CoCO2

Prototype system for a Copernicus CO_2 service

Decision Support Blueprint (preliminary)

WP8

Co-ordinated by ECMWF

CoCO2

Prototype system for a Copernicus CO_2 service

D8.4 Preliminary version of a Decision Support Blueprint

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CoCO2: Prototype system for a Copernicus CO_2 service

Coordination and Support Action (CSA)
H2020-IBA-SPACE-CHE2-2019 Copernicus evolution – Research activities in support of a European operational monitoring support capacity for fossil CO2 emissions

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1 Executive Summary

The CO_2 emissions Monitoring and Verification Support (CO2MVS) is being developed to help support user's verification activities, particularly with the influx of new space-based observations (such as through CO2M). The proposed CO2MVS framework is made of several components: **prior information** (e.g., initial emission estimates) and **observations** (e.g., meteorology, satellites) that require **integration** (e.g., via models) to produce **outputs** (e.g., revised emission estimates), that are then condensed into a **decision support system** (e.g., user functions). This deliverable is about the decision support system. The decision support system translates the complex data and methods into a format that meets user needs, depending on the spatial and temporal scale of interest.

The CO2MVS landscape is growing given new demands stemming from the Paris Agreement and its Global Stocktake. New technology (satellites), improved methods (inversions) and computing power, also open new opportunities for monitoring and verification support. The IPCC reporting guidelines now give guidance on using verification to support inventory estimates, and several countries are applying verification in their national inventory reports. Through research projects, inventory agencies are also getting exposed to ongoing verification activities, particularly through the CO2MVS framework. The lessons learnt through various user events mark a clear path forward for a Decision Support Blueprint.

The current state-of-the-art in verification activities is to bring the different datasets together and make them comparable. The UK and Switzerland perform the most comprehensive comparisons in their inventories. However, to date, there is limited experience of inversions leading to improvements in emission inventories. To many, the overall verification process is still a black box and few inventory agencies understand the details. There is a need for a simple representation of what is behind the data, what it represents, and what is the uncertainty. To make comparisons that are not superficial, inventory agencies need more detailed data, as the total is always the aggregation of components with often very different dynamics. Inventory agencies and researchers still do not have a clear understanding of each other's needs, or a common understanding of the limitations of various datasets. Inventory agencies probably need direct and specific exchange with modellers and data providers, to explain and understand the inversions, suggesting that there may be a greater need to focus on specific case studies.

We have suggested six areas where we see the most productive gains to be made: 1) Building a common knowledge base, 2) Case studies, 3) Technical aspects of inversion modelling, 4) Graphical material and analysis tools, 5) Communication, and 6) Collaboration. Many of these activities have already been initiated but need to be improved and expanded.

This Decision Support Blueprint is the first step in a process in CoCO2 and beyond. This document is a *preliminary* blueprint that will be improved through dialogue with researchers and users in the first half of 2023. An updated version will be completed in July 2023.

2 Introduction

2.1 Background

The scientific community has long focused on understanding the relationship between emissions and atmospheric concentrations. Most research has focused around closing the biogeochemical cycles (Canadell et al. 2021), with particular attention on the global carbon budget (Friedlingstein et al. 2022), the global methane budget (Saunois et al. 2020), and the N_2O budget (Tian et al. 2020). It is now time to operationalise the science in a policy context. The Paris Agreement has essentially shifted the demands on the science community from diagnosing the problem to monitoring and verifying climate action (Peters et al. 2017). The five-yearly Global Stocktakes (GSTs) and ratcheting of policy ambition through updated National Determined Contributions (NDCs) depend on contributions from the scientific community. Policy makers are putting faith in the science, by enhancing observational capabilities, such as through new satellite programmes (e.g., CO2M).

In the EU, a CO2 Monitoring Task Force translated the identified needs into a conceptual framework (Janssens-Maenhout et al. 2020): CO_2 emissions Monitoring and Verification Support (CO2MVS). The structure of the CoCO2 project directly maps to the proposed CO2MVS framework (Figure 1). The CO2MVS is made of several components: **prior information** (e.g., initial emission estimates) and **observations** (e.g., meteorology, satellites) that require **integration** (e.g., via models) to produce **outputs** (e.g., revised emission estimates), that are then condensed into a **decision support system** (e.g., user functions). The decision support system is where the user value is added. It requires translating the complex material into a more comparable and digestible format for users, depending on the spatial and temporal scale of interest. However, to facilitate this it is necessary to understand several concepts associated with the entire CO2MVS framework.

Anthropogenic emissions have been estimated for several decades now (Andrew 2020), typically using a **bottom-up** or **inventory-based approach**. The term *bottom-up approach* can be ambiguous, as it means different things depending on the context. Generally, a bottom-up estimate is a collection of sub-estimates (e.g., at the sector level) which are then combined to get a total. As suggested by their name, emission inventories are primarily based on bottom-up methods: Emission inventories are generally an estimate based on the activity level (or activity data, AD) times an emission factor (emissions per unit activity, EF) by sector or fossil fuel category. However, it is also the case that emissions can be estimated using models or observations, often outside of the notion of *bottom-up*. This is particularly the case in the land-based or agricultural sectors. For this reason, the term *inventory-based approach* may be more appropriate as it refers directly to the emission inventories that countries construct and report to the UNFCCC[1] based on the IPCC guidelines (IPCC 2006). Different methods can be used in different sectors, but they are all fundamentally bottom-up approaches, whether it is the AD×EF approach or by use of more complex models. Most countries construct their own emission estimates (e.g., as reported to the UNFCCC), but some organisations make country-level estimates to estimate a global total (e.g., EDGAR[2]). Emission inventories can be at different spatial and temporal scales (e.g., country-level annual estimates versus gridded monthly estimates). For a more extensive discussion of the history of CO_2 estimates and why they vary, refer to Andrew (2020).

It is also possible to estimate emissions using what is known as a **top-down**, **observation-based**, or **inversion-based approach**. In a *top-down approach* aggregated information, usually based on observations, is used to estimate emissions indirectly. This method works well for trace gases with long lifetimes that have few natural sources and sinks. A concrete example is where observations of SF_6 concentrations can be combined with a simple first-order chemical decay equation to estimate emissions. This method works well for global totals but does not provide information at the sector or country level (without linking to a more complex model with transport of trace gases). For trace gases with shorter lifetimes or with lots of natural sources and sinks, such as CO_2 and CH_4, additional observational data is needed on the sources and sinks together with atmospheric flows to constrain the method. Even though CO_2 has a long lifetime, it has complex interactions with the ocean and land sinks, requiring the use of a carbon-cycle model. CH_4 has a relatively short lifetime (about a decade) but has a complex chemical interaction with other species in the atmosphere, via the OH radical, requiring a chemical transport model. An **inverse model** is often used to estimate emissions from observations. An inverse model is not dissimilar to the simple first-order decay

[1] United Nations Framework Convention on Climate Change (UNFCCC)

[2] Emissions Database for Global Atmospheric Research (EDGAR)

equation for SF_6, just considerably more complex and data intensive. This complexity is essentially why a CO2MVS is needed and explains the dominance of the boxes on **observations** and **integration** (Figure 1).

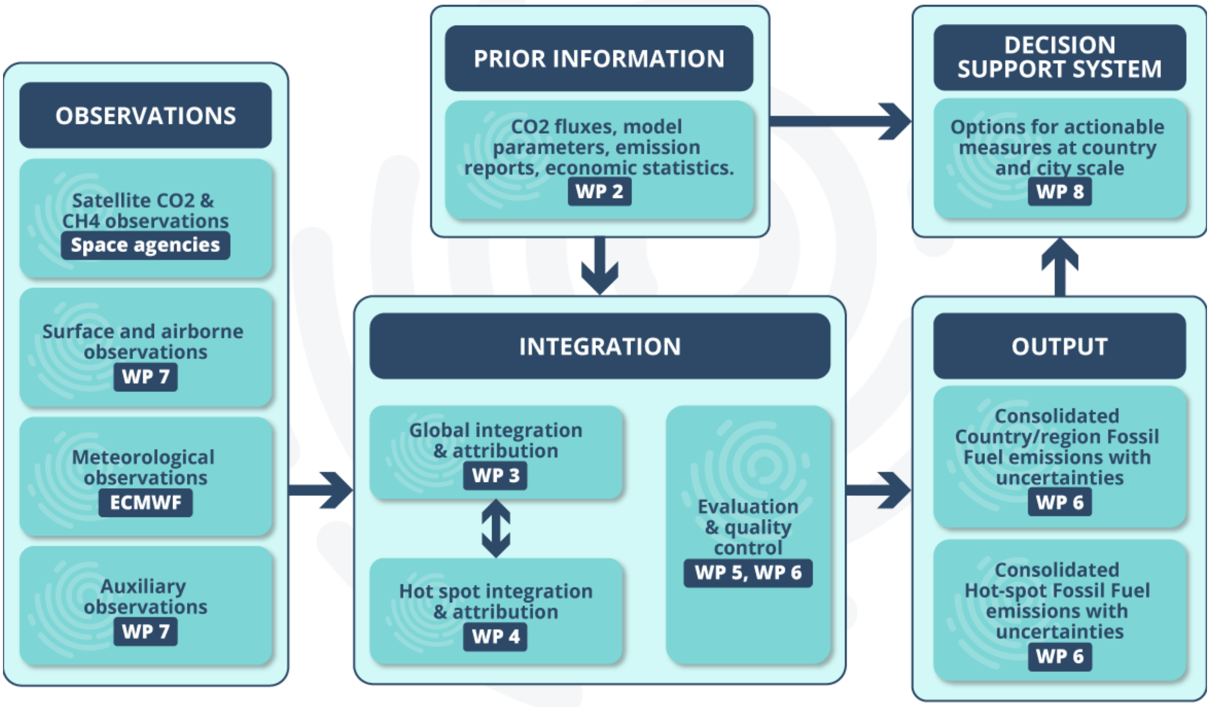


Figure 1: The CO2MVS and linkages to Work Packages in CoCO2.

The existence of top-down and bottom-up approaches, or, preferably, inventory- and observation-based approaches, is where the notion of **verification** arises and why a **decision support system** is needed. If an inventory agency estimates their country's emissions following the IPCC guidelines, then those estimates may need to be compared with independent estimates such as those provided by observation-based approaches. In principle, this sounds easy; in practice, it is more complex. Depending on the trace gas there needs to be a sufficient observational network (ground- or space-based), particularly to resolve country-level estimates. Very few methods can give sector resolution, particularly at the level in inventory-based estimates. Observational-based approaches have been used to identify reporting problems with CO_2 emissions in China (Akimoto et al. 2006), CH_4 in China (Cheewaphongphan, Chatani, and Saigusa 2019), HFCs in Europe (Keller et al. 2011) and China (Rigby et al. 2019), to name a few examples. However, the current observational networks and modelling capacity are not sufficient to routinely resolve country-level estimates in most countries, particularly for the key greenhouse gases CO_2, CH_4, and N_2O. The current CO2MVS developments are largely in preparation for an influx of space-based observations, which will complement but not replace land-based observations. At a minimum, land-based observations are still needed as an important calibration tool to the more extensive space-based observations.

To prepare for the influx of observational data and its applications in CO2MVS, this deliverable is a first step in preparing a decision support system. There is increasing activity comparing inventory-based and observational-based emission estimates, primarily in the scientific literature (Andrew 2020; Petrescu, Qiu, et al. 2021; Petrescu et al. 2020; Petrescu, McGrath, et al. 2021) but also in some National Inventory Reports (e.g., Switzerland or UK). This existing work will act as a starting point, together with dialogues between researchers and inventory agencies in the EU projects VERIFY and CoCO2, and similar ongoing activities.

2.2 Scope of this deliverable

2.2.1 Objectives of this deliverable

The **objective** is to develop a preliminary *blueprint* for a decision support system, with a focus on useable *graphical and analytical comparisons* of inventory-based and observation-based emission estimates at the country level. As a *blueprint*, this deliverable is considered one step in a much longer path leading to an operational decision support system. The ideas will be presented and discussed in user consultation meetings in the first half of 2023 with the final version of the blueprint due in mid-2023.

The decision support system could be quite broad, but here we focus primarily on the country level and how independent inventory-based and observational-based approaches can be used to monitor and support emissions that are reported to the UNFCCC. The focus will be on how to compare different estimates of emissions, in a format that is easily accessible and understandable to users. We recognise that users will come from very different backgrounds and levels of expertise, and the decision support system will need to cater for this. As with many situations of tracking progress, our general approach is to start with a broad and aggregated perspective, and then iteratively zoom in until the necessary level of detail is reached (c.f., Peters et al 2017). We expect some users to go beyond the level of detail possible in a generic decision support system, and we will therefore explore different reporting formats, with suggested tools to automate the development of a range of quality outputs.

2.2.2 Intended audience

Since this deliverable is aimed at country-level emission estimates, the primary audience is national inventory agencies, policy makers at national and regional level, but this will more broadly encompass the European Commission CO2 Monitoring Taskforce, the CAMS implementation team, and those in the European Commission responsible for the CO2MVS or its components.

A secondary audience is the scientific community which will generate much of the data products in the CO2MVS, and user communities interested in smaller spatial and temporal details. The relevant spatial scales could be regions (European Union), countries, cities, and companies.

2.2.3 Work performed in this deliverable

Document analysis, informal discussions with scientists and users.

2.2.4 Deviations and counter measures

Not applicable

3 Current verification activities involving users

This section gives an overview of the current verification ecosystem in the context of emission inventories, and a summary of various relevant user interactions. This acts as a basis for outlining the current knowledge gaps that can be addressed in the decision support blueprint (Section 4).

3.1 Overview of the verification ecosystem

Official reporting of greenhouse gas emission inventories is required by a subset of countries but will soon expand to all countries (Perugini et al. 2021). The UNFCCC follows the IPCC reporting guidelines (IPCC 2006), which now have expanded provisions for quality assurance, quality control, and verification (IPCC 2019). According to the IPCC guidelines glossary:

> **Quality Assurance** (QA) activities include a planned system of review procedures conducted by personnel not directly involved in the inventory compilation/development process to verify that data quality objectives were met, ensure that the inventory

represents the best possible estimate of emissions and sinks given the current state of scientific knowledge and data available, and support the effectiveness of the quality control (QC) programme.

Quality Control (QC) is a system of routine technical activities, to measure and control the quality of the inventory as it is being developed. The QC system is designed to:

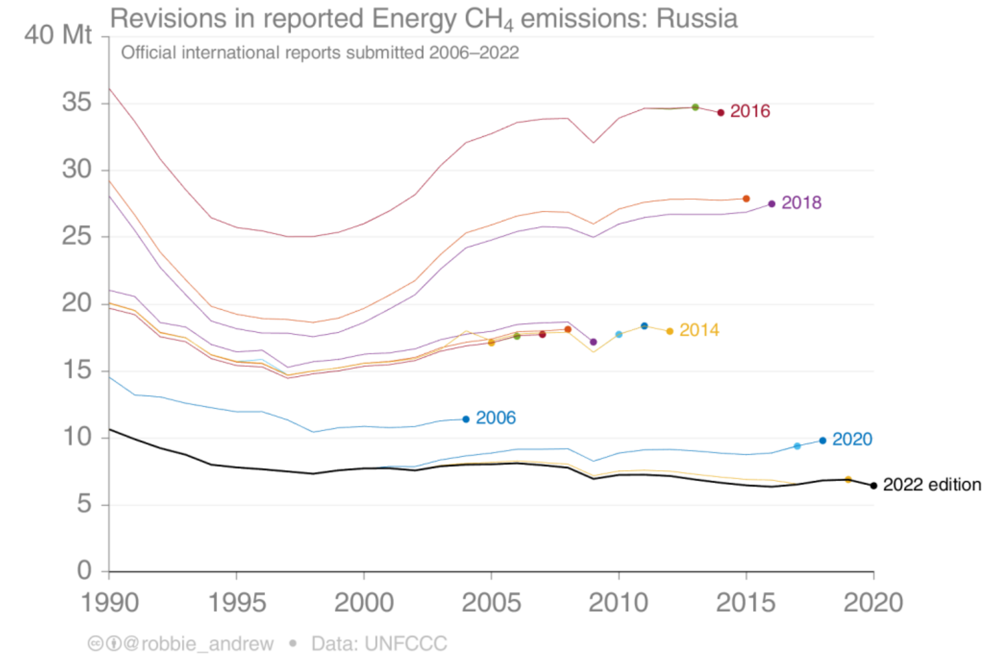
i. Provide routine and consistent checks to ensure data integrity, correctness, and completeness;
ii. Identify and address errors and omissions;
iii. Document and archive inventory material and record all QC activities.

QC activities include general methods such as accuracy checks on data acquisition and calculations and the use of approved standardised procedures for emission calculations, measurements, estimating uncertainties, archiving information and reporting. More detailed QC activities include technical reviews of source categories, activity and emission factor data, and methods.

Verification refers to the collection of activities and procedures that can be followed during the planning and development, or after completion of an inventory that can help to establish its reliability for the intended applications of that inventory. Typically, methods external to the inventory are used to check the truth of the inventory, including comparisons with estimates made by other bodies or with emission and uptake measurements determined from atmospheric concentrations or concentration gradients of these gases.

Understanding these definitions and the associated processes is important. Emission inventories reported to the UNFCCC by the so-called Annex I countries (essentially developed countries) already undergo formal and extensive QA/QC (Perugini et al. 2021) and is something that other independent inventory compilers do not go through, with the exception of the irregular peer review process in scientific journals (Janssens-Maenhout et al. 2019). Given the already existing QA/QC procedures, one expects that emission inventories reported by Annex I countries to the UNFCCC have the highest quality. The QA/QC identifies problems, all of which must be addressed, and thus one can clearly see an evolution of inventory estimates over time as improvements are made (Figure 2).

The **verification** process is to ensure the reliability of the inventory estimates, for their intended purpose, and in the IPCC Guidelines verification includes both inventory-based comparisons and observation-based comparisons. While for some sectors, countries, or greenhouse gases the estimates may be accurate and well beyond the capability of observation-based approaches, even with a QA/QC system, there are cases where independent verification can help support the improvement of inventories (e.g., Figure 2). In many countries, the uncertainty in fossil CO_2 emission inventory estimates may be lower than what is currently achievable with observation-based estimates, but for land CO_2 fluxes, CH_4, or N_2O the observation-based estimates may be a powerful complementary estimate to support inventory-based approaches in regions with sufficient observations. The UNFCCC inventories already do comparisons of the sector-based estimates with a coarser reference approach, which is one form of verification that can identify mass balance inconsistencies. A careful comparison across independent inventory-based approaches can reveal causes of differences (Andrew 2020; Deng et al. 2022) and identify errors (e.g., CoCO2 D8.1 on EIA estimate of oil).



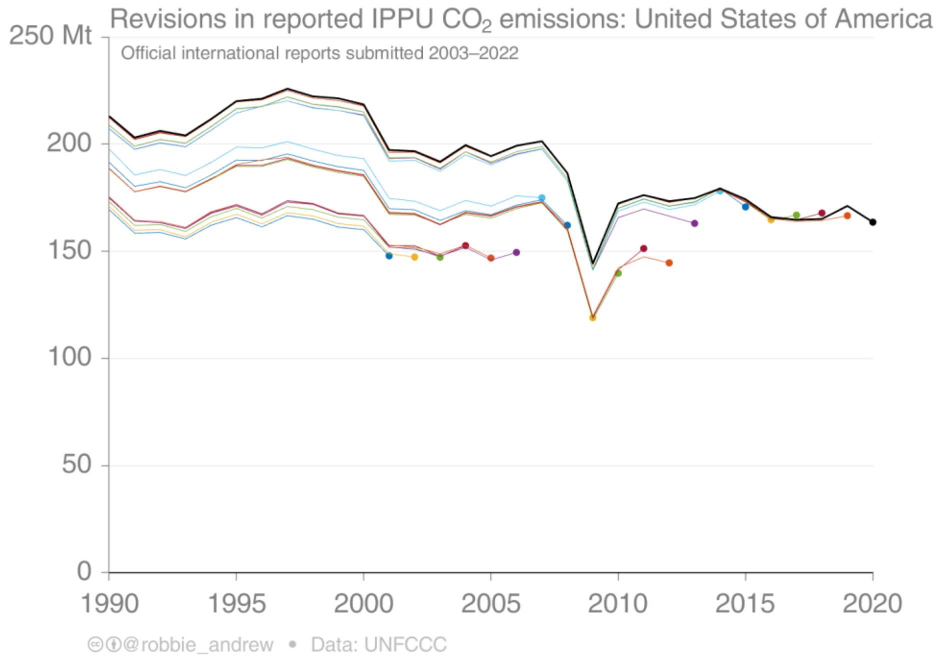


Figure 2: Revisions in reported CH_4 emissions from Russia in the energy sector (top) and CO_2 emissions from the USA in the IPPU sector (bottom), demonstrating how different versions of the inventories have different estimates. The final year of each line indicates the edition of the different inventory reports (as N-2). Depending on the country, sector, and greenhouse gases, the variations differ, from small to large. These figures only represent indicative examples.

3.2 Verification practices in official UNFCCC national inventory reports

It is good practice to implement quality assurance/quality control (QA/QC) and verification procedures in the development of national greenhouse gas inventories to ensure that the quality of the inventory can be readily assessed. Verification refers specifically to those methods that are external to the inventory and apply independent data. There are two main methods of verification: 1) independent inventory-based estimates, 2) observation-based emission estimates.

A challenge with comparisons against *independent inventory-based estimates* is that none are truly independent (Andrew 2020) as they may rely on, for example, the same energy data reported by a country. Experience has shown that performing detailed comparisons can help clarify differences in system boundaries or even identify errors (Andrew 2020). Improving independent emission inventories also has value, as these are often used in global studies where common methods across all countries are desired.

Observation-based estimates require observations of atmospheric concentrations or fluxes, that are then coupled to a transport model. These methods are more complex, uncertain, and computationally expensive, but are also more independent than inventory-based comparisons (although inversions do need prior input on inventories).

In both cases, correspondence between the national inventory and independent estimates increases the confidence and reliability of the inventory estimates by confirming the results. Since most developed countries have reported UNFCCC inventories for decades and these have been continually refined, most focus is on observation-based estimates. As an increasing number of developing countries begin more detailed and frequent reporting, comparisons with independent emission inventories will initially be an important method of verification for those countries.

In the 2019 refinement of the IPCC guidelines, the guidance on the use of atmospheric measurements for verification was extended (IPCC 2019). The refined guidelines highlight that notable advances that have been achieved in the application of inverse models of atmospheric transport for estimating emissions at national scale. Consequently, there are several countries that now use atmospheric measurements for verification of parts of their inventories (Table 1). Several countries use observations to help validate estimates of fluorinated gases as they are most easy to work with due to the absence of natural sources. Australia and New Zealand have estimated regional CH_4 emissions to help better understand the methods and their potential. Germany performs various cross validation checks with available data, some of which is based on observations. The UK and Switzerland, however, have developed more comprehensive methods based on inversion modelling, covering fluorinated gases in addition to CH_4 and N_2O. Building on modelling experience, the country reporting confirms that most potential lies in using observations to verify fluorinated gases, the uncertainty in CH_4 and N_2O gives potential for verification but requires more comprehensive inversion modelling, while challenges remain high to verify CO_2 emissions from both fossil and land sources.

Table 1: Current use of atmospheric measurements for verification (as reported in respective National Inventory Reports 2020, published in 2022)

Country	Gases	Notes
Australia	HFCs, SF_6 CH_4 (one year, one region)	HFCs and SF_6 estimates done by CSIRO based on observations at the Cape Grim Baseline Air Pollution Station in Tasmania In 2019, the CSIRO undertook analysis of CH_4 plumes in the Surat Basin, Queensland, using two flux towers to obtain a 'top-down' estimate of CH_4 emissions, & the regional estimate was within 10% of the top-down estimate
Germany	CO_2, CH_4, N_2O	Verified with the help of the data sets recommended by the 2019 IPCC Refinements: EDGAR inventory, ECMWF's CAMS inverse-modelling data, Pollution Release and Transfer Register (PRTR), EU's ETS. The data are compared on Figure 104 (NIR, 2022), with a descriptive discussion of differences.
New Zealand	CH_4 (regional)	Inverse modelling was tested on regional and national emission estimates for 2011 to 2013 and 2018 using two observing stations. For the South Island results were reasonable, but more observations & research is required. The North Island results are not as robust.
Switzerland	HFCs, SF_6 CH_4, N_2O	Selected observations from Jungfraujoch are used with a simple formula to estimate emissions, with a discussion of divergences for each species. Inverse modelling used to validate total Swiss CH_4 and N_2O emissions, particularly the spatial extent, using Swiss observations. Due to variability & uncertainty, it is not possible to validate the reported emissions.
UK	(CO_2), CH_4, N_2O, HFCs, PFCs, SF_6, NF_3	Inversions are based around observations at Mace Head and supplemented with additional observations since 2012. A dispersion model is used with data from different sites for each species. Results for each species is discussed. Methods for verifying CO_2 estimates are being improved.
USA	HFCs	Additional quality control is performed by comparing the emission estimates derived from atmospheric measurements to the bottom-up emission estimates. Given the magnitude of the uncertainties relative to the size of any apparent emission changes, and the limited time-period of the analysis, overall trends in most of the gases are hard to discern with confidence except in the case of HFC-32.

It is important to understand why there are different challenges, and thereby opportunities, using observation-based emission estimates. These challenges and opportunities vary by the different greenhouse gases (IPCC 2019) and are now discussed in turn.

Fossil CO_2: Estimated uncertainties in inventories of fossil CO_2 emissions are generally quite low in developed countries (at most a few percent), making it challenging for observation-based approaches to provide useful input. The opportunities are larger in developing countries, where studies identified problems with Chinese CO_2 emission estimates around the year 2000 (Akimoto et al. 2006). Currently, observation-based approaches focus on the use of observations of co-emitted NO_x/CO, but as more space-based observations of CO_2 emerge this may change.

Land CO_2: Inventories of land-based CO_2 emissions are highly uncertain, but large natural sources and sinks make verification of anthropogenic sources difficult. There are also significant challenges with system boundaries for land CO_2 fluxes (Grassi et al. 2018). However, there are multiple approaches to verify land-based CO_2 emissions (inventories, process models, inversions), and thus this is a fruitful area to make progress.

CH_4: Even though inversions currently have high uncertainty, verification of CH_4 emissions is still possible since the inventories are sufficiently uncertain. In geographic areas with sufficiently strong ground-based observation networks, the inversions will have more value. In some cases, natural emissions and seasonality can be additional challenges.

N_2O: As for CH_4, N_2O emissions are a good candidate for inverse modelling since the inventories have high uncertainty, which may compensate for the high uncertainty in the inversions. Again, a strong ground-based observational network in the relevant geographic area could improve the inversion.

Fluorinated gases: The use of atmospheric measurements is currently most prevalent for F-gases (HFCs, PFCs, SF_6). F-gases are particularly well suited for inverse modelling as they are solely of anthropogenic origin and are often sufficiently long-lived. In addition, bottom-up inventories for F-gases are generally derived from very limited data and simple models and therefore have large uncertainties.

This short summary by greenhouse gas is consistent with the activities seen in individual countries (Table 1). Nearly all countries using observation-based verification consider fluorinated gases. The analysis is essentially embedded in the inventory-based estimates of emissions, as the inventory-based estimates suffer from insufficient data and high uncertainties. The countries with the most elaborate verification activities (UK and Switzerland) focus on CH_4 and N_2O, which represent a good opportunity for verification. Other countries have explored CH_4 inversions at a regional level where there is higher uncertainty (e.g., leaks in oil and gas infrastructure). No country has yet performed detailed verification for CO_2, either fossil- or land-based, indicating the challenges (Germany does a comparison with off-the-shelf inversion results).

One element that is clear from the country activities is that they generally focus on single models. Much of the inversion analysis in the research community, however, uses multiple models. Inventory agencies, so far, seem to prefer individual models or studies, where they can perform a more detailed analysis and interpretation of the results. The countries doing the most elaborate inversion analysis also have a close working relationship with the inventory agencies and the inversion modelers, indicating that sufficient resources are needed to do a sufficiently detailed analysis for an inventory report.

3.3 Feedback from user experiences with verification

3.3.1 Key activities

There have already been considerable efforts to build competence with verification activities. The work of the European Commission CO_2 Monitoring Task Force laid the foundation for EU funded projects such as CHE (2017-2020), VERIFY (2018-2022), and CoCO2 (2021-2023). Three new EU projects start in 2023 (AVENGERS, Paris, EYE-CLIMA). The US National Academies formed a committee to write a report on Greenhouse Gas Information for Decision Making, which covers many relevant aspects of a CO2MVS. Many individual countries are ramping up activities, particularly given the influx of data and opportunity to come with new satellites (e.g., CO2M). The IPCC already gives guidance to using verification to complement existing QA/QC activities (IPCC 2019). The present Decision Support Blueprint builds on this work. Here we indicate key documents from specific projects that provide information on user needs and experiences.

The European Commission CO_2 Monitoring Task Force provides in-depth analyses and guidance on the many issues associated with the implementation of a ground-based infrastructure in support of an operational capacity to monitor anthropogenic CO_2 emissions:

- CO_2 Blue Report (2015)[3]: Assesses the need and opportunity for an independent European space-borne observation capacity for CO_2 to monitor and to verify the compliance of parties to international climate agreements (Ciais et al. 2015).
- CO_2 Red Report (2017): Describes the baseline requirements, functional architecture and system elements needed to implement an operational CO2 Monitoring and Verification Support capacity (Pinty et al. 2017).
- CO_2 Green Report (2019): Describes the needs and high-level requirements of in situ measurements to help establish an operational Monitoring & Verification Support (MVS) capacity to quantify anthropogenic CO_2 emissions (Pinty et al. 2019).
- The reports are summarised in a scientific publication: Janssens-Maenhout *et al* (2020), Toward an Operational Anthropogenic CO_2 Emissions Monitoring and Verification Support Capacity, *Bulletin of the American Meteorological Society (BAMS)*.

Most relevant deliverables from the EU Horizon 2020 Coordination and Support Action “CO_2 Human Emissions” (CHE[4]):

- D1.3 Reconciliation of top-down and bottom-up estimates of the carbon balance
- D1.4 Stakeholder report on the requirements for future space-based instruments to deliver products suitable for CO2 emission monitoring

Most relevant deliverables from the EU Horizon 2020 Research and Innovation Action “Observation-based system for monitoring and verification of greenhouse gases” (VERIFY[5])

- Work Package 1: Inventories
    - D1.1 MRV User Requirement Document
    - D1.2 Terminology analysis
    - D1.4 Verification requirements assessment
    - D1.5-D1.7: First, second, and third ad hoc meeting for networking between national inventory agencies and the scientific community
    - D1.8: Report on the connection of VERIFY and the IPCC process
- Work Package 5 & 6: Synthesis and Products
    - A comparison of estimates of global carbon dioxide emissions from fossil carbon sources, *Earth System Science Data* (Andrew 2020)
    - European anthropogenic AFOLU greenhouse gas emissions: a review and benchmark data, *Earth System Science Data* (Petrescu et al. 2020)
    - The consolidated European synthesis of CH_4 and N_2O emissions for the European Union and United Kingdom: 1990–2017, *Earth System Science Data* (Petrescu, Qiu, et al. 2021)
    - The consolidated European synthesis of CO_2 emissions and removals for the European Union and United Kingdom: 1990–2018, *Earth System Science Data* (Petrescu, McGrath, et al. 2021)

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[3] It appears that this report was completed before the task force was formally established
[4] https://www.che-project.eu/resources
[5] https://verify.lsce.ipsl.fr/index.php/repository/public-deliverables

    - The consolidated European synthesis of CH_4 and N_2O emissions and removals for the European Union and United Kingdom: 1990–2020, *Earth System Science Data preprint* (Petrescu et al. 2022)
    - D6.11: Report on the future operational transition of the VERIFY observation-based GHG monitoring system
- Work Package 7: Input to international programs and society
    - D7.6: First progress report on the VERIFY cooperation with GEO initiative on C and GHG
    - D7.9: Second and final report on the research needs for verification
    - D7.11: Second and final progress report on the VERIFY cooperation with Global Initiatives including UNFCCC/ SBSTA, GCOS and WMO/IG3IS

Key deliverables EU Horizon 2020 Coordination and Support Action “Prototype system for a Copernicus CO_2 service” (CoCO2[6]):

- D6.1 Fact sheets with national observation-based carbon budgets from T6.1 for year 2021
- D6.2 Scientific review article on carbon budgets for year 2021
- D6.3 User Requirement Document
- D6.4 Functional Requirements Specification Documents
- D6.6 Fitness for Purpose Documents
- D8.1-8.3 Budget Estimates for CO2 and CH4 V1-3
- D8.4-8.5 Decision Support Blueprint (this document)

The US National Academies Committee on Development of a Framework for Evaluating Global Greenhouse Gas Emissions Information for Decision Making

- Greenhouse Gas Emissions Information for Decision Making: A Framework Going Forward (National Academies of Sciences, Engineering, and Medicine 2022)

IPCC

- 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC 2006)
- 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC 2019)
- IPCC Expert Meeting on Use of Atmospheric Observation Data in Emission Inventories (5-7 September 2022)

Various governmental, intergovernmental, and non-governmental bodies have closely connected activities (see VERIFY D7.6, D7.11)

- UNFCCC (through COPs and SBSTAs)
- Group on Earth Observations (GEO)
    - GEO Carbon and Greenhouse Gas Initiative (GEO-C)
- World Meteorological Organization (WMO)
    - Integrated Global Greenhous Gas Information System (IG3IS)
    - Coordinated Global GHG monitoring infrastructure[7]
- Integrated Carbon Observation System (ICOS)
- Global Carbon Project (GCP)
    - REgional Carbon Cycle and Assessment Processes (RECCAP 1 & 2)
- Global Emissions InitiAtive (GEIA)

[6] https://coco2-project.eu/resources
[7] https://public.wmo.int/en/our-mandate/focus-areas/environment/greenhouse-gases/global-greenhouse-gas-monitoring-infrastructure

3.3.2 The VERIFY fact sheets

Through the VERIFY project several synthesis studies were performed (Andrew 2020; Petrescu, Qiu, et al. 2021; Petrescu et al. 2020; Petrescu, McGrath, et al. 2021). Due to space requirements, these synthesis studies were restricted to the aggregated EU level, with only little detail at the country level. However, the key synthesis figures for each country and region were compiled into “fact sheets”. There is an individual fact sheet for fossil CO_2, land CO_2, CH_4, and N_2O. These fact sheets are compiled for 79 countries and regions (individual countries in Europe, plus a variety of aggregations to make more relevant for policy or more scientifically robust due to the size of the region). This means that there are over 300 individual fact sheets. Because of this, the process is highly automated and the text on each fact sheet is general (Figure 3). In addition to the fact sheets, the VERIFY website hosts additional figures and the data behind them.

The VERIFY fact sheets completed one milestone, which was to compile all the information in an accessible, and necessarily automated, format. Many of the figures are too complex for the untrained reader to fully understand but also have limited utility to a user that wants to do more than a simple comparison of datasets. The goal in CoCO2 is to build on, improve, and expand the figures used in the fact sheets, to find ways to make them more accessible to users, without having the burden of users compiling the data and constructing independent figures. The evolution of these figures will occur in D6.1, 6.2, D8.1-3, and this document (D8.4-5). It is further necessary to develop and transition the VERIFY operational software into the CO2MVS system (VERIFY D6.11[8]).

[8] Report on the future operational transition of the VERIFY observation-based GHG monitoring system

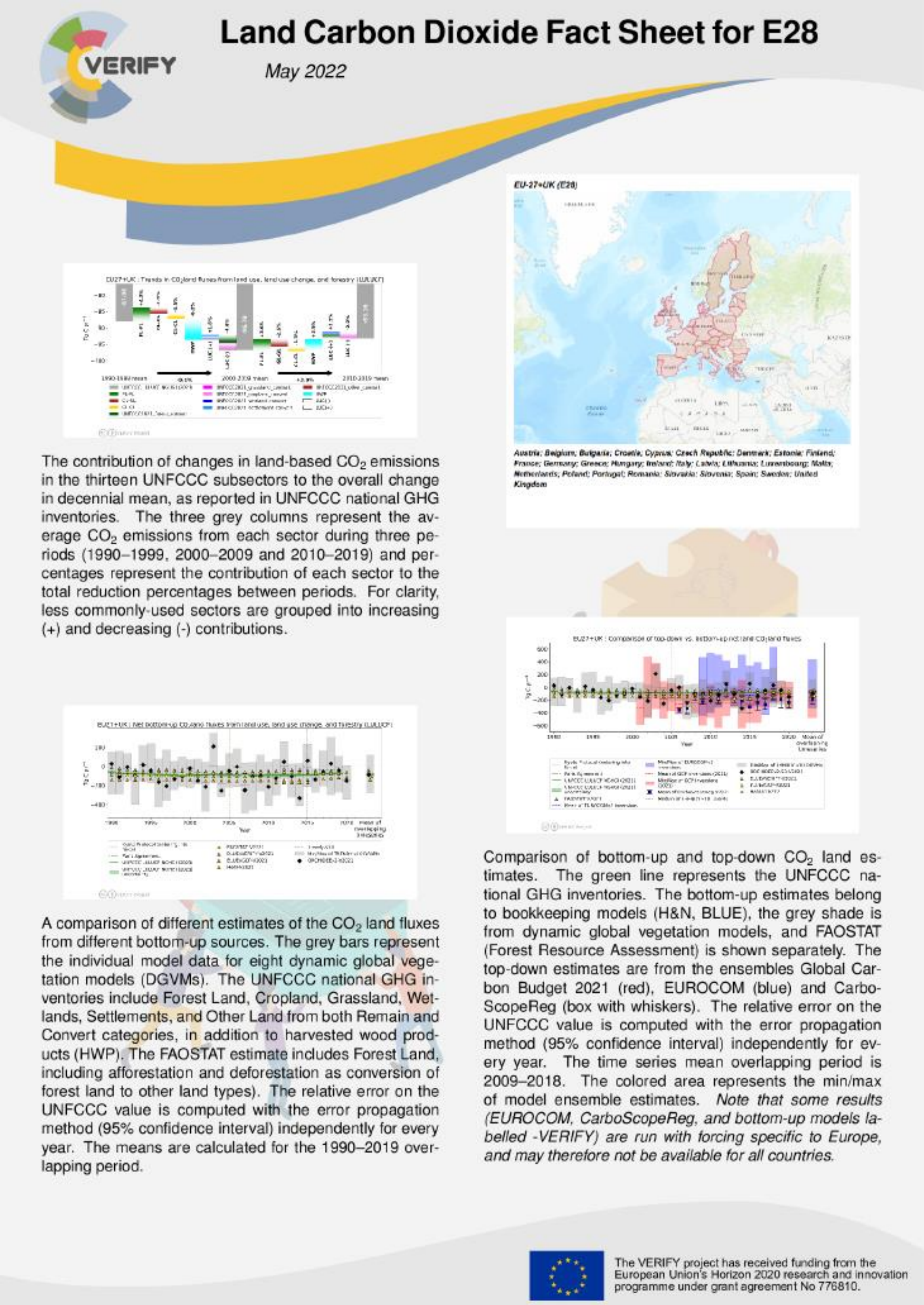

Figure 3: An example of one of the more than 300 VERIFY fact sheets, showing land CO_2 emissions in the EU28.

3.3.3 VERIFY Inventory Networking Meetings

Through the VERIFY project three networking meetings between the project partners and inventory agencies were organised. Based on the final networking meeting, organized in May

2022, some key elements about the feedback from the inventory compilers are summarized in this section. The feedback from the inventory compilers was based on their work with VERIFY data products throughout the project.

A recurring topic was the need to build **competence** in inventory agencies. The starting point for most inventory agencies was a very limited knowledge of inversion modelling. Consequently, there was a broad request for an approach that would not require previous knowledge ("inversion for dummies"). Some of the inventory agencies would welcome specific training in the use of data products, e.g., through workshops and guided hands-on training with Jupyter notebooks. While building competence in inventory agencies was considered crucial, it was also strongly emphasised that continual cooperation between scientists and inventory compilers would be needed. Switzerland was used as an example of how inventory compilers and scientists have worked together for a decade on how to use observational data for inventory compilation.

The inventory agencies need to understand **what lies behind the data** from inversion models. In this respect inventory agencies pointed out several challenges. The variations in system boundaries (e.g., geographical and sectorial scopes) of the inversion models constituted a limitation for making comparisons with inventory data. Inventory agencies would need more information about the system boundaries and would ideally like data products to be further aligned to the IPCC inventory guidelines. Similarly, from the perspective of the inventory agencies, it would be an advantage to use the terminology from IPCC inventory guidelines.

There are **large variations in the estimates** from different observation-based approaches. Inventory compilers need to understand what causes these variations and how to choose among the various estimates or whether it is feasible to use a compilation of all available estimates. Furthermore, information on what data has been used as input to each top-down estimate were requested, as well as clear descriptions of the uncertainties in the models. Another challenge is that inversion models produce results close to the prior information if there is not sufficient information to shift the model away from the prior. This may falsely be interpreted as if the model confirms the inventory (if this is used as prior). There is a need to find ways to communicate whether results depend strongly on prior information.

In addition to clearer communication of what is behind the data, some questions that were raised during the networking meetings would require **further improvements** in the top-down modelling and/ or in the interpretation of the results. First, uncertainties in top-down models are often very large. These uncertainties need, in many cases, to be reduced before the results become useful for verification purposes. Second, the spatial resolution of inventory-based estimates needs to be improved in many cases, with inventory agencies unable to provide prior spatial resolution. Third, data products from VERIFY reveal discrepancies between inventory-based and observation-based approaches, but there is a need to dig deeper into the reasons for these discrepancies. Likewise, in cases where there is a good match between inventory-based and observation-based approaches, it would be useful understand the drivers behind the result to understand whether it indicates that the estimates are good, or whether the match is coincidental.

If using observation-based approaches in their **National Inventory Reports**, inventory agencies expect that they may get questions about these data and methodologies from reviewers during the UNFCCC inventory review. One inventory agency suggested that EU Member States should have a common approach to integrate VERIFY results in national Inventory Reports to lower the burden on each individual country in terms of explaining the use of the data products.

The feedback from inventory agencies during the VERIFY network meetings largely confirms the findings of the European Topic Centre on Climate and Energy (German, Matthews, and Ruyssenaars 2021). They found that the Land Use, Land-Use Change and Forestry sector (LULUCF) was as an area where uncertainties are large, but concerns were raised over the utility of comparisons against inverse model estimates of land-based biogenic CO_2 fluxes due to fundamental differences between LULUCF carbon stock changes and the land-surface exchange of CO_2.

3.3.4 Findings from the IPCC Expert Meeting

The IPCC Task Force on National Greenhouse Gas Inventories organised an IPCC Expert Meeting on the Use of Atmospheric Observation Data in Emission Inventories (5-7 September 2022). The aim of the meeting was to discuss issues relating to the use of atmospheric observation data and models in verification of national GHG inventories, building on the guidance provided in the *2019 Refinement* (IPCC 2019). The meeting was separated into four break-out groups: CO_2 emissions from fuel combustion, fugitive CH_4 emissions, AFOLU GHG emissions, and F-gases. Some of the key findings were:

- Verification may not lead to direct changes in inventories, but rather as a starting point for improvements
- Inverse systems need more standardisation and improvement of the ability to detect robust differences between inverse models and inventory data
- The use of atmospheric observations is a rapidly maturing science, and there is a critical need for dialogue and development of capacity between GHG inventory compilers and atmospheric observation researchers.
- There are some examples of comparisons between atmospheric observations and national inventories.

Each breakout group had specific recommendations in their summary notes (Figure 4). Many overlap, unsurprisingly, with the outcomes from the VERIFY Network Meetings and other dialogues between inventory agencies and inversion modellers. Inventory compilers need to be actively involved in comparisons and modellers need more experience evaluating GHG inventories. Recurring themes in breakout groups include topics such as: terminology, gridding, emission factors, dialogue with modellers and data providers, and similar. Whilst many technical themes around inversion modelling were discussed, most of the recurring themes related to ensuring a common understanding of common objectives. As an example, it is typical that an inventory compiler will be interested in emission factors, however, emission factors play little or no role for inversion modelling, necessitating the need for a bridge between the two different approaches. Any blueprint of the path forward will necessarily require building much stronger bridges between communities with traditionally quite different foci.

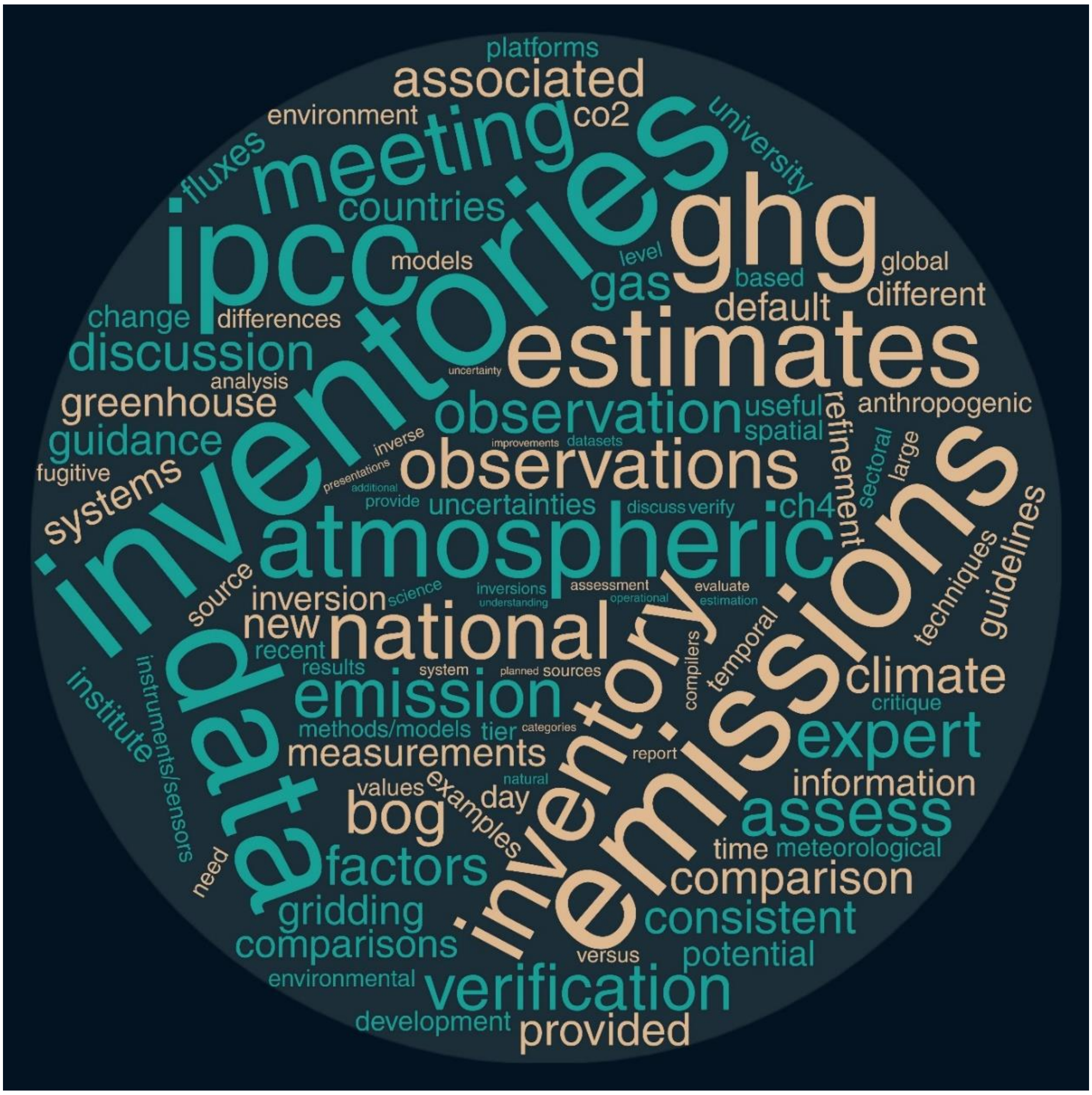

Figure 4: Word cloud of the IPCC Expert Meeting on the Use of Atmospheric Observation Data in Emission Inventories.

4 Decision Support System (DSS) blueprint

4.1 Identified knowledge gaps

The core challenge to a CO2MVS Decision Support System (DSS) is to translate the high volume of detailed data at fine temporal and spatial resolution into a format that is useful to a user which might be interested in annual emissions in a larger geographic location (city or country). Different users will have different levels of competence and therefore different needs. At one level a user might just want a quick comparison of country-level estimates, while another user might have the capacity to perform a detailed analysis across multiple datasets. The DSS is essentially a translation tool, that maps the highly detailed scientific data into a format that meets the user needs.

A synthesis in the VERIFY project identified several areas where further research is needed to meet verification needs (Figure 5), many aspects which overlap with the CO2MVS. This report was focused mainly on the scientific aspects but identified many gaps relevant to meet user needs. The need for more observations was clear, and in part, missions such as CO2M will partly respond to that challenge. Greater interactions between the scientific and inventory community are needed, particularly, in the context of making datasets more comparable.

Simulation tools, such as the community inversion framework, need further development. Targeting specific gases and sectors was identified as a key priority, in contrast to aiming for complete global coverage. Many of the points identified in VERIFY are also identified below in our independent analysis.

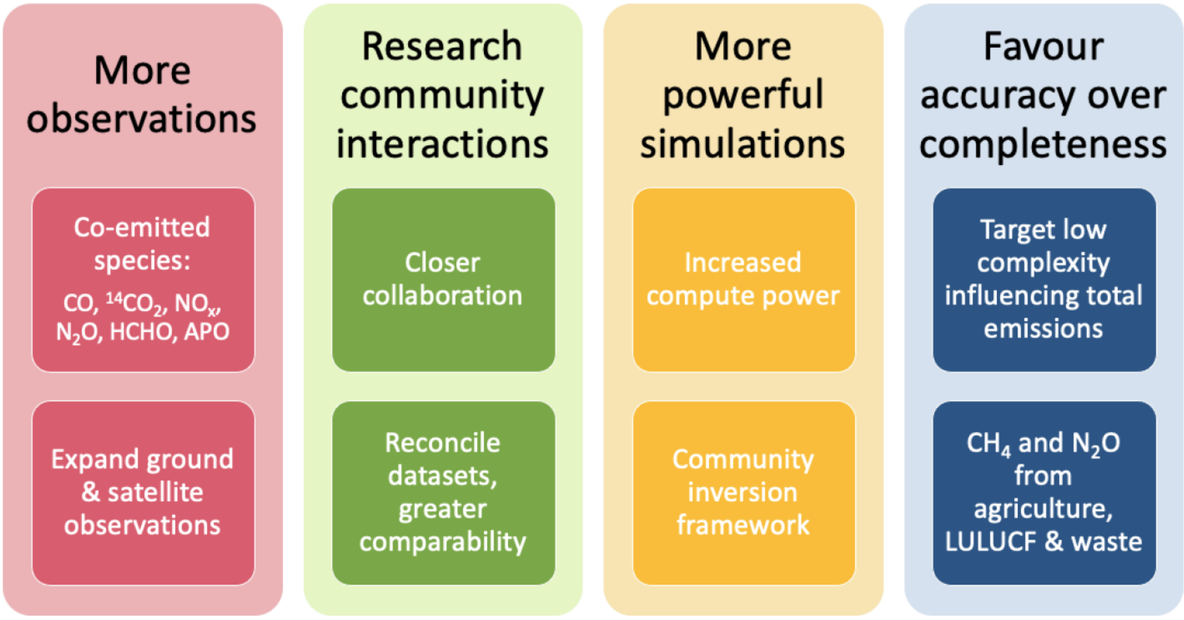

Figure 5: A summary of the future research needs identified in the VERIFY project (D7.9).

In the following, we provide a synthesis of user needs and challenges that need to be dealt with in a DSS. This is based on the author team's summary of user interactions (Section 3), experience in various projects (e.g., VERIFY, CoCO2), and the broader literature. We hope to refine, and potentially expand, the identified issues in partnership with users in the first half of 2023.

Clarifying the aim and managing expectations

Different users see different issues as important, depending on the demands in their current work tasks. These issues likely differ substantially to the issues modellers face in their current works tasks. To take an example, through the UNFCCC inventory review process, it may be identified that the estimates of emissions of wetlands should be improved, and so the inventory compiler may be focused on improving those estimates, such as via improved emission factors to apply to the area of wetlands. This sector may not be an important sector in the overall inventory but is identified as one where an improved estimate is needed. The CO2MVS may not be able to provide any support in improving those estimates, as the signal may be too small and diffuse. Thus, the challenge is to find questions which are relevant for both inventory compilers and inversion analysts, and the relevant spatial and temporal detail.

It is important from the start to clarify the objective of the analysis. What is the research question or what does the user need? Not all inventory questions can be dealt with through a CO2MVS, and not all inversion analysis is relevant for an inventory compiler. Clarifying these issues is important to manage expectations, and to help find areas where common analysis is fruitful and beneficial, and therefore partnerships grow.

Building a common knowledge base

A common theme across nearly all interactions with users is the need to increase the knowledge base. Most users don't know what an inversion is, where the input data comes from, and what are the key assumptions which may affect inversions. Verification can also have multiple meanings and implications. The whole concept of a CO2MVS becomes an overly abstract concept to communicate without a common knowledge base. Without this basic level of knowledge, comparing different estimates has little benefit, and the comparison quickly becomes overwhelmed with questions of clarity. Users have a particularly difficult job, understanding outputs from inversion models, as “the techniques and descriptions can even be hard for other scientists to understand” (National Academies of Sciences, Engineering, and Medicine 2022).

For a CO2MVS to be useful, it is necessary to build up the knowledge base of both users and providers (researchers). Users need to know how the key elements of the CO2MVS and how they work, such as how prior data interacts with models, what important assumptions and definitions are used, and so on. Providers of inversion results need to understand what inventory agencies are trying to estimate and why. An inversion analyst may be interesting in seasonality, sensitivity to extreme events, etc, while an inventory compiler may just want to estimate annual emissions. Particularly through the VERIFY project, it was clear that modellers and inventory experts spoke different languages, often about the same topics (see VERIFY D1.2[9]). It is important that the knowledge base is common to both communities.

Temporal and spatial resolution

The temporal and spatial resolution is an area that is not clearly resolved. Inversion models can produce estimates at a potentially fine grid scale (kilometres) and fine temporal detail (hours), but this is far too resolved for most user applications. As a starting point, a region (e.g., city or region within a country) would be interested in annual emissions, but the availability of more detail could be tempting. At one level, the fine spatial and temporal detail may help identify and manage ‘events’ (acute pipeline leak). Since spatial resolution may help identify individual facilities, such as a powerplant or industrial site, which may help inventory agencies verify emissions from these facilities when they have facility level data. The fine spatial resolution allows aggregation to city- or region-level, matching as close as possible to jurisdiction boundaries. However, challenges may arise in mapping system boundaries: the results of an inversion can easily be aggregated to an arbitrary region, but data limitations may make it difficult for inventory-based approaches to provide estimates with a consistent system boundary, with transport emissions being one good example.

Since COVID19 there has been a growing interest in near real time emission estimates. The advent and growing interest in initiatives like Carbon Monitor and ClimateTRACE, real time emission estimates are implied to have additional value. Though, the policy case for having the June emission estimates available in July, versus in October, or one year later is not clear. It is as yet unclear if inventory estimates providing daily estimates are useful for policy makers. Further, there has been very little work on verifying the accuracy of real time emission estimates against more comprehensive data released at a later point in time. A ‘real time estimate’ does not imply higher accuracy, though, this may depend on a multitude of factors. Many policy mechanisms relate to infrastructure turnover (coal power to wind power, petrol car to electric car, etc), and the high temporal detail or real time nature of some estimates may deliver limited value. Real time estimates will also be highly dependent on sub-annual factors, like weather, requiring additional methods to consider these affects, such as temperature or seasonal adjustment.

There needs to be a better understanding on the preferred level of spatial and temporal resolution to meet user needs, and how observation-based approaches can meet those needs. The spatial and temporal unit of comparison may be a critical design feature in a CO2MVS.

Trends and variability

Many emission estimates are reported at the annual level, and inventory-based approaches often do not consider variability. Further, the Paris Agreement is set around five yearly global stocktakes, which indicates a desire to average trends over different time periods to remove

[9] Terminology analysis

interannual variability, from both weather or socioeconomic events. Inversion models, on the other hand, naturally include interannual variability. It is likely that inversion-based methods will need to somehow remove the variability, such as via averaging over periods (e.g., 5-year or 10-year) or by looking at trends. However, there are many ways that these comparisons could be done. There is the additional issue of identifying if a difference between two independent datasets is statistically significant. There is a clear need to better develop methods to deal with variability and statistical significance. There is also a need to estimate uncertainties in trends, not just the aggregate values, which is far more challenging as it requires understanding the correlations over time. With a user perspective in mind, there is a need to map to the policy needs, which may value trends over levels and may want to ignore variability. The methods used to compare aggregated emissions and trends, and how to deal with temporal and spatial resolution, will be important for the design and usefulness of a CO2MVS.

Priors

The prior emission estimates are an important input to the CO2MVS and the specific inversion systems. When combined with observation data, the inversion system produces a new posterior estimate of emissions, which can then be compared back to the prior estimate, preferably incorporating a full uncertainty analysis. It is this comparison that is the core objective of inversions systems and thereby the CO2MVS. Therefore, it is critical that the prior data is of high quality and robust.

The UNFCCC inventory data is rarely used as a prior, as it 1) rarely has the necessary spatial and temporal resolution, and 2) the UNFCCC data does not have global coverage. Other data sets are often used, such as EDGAR. Further, quite often older datasets are used as they have the preferred resolution: EDGAR version 4.2, from 2012, is often used because of its spatial and temporal resolution, and global coverage, with various extrapolation schemes used to extend the data to the most recent years. However, the prior emissions can often differ substantially from the UNFCCC National GHG Inventories. It is hard to determine the importance of the prior estimate on the posterior estimate and the resulting uncertainties. In many countries, prior estimates can already differ from UNFCCC estimates by up to a factor of ten (e.g., CH_4 in the Nordic countries). Key reasons for differences are often the fact that global datasets (e.g., EDGAR) do not use country specific emission factors or activity data. While there are many initiatives to produce datasets of high spatial and temporal resolution (e.g., in CoCO2), often national inventory agencies do not have sufficient resources or mandate to provide spatially or temporally resolved datasets.

A further challenge is the uncertainty data on prior estimates. While some datasets provide uncertainties (e.g., UNFCCC and EDGAR for a single year), these uncertainties often only capture parametric uncertainties and not structural uncertainties. For example, the aforementioned biases in EDGAR estimates for the Nordic countries do not have uncertainties that capture the UNFCCC estimates.

There is a need to improve the prior estimates used as input into inversion systems. This really has three components: 1) ensuring the availability of updated emissions data at an appropriate level of sector, temporal, and spatial detail, 2) ensuring inversions systems assimilate the latest data estimates from verified sources, and 3) ensuring that prior estimates have fully characterised uncertainties.

Aggregation

Inversions are affected by the size of the country, location (latitude, longitude), geography, albedo, number of observations, types of observations, and so on. An experienced modeller may implicitly (and even subconsciously) weigh this information when analysing results from a given country but would not mention this information explicitly as it is common knowledge within the inversion community (National Academies of Sciences, Engineering, and Medicine 2022). This makes it hard for a user to understand the implicit weights put into different comparisons. There are, potentially, some methods to alleviate some of these issues, such as through maps which show the uncertainty across geographic regions, and how they change with given factors (such as new observations, VERIFY D6.13). Because of some of these issues, modellers often aggregate regions together as there is more confidence in the aggregated results. The reasons for some groupings and the optimal size of regions as an element analysis are often unclear and unstated.

Further, many countries border with other countries, requiring a method to aggregate the grid level inversion data to a country. Particularly for inversion models with a coarser grid, aggregation of the grid cells will not necessarily be a perfect match to country boundary. This problem becomes smaller with bigger regions, or regions with long coastlines, and is one reason that VERIFY aggregated many smaller countries together to bigger regions.

Statistical significance

One method that modellers use to determine if an inversion gives an improvement over the prior emission estimate is to assess a reduction in the uncertainty. The prior emissions used as input into an inversion model should have uncertainties, and a full inversion analysis will include uncertainties on the posterior estimate, with the reduction in uncertainty between the two estimates of particular interest. In a well constrained inversion, the uncertainty of the posterior emissions should decline, and the posterior emissions should converge to the ‘true’ value. If the difference between the prior and posterior estimate is statistically significant, then this would suggest that the inversion has identified an incorrect prior emission estimate. The inventory-based emission estimate will additionally have uncertainties, though some argue these are not sufficiently robust for verification purposes (National Academies of Sciences, Engineering, and Medicine 2022). It is not generally clear how inventory uncertainties can be compared to inversion uncertainties, as the methods to produce the uncertainties differ.

Methods to reveal statistically significant, levels or trends, need to be developed. There are often offsets in inversion models, because of inconsistencies in observations, which may make trends more robust. In a policy context, the uncertainty on the emission trend may be more important, but also this is harder to estimate as it requires knowledge of correlations in emission estimates over time.

Model ensembles

Research projects, such as VERIFY, often focus on multiple model analysis (ensembles). The UNFCCC emission inventory would be compared against, for example, 17 land surface models and five inversion models. From a scientific perspective, the model ensemble is often considered a more robust estimate of the mean and uncertainty, as inherent model biases can be captured. From an inventory perspective, individual model comparisons may be more productive, as various input variables or processes can be compared directly to the inventory. Doing this for each model becomes time consuming. The CO2MVS system is currently envisaged to be one global modelling and data assimilation system based on ECMWF’s Integrated Forecasting System (IFS). Understanding the implications of these different choices, and how to capture structural uncertainties across models and methodologies, will be a challenge for a single IFS that needs to be resolved. Currently, most inventory comparisons in UNFCCC National Inventory Reports (UK, Switzerland) use single model comparisons.

Anthropogenic and natural fluxes

Most emission inventories aim at estimating anthropogenic emissions, while most inversion models see both anthropogenic and natural emissions. Thus, methods are needed to separate the anthropogenic flux from the total flux (Deng et al. 2022). This is a particularly important issue for CH_4 and N_2O where globally natural emissions are of similar magnitude as anthropogenic emissions, with bigger variations at the regional level. Further, climate change may mean the natural emissions change in ways that models can’t yet resolve, for example, a warmer climate may increase natural emissions of CH_4.

In land use change, there are significant issues with definitions of anthropogenic, with the science and inventory communities using different definitions of anthropogenic (Grassi et al. 2018). Science-based estimates of net land CO_2 emissions focus on anthropogenic land-use changes and direct CO_2 effects, such as afforestation or deforestation under an assumption of constant steady state carbon densities. The inventory-based estimates of net land CO_2 focus on a self-defined managed land proxy and direct, indirect, and natural effects, such as increased carbon update in land that has remained forest but has taken up additional carbon due to CO_2 fertilisation. This effect has been quantified in several studies (Grassi et al. 2018; 2021; Schwingshackl et al. 2022; Friedlingstein et al. 2022), but comparing independent estimates of net land CO_2 emissions requires making adjustments for these differences.

System boundaries

When comparing datasets, a variety of system boundary issues arise (Andrew 2020; Grassi et al. 2018). Additional issues arise when comparing results from inversion products. Key issues are mentioned here.

Country borders. Transforming a gridded dataset into country totals requires dealing with grid cells that overlap country boundaries.

Domestic aviation. Domestic aviation occurs at altitude, and only the take-off and landing emissions may be relevant for an inversion system. This requires necessary adjustments to the prior emission dataset used in the inversion and comparisons needs to be made with a consistent inventory-based emission estimate.

International bunkers (aviation and maritime). In addition to height effects, additional care is needed for international bunkers (fuels used in international aviation and maritime activities). Bunker fuels are not allocated to country emission totals but are reported as a ‘memo’ based on the territorial sale of bunker fuels. A prior inventory into an inversion will need to consider the take-off and landing cycle for international aviation, in addition to included inland shipping that crosses borders (e.g., The Netherlands to Germany). For consistency, the resulting emission estimates need to be compared with a consistent emission inventory.

Managed forests. In the IPCC reporting guidelines, anthropogenic emissions on land are defined based on a self-defined managed land proxy. In addition, the methodology includes indirect emissions, such as resulting from CO_2 fertilisation. In the carbon cycle community, anthropogenic is defined as only the direct emissions from the activity and only on land where the land use category has changed. These two definitions lead to a significant different in estimated LULUCF emissions (Grassi et al. 2018). To make any sensible comparison with LULUCF emissions, the managed land issue needs to be addressed.

Lateral fluxes. Carbon can cross national borders in a variety of methods, not all of which are well captured in models. Key processes include river transport and trade in agriculture commodities.

Standardisation

Inverse analysis systems are not yet standardized; therefore, there is room for additional progress and refinement of emission estimates and uncertainties derived from atmospheric observation and inverse models. The Community Inversion Framework (CIF) is a move in this direction. However, improvements are still needed to ensure common formatting and presentation of the results, in addition to the use of common language and terminology, as discussed earlier.

4.2 Improvements of figures and graphical communication

The figures produced in the VERIFY project generally compared multiple datasets on one figure, with various explanations of the differences when available (Andrew 2020; Petrescu et al. 2020; Petrescu, Qiu, et al. 2021; Petrescu, McGrath, et al. 2021). These figures were reproduced in the VERIFY fact sheets (D5.6, D5.7, D5.8). Figure 6 shows a sample figure used in VERIFY for the net CO_2 land fluxes, a variety of bottom-up and top-down estimates. These figures show an immense amount of information, which are hard to separate and digest – there is simply too much content on the figure. The purpose of graphical displays of data is to communicate messages more clearly than tables of data would, but it's unclear whether this was achieved in these examples.

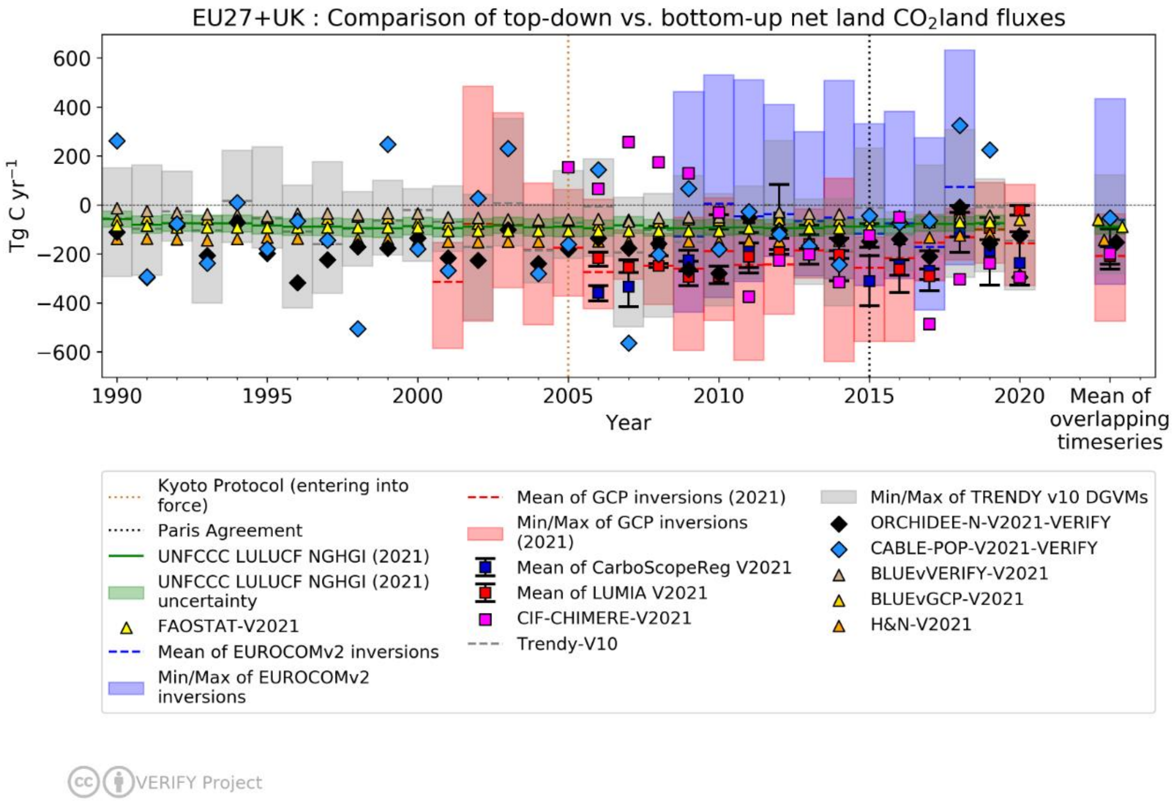

Figure 6: A VERIFY figure showing observation-based (top-down) and inventory-based (bottom-up) estimates of net land CO_2 fluxes.

Initial work in CoCO2 simplified these figures somewhat (e.g., Figure 7, D8.1), but further work is required (see D8.2). The general approach is to start with coarse overview figures, but then allow an iterative process to obtain more detail until the user needs are met (analogous to the hierarchical approach proposed in Peters et al 2017). Initial steps will be to do more one-on-one figures, such as comparing the UNFCCC inventories with only inventory-based estimates (Figure 8), UNFCCC with land surface models, and UNFCCC with observation-based inversions. Within these three variants of figures, other more detailed versions are possible. Inventory-based comparisons can compare estimates by sector or by sources (for land, this may be afforestation, deforestation, forestry, and similar, as done in Friedlingstein et al 2022). Similar details are likely to be taken for inventories estimated with land-surface models, but with the added advantage of being able to bridge the different definitions of managed land (e.g., Grassi et al 2022). Particularly for net land CO_2 fluxes, there are multiple layers of definition issues, making comparisons of raw data sets difficult. These sorts of improvements will be gradually included in D8.2 (due December 2022) and D8.3 (due December 2023), depending on data availability.

Very few figures have sufficiently incorporated uncertainty. On the inventory side, UNFCCC National Inventory Reports contain uncertainties, which are now harmonised across the EU in work supported by the EEA. EDGAR provides uncertainties for the year 2015 (Solazzo et al. 2021). Most other inventories do not provide uncertainties. For most inversion and land-surface models, uncertainty is indicated by model spread. However, more can be done. For inversion models, a full analysis can generate prior and posterior uncertainties, to give some understanding of statistical significance. However, this requires considerable analysis, and such uncertainty information is not readily available. The land-surface models (DGVMs) do not provide uncertainty information. Without uncertainty information, it can be difficult to determine with confidence if an estimate differs from a UNFCCC national GHG inventory.

One challenge with the graphical based approaches is to show if differences are statistically significant. An inversion may agree quite well with a UNFCCC inventory, but this could also be coincidental. The figures need to come with additional information, whether embedded within the figure or alongside it in a text, to provide key assumptions which may affect the results, and given some indication on whether the similarity or differences between datasets is statistically significant.

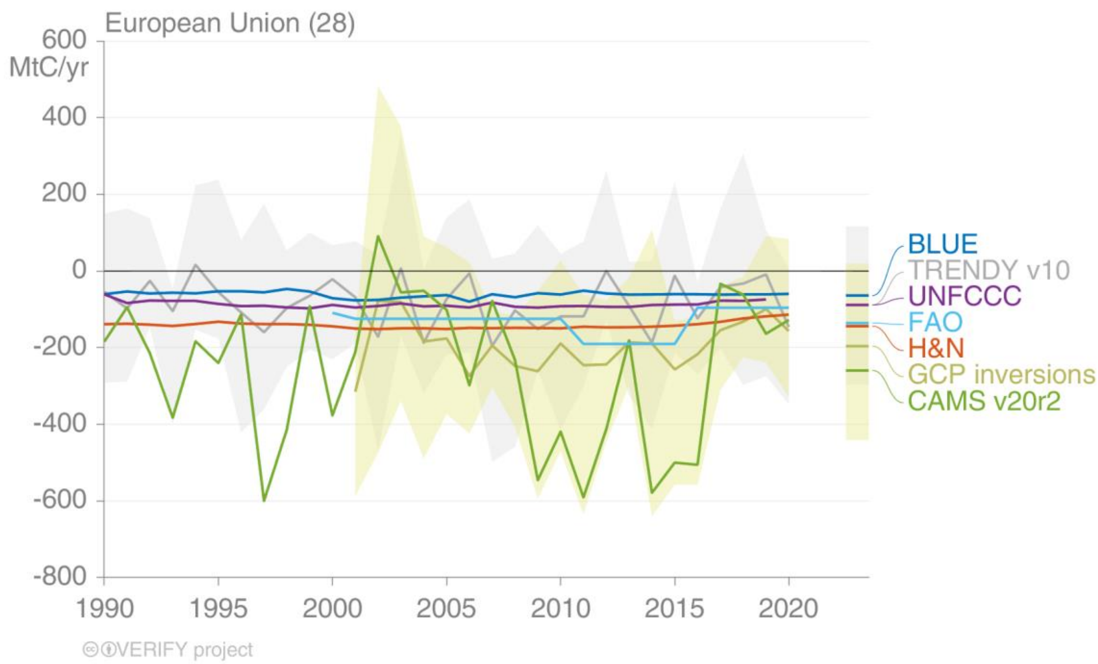

Figure 7: A CoCO2 figure showing observation-based and inventory-based estimates of net land CO_2 fluxes.

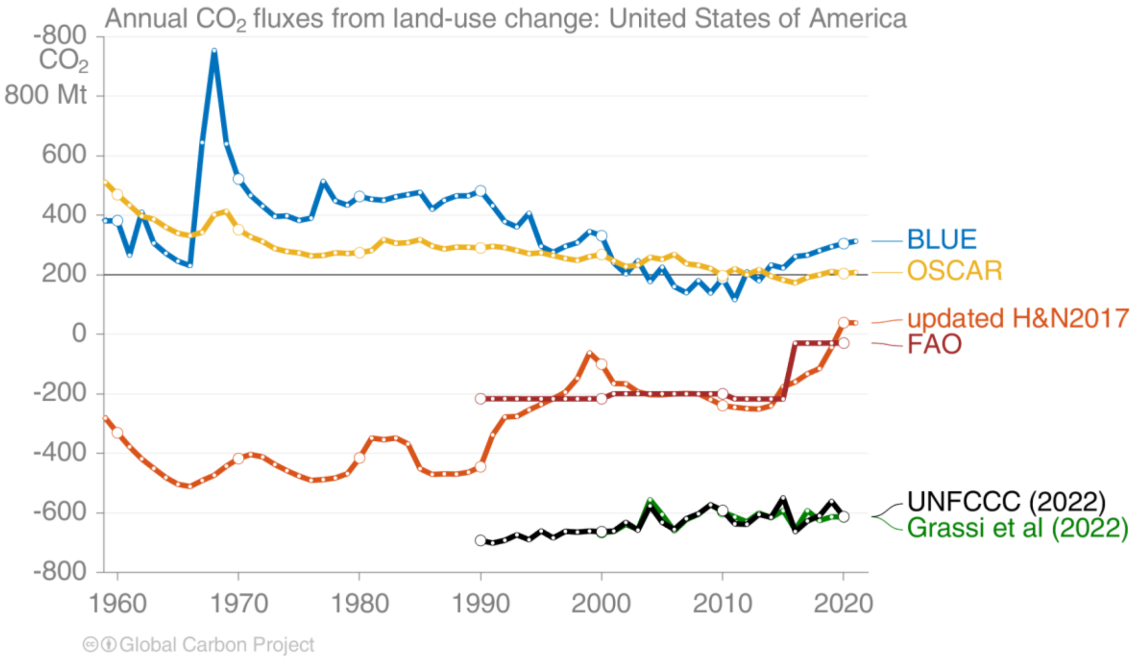

Figure 8: A CoCO2 figure showing only inventory-based emission estimates of net land CO_2 fluxes, with separate figures making comparisons based on the methodology (e.g., a figure for land-surface models and a figure for inversions).

The method to deliver products within the CO2MVS is something that will be designed later, but there is a considerable base to build on through the existing Copernicus Climate Change Service in terms of applications and tools.

An approach that will be used going forward is to shift from a goal of presenting all data on a plot to a goal of deciding what the intention behind each plot is and what messages it should be designed to convey. When too many messages are conveyed in a single plot, the burden on the user to interpret it grows substantially. Given the quantity of data available to present in the CO2MVS, choosing to reduce the amount on each plot could lead to an explosion in the number of plots, but this can be mitigated by keeping in mind the key messages that we intend to present with the graphical representations of the data.

Important next steps will be specifically to identify what the core messages are that we wish to present, and to more consciously address whether a plot is designed to present a conclusion or whether it is designed to initiate a discussion. The latter is an approach more often used in the process of research rather than in the process of communicating results to an audience.

4.3 A roadmap forward

The current state-of-the-art is to bring the different datasets together and make them comparable (e.g., VERIFY fact sheets and synthesis products). The overall process is still a black box and not many inventory agencies understand details. There is a need for a simple representation of what is behind the data, what it represents, and what is the uncertainty. To make comparisons that are not superficial, inventory agencies need more detailed data, as the total is always the aggregation of very different components. Inventory agencies and researchers still do not have a clear understanding of each other’s needs, or a common understanding of the limitations of various datasets. Inventory agencies probably need direct and specific exchange with modellers, to explain and understand the inversions, suggesting that there may be a greater need to focus on specific case studies as opposed to automation and generalisations.

Through this section we hope to bring together the key lessons from this report and structure them into concrete actions moving forward that can help bring the inventory agencies and inversion modellers together with a common understanding of the challenges and common objectives to ensure that observations can make a meaningful impact on the emission inventory estimates. Many of our conclusions map well with a US-based study with similar goals (National Academies of Sciences, Engineering, and Medicine 2022). They identified six pillars where improvements are needed: useability and timeliness, information transparency, evaluation and validation, completeness, inclusivity, and communication. Most of these pillars were assessed as having a low or medium evaluation (Figure 9). While we do not perform such a comprehensive analysis, many of our conclusions are consistent.

Approaches		Pillars: Usability and Timeliness	Information Transparency	Evaluation and Validation	Completeness	Inclusivity	Communication
Activity-based	*Methods*	Medium	High	Medium	Medium	Low	Medium
	Data	Medium	Medium	Low	Medium	Low	Medium
Atmospheric-based	*Methods*	Low	High	Medium	Medium	Low	Low
	Data	Medium	Medium	High	Medium	Low	Medium
Hybrid	*Methods & Data*	Low	Low	Medium	Medium	Low	Low

Figure 9: The six pillars and their assessment in "Greenhouse Gas Emissions Information for Decision Making: A Framework Going Forward" (National Academies of Sciences, Engineering, and Medicine 2022)

Our suggestions are ***preliminary***, and the intention is that they will act as a starting point for discussions in the first half of 2023. A new version of this report, including new these suggestions, will be published in July 2023.

Building a common knowledge base

A recurring theme is that the common knowledge base must be increased. Various EU projects have had a variety of deliverables that help in this regard but are not widely known or assessable. There are also some very fundamental concepts where common understanding is required: what is the objective, what is verification, what is an inversion model, what is a CO2MVS, common glossary of terms, and so on. With a common knowledge base, more detailed and productive discussions on model results and comparisons can happen. The knowledge base also serves two time periods: 1) quickly get the current community to a common knowledge base (e.g., via fact sheets), 2) allow for future generations to obtain the common knowledge base over time (e.g., textbook or enhanced guidelines).

Suggested paths forward are to co-produce a range of fact sheets or courses of the agreed level of detail. It may be necessary to set up specific working groups, involving different levels of competence, to develop this material. Over time, these materials may lead to a more elaborate document, such as a book, or specific chapter in the IPCC reporting guidelines, building on, and expanding, the current 2019 refinement.

The ongoing EU project (CoCO2), new EU projects (EYE-CLIMA, AVENGERS, Paris), ongoing US processes (e.g., the National Academy report) are ideal forums to initiate these processes, but it is critical that inventory compilers and modellers from the global South are integrated into these processes.

Case studies

The CO2MVS is designed to have broad appeal and be generic to a wide range of users. However, dialogues with inventory agencies end up in very specific and technical discussions, that often map to specific national circumstances (geographic location, coastline, mountains, forests, types of industries and sectors, etc). To identify the generic needs, it may be necessary to have a much deeper focus on case studies. This can already be seen in the Swiss and UK inventories, where the most elaborate verification activities are the result of detailed collaboration between inventory compilers and modellers. The case studies would presumably draw out generic lessons that are applicable to all users of the CO2MVS.

Steps to achieve more case studies is to identify willing inventory agencies and modellers who have the time, capacity, and interest to perform detailed verification exercises. The lessons learnt need to be documented and can inform more generic lessons for a wider user group. Case studies may need to be bottom-up processes with a coalition of willing participants but could be done under the auspices of ongoing projects (e.g., in the EU CoCO2, EYE-CLIMA, AVENGERS, Paris).

Technical aspects of inversion modelling

There is a range of technical details that need to be discussed and solved at the more technical modelling level. The most relevant need is for developments that lead to better quantified estimates of statistical significance and robustness of results. Inversion modellers often have a good sense of the key issues and their significance, but quantifying them and communicating them to inventory agencies, or users more generally, is difficult.

A potential avenue here is a scientific publication which brings together in a concrete way the knowledge needs and knowledge gaps in current inversion modelling practices that currently inhibit the ability of inventory agencies to verify emissions. The relative importance of certain factors is likely to vary by gas and by geographic location. But there is a need to explicitly outline the issues that need resolving and a pathway for how they can be resolved. This is also a potential avenue to build a common knowledge base. The VERIFY deliverable D7.9 was a step in this direction but needs a more focused community effort. This could be a constructive collaborative exercise across ongoing projects (e.g., in the EU CoCO2, EYE-CLIMA, AVENGERS, Paris).

Graphical material and analysis tools

Particularly for a CO2MVS with a broad user base, there is a need for common graphical material and tools. Understanding the needs requires interaction and feedback from users. Some steps have been made in VERIFY and CoCO2 (Section 5.2), but a hierarchical system that can flexibly zoom into more details is important. Also, a method of communicating key assumptions behind different graphical material and analysis tools is key: robustness, uncertainty distributions, system boundaries, etc. It is also clear that the needs will vary depending on the specific users. There is already a wealth of experience from existing activities, such as the Copernicus Climate Change Service (applications and tools). The VERIFY project has also made a range of products available, ranging from reports, visualisation tools, data repositories, and the community inversion framework which make a useful starting point for user orientated services (Figure 10).

The most productive pathway to elicit this feedback is through case studies (see previous points on this) and dialogue with user communities. Experience has shown that inventory agencies have very specific questions and needs. They are less interested in national totals, but more interested in sectors or point sources, as a way of specifically supporting elements of the inventory. The CoCO2 deliverables D8.1, D8.2, and D6.2 offer a useful starting point, in connection with this deliverable, and dialogue is planned for the first half of 2023.

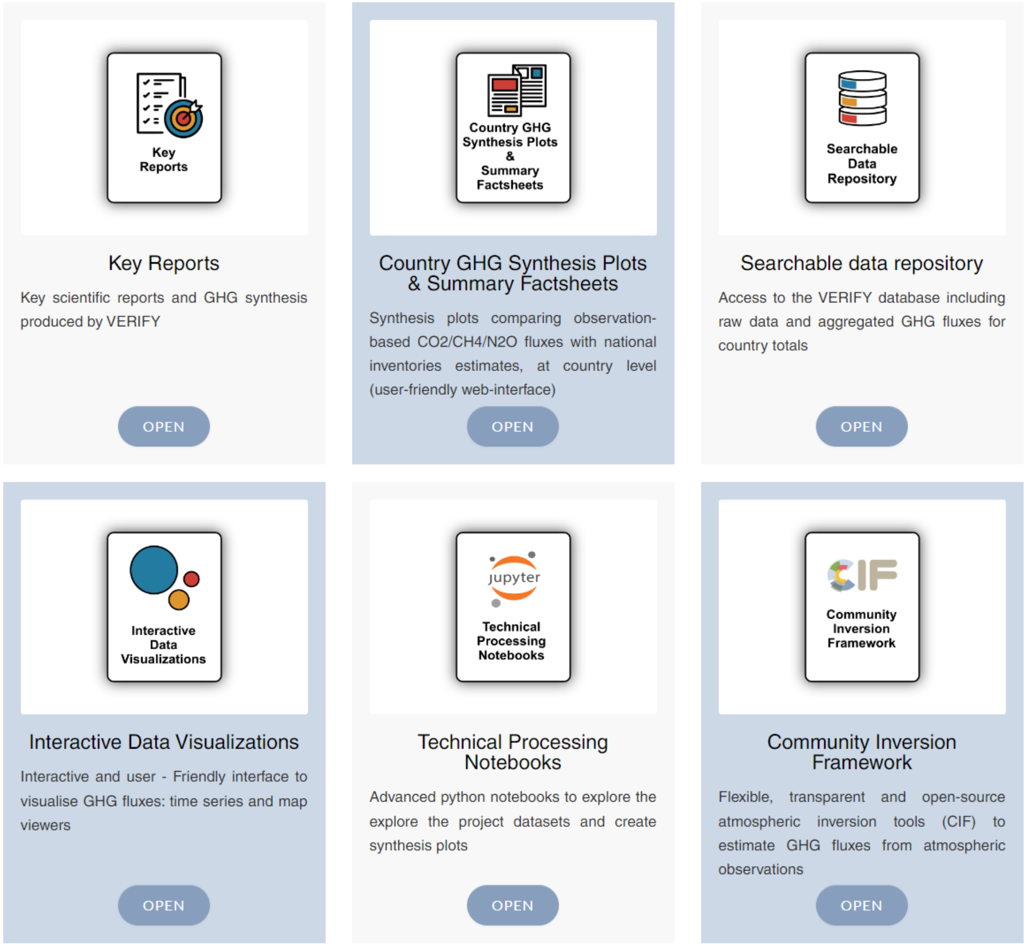

Figure 10: A screenshot of the VERIFY website giving a flavour for the user orientated material developed.

Communication

A key advantage of increasing communication activities is that it forces the communicator to develop material that the reader (user) wants to read and can understand. A scientific audience already working on inversions will likely be able to parse the text produced by colleagues working on the same topic. However, to communicate the underlying data, methods, and associated uncertainties to inventory communities, even with scientifically trained backgrounds, requires additional efforts. Researchers should be encouraged to write about their work to a broader audience, including those in the global South, to ensure greater understanding and eventually uptake of their work. While *translators* may help facilitate this work, such as through synthesis products (e.g., VERIFY and CoCO2), they are still dependent on explanations on input data, methods, and explicit and implicit assumptions to provide synthesis products.

Collaboration

There are several new projects in the EU (EYE-CLIMA, AVENGERS, Paris), other regional/continental focused scientific initiatives (e.g., RECCAP2), interest amongst some inventory agencies to expand capabilities, and likely activities outside of the EU, that all move in the same direction of verification and need for a CO2MVS. Many of these projects have similar tasks where there are many synergies in collaborating. There are already good signs of collaboration, such as through the Community Inversion Framework (CIF, http://community-inversion.eu/) developed under VERIFY. The air quality community has a long history of linking to user needs, with high spatial and temporal detail, but there has historically been limited collaboration between the GHG and air quality communities (National Academies of Sciences, Engineering, and Medicine 2022), indicating another area of potential fruitful collaboration. New initiatives need to build on these existing activities but go a step further to lower the barriers to entry of both researchers and users.

5 Conclusion

This Decision Support Blueprint is the first step in a process in CoCO2 and beyond. This document is a *preliminary* blueprint that will be improved through dialogue with researchers and users in the first half of 2023. An updated version will be completed in July 2023.

The verification landscape is growing given new demands stemming from the Paris Agreement and its Global Stocktake. New technology (satellites), and improved methods (inversions) and computing power, also open new opportunities for monitoring and verification support. The IPCC reporting guidelines now give guidance on using verification in inventories, and several countries are using verification to different degrees. Through new projects, inventory agencies are also getting exposed to ongoing verification activities. The lessons learnt through various user events mark a clear path forward for a Decision Support Blueprint.

The current state-of-the-art in verification activities is to bring the different datasets together and make them comparable. The UK and Switzerland perform the most comprehensive comparisons in their inventories. However, to date, there is limited experience of inversions leading to improvements in emission inventories. To many, the overall verification process is still a black box and not many inventory agencies understand the details. There is a need for a simple representation of what is behind the data, what it represents, and what is the uncertainty. To make comparisons that are not superficial, inventory agencies need more detailed data, as the total is always the aggregation of very different components. Inventory agencies and researchers still do not have a clear understanding of each other's needs, or a common understanding of the limitations of various datasets. Inventory agencies probably need direct and specific exchange with modellers, to explain and understand the inversions, suggesting that there may be a greater need to focus on specific case studies.

We have suggested six areas where we see the most productive gains to be made: 1) Building a common knowledge base, 2) Case studies, 3) Technical aspects of inversion modelling, 4) Graphical material and analysis tools, 5) Communication, and 6) Collaboration. Many of these activities have already been initiated but need to be improved and expanded. Through stakeholder dialogue in the first half of 2023, we hope to gain feedback on these suggestions, and look at a pathway forward to build a useful and robust Decision Support System.

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