Attributing and Verifying European and National Greenhouse Gas and Aerosol Emissions and Reconciliation with Statistical Bottom-up Estimates

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AVENGERS User Stories and Case Studies prepared by the AVENGERS Emission Inventory Team

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Attributing and Verifying European and National Greenhouse Gas and Aerosol Emissions and Reconciliation with Statistical Bottom-up Estimates (AVENGERS)

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1 Executive summary

In this document the AVENGERS emission inventory team presents their user stories to the atmospheric scientists. The presented use cases reflect the needs of the participating inventory partners towards data and knowledge to implement the 2019 refinements on QA/QC for greenhouse gas reporting, compiled by the IPCC to further improve transparency, accuracy and completeness of submitted national inventory documents. The document informs the atmospheric science partners in their respective work packages and helps to focus the work within AVENGERS towards data products and methods that can be taken up by the inventory partners.

Additionally, this document could help to stimulate other inventory agencies throughout the world to implement verification of their greenhouse gas inventory with independent datasets, by showing state of the art data usage as well as future options in data and methods towards a verification of the inventory with independent data. The six use cases can be divided into actions for the improvement of the agriculture forestry and land-use sector, with the Italian user story (3) and the Dutch user story (4). User stories that deal with capacity building are user story 1 (sensors for GHG mapping) and 6 (the FIT-IC tool), which are setup with a strong focus of knowledge transfer from the atmospheric science community to the emission inventories. User stories (2) and (5) involve modelling work, which is to be carried out to deliver data directly for verification, further strengthening the collaboration between inventory compilers and atmospheric scientists.

2 Deliverable objectives

This document is designed to be an entry point for inventory compilers that seek further information on datasets and methods for inventory improvement with a special emphasis on complementing their inventory data with research data from the atmospheric science community. The atmospheric science community should, likewise, benefit from the user experiences that are reported here about the use of atmospheric science data for verification, in order to even further optimize their methodologies and products towards targeted user needs. The following information shall be seen as an inspiration to interested inventory compilers that feel the need to incorporate state of the art scientific data from "top-down" methods, such as remote sensing or inverse modelling. These are different from the typical inventory methods as they offer a more global, aggregated view, drawing on atmospheric concentration measurements from different platforms and sensors, often in combination with sophisticated modelling frameworks, that may include meteorological data (e.g. temperature, wind, precipitation) and atmospheric chemistry (e.g. concentrations of individual gases). These models produce outputs at several atmospheric layers, in consecutive time steps, taking into account physical processes such as heat, mass and moisture transfer as well as chemical processes such as photolysis, catalysis and other chemical interactions of atmospheric components.

Comparison of these inversion data to inventory data requires a good understanding of data complexity, limitations and uncertainties, on the inventory compiler side, to fully appreciate and employ this data in the scientific consulting tasks for their political stakeholders and the general public. On the other hand, a deep understanding of the methodologies used by greenhouse gas (GHG) inventories, fulfilling the Paris Agreement's requirements (i.e., the Enhanced Transparency Framework – ETF) and based on the IPCC guidelines, is key to use "top-down" data in the framework of the Paris Agreement. One of the main goals of AVENGERS is served if this document could bring inventory compilers as well as the atmospheric scientific community closer together by further deepening the understanding between them.

3 Glossary and Abbreviations

Abbreviation, Word or Phrase	Meaning
AFOLU	Agriculture Forestry and Other Land Use, Sector that combines the human induced emissions and removals of the land Use and agricultural sectors.
AVENGERS	Attributing and Verifying European and National Greenhouse Gas and Aerosol Emissions and Reconciliation with Statistical Bottom-up Estimates.
Bottom-up	For the atmospheric science community a term for referring to statistically compiled inventories in general. For the inventory community the term refers to local data i.e. local GHG inventories e.g. by cities, counties or provinces.
BP	British Petroleum
CAMS	Copernicus Atmospheric Monitoring Service, Service of the EUs Copernicus programme to provide scientific data on the atmosphere to a large community of users.

CDIAC	Carbon Dioxide Information Analysis Center, initiative of the US department of energy to supply the US administration and research community with data on global warming.
CEDS	Community Emission Data System, emission estimates for earth system models, open source
CLC/ CLC +	Corine Land Cover data product. Land cover data of the Copernicus land monitoring service, with CLC+ being the spatially higher resolved next generation land cover data product. Provides spatial land cover data for the whole of the EU with a resolution of several years.
CLRTAP	Convention on Long Range Transboundary Air Pollution
CRF/CRT	Common Reporting Format (Kyoto Protocol), Common Reporting Tables (Paris Agreement). Formatted table in which Greenhouse Gas Emissions need to be reported.
CSV	Comma Separated Values, Textfile where individual data is separated by a separation character, i.e. a comma character.
COCO2	EU-Project tasked with building a prototype monitoring and verification support capacity to characterize anthropogenic CO_2
Copernicus	Earth observation programme of the EU, implemented via ESA. Data and products from spaceborne and in situ sensors is offered at specific thematic hubs (see e.g. CAMS).
ECMWF	European Center for Medium-Range Weather Forecast hosting the Copernicus Atmospheric Monitoring Service as well as the Copernicus Climate Change Service. It acts as important data provider for EU and worldwide data for climate, weather as well as atmospheric composition data in general.
EDGAR	Emission Database for Global Atmospheric Research, worldwide datasets on greenhouse gases and air pollutants, compiled and curated by the Joint Research Center of the European Union (JRC)
EIA	Energy Information Administration
EnMAP	Hyperspectral Satellite Mission of the German Space Agency (DLR), Environmental Mapping and Analysis Programme
ESA	European Space Agency
ETF	Enhanced Transparency Framework
ETS	Emission Trading System
FIT-IC	Flexible Inversion Tool for the Inventory Community. Inversion demonstrator tool specifically designed for inventory experts to demonstrate the capabilities and limitations of inversion systems. output of WP6.1
GCP	Global Carbon Project, international organization that provides global data on carbon emissions as well as on their causes.
GDAL	Geospatial Data Abstraction Library, is an open source software library for reading and writing geospatial data in raster and vector formats.
GHG	Green House Gases
GIS	Geographic Information System, Computer system that is capable of processing and displaying various geographical data types such as e.g. raster and vector data as well as different database formats.
Gridded Emissions	Data of an emission inventory spatially distributed to a specific geographic grid of a region, or country in form of a machine-

	readable geographic dataset or database, which may serve as input for atmospheric modelling systems (priors).
GNFR	Gridded NFR, aggregated NFR sectors
IEA	International Energy Agency
IG3IS	Integrated Global Greenhouse Gas Information System, global monitoring system network that provides information on global GHG trends and distributions. An initiative of WMO.
IMEO	International Methane Observatory (part of the United Nations Environmental Program)
IPCC	Intergovernmental Panel on Climate Change
Julia	Interpreted computer language for data science with a special emphasis on performance for large numeric computations and simulations.
JUPYTER	Julia, Python and R, interpreted cross platform computer languages, which are used for data analysis and visualisation. All of the aforementioned languages have a package management system, which manages the capabilities of those languages via software libraries (packages). JUPYTER is a notebook style editor that can be used to showcase specific data analysis process chains.
Landsat	Worldwide longest continuous earth observation satellite programme, operated by NASA.
LULUCF	Land Use Land-Use Change and Forestry, Sector that comprises of the human induced emissions on the land sector, e.g. via land use change, and forestry.
MARS	Methane Alert and Response System (IMEO activity)
Memo Item	Emissions, e.g. from international bunker fuels or international aviation, which are not part of the reported national total and reported under Memo items as by the IPCC guidelines on emission reporting.
NASA	National Aeronautics and Space Administration
Net-CDF	Binary data format for reading and writing large array oriented scientific data. Very common in the atmospheric science community.
NFR/Tables	Nomenclature For Reporting, used for reporting emission inventories of air pollutants under UNECE.
NIR/NID	National Inventory Report (Kyoto Protocol), National Inventory Document (Paris Agreement), where a country describes its methodology for compiling its national GHG inventory.
PRIMAP	Dataset and models on GHG emissions compiled by the Potsdam Institute for Climate Impact Research
Priors	Prior data is defined as prescribed information (e.g., in form of a dataset containing inventory-based fossil fuel emissions or the flux results of a Terrestrial Ecosystem Model), which is used and optimized by an inverse modelling system.
PRISMA	Hyperspectral Mission of the Italian space agency (ASI)
PRTR	Pollution Release and Transfer Register, provides emission data
PYTHON	Interpreted programming language for data analysis.
QA&QC	Quality Assurance and Quality Control
R	Interpreted programming language for data analysis, with a special focus on statistical analysis.

SCIAMACCHY	Scanning Imaging Absorption Spectrometer for Atmospheric Cartography, first global European atmospheric monitoring instrument aboard the ENVISAT satellite.
Sentinel	Space component of the ESA earth observation program Copernicus consisting of a fleet of satellites. Each one is tasked with a specific continuous mission portfolio.
TACCC	Transparency, Accuracy, Consistency, Completeness and Comparability. Major qualities of an emission inventory, which are at the core of emission reporting. Each emission inventory with its accompanying report is subject to an international expert review process, which assesses the respective submissions in terms of TACCC.
TEMPO	Tropospheric Emissions Monitoring of Pollution, Atmospheric research instrument of NASA to measure pollution over North America
Top-Down	For the atmospheric science community any method that involves observations other measurements for compiling e.g. national totals of Greenhouse Gas Emissions. For the inventory community the process of compiling a countries national emission inventory, following the international guidelines on emission reporting.
TROPOMI	Tropospheric Monitoring Instrument, ESAs atmospheric science sensor aimed at monitoring the atmospheric composition on board of the Sentinel-5 precursor satellite.
UAV	Unmanned Aerial Vehicles, often referred to as drones.
UNFCCC	United Nations Framework Convention on Climate Change, International treaty that is in place to limit climate change via international negotiations and agreements (see e.g. Kyoto Protocol, which has been superseded by the Paris Agreement)
VERIFY	EU-Project, tasked with delivering data to deliver complementary data to enhance GHG reporting in Europe.
WMO	World Meteorological Organisation
XARRAY	A python specific software library that implements complex data structures e.g. for a labelled access to complex, large arrays and designed to work easily with NET-CDF files

4 Who should read this document?

The AVENGERS project was set up to further foster collaboration between atmospheric scientists and inventory compilers. This document has primarily been written by inventory compilers to inform other inventory staff, as well as the atmospheric science community, about the current state of the art in inventory verification and the relevant planned work within the AVENGERS project. It shall also be informative for political stakeholders and the interested public to illustrate the complexity of this undertaking, to identify research needs, and to understand method limitations that arise from different datasets and techniques. Another important audience of this document is the atmospheric science community, which is invited to specifically examine those chapters, which discuss research data and uptake by the inventory community as well as the user stories, to better understand the needs of the inventory community towards data for inventory validation and improvement. This may help the atmospheric science community to focus in particular on priority research topics that are of high interest to the inventory community. The document starts with a general discussion on the use of inverse modelling and remote sensing data in emission inventory compilation, before focussing on detailed aspects in the six user-stories. Due to its orientation towards the work carried out in AVENGERS it cannot offer a full comprehensive and exhaustive discussion of each method and dataset. It shall rather inspire inventory compilers to look at the wealth of external data and not feel discouraged by the complexity of the methods employed or the data generated. Interested readers from the inventory community are encouraged to follow the cited sources or examine the guidelines for inventory compilers that will also be produced by the AVENGERS project (deliverable D6.1), should they wish to learn more about individual methods and datasets.

5 Introduction

The user stories of the emission inventories in the AVENGERs project are the driving force and the cornerstone of the project in developing data products and knowledge needed by inventory staff to implement the 2019 IPCC Refinements on QA&QC [1]. Each work package involves at least one emission inventory member of AVENGERS that challenges the respective ”top down” counterpart in that work package to explain and document methods and data, as well as adapting the developed methods where needed, towards the usability for their inventory work. This is carried out by a close collaboration between atmospheric scientists and inventory compilers within AVENGERS.

The previous Horizon2020 project (VERIFY) and other projects, such as COCO2, have helped to build the understanding in the inventory community about data, which are not core of the traditional inventory work, to their national GHG inventories, in line with IPCC guidance [2],[3]. These data have also found their way, e.g. into the national inventory document (NID) of Germany [4], where they have been used for trend and level verification of national totals of three major greenhouse gasses (GHGs) (N_2O, CH_4 and CO_2). In addition to the verification examples of the Swiss, UK and Australian NIDs, also cited in the 2019 IPCC Refinements on QA&QC [1], the verification efforts from other former Annex-I countries show room for improvement [5].

Currently there are numerous GHG monitoring activities in progress, for which the World Meteorological Organisation’s (WMO) IG3IS initiative (https://ig3is.wmo.int) acts as an umbrella framework. Some countries, such as e.g. Germany, are in the process of setting up a country-wide GHG monitoring system, whilst UK and Switzerland already have their monitoring systems in place, as mentioned in the 2019 refinements of the IPCC reporting guidelines [1]. For instance, in Germany, it is named integrated GHG monitoring system (ITMS, https://www.itms-germany.de/) and it implements the recommendation of the IPCC 2019 refinements for the close collaboration of atmospheric modelling groups and local inventory agencies to implement inverse modelling for the verification of the national GHG budget. However, the work commitment and knowledge required for this purpose should not be underestimated. Other inventory agencies within the AVENGERS project have other needs for the improvement of their national inventory, e.g. carrying out work on the LULUCF sector, which is crucial with respect to the revised EU-LULUCF regulation (Regulation EU 2023/839) [6]. To facilitate these developments, the inventory teams of AVENGERS formulated user stories, which are implicit to the work package structure of AVENGERS as they address the capabilities of atmospheric science that cannot be met by most inventory agencies on their own (see figure 1).

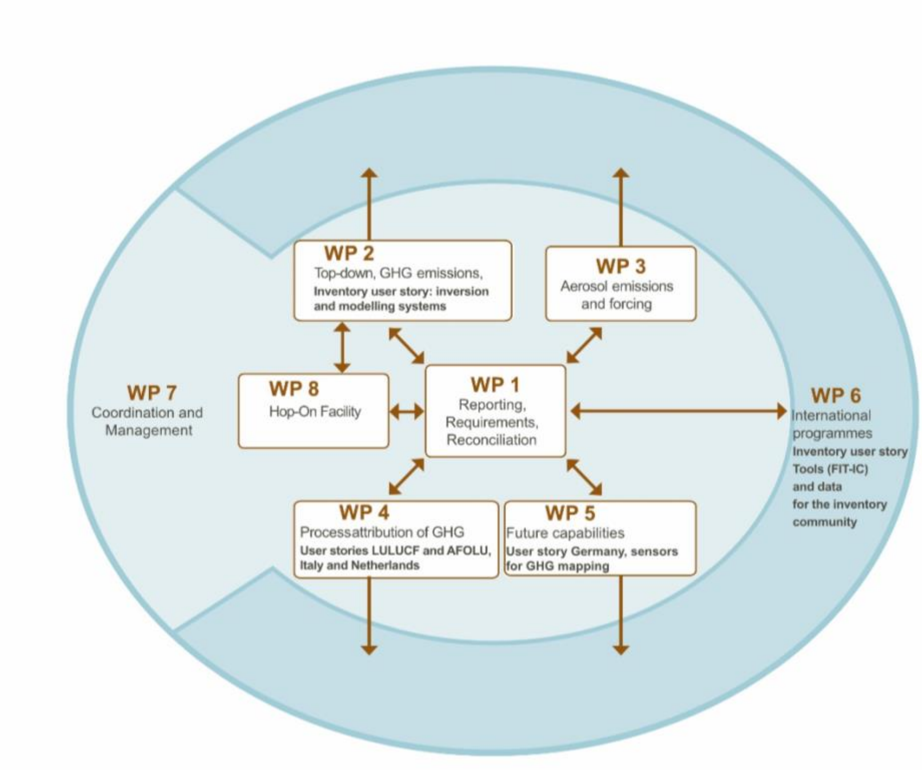

Figure 1 From Scholze et al. 2023 (WMO IG3IS Meeting 02/2023 Geneva, Poster) [7], AVENGERS work package and project structure illustrates the importance of user stories and requirements with respect to the other scientific work packages.

These user stories have a clear focus on the needs of each individual AVENGERS inventory team and have arisen as follow-on-needs from the VERIFY results that have been provided to inventory compilers by the atmospheric science community. The products of VERIFY, published for example in [3], [2] required further explanation and background knowledge on the inventory compilers' side in order to exploit these data to the full extent. The user stories described below are acting as a guiding principle that formulates the needs for data products, their specification, as well as knowledge transfer from the atmospheric science community in AVENGERS towards the participating inventory compilers of Sweden, the Netherlands, Italy, Germany and Cyprus.

The aim is that AVENGERS results and outcomes will be taken up by the inventory agency partners and inventory agencies worldwide, and assist them to include respective data products as annexes to the national inventory documents (NID), and to adopt these data to provide scientific consultation for political stakeholders and the general public.

6 Current State of the Art

All reporting to UNFCCC under the Paris Agreement must follow the TACCC principles, which are transparency, accuracy, consistency, completeness and comparability. In this framework, the key tool is the GHG inventory, which estimates emissions for different sectors/categories/gases based on the IPCC guidance: i.e., the 2006 IPCC Guidelines for National GHG Inventories https://www.ipcc-nggip.iges.or.jp/public/2006gl/ [8] and the 2019 IPCC Refinements https://www.ipcc-nggip.iges.or.jp/public/2019rf/index.html [9]. The 2019 IPCC Refinements, in the QA&QC section [1], contains a substantial chapter which outlines and describes the role of "top down" approaches (meaning in this context the use of earth observation data and inverse atmospheric modelling) to be potentially used to support GHG inventories. In the 2019 IPCC Refinements, examples from

Switzerland, the UK and Australia, which use inverse modelling for verification of the national emission inventories are highlighted. In the afore mentioned examples, the setup of a country specific observation system for GHGs is also cited within the 2019 guidelines' refinements [1]. However, not all countries are able to set up such a system. Therefore, the 2019 IPCC Refinements [1] are listing several data sources, where independent emission data for inventory verification could be obtained. These include three major categories which are global inversion results and atmospheric measurements as well as other independent emission databases, including global emission inventories.

6.1 Global Emission Inventories

Global emission inventories rely on the same principle as national emission inventories, by using emission factors and statistical activity data to estimate emissions. VERIFY already provided a comparison of different global emission inventories for the different GHGs [2], [3]. Furthermore, a study by Minx et al. [10] provided detailed insight into several global emission inventories. Here, we have to acknowledge that there are significant differences between the individual emission databases, which need to be considered to choose a suitable dataset for comparison. For this, the approach of Minx et al. [10] has proven very effective as they list several emission databases with their individual properties. Amongst them are the type of emission factors used, the inclusion of important sectors, e.g. venting and flaring or cement production, sectoral disaggregation and the inclusion of non-fossil fuel related GHGs. Table 1 (modified after Minx et al. [10]) provides an overview in the form of binary score values. We added the category "For inventory compilers", which highlight datasets, which may be useful for inventory comparison work, also according to the comments of the IPCC 2019 refinements [1]. Finally, a total score value is computed from the sum of the individual score values. The result shown in Table 1 highlights the suitability of each of the databases for comparisons with the emission inventory of a country. The high score value of EDGAR (Emission Database for Global Atmospheric Research) [11] and CEDS (Community Emission Data System) [12] show that they are particularly useful to complement the estimated emissions of the national GHG inventories. Germany has chosen EDGAR as a primary dataset for a comparison of its national GHG inventory in its verification chapter as it is by far the most comprehensive and continuous data set. EDGAR is also a major source for inverse modellers, which use the gridded EDGAR datasets as prior emissions for their inverse modelling runs. EDGAR can therefore be seen as a gold standard for global emission inventories and is therefore a valuable verification source, which is also mentioned in the 2019 QA&QC refinements to the 2006 IPCC guidelines [1]. Since most of the datasets are databases, their adoption by inventory staff is relatively straightforward, as their design closely resembles that of national emission inventories. However, for a better comparison between individual datasets in table 1, as well as the links to the individual sources of data, [2], [3], [10] should be consulted for more information to be able to interpret the comparison results between individual databases in more detail.

Table 1 Modified after Minx et al. (2021) [10], illustrating the properties of different emission databases towards inventory compilers.

Database	Primary Source	IPCC EF?	Venting Flaring?	Cement	Carbonates	Non FF GHG	Bunkers Separate	Fuel Type	Sector Data	For Inventory Compilers	Score
CDIAC	1	0	1	1	0	1	1	1	0	1	7
BP	1	1	0	0	0	1	0	0	0	0	3
IEA	1	1	0	0	0	1	1	1	1	0	6
EDGAR	1	1	1	1	1	1	1	0	1	1	9
EIA	1	0	1	0	0	0	0	1	0	1	4
GCP	0	0	1	1	0	1	1	1	0	0	5
CEDS	1	0	1	1	1	1	1	1	1	1	9
PRIMAP	0	0	1	1	1	1	1	0	1	1	7

Besides these global emission inventories, there also exist more specialized regional inventories, for example the European Copernicus Atmospheric Monitoring Service (CAMS) Regional inventory (https://permalink.aeris-data.fr/CAMS-REG-ANT). Regional emission inventories may reflect local emission factors better than global inventories that aim at consistency of methods worldwide.

When using the independent emission inventories for emission verification, one has to keep in mind that they do not represent truly independent datasets, since they use the same methods and frequently use the same activity data or emission factors as the national inventory agencies. In that sense they are fundamentally different from atmospheric measurements, which introduce an independent source of information.

6.2 Modelling and Atmospheric Measurements

Modelling and atmospheric measurements are an integral part of GHG observation systems. To use data from atmospheric measurements and inverse modelling, a basic understanding of these methods is required. An introduction to atmospheric inverse modelling exceeds the scope of this document, but will be produced as a deliverable by the AVENGERs project. Furthermore, members of AVENGERS did an introductory webinar about inverse modelling that is freely available [13]. IG3IS also organizes webinars that are very informative [14]. One crucial point to keep in mind is that concentration measurements cannot be directly compared to emissions, but models that estimate the most likely emissions that fit the measured concentrations have to be applied. This is commonly referred to as inverse modelling, as it requires the solution of an inverse problem.

There are several datasets already available to inventory compilers that provide results from global GHG inversion systems and, therefore, are of great value to any country that may not be able to run its own GHG observation system. The most challenging part in applying these datasets is the heterogeneity of the available data and the processing of all the knowledge published on different sensors, platforms and ultimately inversion systems. The access to the individual datasets, their documentation and their spatial and temporal resolution as well as continuity are key factors that need to be considered in case a national GHG inventory compiler wants to choose a suitable dataset for comparison. Please also see box 1 which describes an optimal inversion dataset from the inventory point of view. Without this information it is not possible to draw the correct conclusions from a comparison between inventory data and inversion results.

Table 2 highlights these properties for the individual datasets for inventory compilers, similarly to table 1. Here we compared the CAMS inversion optimized GHG flux data (https://ads.atmosphere.copernicus.eu/cdsapp#!/dataset/cams-global-greenhouse-gas-inversion?tab=overview)[15], the World Emission data offer in form of a dashboard (https://app.world-emission.com/) [16], data from regional European models, or data from country specific inversions, as in case of the UK and Switzerland, examples mentioned in the IPCC guideline refinements of 2019 [1]. Next to these emission data produced by inverse models, the table also lists measurements of atmospheric concentrations. As a proxy for spaceborne data, we consider Sentinel 5-P with its TROPOMI instrument (https://dataspace.copernicus.eu/explore-data/data-collections/sentinel-data/sentinel-5p), while station data is for example available from the ICOS network (https://www.icos-cp.eu/data-products) [17].

The term resolution in table 2 refers to spatial resolution in a semi-quantitative sense, where individual medium-sized middle European countries should be covered by a spatial resolution that permits a clear spatial allocation of emissions to individual regions or provinces within a country (e.g. more rural areas with farmland and therefore more methane emissions, whilst large industrial centers are more prominent in the combustion related CO_2 data). The column “IPCC endorsed” refers to an active workflow or example in the 2019 IPCC Refinements where a dataset is actively flagged and recommended as a tiered method for verification [1]. The column “inventory compilers” refers to a dataset directly compiled by inventory compilers themselves. Table 2 shows that the Copernicus Atmospheric Monitoring Service (CAMS), which is operated by the European Center of Medium range Weather Forecast (ECMWF) contains global inversion datasets for the three major GHGs [15], which can be readily downloaded and used by emission inventories. Spaceborne data as well as data from station networks are measurements of atmospheric concentrations and used as input into inverse models. Currently, the Copernicus spaceborne data products, e.g. from TROPOMI may only be used to identify large emission plumes [18], [19], [20], or characterize the air quality locally [18], [19], [21] . Any kind of emission estimates from spaceborne or sensor data requires further data processing and modelling [18]. Therefore, these data on their own are not useful for inventory compilers. Further processing to higher level data products is needed. Even the higher level data products, e.g. the vertical column density data from TROPOMI are not useful to inventory compilers for direct comparison. They require further work such as modelling to retrieve emission data [18].

Table 2 Properties of datasets from inversions and direct observations, after the scheme introduced in table 1. The most important part for datasets is the availability of a long time series, the availability and its spatial and temporal resolution.

Dataset	Type of data	Resolution	IPCC Endorsed	Direct Use?	Long Time Series	Temporal Continuity	Sector Data	Open Data?	Root Data	Inventory compilers	Score
CAMS Global	Emission	0	0	0	1	1	0	1	1	0	4
World Emission	Emission	1	0	1	0	0	1	1	1	0	5
Space borne Data	Concentration	1	0	0	0	0	0	1	1	0	3
Station Data	Concentration	0	0	0	0	0	0	1	1	0	2
Regional Models	Emission	1	0	0	0	1	0	0	1	0	3
Own Models (Inventory Agencies)	Emission	1	1	1	1	1	0	0	1	0	6

6.3 Best Practice Examples from Current Data

Verification data, in the context of the GHG inventories, have to be transparent and accurate, while ensuring that consistency is maintained. A key requirement under UNFCCC and the Paris Agreement is the provision of all activity data, emissions factors, parameters and model information prior to their use to provide verification estimates of GHG emissions. This requires extensive understanding of the external data product and the methods used to obtain them in order to be able to answer potential reviewer questions. The establishment of such a transparency hub for each model and top-down approach would be crucial to have the outcomes of the above mentioned products be used in the verification activities by GHG inventories.

Temporal consistency is mostly needed in form of temporal continuous datasets that ideally are updated on a regular level. Transparency and temporal consistency might be limited for discontinuous data, which is offered by temporal limited scientific project work and fixed term contracts at academic research institutes. Project members might have moved on and contact points for questions to datasets might not be available in the future. Datasets which have not been updated can only be compared for a specific window in time with the actual inventory data which may limit their usage in future inventory data comparisons and, thereby, cause a problem with the completeness of the data.

Another important aspect is the offer of sectoral disaggregation in the inversion datasets. The national GHG Inventories deal with a comprehensive list of sectors/categories/pools based on the modalities, procedures and guidelines for the transparency framework of the Paris Agreement (https://unfccc.int/sites/default/files/resource/CMA2018_03a02E.pdf). Therefore, the provision of top-down products with sectoral disaggregation and source apportionment, while ensuring that products are pertaining to national borders, is needed although national totals may be verified with current datasets (please see the example from the German NID).

Another important factor for the usability of inversion data sets by GHG inventory compilers, is their spatial resolution. The spatial resolution for any given country needs to be large enough to at least discriminate areas inside a country that have a distinct spatial GHG emission fingerprint. This means that areas, which are e.g. dominated by farming activity show higher values in methane and nitrous oxide than combustion related activities (power generation and transport), which are dominated by CO_2. Or a larger concentration of fossil power plants for electric power generation that show appreciable large-point-source-attributed combustion emissions. This requirement may be different for every country. Figure 8 shows for example that for methane this criterion is not really met for Germany as there are far too few pixels available for a visual evaluation of the data with a spatial resolution of 2° x 3°. Spatial resolution improvements have been made for nitrous oxide and CO_2. One could argue that for those two gases one could think that the above stated barest minimum criterion has just been touched. This point is even more relevant for smaller countries, like the Netherlands, where a low resolution can make it even impossible to determine national total emissions.

A user-friendly approach to verification is offered by the World Emission project (https://eo4society.esa.int/projects/world-emission/), which is financed by ESA and led by GMV in Spain with participation of the Barcelona Supercomputing Centre, LSCE, Kayrros, Capgemini, MPI-BGC Jena, the University of Brussels as well as the Cyprus institute. This project provides a unique emission inventory dashboard (https://app.world-emission.com/) [16] where users are able to directly download results from super-emitter point source detection (for methane), or direct results from fossil fuel related GHG inversions (for combustion related CO_2). The combustion related CO_2 data are disaggregated into subcategories which could be compared to selected GNFR sectors at regional level. The dashboard offers advanced visualisation tools and downloads oriented towards the inventory community (e.g., already spatially aggregated .csv files) while also offering the full data output in a standard format (netcdf). This unique data offer has been constructed through direct consultation of the emission inventory community by the world-emission team. This dashboard can be seen as a case or template of an ideal data delivery for a wide audience of emission inventory compilers. However, the set up and maintenance of such an elaborate portal needs appreciable resources that may not be available to other data providers.

7 Technical aspects of using emission datasets

There is a certain technical barrier to the use of emission inventories such as EDGAR [11] or inversion results [15]. Since these data sets have a higher dimensionality (at least two spatial coordinates and a time coordinate) they can become quite large. This also let to the adoption of a specialized data format in atmospheric science, netcdf, which might be unfamiliar to inventory compilers. This poses an additional barrier towards using emission data sets. These files should in principle be fully documented and can be read and opened with many commonly used software packages. GIS software can natively process netcdf files. In addition, python-packages (xarray, gdal) and R-libraries (Raster, Terra, Ncdf4) allow using these established data science tools to analyze netcdf files. There exists also Panoply, a specialized tool for the inspection and visualization of netcdf files developed by NASA [22].

Besides loading the data, the next technical challenge lies in extracting emission data that is comparable to inventory data, i.e. calculating a national yearly emission total instead of daily or monthly fluxes on a grid. These operations might seem straight forward but can have difficult details. For this, we would usually recommend to use established software (e.g. GIS software) or python/R-packages for this task. Finally, one needs to pay attention to the units used in the data. While emission inventories report emissions usually in units of weight, like kg or kt, inverse modelling outputs are often reported as particle fluxes in units of mol/m^2/s (but also particle numbers or the mass of carbon in the CO_2 are sometimes used). That means one needs to convert them considering the molar weight of the gas, the area of interest and the number of seconds in a year.

The more degrees of analytical freedom are offered to users of verification data the more of a greater level of sophistication in data science skills and programming is required by inventory staff to fully exploit the level of detail in the individual data sets. This is also one of the core aims of AVENGERS to give inventory agencies examples on how to start using these more complex datasets e.g. through the activities of task 1.4 in AVENGERS, where inventory compilers and inversion experts come together to reconcile their respective emission data.

8 Research and Data Uptake by Inventory Agencies

Research and data uptake depends on the objectives and resources of a given inventory teams . Any work done on the national GHG inventory and its data has to be compliant with the 2006 IPCC Guidelines for National GHG Inventory and their consecutive refinements, and has to fulfil requirements provided by the Enhanced Transparency Framework of the Paris Agreement. Scientific work to constantly improve the reporting is annually done and ensured by the UNFCCC review process. This usually results in the use of higher tier methods for the description of key categories (major emission sources or sinks) or by adding new categories in the reporting cycle as technology or legislation change. The exploitation of atmospheric science data that is potentially suitable for inventory work has rapidly evolved during the 2010’s due to an ever growing pool of data from different sensor networks and measurement platforms that drove the development of novel techniques for super emitter characterization [23], the characterization of large point sources and even in situ emission measurements from imaging spectroscopy platforms [24] at the individual facility level [25]. Each of the individual measurement techniques require highly specialized equipment, methodology and scientific personnel operating them. Further data processing and modelling is usually required to derive GHG emission values from the sensor networks or sensing platforms mostly carried out by atmospheric science groups. To fully utilize these data, it is necessary to provide inventory compilers with knowledge and data to communicate the complexity of an integrated GHG monitoring system as illustrated in figure 2 towards political stakeholders and the general public in order to be able to convey benefits and shortcomings of individual methods. This is a very complex undertaking: each individual topic has several underlying subtopics, each of these with several scientific working groups worldwide working on each of these highly specialized topics. It is, therefore, of great importance for the atmospheric science community to provide transparent and accessible information (possibly with open source code) in order to communicate the produced data to the national GHG inventories community. It is therefore suggested to offer concise tools for handling data packages for inventory compilers e.g. by offering jupyter notebooks that enable them to move forward with exploring new data and methods for the inventory. The atmospheric science community should actively "rope in" data users from national inventory agencies through code examples, hands-on code recipes, in person trainings and short courses or webinars.

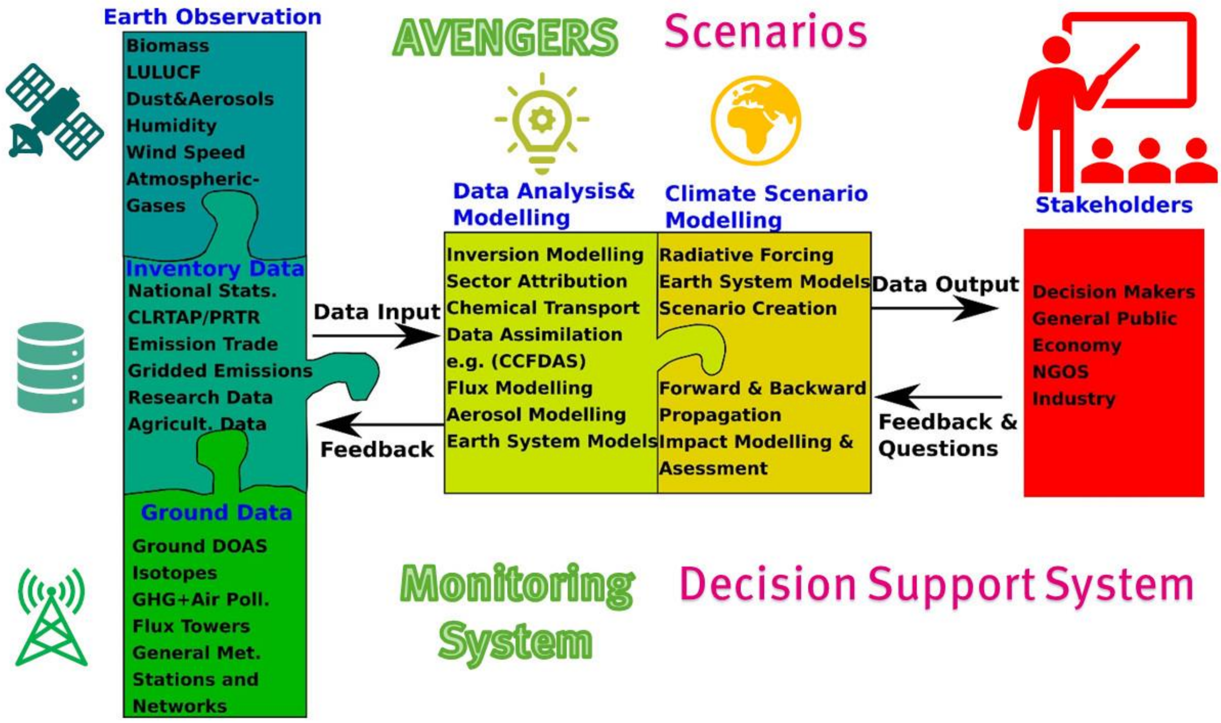

Figure 2 Illustration of a monitoring and scenario pipeline after Mielke et al. 2022 (ESA Living Planet Symposium, Talk: "All sensors on the environment") [26]. The AVENGERS work packages contribute to the most critical building blocks of a monitoring system which encompasses the delivery of data from different sensors (WP 5&2 as well as inventory data task 2.1 and WP 4), which are processed by WP 2 in order to verify and improve reporting in WP1.

8.1 Which verification data could be used?

If we compare the properties of the datasets listed in table 1 and table 2 to the aforementioned TACCC requirements it is obvious which datasets can be used for verification today. EDGAR as the worldwide standard, which is used for global atmospheric modelling, is the logical choice for any inventory compiler who wishes to start comparing their national inventory to an independent global emission database. CAMS is Europe's most important source for atmospheric data. It offers global "inversion optimized data" of GHG fluxes [15] for the three major GHGs, see figure 8. It has to be noted that the current inversion-optimized CAMS data [15] offers national totals for each gas only, which can impede detailed comparisons with national inventories. Other data such as station data and/or spaceborne measurements can be selected as additional input from the CAMS user interface to select the correct inversion results for the inversion optimized data for download. Spaceborne data on its own in form of raw vertical column concentrations cannot be used by inventory compilers, since there are several problems related to solving the inverse problem of converting concentrations to emissions, and it does not provide disaggregated data for sector/categories. All of the four data sets (the large point source register [27], the EU-Emission Trading system data [28], EDGAR and the inversion optimized GHG data from CAMS) are currently used for national trend and level verification for the three major GHGs in the German national inventory document since the 2022 submission. Please refer to the latest NID submission of Germany [4] on the UNFCCC portal (National Inventory Submissions 2024 | UNFCCC) for more detail on data sources and methods. The usage of discontinued project data, however, remains problematic for inventory compilers. However, this should not discourage inventory compilers in using this data for their national inventory report. These data products, where deemed useful and understood, can be used with a disclaimer explaining their project-based nature. This has for example been done with data from VERIFY in the German NID. In general, it can also be useful for inventory compilers to examine and explore different emission data products, even if they do not end up being used for official reporting.

8.2 What are the needs of inventory compilers for emission reconciliation?

The data potentially usable by inventory compilers is rapidly growing with new sensors platforms and techniques being added each year. It is therefore of vital importance that new scientific modelling techniques and monitoring data from a wide variety of sensors and databases provide transparent and clear information to the inventory compilers. One of the biggest issues in data uptake clearly is the discontinuous nature of datasets that are developed by research projects. This issue can only be addressed if large research institutes take up the responsibility and product ownership of scientific data. International key examples would be the EDGAR database by JRC [11] as well as regularly updated CAMS data products [15], which are developed and/or curated under the umbrella of the Copernicus Atmospheric Monitoring Service (CAMS) by ECMWF and its contractors. An example for observational data (that is needed in e.g., CAMS) is the European ICOS (Integrated Carbon Observation System) infrastructure [17] that secures long-time, standardised and high quality in situ measurements of CO2, CH_4 and (partly) N_2O. This requirement emerges from the importance of time series data in emission verification, which also need to be constantly updated with each national inventory submission. These temporal continuous data are of the highest value to GHG inventories to complement their data.

These data sets need to be well documented and quality approved e.g. by peer reviewed scientific publications and ideally by accompanying reports to be able to answer potential future review questions, with respect to the data and analysis presented in each countries NID. A good example of a very general first order verification exercise would be to compare these independent data to the national reported data to verify trends and levels for the three major GHGs as illustrated for Germany in figure 3. All of the presented data in figure 3 show an overall trend consistency, except for the N_2O data from CAMS inversion optimized GHG data [15], which needs further investigation. For a quantitative comparison, correlation scores are computed between the reported data via their correlation scores. Further comparisons that might actually uncover problems with the inventory may only be facilitated by comparing more disaggregated data (at least on the GNFR level). The level of detail of the datasets determines their usability for such a more detailed investigation. For the three datasets, only EDGAR is able to deliver more disaggregated data for a comparison of sectors and aggregated categories. EDGAR data is available in a standard spread sheet format that can be used by most inventory compilers. Comparisons between national inventory data and EDGAR have limitations. These are due to the different statistical data used for the EDGAR inventory with EDGAR aiming to produce a worldwide comparable emission dataset. Contrary to that, national inventories aim to produce the most accurate national emission estimates for individual categories, which consider more detail on individual emission sources; the exact technology used in a specific source category to map emissions via specific emission factors that might, e.g., emanate from local legislation.

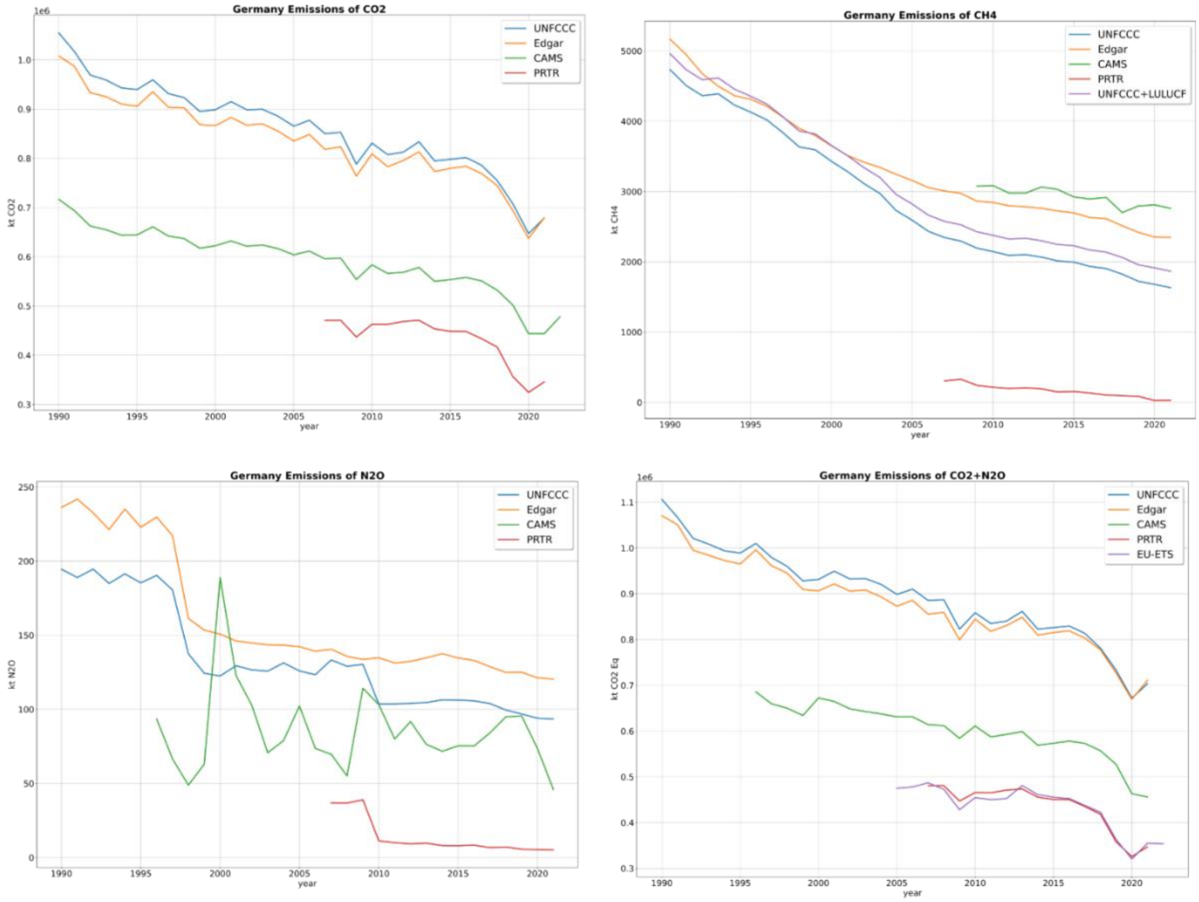

Figure 3 Comparison of national total inventory data vs. EDGAR and CAMS together with data from the EU-Emission Trading System as well as data from large point sources, from the German national inventory document (NID, available at UNFCCC: [Germany. 2024 National Inventory Document (NID) | UNFCCC]).

Other data such as inversion-optimized CAMS data does not deliver this level of source attribution, which is critical in the assessment of emissions from different sectors. The usage of CAMS inversion optimized GHG data for verification also depend on the personal ability of inventory compilers to transform the data to a yearly time series for their country to be able to compare them with their national total results (please refer to the technical aspects chapter which also highlights these challenges). The global inversion-optimized CAMS data set have also relative low resolutions of 1.95° x 3.75° for N_2O and CO_2 and 2° x 3° for CH_4 hampering their use for small countries. Data from temporary research projects such as e.g. VERIFY can also be included as part of the national inventory documents, however, they must be accompanied with a disclaimer highlighting the temporary nature of these datasets to state that they cannot be updated in the future.

In summary, the most important entry barriers for inventory compilers in using other data are: 1. Transparency of top-down products for potential verification use, 2. Other data product-intrinsic specification that hamper the uptake of the individual data product, such as formats and necessary APIs and libraries, 3. Individual knowledge about specific methods and data products. AVENGERS with its work package structure aims at addressing the first two points via its data offer and capacity building actions. Point number three can only be addressed by inventory compilers working closely together with the data providers, which is possible in AVENGERS because inventory staff is directly involved in the different work packages of AVENGERS.

9 User Stories

In the following we will share and discuss six user stories, which represent exemplary needs of the AVENGERS emission inventories towards the scientific community and atmospheric scientists working in AVENGERS. However, all of the user stories also contain a description of the current state of the art to also clarify the current status of data products and services offered for emission inventory users, followed by a chapter of potential work that could be done within the AVENGERS project. Of course, not all of the here listed open questions can be answered by AVENGERS. The user stories presented here should start a conversation and collect interesting questions and problems, which can be selected by the scientific partners at their convenience to be addressed either in part or full by the respective work packages. Therefore, the user stories can be subdivided into two groups. User stories 1, 2 and 6 are broad user stories that address complex topics e.g. remote sensing and inverse modelling. Both topics cover huge thematic blocks in figure 2 as part of the displayed climate science pipeline. User story 1 discusses developments of sensors, user story 2 discusses inversion systems while user story 6 revolves around the development of the FIT-IC tool. The major contribution of these user stories is capacity building for inventory agencies, which is the most important task in order to enable inventory agencies to implement the 2019 refinements on GHG reporting for QA & QC [1]. User stories 3, 4 and 5 more directly focus on particular needs of inventory staff, such as the presented two AFOLU cases revolving around land-use in Italy and agriculture in the Netherlands, whilst the Cyprus case deals with methane emissions in the inventory.

9.1 User story 1: Sensors for GHG mapping

9.1.1 State of the art

Detailed analysis of potential sensor-platform combinations as well as the accompanying algorithms and modelling pipelines are not yet part of the active inventory work today. However, there are multiple initiatives that aim to establish the usage of remote sensing data and sensors for GHG monitoring and reporting. These activities can be divided into two parts: First, the actual atmospheric remote sensing work, which is part of AVENGER WP 5 that demonstrate the capabilities of sensors such as CO2M for GHG monitoring. The second part is the usage of remote sensing data or data products e.g. via LULUCF mapping and monitoring to assess LULUCF based carbon stock changes, which is part of AVENGERS WP4. Both remote sensing fields deal with similar challenges in their detection limits and spatio-temporal resolution due to the nature of passive remote sensing sensors in the solar reflective region from 350 nm – 2500 nm. Figure 4 after [29], illustrates the properties of selected remote sensing sensors for land surface characterization. Remote sensing sensors can be subdivided into global mappers, continental coverage with at least one day temporal resolution, large scale regional mappers, and missions that are able to provide more details at the local level. The mission objectives of these platforms and sensor designs have to be complimentary to balance the physical realities of remote sensing with passive optical sensors. Spatial and spectral resolution and revisit time have to be balanced in order to achieve the application specific target that a certain remote sensing mission was designed for. Figure 5 shows example Sentinel-2 data for the Berlin and Potsdam region in Germany. The loss of detail with each resolution step is remarkable and needs to be considered if e.g. land and land uses changes have to be classified and monitored for GHG emission estimates. Likewise the size and concentration contrast of emission plumes have to be considered, when choosing the correct spatial resolution. This example also shows that a smaller urban region such as Potsdam becomes nearly indistinguishable at the 500 m resolution level, whilst even large cities such as Berlin become indistinguishable on the several kilometre scale in figure 5. Figure 6 shows hyperspectral radiance data from the Mjolnir sensor. Whilst the atmospheric gas bands of e.g. CO_2 at 2010 nm and water vapour e.g. around 1130 nm and 1900 nm are clearly visible, these features will be unavailable at a lower spectral sampling interval or even with a multispectral instrument such as Sentinel-2. Therefore, it is not possible to clearly resolve and use these characteristic absorption features for surface cover type discrimination as well as gas absorption quantification beyond a certain resolution. The compromise between spatial and spectral resolution is oriented towards the application. Regional land cover mappers, such as Sentinel-2 and Landsat, have a clear mission focus on LULUCF to map and monitor environmental changes. One application is the mapping of vegetation and the determination of its phenological state or for crop type mapping [30]. This has profound implications for the users of the data as well as for those who develop user-oriented services from that data e.g. for remote sensing based GHG estimates [31]. Last but not least, there is the provision of a longer time series for GHG reporting, which is at the heart of inventory work. It relies on continuous data to develop a long time series for UNFCCC reporting, with 1990 as one of the most important reference baseline years. Only the Landsat satellite fleet, going back to Landsat 4&5 covers the entire time series. Better sensor technology introduced by Landsat-7 and the most recent Landsat 8 & 9 missions improved on the data quality [32]. The Landsat constellation acted as a blueprint for the European Sentinel-2 missions, which deliver data since late 2015, in greater spectral and spatial detail than the Landsat fleet. However, they still offer compatibility in its spectral band design towards the Landsat fleet for synergetic data use [33].

SCIAMACCHY (Scanning Imaging Absorption Spectrometer for Atmospheric Cartography) was one of the first high spectral resolution spectrometers designed to target a large variety of atmospheric absorption features. It was able to map and monitor a wide variety of atmospheric pollutants and other trace gasses, such as CH_4 and CO_2 [34]. Since its launch in 2002, it has been one of the global mainstays for spaceborne atmospheric research for about a decade. This time frame also marks the potential onset for GHG data from spaceborne sensors. This has further been enhanced by the advent of Sentinel 5P with its TROPOMI instrument, which offers atmospheric trace gas column concentrations as an operational service element of the Copernicus Atmospheric Monitoring service from 2018 onwards. Today's applications specifically target the inventory community e.g. such as the world emission project, which for the first time offers a dashboard-based interface to download GHG as well as air pollution data for point sources and regional scale emissions (https://app.world-emission.com/) [16]. It uses several different spaceborne sensors for its data products with TROPOMI being the most prominent instrument amongst them.

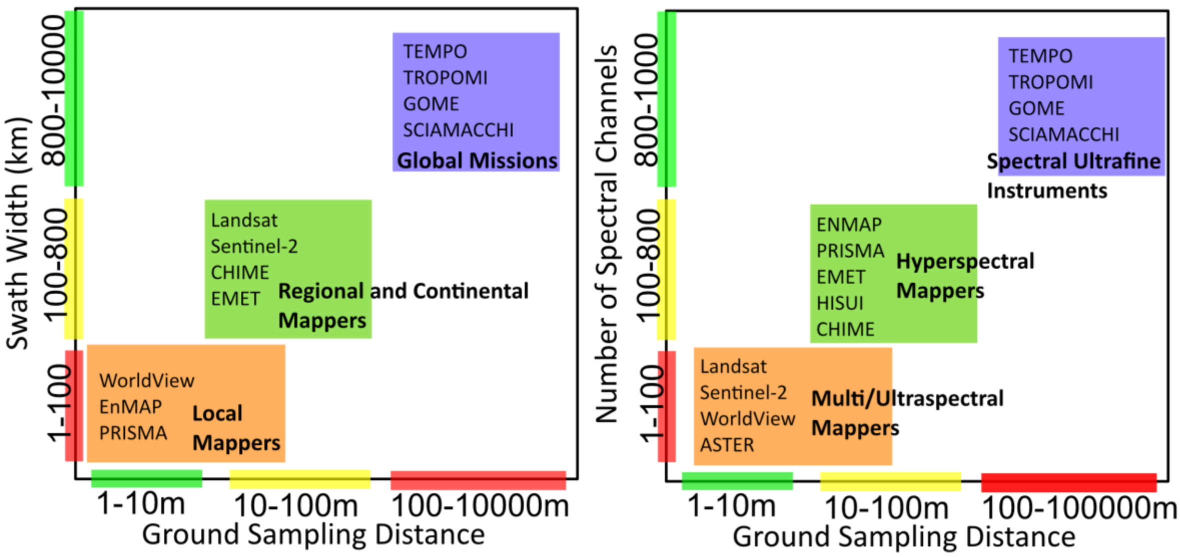

Figure 4 Properties of selected sensors in the solar reflective region. Please note the differences in sensor parameters such as spectral and spatial resolution, which are determined by the underlying application that these sensors have been constructed for, which are e.g.: (land surface applications, coastal and ocean applications or atmospheric monitoring.).

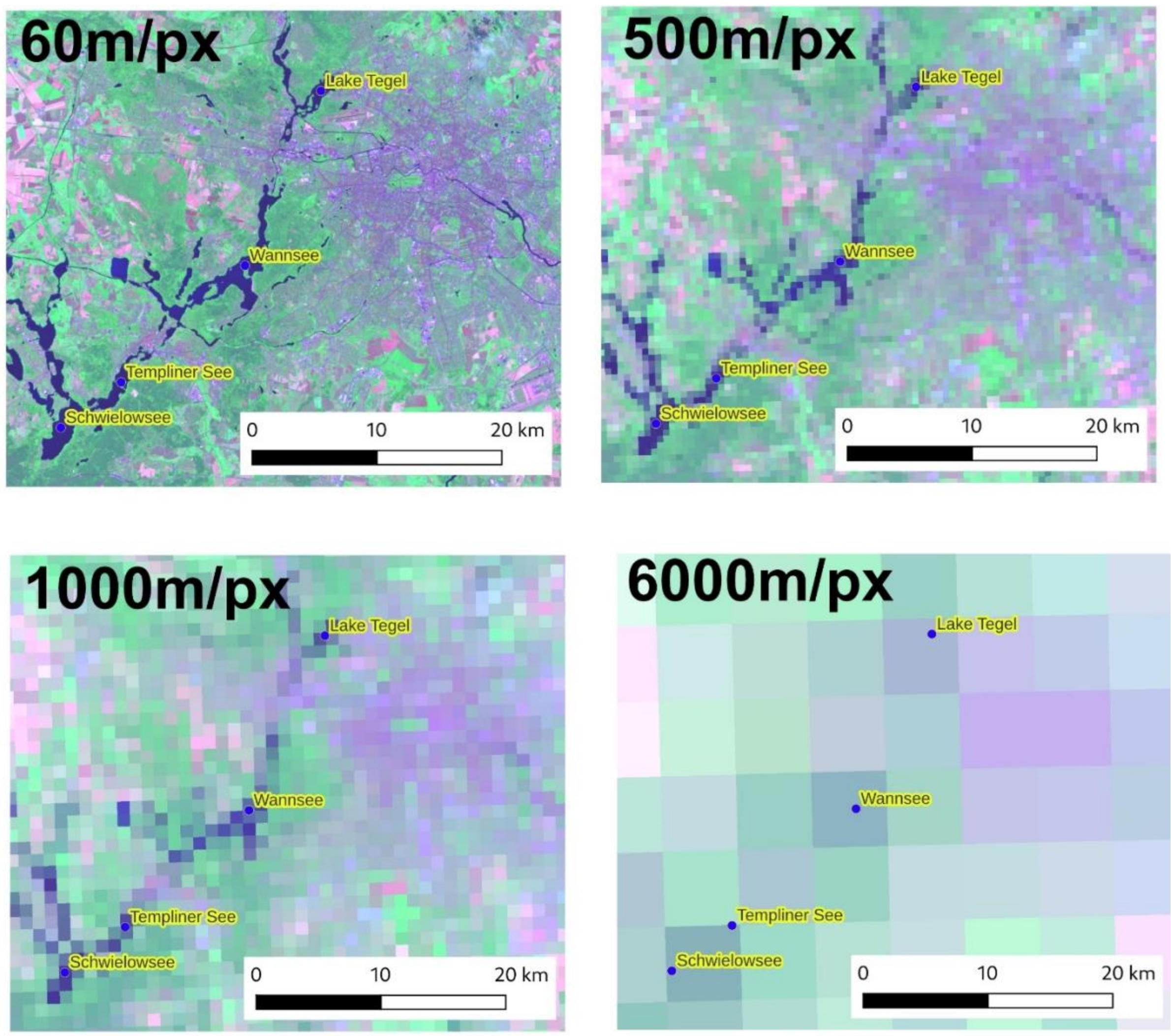

Figure 5 Multi-Resolution example from Copernicus Sentinel-2 data 2024 to illustrate the impact of variable spatial resolution on the discrimination of surface features. Please note that the urban area of Berlin in the northeast still is visible on the coarse resolution example of 1km/px whilst the urban area of Potsdam (just north of the Templiner See) is barely visible on the 500m/px resolution.

9.1.2 Work carried out in AVENGERS

The above description can only highlight some of the most critical points of remote sensing data that inventory agencies should be aware of if they seek to employ this data or derived data products in their inventory compilation pipeline. AVENGERS offers inventory relevant details on LULUCF monitoring and reporting with WP4 whilst WP5 focusses on the capabilities of sensors for atmospheric GHG characterization. It is the aim of AVENGERS to highlight the technical limitations in both fields most relevant to inventories and give examples for their potential use for the inventory community. Both use cases become ever more important as the EU-LULUCF regulation [35] encourages the usage of remote sensing data products for land classification, as the key step for GHG emissions and removals estimates and reporting. Meanwhile global atmospheric monitoring by the UNs International Methane Observatory (IMEO) with its Methane Alert and Response Service (MARS) aim to curb large methane point sources worldwide using spaceborne data [20]. Spaceborne data from methane observations is also in focus of the new EU methane regulation [36] and the arising additional communication need towards their political stakeholders and the general public in relation to the potential of different technologies for methane quantization. AVENGERS can act as a pool of knowledge about the current and future potential of spaceborne sensors, highlighting spatial, temporal and quantitative detection limits of different sensors and platforms. The sensitivity of individual sensors and data products for different trace gases is of vital importance for emission inventories. They govern which applications may be useful for particular use cases. TROPOMIs sensitivity towards methane is limited towards large point sources, of which only a few have been described in Europe. However, a large number have been detected worldwide as described in Schuit et al. [20]. The monitoring of these large point sources is not critical in the European context, whilst it may show large super emitters worldwide, as can be seen in the world emission point source data set for methane: (https://app.world-emission.com/detail/pointSources/ch4/ch4). In the European context methane data from TROPOMI may act as additional data input into the inversion systems of e.g. ECMWF for the generation of even better inversion optimized methane flux data to enable a better quantification of methane in atmospheric chemistry models. All of these individual tasks, which are carried out in detail by atmospheric scientists, need to be understood by inventory staff at a higher level to be able to assert data products from complex process chains (see figure 2). Commercial satellite providers such as GHG Sat offer sensitivities in the range of several hundred kg per hour compared to the sensitivity of TROPOMI in the range of several tonnes per hour [20]. The most important aspects of methane detection and its sensitivity, that should be highlighted by AVENGERS, are other influencing factors such as surface albedo, varying sun-observation geometries, cloud coverage, as well as background concentrations of methane that influence the detection limits of the different sensors. It is the aim of AVENGERS WP5 to demonstrate the influence of these parameters on the quantification of CO_2 and methane for next generation missions such as CO2M. This will help inventory staff to better understand the capabilities of current and future missions to give a realistic expectation on potential future data products. Figure 6 shows example spectra from hyperspectral data from field scans where we see the challenges associated with the detection of atmospheric compounds with lower spectral resolution. The detection of CO_2 is even more challenging as the SNR of current spatial high resolution, spectral medium resolution spectrometers such as the Mjolnier still is limited due to the necessary signal to noise ratios for a given application. Here, sensor parameters still need to be improved for an even more robust CO_2 retrieval. For NO_2 it was shown that the spatial pattern of the spaceborne data agrees with the NO_2 prior data from GRETA [21] and that through this a comparison with emission trends from fossil fuel combustion in the public power sector during the Corona lockdown in Germany was possible. This shows that co-emitted species data from spaceborne sensor are valuable for a further disaggregation of inversion results or for a verification of certain priors.

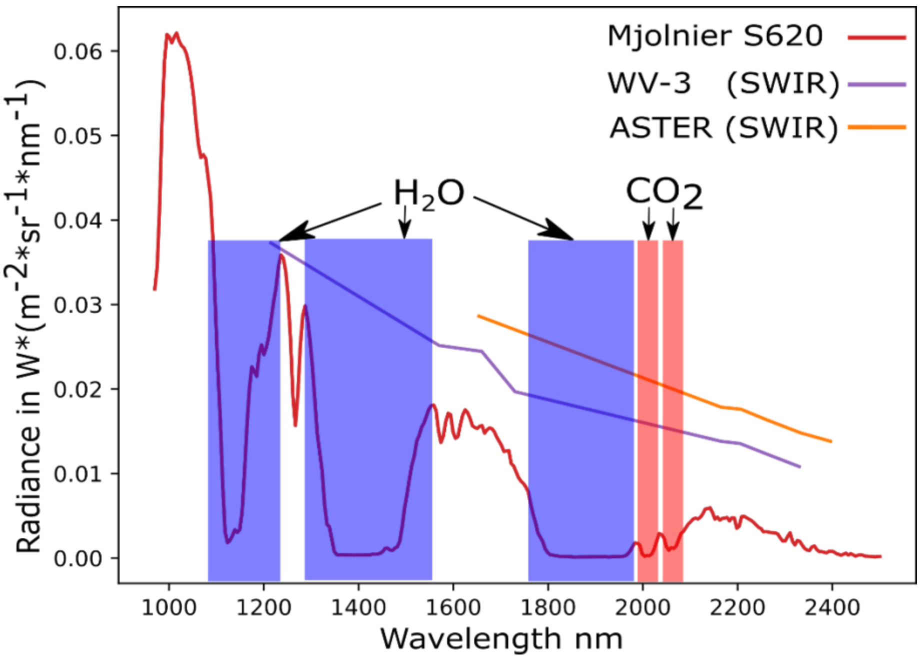

Figure 6 Example of varying spectral resolution on the discrimination of selected absorption bands of CO_2 and water vapor in a HySpex Mjolnier S620 spectrum. The spectrum was resampled, with an offset for clarity, to the sensors Worldview-3 and ASTER. Please note that a discrimination of the highlighted absorption features is only possible in the hyperspectral instrument data.

An interesting aspect for both atmospheric scientists and inventory specialists is the provision of a longer diurnal time series for emission monitoring from spaceborne instruments. These may be generated from the TEMPO [37] mission to better understand weekly and daily emission profiles from combustion activities, which may help to improve the spatial and temporal emission priors in an attempt to provide yet even more realistic emission prior for inversion modelling.

9.1.3 Outlook on future developments

The data for GHG assessment and quantification is becoming more complex as ever new sensor data and derived products are developed [23]. Data for LULUCF characterization have long been advocated for land management by national and local authorities to monitor e.g. crop rotation. This kind of low-cost local to regional scale monitoring principle cannot be ported to emission monitoring on the local level, although interesting facility specific technology demonstrations exist [24], [25]. These facility level monitoring applications represent an interesting method to derive or complement facility specific emission factors, provided that the detection limits of future sensors for CO_2 and CH_4 will be lower than these of current instruments. The setup for ground-based methane measurements after Knapp is shown in figure 7. Here an imaging spectrometer for rotational scans is deployed together with a LIDAR instrument to measure the wind speed for a facility level emission rate calculation. However, as new more elaborate measurement programs on methane need to be carried out by facility owners in the framework of the EU-methane regulation, these more expensive, imaging spectroscopy-based measurement programmes may prove to be of only limited value as the technology readiness levels of such systems still remain in the applied research domain. Airborne campaigns by UAVs and planes have an even greater cost factor attached and offer an even sparser spatio-temporal coverage. Therefore, airborne data may only become useful in a number of very limited use cases, especially in the research domain, where new sensors and retrieval chains need to be tested on a variety of larger facilities in short time. It is also in the collaborative work of AVENGERS to discuss and monitor these scientific developments to anticipate new applications for GHG mapping and monitoring.

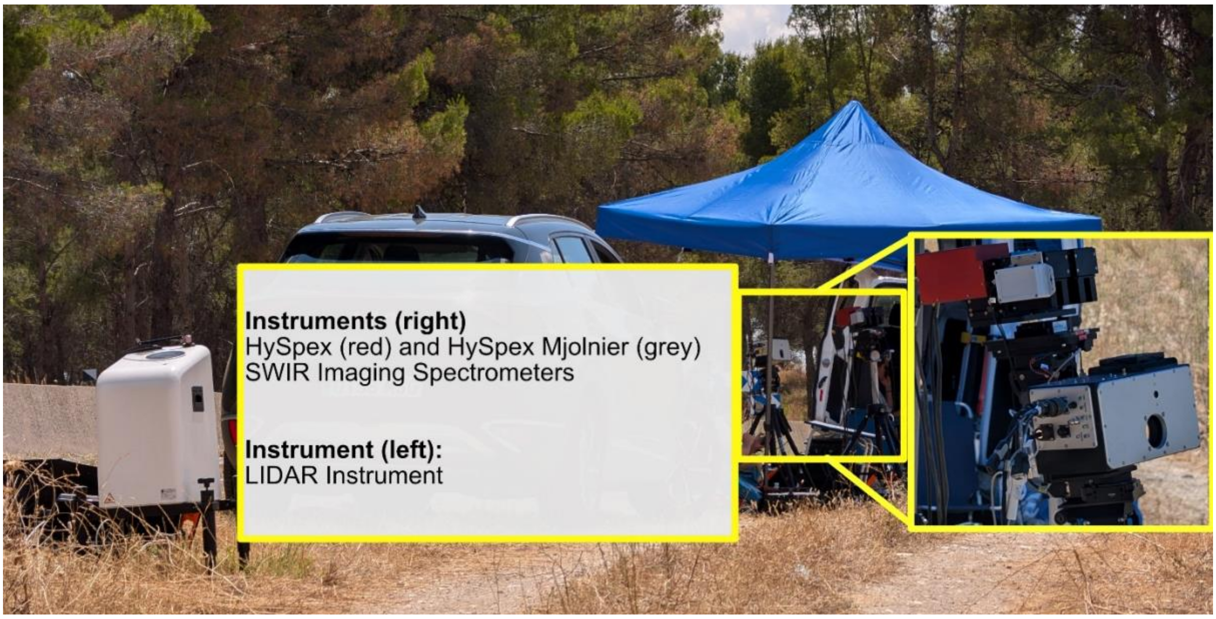

Figure 7 Field deployment of imaging spectrometers for rotational imaging spectroscopy for an assessment of facility level emissions.

9.2 User story 2: Inversion and other modelling systems

Box 1: The ideal inverse modelling data set from an inventory compilers perspective

Transparency, consistency and continuity: Only if methods and assumptions behind a published data set are accessible, complete and up to date, these data can be fully adopted by inventory compilers. This also includes support and a contact address that is not dependent on temporary scientific personnel or a temporary project.

Accessibility and usability: Easy access to data according to modern standards and the adherence to good practices greatly facilitates uptake of data by inventory compilers. This includes accessibility with a variety of different software solutions, strict adherence to community standards for file formats like netcdf and at least a rudimentary documentation.

Which gases: Uncertainties of fossil fuel CO_2 emissions in emission inventories of Annex 1-countries are usually very low (on the order of a few percent), as they are calculated from the known carbon content of fuels and high-quality fuel-use statistics. That means they are often more certain than inversion results making these less interesting for inventory compilers. By contrast, uncertainties of other greenhouse gases like N_2O and CH_4 are generally much higher making them very attractive targets for inverse modelling. Note that for non-fossil fuel CO_2 emissions (e.g. Land Use, Land-Use Change and Forestry (LULUCF) emissions) and CO_2 emissions from non-Annex 1 countries, inventory uncertainties can be higher making them again more interesting for inverse modelling.

Time series: The reference point for emission reduction is 1990 making time series that include this landmark very valuable to inventory compilers. However, it is clear that historic data is less accurate leading to increasing uncertainties. On the other hand, inventories usually report on a yearly basis, making high time resolutions less relevant. The reference frame for emission reduction targets might also change in the future, for example with the 5-year pattern of the global stock take.

Sectors: Emission inventories define key sectors based on a combination of emission total and emission uncertainty. Emission estimates for these key sectors are especially valuable. The comparison between inversion and inventory emissions is in general greatly supported by reporting of sectorial emissions. However, it is understood that a sectorial split requires additional data sources besides atmospheric concentrations and results in higher uncertainties.

Resolution: The importance of spatial resolution depends partially on the size of a country. For small countries such as the Netherlands a resolution of 0.5° x 0.5° (approx. 50 x 50 km) or higher is crucial to allow faithful determination of a country total, which is usually what emission inventories are interested in. A high spatial resolution can also help to attribute observed differences to specific emission sources.

9.2.1 State of the art

Inversion systems are an important tool for assessing emissions of GHGs worldwide, by delivering a continuous picture in space and time, and providing global monitoring of GHG trends and levels. These data may be used to complement the global stocktake under the Paris agreement (UNFCCC, 2015) as well as country level monitoring as in case of the UK or Swiss inventory reports, to highlight agreements and differences between top-down and bottom-up estimated emissions. The setup and usage of these inversion systems requires an appreciable amount of computer and expert resources that need to be considered to construct a country wide GHG monitoring system. The 2019 IPCC refinements on QA&QC [1] include the possibility to establish a country wide GHG monitoring system based on inversion modelling. Germany with its ITMS project (Integriertes Treibhausgas Monitoring System) is currently in the process of constructing such an operational system with atmospheric scientists, from the German Weather Service (DWD) and the Max Planck Institute in Jena, with experts in observation (from the DWD, the Alfred Wegener Institute, the Universities of Heidelberg and Bremen), with LULUCF Experts from the Thünen Institute and the KIT as well as with the inventory team of the federal environmental agency (UBA). This complex multi-year process may, however, be not always suitable for every country, due to its size or the resources that are required to construct such a system. However, there are scientifically approved and curated resources for inversion optimized emission data of GHGs that may already be used by large to mid-sized countries to complement data in particular emission categories or gases in their national GHG emission inventories. Figure 8 shows an example for Germany from a global CAMS inversion optimized GHG flux data [15] that are available for CO_2, CH_4 and N_2O. These data are regularly compared to the national totals in the German national inventory document [4] as suggested by the 2019 IPCC Refinement. Though the spatial resolution of the inversion data from CO_2 and N_2O has been improved, it may not be suitable for smaller and more complex countries or regions such as the Benelux region or the Baltic countries. The most critical aspect for most inventory agencies is the access to the data, their transparency in relation to the applied methods/parameters/assumptions, and the overall uncertainties related to the inversion results (see also box 1). The World Emission project for example offers a user tuneable emission dashboard, where emission inventory staff is directly able to download and use the data in a time series format enabled spreadsheet, which is very close to the format that is used by most inventory personnel. This kind of data offer really lowers the barrier compared to accessing e.g. complex netcdf data.

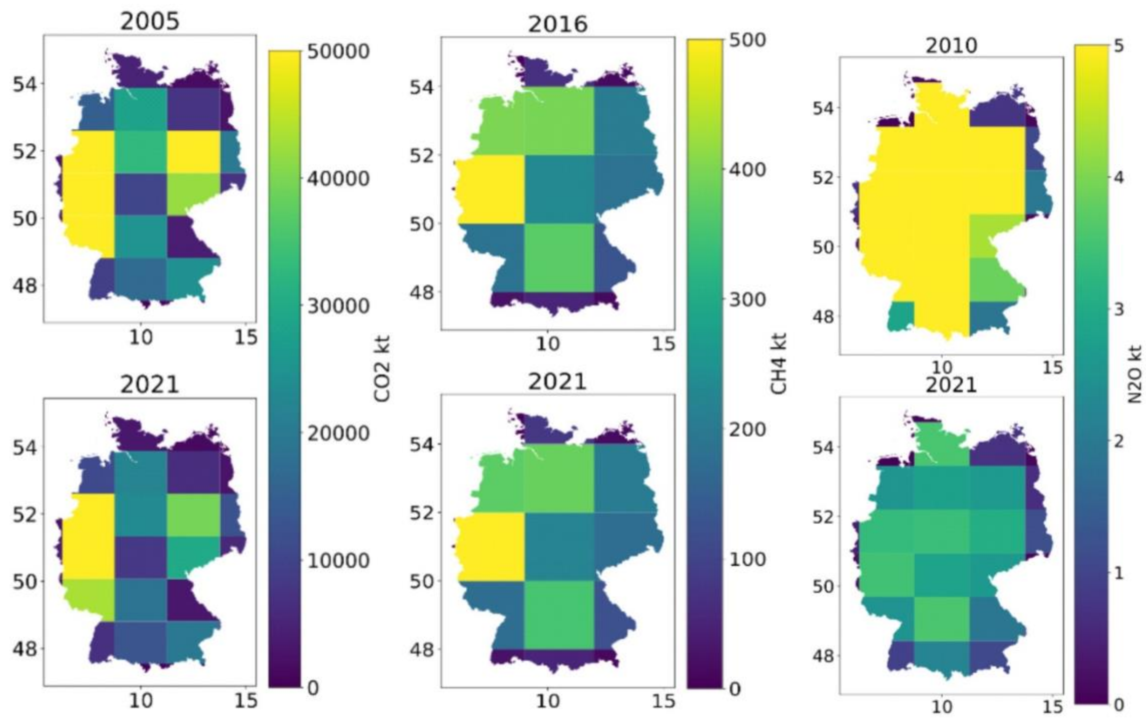

Figure 8 Example maps of CO_2, CH_4 and N_2O emissions compiled from monthly CAMS inversion optimized GHG data. Please note the spatial resolution of several degrees per pixel.

9.2.2 Work carried out in AVENGERS

The above discussed cases already show the complexity of reconciling bottom-up emission inventories with outputs from inverse modelling. Inversion data should also try to deliver sectoral disaggregated information e.g. delivering data for GNFR categories in addition to the total amount of each gas. This can be done by integrating data on co-emitted species, as in case of the world emission project [16], which delivers e.g. disaggregated fossil fuel related CO_2 emissions. Ideally, this can be expanded for AVENGERS to other GHGs such as methane, by using TNO's TOPAS dataset. This disaggregation is ultimately needed to identify problematic source categories. A closer scientific investigation on the feasibility and robustness of disaggregating individual GHGs into sectors also provides inventory agencies with a deeper understanding of the limits of these methods. The critical balance between disaggregation level and data accuracy in the output data would be a key objective in WP 2 for the work of any inventory compiler as this then demonstrates the ultimate capabilities of the respective inversion systems. For this approach one could focus on delivering GNFR disaggregated emissions from the inversion results for each AVENGERS country that could directly be compared with inventory data. This of course cannot be done for every key category and gas species as many sources would yield a too low spatial emission contrast in their respective gas category. Another interesting aspect would be the needed spatial resolution of the data product. The minimum acceptable spatial resolution of the output data product of each gas species should be related to the country size and the spatial emission distribution patterns of the priors. If large industrial or agricultural dominated areas or urban areas cannot be spatially separated from the respective combustion-related, or biotic and abiotic process-related emissions then the spatial resolution of the model still is too coarse as can be seen in figure 8. Here the spatial resolution is in the range of 1.8° – 3.8°. Finding this particular, spatial "sweet spot" is an interesting scientific challenge for the atmospheric science community in AVENGERS. Another important point is the sensitivity of inversion results towards the available station network, i.e. how much additional stations improve the results, in to justify the funding of a nearly optimal ground station network that is needed to deliver high quality inversion results. An interesting aspect here is, how are countries with long coastlines, large number of islands and complex orography affected by this fact. How well could a measurement network adopt to a country with a long and complex coastline as for example in the case of Italy? How much do "border effects" govern the results of inversions e.g. at the border between Poland and Germany? These questions could be answered by the work of the atmospheric science community within WP5 to educate emission inventory staff in understanding and interpreting the output data.

The delivery of prior emissions as input into inverse modelling is also of great importance for robust inversion results. Therefore, inventory compilers should aim to understand the generation process of the necessary prior emissions and how MEMO items (emissions that are accounted for but are not part of the official national total under UNFCCC) are handled by the atmospheric science community. The most important aspect for inventory compilers is to understand prior emissions and their influence on the output result. How much influence do they have on the actual inversion result? How much effort needs to be put towards the improvement of priors for atmospheric inversion by the national inventory agencies? These questions could be answered by comparing the results of inversions with different prior emissions and prior weights. These experiments then demonstrate the sensitivity of the results with respect to the prior emission for the emission inventory community. Another important factor is the minimum country/domain size for which individual output results are valid, or in other words: What would be the smallest still viable country/domain size to construct an inversion system for? Furthermore, AVENGERS will offer self-taught jupyter notebooks for accessing and plotting the project data, even for inventory compilers with only very limited data science skills to enable them to integrate AVENGERS, as well as external data into their emission reporting framework. This is also going to help inventory compilers towards an implementation of the 2019 IPCC refinements on emission reporting and QA&QC [1]. This will be one of the most valuable contributions from the reconciliation task 1.4 in WP 1 within AVENGERS. If trends in the emissions of N_2O could be explained and ultimately reconciled between inventories and inversion data (see figure 3), then the AVENGERS atmospheric science community would make a great contribution towards trust in its data products and inventory improvement.

9.2.3 Outlook on future developments

AVENGERS acts as a platform to ask and answer critical questions from the inventory community towards the modelling community, which is a fundamental building block to create mutual understanding and trust in data products. Without this, it may not be possible to integrate or even plan to integrate inversion results as a regular part into the framework of the emission inventory. IG3IS is globally coordinating the process of emission inventory verification with inversion data. However, it is up to the member countries to construct their own local systems that may be used for complementing the data of the global stocktake process. This requires a substantial capacity building effort to which AVENERGS with its results would like to contribute even after the project has finished. To achieve continuity, the Umweltbundesamt (UBA) will curate scripts and notebooks for data access and inventory comparison towards other data for the inventory community.

9.3 User story 3: Improvement of individual sectors (LULUCF)

9.3.1 State of the art

A summary of some of the contents provided in the LULUCF Handbook developed by the European Environmental Agency [35] is provided in this paragraph describing the state of the art.

The LULUCF Regulation (EU 2018/841), introduced in 2018 [35] and revised in 2023, is the primary regulation for utilising the land sector's potential for mitigating climate change. It sets net carbon removal targets for the EU and each Member State and mandates high monitoring standards for all land-based emissions and removals across the EU. IPCC Guidelines for national GHG Inventories (IPCC, 2006) provide methodologies at different levels of complexity. For the representation of land areas, these levels are called ‘Approaches’; and for estimation methodologies, they are called ‘Tiers’.

In brief, Tier 1 (default method) consists in using readily available statistical data and default emission factors from the 2006 IPCC guidelines [8] or 2019 IPCC Refinements [9]; Tier 2 (intermediate method) is similar to Tier 1 in terms of methodologies, but default emission factors are replaced with country-specific emission factors developed on the basis of knowledge of the types of processes and specific conditions that apply in the country; Tier 3 (most detailed) are country-specific methodologies based on measurement data at high level of resolution and repeated measurement campaigns (e.g. National Forest Inventories, soil inventories), and can also entail specific modelling approaches calibrated and validated for the country against measurements.

The three approaches for land representation are:

1. total land-use area, no data on conversions between land-uses (national statistics);
2. total land-use area including changes between categories (land use change matrix);
3. spatially-explicit land use/land use change data (estimation through three alternative methods: wall-to-wall, sample based, survey based).

From the 2028 GHGI submission onwards, the LULUCF Regulation [6] requires the application of at least Tier 2 methods for all managed land categories and emission sources. From the 2030 submission onwards, the LULUCF Regulation [6] requires the application of Tier 3 methods for most forest land, grassland, and wetlands (in general on land use with high carbon stock, under protection, restoration or need of restoration, facing high future climate risks meaning natural disturbance or climate related disasters).

About land-use representation, the LULUCF Regulation [6] requires Member States to apply a geographically-explicit framework already for the reporting year 2021, i.e. with the submission 2023. A difficulty in this is that all time series reported for UNFCCC reporting shall be consistent, even though there is no high-quality land-use change data for past periods. For the monitoring of land use and land-use change, in particular, each country should select the most suitable dataset or apply a multi-source approach to use several datasets. The requirement to use geographically-explicit land use datasets does not impose a specific data format, such as ‘wall-to-wall’, raster, or continued sampling. What is intended is that such data remains interoperable with other datasets to facilitate carbon calculations at high spatial resolution. It has to be noted that both sample-based and wall-to-wall methods can be considered Approach 3:

- sample based methods: from ground surveys (such as a national forest inventory or national land survey) or remote sensing. Sample-based methods provide an accurate statistical representation of land-use and land-use change but do not provide information on every specific area of the land territory (i.e. is not wall-to-wall spatially explicit);
- wall-to-wall maps of land cover and land cover change that, when combined with other data, can be used to generate land-use and land-use change information;

These methods are not mutually exclusive; for example, wall-to-wall methods typically require samples for calibration, validation and uncertainty analysis, and some sample methods require wall-to-wall maps for scaling as well as for dimensioning the sample size and designing the sample grid.

So, a key objective of the LULUCF Regulation [35] is to push Member States to move towards better approaches and higher tiers. Using geographically-explicit monitoring of land use changes allows Member States to precisely track what is happening on the field. Combining high quality datasets in a geographically-explicit framework helps policy-makers to have a comprehensive and detailed view of the evolution of carbon fluxes and assess the effect of their policies in a timely manner. Some countries however are far away from these targets.

A wall-to-wall product is the **"CLC+ LULUCF instance**" made recently available (Q2/2023) in the framework of the new generation of Corine Land Cover products (CLC+), delivered by the CLMS (Copernicus Land Monitoring Service): it is a **100 m grid** product that tries to approximate LULUCF activity data categories, combining existing land cover and land use data available in a web-application/database called **CLC+ Core**. The main use case for CLC+ Core is to derive **tailor made** land cover and land use products (so called "Instances"), on a 100 m grid level, based on an on-demand combination of available (EAGLE model based) land cover and land use information. This allows to combine previously non harmonized datasets in new ways, in particular land cover information coming from the CLMS products with specific land use information from the countries. Among the CLMS land cover datasets available in the CLC+ Core there are:

- the **CLC+ Backbone**[1] (18 thematic classes vector products not yet available, and a 11 land cover classes 10 m spatial resolution raster product) available for 2018 and 2021, with foreseen updates every 2 years;
- The **High-Resolution Layers** (HRLs) provide maps of vegetation and vegetation change (tree cover and forest, grassland) as well as non-vegetated areas (impervious areas, water), with a 3-years update cycle from 2012 up to 2018. The vegetation related products move to yearly updates from 2018 onwards and will be complemented by a new annual crop type layer. The 2018 editions of the HRLs are available at 10 m spatial resolution while earlier versions have a resolution of 20 m;
- Hedges, agroforestry, trees outside forests are included in the special product called **Small Woody Features**, available for 2015 and 2018, at 5 m spatial resolution.

[1] https://land.copernicus.eu/en/technical-library/clc-backbone-product-user-manual/@@download/file

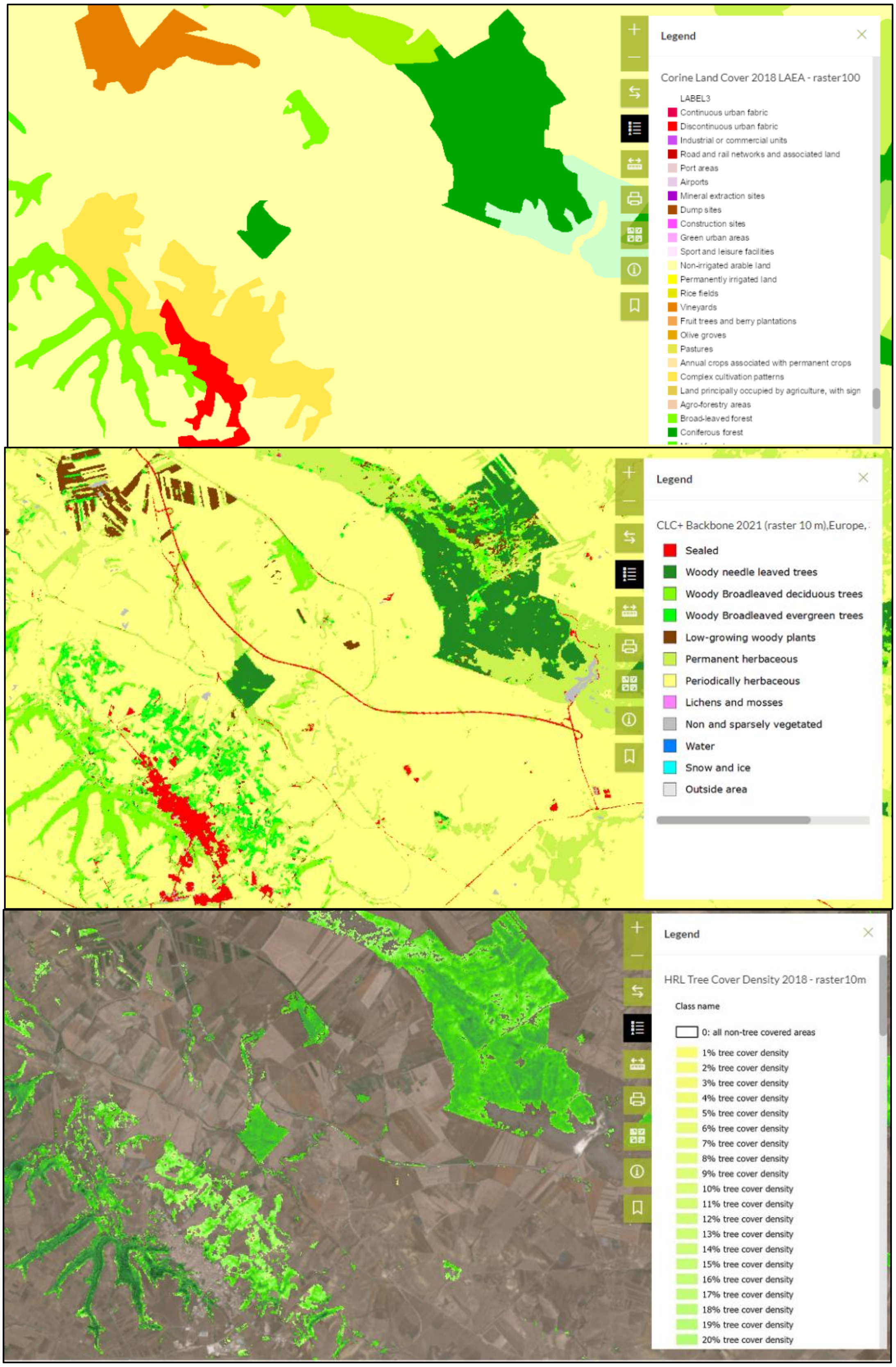

Figure 9 Different CLC products on the same area showed through the [CLC data viewer]() offered by the Copernicus Land Monitoring Service

EEA intend to explore the use of the CLC+ LULUCF instance data as independent activity data proxies on EEA side for the LULUCF MRV, to make this data available to countries together with the CLC+ Core database/web interface for the adaptation of the LULUCF instance to national needs. Countries might want to use it to support parts of their own LULUCF reporting and monitoring (by feeding their national data into the system).

In the past, the basic CLC product were judged not suitable for land use representation in national GHG inventories, as often large discrepancies were found comparing this system with the approach used for LULUCF reporting in some countries. For example, in Italy CLC forest surfaces are underestimated by nearly 20% with respect to National Forest Inventory (NFI) in 2018. In general, at European level, main discrepancies from the two systems were probably linked to differences in minimum mapping unit, land use category definitions (which can also vary from country to country), and the difficulty of remote sensing to clearly identify land use instead land cover (e.g., distinguish annual crops from herbaceous grassland and vice-versa).

Even with the new CLC+ LULUCF instance data there are still challenges to overcome. An evaluation in Sweden of the CLC+ LULUCF Instance concluded that it is not considered suitable as a product for reporting carbon store changes in vegetation and soil. The product will probably be developed and improved, but today it does not have a high enough quality. Most classes and their areas can be questioned and, for example, being able to follow felled forest will not be possible. With more high-resolution national data inputs, it should be possible to create a product with higher accuracy that can also be validated and evaluated based on national inventories.

In addition, CLC datasets were available only for the years 1990, 2000, 2006, 2012 and 2018, while national inventory agencies need to report emissions and removals due to land use and land-use change on an annual basis. The new set of CLC+ products could overcome these limitations, if integrated with country specific information and knowledge.

9.3.2 Work carried out in AVENGERS

ISPRA is testing these products on IT, SE and NL within the AVENGERS project, opening a dialogue on these matters with EEA. A training on the use of CLC+ Core web interface will be provided to AVENGERS partners (Inventory Agencies involved) in Autumn 2024.

A methodology to compare and reconcile National Inventory land use activity data and land use data of CLC+ instance LULUCF has been developed; the resulted wall-to-wall land use data will be used to produce an enhanced spatial disaggregation of LULUCF emissions and removals and N_2O from managed soils, for the year 2018 as a test exercise on Italy, Netherland and Sweden; this spatialization could be used as enhanced priors for WP2 inversions within the project.

9.3.3 Outlook on future developments

In the future, the experience developed in the project about the CLC+ Core database/web interface's features and potentials could be used by countries to apply the approach 3 required by LULUCF Regulation and for the implementation of Tier 3 modelling estimation in LULUCF sector. The inventory agency of Cyprus (The Cyprus Institute), which recently joined AVENGERS with the Hop-On Facility is interested in testing this approach and will be involved in the training activities.

9.4 User story 4: Improvement of the agricultural sector in the Netherlands

9.4.1 State of the art

Despite its small size, the Netherlands are one of the world's largest agricultural producers. Therefore, emissions from agriculture play a big role in the Netherlands and form several key categories according to the Dutch National Inventory Report 2024 [38]. This includes direct and indirect N_2O emissions from managed soils (CRF categories 3Da and 3Db) and CH_4 emissions from enteric fermentation (CRF category 3A) and manure management (CRF category 3B). These emissions contribute substantially to the total greenhouse gas emissions of the Netherlands, with CH_4 and N_2O emission from agriculture contributing 11% to the Dutch GHG emissions in CO_2-eq. in 1990 and 12% in 2022. Agriculture contributed 71% (~500 kt) of the total Dutch CH_4 and 72% (~18 kt) of the total N_2O emissions in 2022.

Agricultural emissions in the Netherlands are calculated using the National Emission Model for Agriculture (NEMA) [39], which is developed and maintained at Wageningen University and Research. This model does not only consider livestock numbers and fertilizer consumption, but also animal housing type, the composition of the animal feed, the age of animals and many other factors. Despite these substantial efforts, these emissions are still associated with large uncertainties. Due to the physical and chemical complexity of these emissions, the uncertainty of emission factors used in bottom-up emission estimates are usually on the order of 30-50% (expressed as 95% confidence interval). For indirect emissions of N_2O from managed soils (after deposition of nitrogen in the form of NO_x or NH_3) the uncertainty even exceeds 200% as it requires prior modelling of nitrogen deposition. This combination of relatively large uncertainty and big contribution to total emissions make agricultural emissions a promising target for top-down emission estimates in the Netherlands.

Even the simplest data product, national total N_2O and CH_4 emissions for the Netherlands would help to assess agricultural emissions and reduce emission uncertainty. Additional constraints on the emissions can presumably be extracted quite straightforwardly from spatio-temporal information about emissions. Spatial information (see figure 10) might allow to distinguish agricultural emissions from the largest non-agricultural source of CH_4 and N_2O, waste management (CRF categories 5A and 5D). Temporal variations, between years or within a year, might be very insightful. The Dutch emission inventory does not provide monthly emissions, so this comparison would rely on using the temporal emission profiles developed in WP2. Emissions related to waste management are key categories themselves, which makes any additional insights into them of additional value. The final major source of CH_4 in the Netherlands is the extraction of natural gas, which also forms a key category.

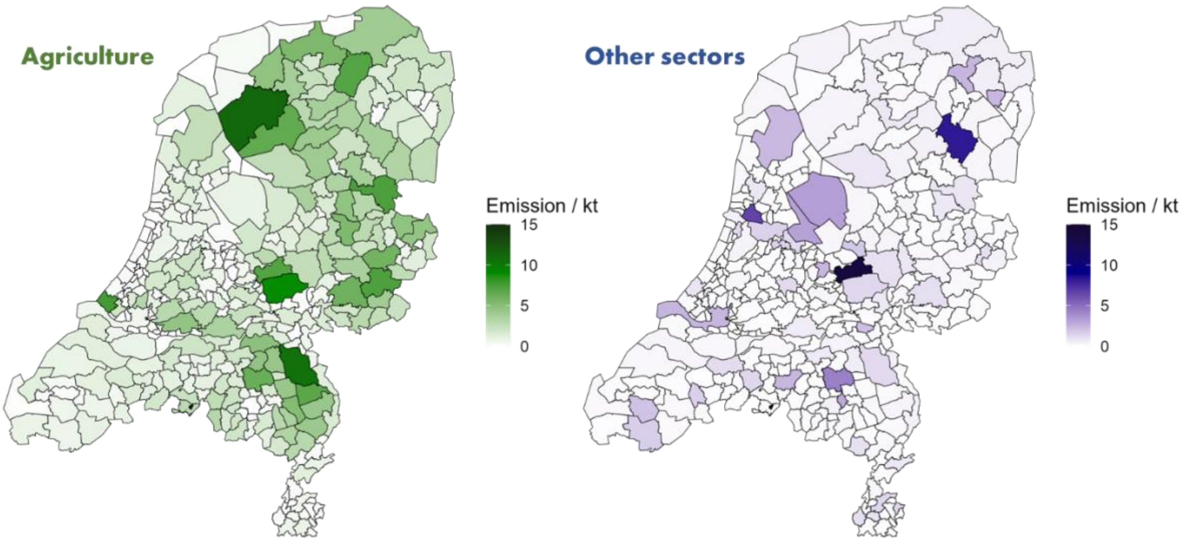

Figure 10 Spatial distribution of Dutch methane emissions for the year 2022 from agriculture (left) and other sectors (right) showing distinct patterns that might allow sectorial attribution.

9.4.2 Work carried out in AVENGERS

This user story directly relates to the AVENGERS WP2, where top-down emission estimates of CO_2, N_2O and CH_4 are produced. Comparison with inventory estimates is facilitated by using prior emissions as model inputs that are consistent with inventory emissions. This will be supported by estimates of natural CH_4 emissions from wetlands from WP4. Finally, the comparison and reconciliation of top-down and bottom-up emission estimates will be carried out in WP1 in close cooperation between inventory compilers and atmospheric scientists.

9.4.3 Outlook on future developments

The big question remains how top-down emission estimates can be translated into improved inventory emissions and into actionable steps. This can be answered relatively easy if we find large sources that are absent from the inventory and can be added to make the inventory more complete. However, this is unlikely given the continuous improvement of the national inventories. It remains unsure if smaller, quantitative differences between top-down and bottom-up estimates can be directly translated into improved emission factors, or if they are not specific enough. In that case they might get relegated to “only” inform and direct additional research effort, which would already be of great value.

Additionally, it will be very interesting to compare long term emission trends between the inventory and inversions, not only to get insights into the quality and completeness of the emission inventory, but also because of the great public and political interest in emission trends and emission reduction. Finally, it will be interesting to see how the lessons learned for the Dutch agricultural sector can be translated to other countries to support their emission inventories.

9.5 User story 5: Methane Emissions in the inventory of Cyprus

9.5.1 State of the art

Emissions from the waste sector in 2022 contributed to 7.5% of the total GHG emissions in Cyprus, and 59.7% of the total national methane emissions (without LULUCF). 86.4% of these emissions are from solid waste disposal. Although a modest component of the current total GHG emissions, the amount of methane emissions from the waste sector will become increasingly important to the achievement of national reduction targets. In GHG projections, the waste sector is second only to the energy sector in terms of overall emission reductions for the year 2030 [40].

Despite its relevance to national targets and totals, the quality of waste activity data is limited by the nature of historical waste management practices on the island. The first managed waste disposal site was introduced in Cyprus in 2006 in Pafos [41]. Then the second Integrated Waste Management Plant (IWMP Koshi) started its operation in 2010, serving the districts of Larnaca and Ammochostos. The IWMP Koshi is also serving the district of Nicosia since 2019. Another IWMP (Pentakomo) started its operation in 2018, serving the district of Limassol. Prior to this introduction, waste disposal was unmanaged. Five disposal sites were in operation in 2005, operating under semi-controlled deposition and outside the standards of the EU directives [42]. Up until 2010, 113 uncontrolled disposal sites were in operation, with 48% of these sites starting their operations during 1990–2000, a significant number between 1980–1990, and just two sites in operation prior to 1970. Waste disposal practices have recently improved, but accurate emission calculations are still hindered by the uncertainty of activity data. Methane from managed and unmanaged waste disposal sites are two of the largest contributors to the overall uncertainty in the inventory. The uncertainty given for CH_4 emissions for this sector reaches 42%.

An observational study by Liu et al. (2023) [43], in collaboration with the emissions team of the Climate and Atmosphere Research Center (CARE-C) studied methane produced by landfills in Cyprus and estimated emissions 2.6 times higher than what is reported in the national inventory. The surveyed landfills included a large active landfill (Koshi, 8 % of total methane emissions) and a large, closed landfill (Kotsiatis, 18 %), with measurements taken over 24 intensive survey days from October 2020 to September 2021. The study surveyed also an area with relatively concentrated cattle farms and about 5.2% of the total cattle population (see figure 11). Surveyed areas account for about 28% of the total CH_4 emissions in Cyprus. Emission rates for each site were estimated using repeated downwind transects and a Gaussian plume dispersion model. The study estimated methane emissions from landfills to be 129% higher than what is reported in the national inventory, respectively, with an uncertainty of 21% (see figure 12).

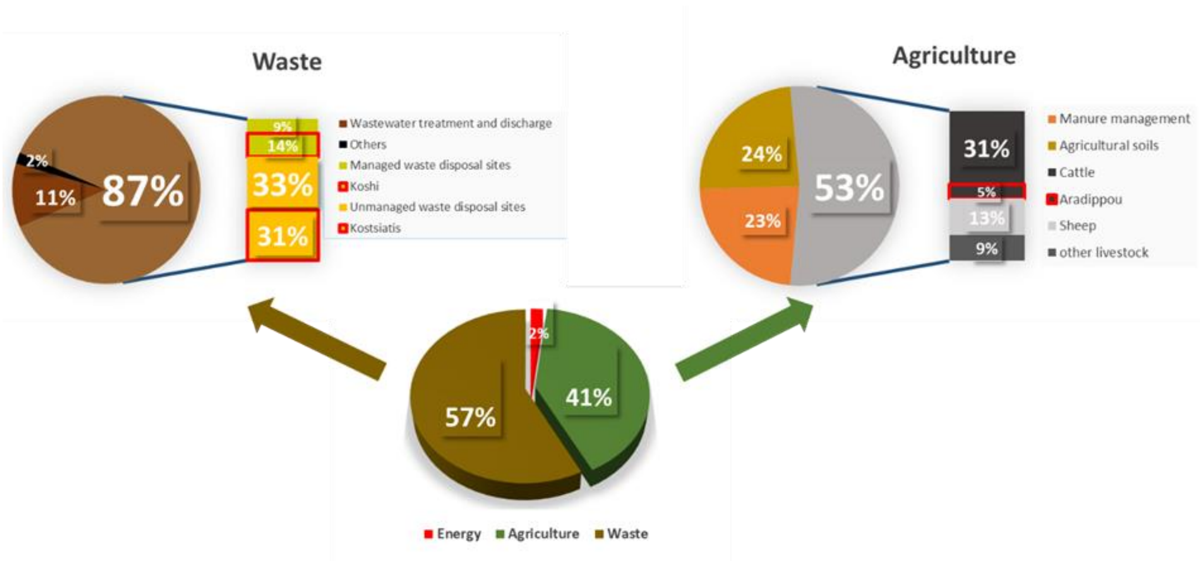

Figure 11 The sources categories of methane emissions in Cyprus (UNFCCC, 2021) .

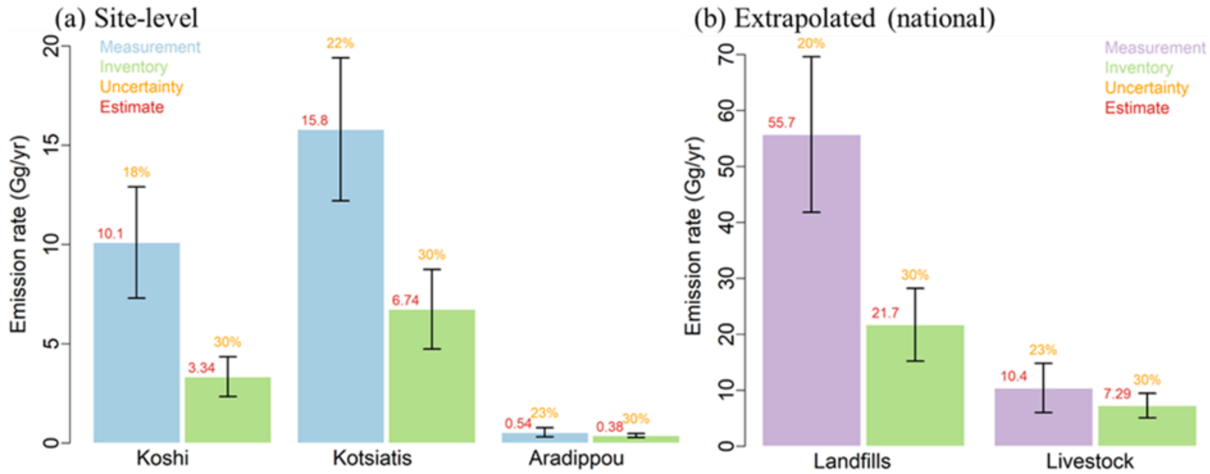

Figure 12 Methane emission rates calculated from in situ CH_4 measurements and bottom-up inventory estimates: (a) presents the site scale and (b) presents the extrapolated estimates (national scale) (Liu et al) **[43]**.

9.5.2 Work carried out in AVENGERS

The indication from Liu et al. that bottom-up emissions from waste are underestimated is contrasted by the expectation from officials that, due to the characteristics of the IPCC model used for estimates, bottom-up emissions are overestimated. This conflict between measurement and expectation could be resolved through additional monitoring and verification. The insights from past observations and planned future observations are valuable but limited in spatial and temporal cover. Given the relative importance of waste to the national methane emissions and the achievement of future emission reductions, a top-down estimate would be a valuable step in reconciling the general debate regarding bottom-up emissions from waste, and possibly in reducing the uncertainty of methane in the waste. Regular inversions over the island could shed further light on this issue, and perhaps give an indication of any progress toward methane reduction for 2030 targets and beyond. The potential information from an inversion for the case of Cyprus can be also applicable to other countries in the region, which are similarly challenged in obtaining accurate waste activity data and emission estimates. For inversion data to be relevant to such countries and their inventory compilers, data would need to be of sufficiently high resolution, and obtainable without a great demand on personnel and resources.

The applications for top-down estimates of methane in Cyprus extend beyond the waste sector. The key part of Cyprus' plan to reduce GHG emissions for 2030 and beyond is the incorporation of natural gas for electricity production, currently planned to be introduced via Liquified Natural Gas imports in 2026 [40]. Alliance with natural gas could be increased should any extraction project from one of Cyprus' five discovered natural gas fields ever go forward. Regardless of how Cyprus' relationship to natural gas may proceed, the fugitive emissions associated with the use of the fuel add further value to achieving top-down estimates for methane in Cyprus via inversions.

While uncertainties are generally larger for CH_4 and N_2O, there are situations where CO_2 inversions could also be useful to inventory agencies. One example, relevant to inventory compilers in general, is dealing with abrupt changes in national emissions due to unforeseen circumstances. The Covid outbreak changed bottom-up estimates, particularly during the lockdown, with top-down estimates being an important step in verifying these changes. A second example, relevant due to the geopolitical situation in Cyprus, is the verification of estimates from fuel sales. CO_2 emissions in road transport account for over 20% of total GHG emissions in Cyprus and are estimated using fuel sale data (within the area governmentally controlled area) and the COPERT emissions model. However, Cyprus is a divided island, and apart from the illegal trafficking of fuel, drivers can acquire fuel by traveling to the northern occupied area to fill their tanks for cheaper. A top-down estimate of CO_2 over the island could give some indication of the extent to which cross-border sales might influence CO_2 emissions from road transport in the Republic.

9.6 User story 6: Tools (FIT-IC) and data for the inventory community

9.6.1 State of the art

The 2019 IPCC Refinements [1] recommend a close collaboration between inventory compilers and atmospheric modelling groups as is the case with the role model countries Switzerland, UK and Australia. These countries already have inversion systems with a national focus that supply data as well as text to the coordinators of the national inventory document. Most of the national inventory compilers do not have an in-depth understanding of inversion models and are, therefore, dependent on the expertise of the modelling community to understand these systems. This can be done through capacity building efforts, which is also part of AVENGERS. However, having a technology demonstrator system for inversions, i.e. inversion software aimed at non-expert users, will further boost and reinforce the understanding of these systems. Currently, all inversion systems have been designed for expert use, often only within the own research group or institute, which hampers the usage of these systems by inventory staff without a comprehensive scientific modelling background.

To our knowledge there exists only one software package for inversions that is designed specifically with ease of use in mind, the Integrated Methane Inversion (IMI) software [44], which can be run directly on the Amazon Web Service cloud and should in principle be usable by any scientifically minded person with basic command of python. It is relatively well documented. However, it lacks a graphical user interface and while it is straightforward to run “out of the box”, the entry barrier to adopting it to a desired target region are a bit higher.

9.6.2 Work carried out in AVENGERS

The usage of inversion data as well as its interpretation is of vital importance to independently verify emission inventories. For this it is necessary to not only have a basic understanding of the science behind atmospheric inverse modelling, but also know about practical limitations and common pitfalls and develop a feeling or intuition for inversion results. The best way to do that is in a “hands on” way. Therefore, the AVENGERS project will develop a Flexible Inversion Tool for the Inventory Community (FIT-IC), which aims at developing a tool for methane inversions that can be used directly by inventory experts. Box 2 discusses specifications of the FIT-IC tool [45] with respect to the current state of the art available inversion data for inventory experts. It will be designed such as to illustrate the impact of different settings, such as prior emissions, station network and other properties to show the impact of parameter changes towards the final data product.

As has become clear already in our discussion of available emission inventories, a critical step of inverse modelling is selecting sensible data from the wealth of available information. FIT-IC will support the inventory experts also in this step, thereby building knowledge about the impact of different choices. The system design is planned to be able to run on a regular personal computer with computing times on the order of a day, which allows the inventory compilers to “play around” with the system. The development of FIT-IC is part of WP6.

Box 2: Properties of FIT-IC with respect to the current status of data products for inventory experts.

Current Status:

- Inversion data with low spatial resolution for GHGs, see figure 8.
- No modification points for inventory staff, therefore, no entry point to understand how the system works.
- No easy way to handle the data for non-expert users

With FIT-IC:

- High resolution data <= (1° x 1°) **CH_4** with optional (N_2O +CO_2)
- GUI Interface and jupyter scripts, to make inversion demonstrations accessible for non-expert users
- Material and documentation curated by UBA
- Will contribute to a high-level understanding of the topic inversions at the non-expert users level.

9.6.3 Outlook on future developments

The tool will be curated by the partner UBA to also attract interest from other inventory agencies in using the demonstrator system for capacity building in their own entities as well as to possibly integrate additional use cases in the future to serve other gas species than methane or highlight other inversion parameters. This will also allow maintenance of the software after the end of the project.

10 Conclusions

10.1 General Remarks

The collaboration between inventory community and atmospheric scientists in joint research projects is fundamental to the success of any activities that focus on independent monitoring reconciliation and verification activities of emission data. Any type of national or international project or initiative for emission reconciliation should strive to go out and invite emission inventory experts and atmospheric scientists to actively develop and shape data products and services together for complementing classic emission data as it is reported to UNFCCC. These data products that are to be used in official emission reports can only be developed through a constant bi-directional communication between the two science communities. Therefore, it is critical for inventory compilers to move out of the comfort zone and engage in the analysis of more complex data and processing streams, schematically outlined by figures 1 and 2 to be able to finally implement the 2019 Refinements for QA&QC for GHG Reporting [1]. The atmospheric science community likewise needs to actively collect feedback and input from emission inventory experts, who have to report to UNFCCC, to develop new datasets and services that are then taken up in the reporting cycle. The political stakeholders have to ensure sufficient funding for the atmospheric science community that at least selected prototype products are continued past the limited time of a scientific project, e.g. highly valuable initiatives with an elaborate dashboard such as ESA's World Emission project that is directly tailored for the emission inventory community. This usually is done by transferring the projects tools to larger organisations that support operational activities such as ECMWF for continuation funded by public stakeholders as their contribution towards GHG monitoring.

10.2 AVENGERS Vision

One of the major aims of the project is to provide capacity building and knowledge transfer from the atmospheric science community towards the inventory compilers within each of the work packages, shown in figure 1. This is ensured by common activities within the work packages, which are guided by the here presented user stories. General more broad topics or questions, which are addressed by the AVENGERS atmospheric science team and have been formulated by the AVENGERS inventory team are shown in box 3. They usually provide the link in figure 2 between the empiric side, shown in green and the modelling side outlined in yellow colours. These user stories also contribute greatly to capacity building for inventory staff. These user stories are focussed at enabling inventory experts in working with model data as well as remote sensing data from the atmospheric science community with the goal to integrate these data into their data portfolio that is used for emission reporting.

Box 3: General emission inventory needs as they are potentially addressed by the atmospheric scientists in the AVENGERS work packages, more details can be found in the individual user stories.

Sensors for GHG Mapping (WP 5 & T1.3):

- Capacity building on sensor types, sensing platforms and their properties (detection limits, usage scenarios, prerequisites)
- Examples for methane detection and quantification from current spaceborne sensors (TROPOMI and EnMAP)
- Examples for methane detection and quantification from ground-based sensors (HySpex imaging spectrometers)
- Sensitivity Study for future sensors (CO2M)

Inversion and other modelling systems (WP 2, 3 & 4 + T1.4):

- More detail and feedback for prior construction (T 2.1)
- Construction of data products for complementing classical inventory data for the three major GHGs (see figures 3 and 8).
- Feedback on measurement network data coverage with respect to AVENGERS countries and its impact on the inversions
- Attempt on a coarse source attribution in addition to
- Provision of tools for inventory compilers to analyse and integrate AVENGERS data into their reporting cycle (T1.4)

User stories and tools (WP 6):

- Joint development and deployment of an inversion demonstrator tool FIT-IC for non-expert users
- Definition of FIT-IC interface and scenarios for user interaction

More detailed information on more sectoral target user stories can be found in box 4. Here we see that the largest source of uncertainty is targeted with the AFOLU sector. User stories from the Netherlands and Italy are specifically targeting this sector. The inventory of Cyprus is interested in addressing methane emissions in their inventory. These user stories are directly related to improve data in individual sectors by complementing classical inventory data with independent data, e.g. from modelling.

Box 4: Emission inventory needs with respect to individual sectors as they are potentially addressed by the atmospheric scientists in the AVENGERS work packages, more detail can be found in the individual user stories.

Individual sectors LULUCF (WP 4 & 2):

- Tests of Copernicus Land Service product CLC+ instance LULUCF and improvement with respect to national data
- Potential input for Top-down modelling in WP4
- Data comparison LULUCF inventory vs. complementary data
- Potential integration of output of WP4 data into T2.1
- Capacity building for inventory agencies on CLC(+)

Agriculture and wetlands (WP 4 & 2):

- Analysis national totals of the three major GHGs
- For evaluation of uncertainty for N_2O and CH_4 in the AFOLU sector
- Analysis of methane in wetlands

Methane Emissions (WP 2):

- Assessment of methane emissions in the inventory
- Determine level of underestimation in the waste sector and its potential causes
- Assessment of methane in the inventory with complementary inversion data

11 References

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