calculations can take into account variability of climate and mitigation activities, but require much more data than the Tier 1 approach. Tier 2 or Tier 3 methodologies do not necessarily reduce the uncertainty of the emission estimates[11,12], but can provide more effective monitoring of mitigation measures and, therefore, should be used for emission hotspots.

Bottom-up methodologies provide estimates for certain sources that are scaled-up assuming representativeness of the EFs applied to activity data (e.g. nitrogen fertiliser rate, livestock type, megawatts produced from coal power plants). For national emission inventories, the more the activities that are disaggregated into e.g. geographic entities or production systems, the more confidence is assumed in the estimated fluxes. However, this requires that for each disaggregate activity data have to be collected, and appropriate EFs determined. At country level, and for emission sources that are characterized by a high level of spatial and temporal variability, high accuracy can only be achieved on the basis of a high number of observations at prohibitive costs.

b) Top-down methods

Gases emitted into the atmosphere are dispersed through atmospheric turbulence and transported by winds while large-scale circulation patterns mix gases at the global scale. Atmospheric transport is modelled by numerical “atmospheric transport models” driven by meteorological data. Atmospheric transport models can be used to simulate changes in atmospheric concentrations given the surface fluxes and taking into account deposition and atmospheric chemistry. Some atmospheric transport models can also be run in a backwards in time mode, reversing the direction of transport and other processes, to determine the sensitivity of change in concentration to surface fluxes resolved in space and time. In this way, atmospheric concentrations can be related to surface fluxes and forms the basis of inverse modelling. Using time series of atmospheric concentrations from many locations, and prior information about the expected fluxes to further constrain the problem, inverse modelling can be used to provide optimized estimates of the fluxes. The inverse modelling approach can be used at different scales to provide estimates of emissions at landscape, national or continental scale, depending on the number and distribution of atmospheric observations. Increased computer capacity, advances in numerical algorithms, improved transport models and a greater number of atmospheric observations have all contributed to a recent leap forward in this method. The accuracy of the spatial distribution of the emissions from inversions is strongly dependent on the observation frequency and density of the network. How well the observations constrain the emissions is reflected in the posterior uncertainty (i.e, the emission uncertainty after assimilating atmospheric observations). Future improvements will arise through using atmospheric observations of multiple tracers (e.g. isotopes and gases which are co-emitted in different processes), combining different observation streams (e.g. ground-based and satellite) and by using ensembles of transport models to better quantify uncertainties.


Prior Flux Estimates
Empirical & processed-based models
a
Atmospheric Measurements
b
Inverse modelling
Mesoscale inversion resolution ~10 km²
Posterior flux estimates resolution ~100 km²
c
Bottom-up and mitigation experiments
field scale (~1 km²) and landscape scale (~10 km²)
d
Key:
Flux chamber
Eddy covariance tower/site
Atmospheric measurement site
Flux
Timeseries of observation: c = concentration; f = flux
Flux sensitivity area