Fluxes of carbon dioxide from managed ecosystems estimated by national inventories compared to atmospheric inverse modelling

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Key Points:

- There are large conceptual differences or ambiguities between country reports to the United Nations Framework Convention on Climate Change (UNFCCC) and between them and what the atmosphere sees
- Bayesian atmospheric inversions can quickly inform the evolution of CO2 surface fluxes in managed lands in large countries
- The inversion full uncertainty covariance matrix can be used as a comprehensive quality indicator of inversion products

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Fluxes of Carbon Dioxide From Managed Ecosystems Estimated by National Inventories Compared to Atmospheric Inverse Modeling

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Abstract The UNFCCC reporting guidelines on annual emission inventories have been encouraging comparison of national inventory reports with atmospheric measurements or atmospheric inverse modeling. We have initiated a framework to compare two CO_2 atmospheric inversions with the net agricultural, forestry and other land use (AFOLU) fluxes reported by 10 parties to the UNFCCC. Our study highlights large conceptual differences or ambiguities (temporal support, spatial perimeter, scope of the processes) between inventory reports and between these reports and what the atmosphere sees. We recommend that more effort be invested into documenting the inventories in order to allow unambiguous conversion between reported values and the way they are seen by the atmosphere. We also highlight the potential of Bayesian atmospheric inversion products generated in quasi-near-real time with robust error bars and consistently across the world, to directly inform international CO_2 flux accounting for the AFOLU sector in large countries or groups of countries.

Plain Language Summary We compared the sum of CO_2 emissions and removals on managed land declared by 10 large parties to the United Nations Framework Convention on Climate Change, with the corresponding figures deduced from atmospheric observations. Our study highlights great conceptual differences or ambiguities between country declarations and between these declarations and what the atmosphere sees. We recommend that these declarations be further documented using computer programs and ancillary data that allow unambiguous definition of the various CO_2 fluxes. We also highlight the potential of atmospheric observations processed in quasi-near-real time with robust error bars and consistently across the world, to directly inform international CO_2 flux accounting for managed lands in large countries or groups of countries.

1. Introduction

There is broad scientific consensus on the causes of current climate change and the far-reaching threat it poses to human societies in general (IPCC, 2018). By 1992, the need to stabilize emissions of carbon dioxide (CO_2) and other anthropogenic greenhouse gases motivated the United Nations Framework Convention on Climate Change (UNFCCC). However, the role of current energy and food production in these emissions has made progress very slow relative to the stakes (IPCC, 2018; UNFCCC, 2021). In the absence of collective enthusiasm on the modes of action, the focus has been placed on detailed emission accounting. Each party to the UNFCCC already committed to "develop, periodically update, publish and make available to the Conference of the Parties (..) national inventories of anthropogenic emissions by sources and removals by sinks of all greenhouse gases not controlled by the Montreal Protocol, using comparable methodologies to be agreed upon by the Conference of the Parties" (UNFCCC, 1992). In practice, this commitment was modulated by "common but differentiated responsibilities and (…) specific national and regional development priorities, objectives and circumstances." The reporting rules defined in 2003 (UNFCCC, 2003a) distinguish countries listed in the Annex I of UNFCCC, that is, the industrialized countries that were members of the Organisation for Economic Co-operation and Development (OECD) at the time, plus countries with economies in transition, including the Russian Federation, the Baltic States, and several Central and Eastern European States (https://unfccc.int/parties-observers, accessed 15 March 2021): For those parties, detailed annual reports on anthropogenic emissions and removals of CO_2, methane (CH_4), nitrous oxide (N_2O) and fluorinated gases have to be submitted with a given format for text (the structure of the national inventory report, NIR) and quantitative data (the table common reporting format, CRF) (UNFCCC, 2003b), before being examined by expert review teams. In 2009, Kazakhstan joined the list of Annex-I parties for the reporting. Other parties are just encouraged to provide less detailed information (UNFCCC, 2003a). The reporting process intensified, including refinement of guidelines (IPCC, 2006, 2019; UNFCCC, 2014a), with the progressive failure of the parties to collectively meet the key UNFCCC goal to return "to their 1990 levels these anthropogenic emissions of carbon dioxide and other greenhouse gases not controlled by the Montreal Protocol" (see Figure 4a of Friedlingstein et al., 2020, for the fossil CO_2 emissions). Nationally determined contributions (NDCs, initially called *intended NDCs*) that report formal climate action plans with quantitative objectives were initiated at the 19th Conference of Parties to the UNFCCC (COP) in 2013 (UNFCCC, 2014b). The NDCs are self-imposed and not legally binding, but they bring to a higher political level (and within a different context) the general description of steps taken or envisaged by the parties to implement the UNFCCC goals that have been provided with the NIRs. The 2015 Paris Agreement placed the NDCs at the center of a collective dynamic called the Enhanced Transparency Framework (ETF). The ETF will work as a repeating cycle in which parties periodically report their own progress in implementing their NDCs, receive feedback from peer review (to ensure accurate reporting), assemble the results together in a *Global Stocktake* (GST) to assess collective progress toward the long-term goals of the UNFCCC, update their own NDCs, and so on. The first GST exercise will take place in 2023. The role of these NDCs will likely increase as momentum around political and corporate action on climate change increases, for instance as evidenced by the already growing number of commitments from local governments and businesses to reach a zero-carbon economy by the middle or the end of the century (https://racetozero.unfccc.int/, accessed March 15, 2021).

National reports primarily rely on "bottom-up" methods in which either anthropogenic activity data are multiplied by an emission factor or carbon stock changes are directly sampled (see Chapter 1 of IPCC, 2006). The focus on human activity data or on specific carbon stocks (living biomass or pools of dead organic matter in managed ecosystems as defined by IPCC, 2006) fits naturally into the framework of the UNFCCC and easily distinguishes many individual emission or removal process for each heat-trapping gas considered by the UNFCCC, provided the data collection is sufficient. However, in the end, only the resulting CO_2-equivalent emission matters for the climate, and there has been increasing incentive to confront the inventories with atmospheric observations for the purpose of evaluation (see Chapter 6 of IPCC, 2006, 2010, and Chapter 6 of IPCC, 2019). Switzerland and the UK already append such comparisons for CH_4, N_2O or fluorinated gases to their NIRs (https://unfccc.int/ghg-inventories-annex-i-parties/2020, accessed March 15, 2021). The approach remains much more challenging for CO_2 because of a smaller signal-to-noise ratio and because of the mixture between emission and absorption processes over lands (see Chapter 6 of IPCC, 2019): The observation system is consequently being expanded to better address this objective (Janssens-Maenhout et al. 2020). The CRF table separates between tens of anthropogenic emission and removal processes, but here we gather these into two broad categories: Emissions from the use of fossil fuels or the production of cement, and emissions or removals from agriculture, forestry and other land use (AFOLU). Chevallier et al. (2020), Ciais et al. (2020) and Miller et al. (2020) discussed the difficulty to estimate the former with current satellite data at the national and annual scales. Here, we discuss current capability to estimate the latter with satellite CO_2 retrievals and surface CO_2 measurements. We extract time series of these fluxes (i.e., the sum of these emissions and removals) estimated by the Copernicus Atmosphere Monitoring Service (CAMS, https://atmosphere.copernicus.eu/, accessed March 15, 2021) based on the assimilation of surface air-sample measurements or satellite CO_2 retrievals. These data are provided with Bayesian uncertainty statistics. We aggregate the grid point fluxes of managed areas and their uncertainty at the annual national scale and compare them with numbers reported in the NIRs by 10 parties to the UNFCCC with very large geographical area: Brazil, Canada, China, the Democratic Republic of the Congo (hereafter DR Congo), the 27-member European Union and United Kingdom together (hereafter EU27+UK), India, Kazakhstan, Mongolia, Russia and the United States (USA). The comparison is presented in Section 3, after the description of our data and methods in Section 2. General conclusions are drawn in Section 4.

2. Data and Methods

2.1. Inversion Data

Twice per year since 2011, CAMS and its three precursor projects Monitoring Atmospheric Composition and Climate (MACC, https://www.ecmwf.int/en/research/projects/macc-ii, accessed March 15, 2021) have been producing multi-decade analyses of CO_2 surface atmospheric measurements over the globe in the form of optimized gridded surface fluxes with associated 3D concentration fields (Chevallier et al., 2010, with successive updates described in https://atmosphere.copernicus.eu/supplementary-services, accessed March 15, 2021). In 2019, the operational chain has been paralleled with four-monthly "Fast Track" experimental analyses of the column-average CO_2 dry air-mole fraction (XCO_2) retrieved from the second Orbiting Carbon Observatory (OCO-2), a satellite that was launched in 2014 (Chevallier et al., 2019, with successive updates described in https://atmosphere.copernicus.eu/supplementary-services, accessed March 15, 2021). At the time of writing, the latest versions of these two products have been: (a) v20r1, that assimilated surface air-sample measurements of the CO_2 dry air mole fraction made at 156 sites over the globe, from January 1979 to September 2020, and (b) FT20r2 that assimilated NASA's Atmospheric CO_2 Observations from Space (ACOS) bias-corrected land XCO_2 retrievals, version 10 (Osterman et al., 2020) from September 2014 until September 2020. "FT" stands for Fast Track, since the satellite observations are available faster than most surface measurements, but the surface-driven inversion remains the CAMS reference product due to slightly lesser agreement with independent atmospheric measurements, as reported in the product documentation.

The inversion system follows Bayesian principles formulated within a variational framework. The Bayesian approach compensates for the irreversibility of atmospheric transport and for the limited observational coverage by the use of prior information on surface fluxes provided by inventories (for fossil fuel use, cement production or biomass burning), a model (for terrestrial ecosystems) and the interpolation of measurements of surface ocean CO_2 fugacity combined with a simple gas transfer velocity model. For the interpretation of the following results, it is important to note that the annual average of the prior fluxes from terrestrial ecosystems have no interannual variability: All interannual variations in the optimized (or "posterior") vegetation and soil fluxes are therefore driven by the assimilated observations, modulated by the interannual variations in atmospheric transport represented in the underlying observation operator. The inversion does not solve for the emissions from fossil fuel use and cement production, the prior values of which come from the UNFCCC NIRs as much as possible (Jones et al., 2021). The variational framework makes it possible to estimate the other CO_2 surface fluxes at the weekly grid-point scale, with day and night separation, in a unique assimilation window (41.75 years for v20r1 and 73 months for FT20r2), thus ensuring physical and statistical consistency of each inversion throughout the years and decades. The size of the grid points corresponds to that of the underlying global atmospheric transport model, currently 3.75° in longitude and 1.875° in latitude. The reader is referred to the above articles and technical reports for a detailed description of these products and of the processing chain that generated them.

2.2. Aggregation in Space and Time

The relatively high resolution of the inversion (73,700 variables controlled per month) compared to the density of the assimilated atmospheric data, at least for the surface-air-sample-driven inversion, is motivated by the risk of degradation of the inversion product by the *aggregation error* studied by Kaminski et al. (2001) and Bocquet et al. (2011), when running at coarse resolution. Despite the availability of high-resolution outputs, the inversion product is typically post-processed to be presented at annual subcontinent scales (Chevallier et al., 2010) or even in broad latitudinal bands (e.g., Friedlingstein et al., 2020). Here, we examine both CAMS CO_2 inversions products v20r1 and FT20r2 at country-scale resolution. In most cases, the country-scale resolution is an intermediate between the usual subcontinent resolution and the grid point resolution. In time, we choose the usual annual scale of the national reporting to the UNFCCC.

We use the $0.08° \times 0.08°$ country mask of Klein Goldewijk et al. (2017) to determine, for each UNFCCC party, the fraction that it occupies in each land portion of the $3.75° \times 1.875°$ model grid points. We multiply this fraction by the fraction of non-wild area deduced from the 1 km^2 global terrestrial human footprint maps of Venter et al. (2016, 2018a, 2018b) that synthesize diverse information on human population pressure (population density), human land use and infrastructure (built-up areas, nighttime lights, land use/land cover), and human access (coastlines, roads, railroads, navigable rivers) into a generic Global Human Influence Index with values between 0 and 50. In the absence of a clear delineation between managed and unmanaged plots in the UNFCCC reports, all index values larger than zero (i.e., all values that indicate some human influence) are considered to correspond to managed areas here. The maps are available for years 1993 and 2009: We linearly interpolate the fractions in-between those years and keep the 1993 and 2009 values for earlier and later years, respectively. This fractional coverage allows us to aggregate the grid-point land vegetation flux values (i.e., the total posterior fluxes minus the prior emissions from fossil fuel use and cement production), while conserving the mass of carbon fluxes at all spatial scales. Lastly, weekly diurnal and nocturnal fluxes have been aggregated on an annual scale.

2.3. Uncertainty Statistics

The uncertainty of the posterior fluxes provided by the inversion system is directly deduced from the Bayesian framework which combines the uncertainty in the prior fluxes, the uncertainty of the observations as defined from the inversion observation operator (consisting mainly of an atmospheric transport model and, for the assimilation of satellite retrievals, of a vertical averaging kernel) and the observation operator itself, to estimate it. The statistical models of the CAMS inversion system represent error variances and correlations at various spatio-temporal scales. They have been the subject of dedicated studies at different scales which give us confidence in their broad realism (Chevallier et al., 2006, 2012; Chevallier & O'Dell, 2013). In practice, we use a robust Monte Carlo method, made of ensembles of two-year inversions (much easier to parallelize than the inversions made on the full inversion periods), to explore the uncertainty space in a manner consistent with the assigned prior and observation error statistics (Chevallier et al., 2007). Each member of the inversion ensembles was aggregated as the reference data, as described Section 2b, to produce the uncertainty statistics at the annual scale and at the appropriate spatial scale. Note that the ensemble of inversions over two years barely describes the interannual correlation of the uncertainty. These correlations would prevent the uncertainty of multi-annual averages from decreasing with the square of the number of years, n. In this context, we suggest a linear dependence with $n^{0.25}$, which is an intermediate behavior between no interannual correlations ($n^{0.5}$) and full interannual correlations (n^{0}). For a 10-year average, this corresponds to a 1-σ uncertainty equal to half of the annual 1-σ uncertainty. This potential for multi-year averages is discussed but not exploited here.

2.4. Inventory Data

We have used the latest AFOLU data reported under the UNFCCC at the time of writing and available on the UNFCCC portal (https://unfccc.int/ghg-inventories-annex-i-parties/2020, accessed March 15, 2021). They cover the period between 1990 and 2018, at least partially, depending on the party. Their territorial scope differs from the data reported within the framework of the Kyoto Protocol and available on the same portal with the same format: Our land mask for each party described in Section 2b accounts for these subtle differences that involve the status of overseas territories, although they play an insignificant role in the following results. For Annex-I parties (Canada, EU27+UK, Kazakhstan, Russia and USA), we simply use the sum of the net CO_2 fluxes from the agriculture sector and the land-use, land-use change and forestry (LULUCF) sector reported in their CRF tables submitted in 2020. Reported CO_2 emissions from the agricultural sector are relatively small and consist of the categories *liming* (not reported by Kazakhstan), *urea application*, *other carbon-containing fertilizers* (only reported by Canada and EU27+UK) and *other* (not used by these five Annex-I parties). CO_2 emissions from the LULUCF sector consist of the categories *forest land*, *cropland*, *grassland* (not used by Canada), *wetlands*, *settlements*, *other land* (only used by EU27+UK and Russia), *harvested wood products* (not reported by Kazakhstan) and *other* (only used by EU27+UK). Some of the missing categories in the individual party reports correspond either to the absence of suitable activity data or carbon stock change observations, or to the risk of double counting (e.g., *harvested wood products* for Kazakhstan are indirectly accounted in *forest land*). Some of the LULUCF categories are themselves made of subcategories, such as subcategories *forest land remaining forest land* and *land converted to forest land* for category *forest land*, that themselves can be subdivided. In contrast to our uniform definition of managed versus unmanaged grid points for the inversion data described above, parties to the UNFCCC mainly determine which areas are managed themselves, as long as they apply their definition consistently over time and report it in a transparent manner (see Chapter 3 of IPCC, 2006). For instance, the definition of managed land for the USA fills a whole page of the corresponding NIR and includes various considerations on the LULUCF category, the type of existing and past activity, the fire protection measures, and the proximity to infrastructure (Section 6.1 in USA, 2020). For Canada, the definition of managed forests requires detailed analysis of forest resource exploitation and of the level of protection against natural disturbances, and temporarily excludes managed stands dominated by natural emissions and removals from the reporting (Annex 3.5.2.4 in Canada, 2020). In contrast, for example, for Sweden, all forests and grasslands are considered managed (Section 6.2 in European Union, 2020).

For Brazil, we use Appendix I of its fourth biennial update report (BUR) (Brazil, 2020) that give emission values for years 1994, 2000, 2010, 2012, 2015, 2015, but note that no values are reported for the agriculture sector. Methodological details were taken from Brazil's Third National Communication (Brazil, 2016).

For China, we use Tables 2–7, 2–13, 2–14, 2–15 and 2–16 of its second BUR (China, 2018) that give emission values for years 1994, 2005, 2010, 2012, and 2014.

DR Congo has not submitted any BUR to UNFCCC yet and we rely on its third national communication to UNFCCC (République Démocratique du Congo, 2015), that provides CO_2 net emissions values for LULUCF sector for the years between 2000 and 2010, but none for agriculture.

For India, we use Tables 2.2 and 2.19 of the initial and second national communications to UNFCCC, respectively (India, 2004, 2012), and Tables 2, 2.2 and 2.4, respectively, of the three successive BURs (India, 2015, 2018, 2021).

For Mongolia, we use Tables 2–4 of its first BUR (Mongolia, 2017). That table combines all reported greenhouse gases for each year between 1990 and 2014, but, consistent with the remark in Section of that BUR, its LULUCF values are very close to those for the AFOLU numbers for the sole CO_2 fluxes given in the annex for years 1990 and 2014. We therefore use the full time series of Table 4. Note that Mongolia only reported source categories *forest land remaining forest land* and *harvested wood products* for the LULUCF sector.

The various documents or the Annex I NIRs report an uncertainty analysis of the numbers. The two-sigma uncertainty is usually of a few tens of percent for the fluxes from the LULUCF sector (32% for Brazil in 2016, ~40% for Canada, 21% for China, ~20% for EU27+UK, 36% for Forest land Remaining Forest land in Mongolia in 2014, ~20% for the USA, no estimate for DR Congo and India for that CO_2 sector). NIRs of Kazakhstan and Russia are in Russian and have not been exploited in order to avoid any misinterpretation.

2.5. Party Selection

Our rationale for limiting our analysis to the 10 parties named earlier is as follows: We limit the analysis to the parties whose geographical area is much larger than the inversion grid resolution and where the inversion provides a significant improvement to the prior fluxes. The first criterion is represented by a threshold on the surface areas: Parties smaller than 1 million square kilometers (i.e., about 15 times the grid point size) are excluded. The second criterion is represented by a maximum value of two thirds imposed on the ratio of posterior over prior uncertainty standard deviations (see Section 2c for the definition of these) for both v20r1 and FT20r2 for the party annual flux in 2015.

This selection leads to the 10 parties listed in the introduction: Brazil, Canada, China, DR Congo, EU-27+UK (called "EUA" in the submission to UNFCCC), India, Kazakhstan, Mongolia, Russia and USA.

3. Results

We first look at the fraction of managed land in each party estimated by us from the global terrestrial human footprint maps on the one hand and by the parties on the other hand. For the year 2009, or the closest available year in the party reports, our estimate minus the party estimate equals +14% of the party total area for Brazil, −13% for Canada, +7% for China, +3% for EU27+UK, −4% for India, 0% for Kazakhstan, −19% for Mongolia, −33% for Russia and −14% for USA. The area of managed lands for DR Congo is not clearly reported (the third national communication to UNFCCC reports, for example, the difficulty to estimate

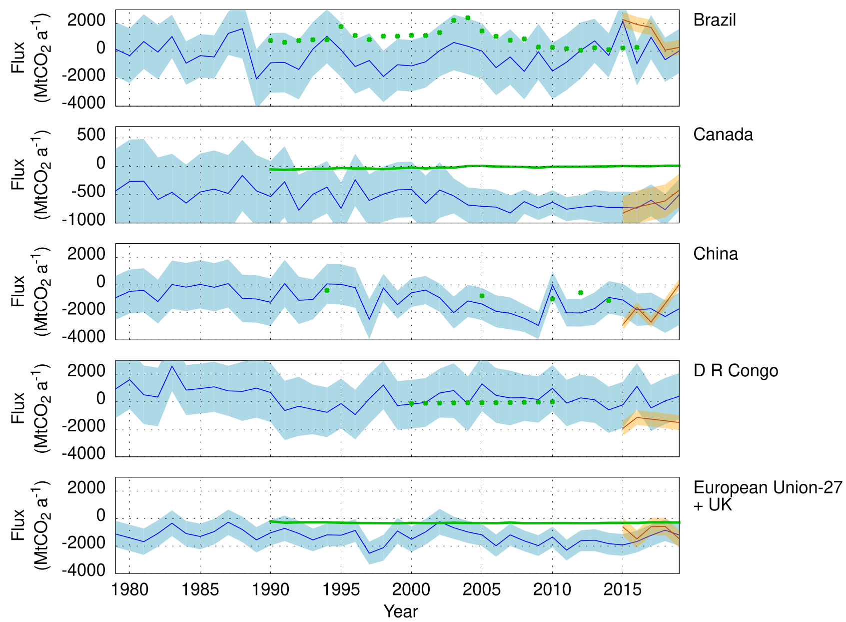

Figure 1. Annual CO_2 flux from the agricultural, forestry and other land use (AFOLU) sector in five large parties to the United Nations Framework Convention on Climate Change (UNFCCC) estimated by the parties themselves (green lines for the Annex-I parties, green disks for the non-Annex-I parties when available) and by the 1-σ uncertainty envelope of the two Copernicus Atmosphere Monitoring Service (CAMS) inversions (blue for v20r1 and orange for FT20r2). Positive values indicate that the party is a source of CO_2 to the atmosphere. Note that two different ordinate axes are used among the plots, depending on flux magnitude.

reforestation areas, République Démocratique du Congo, 2015). For comparison, our fraction of managed land is of 75% for Brazil, 16% for Canada, 87% for China, 100% for DR Congo, 96% for EU27+UK, 99% for India, 99% for Kazakhstan, 81% for Mongolia, 44% for Russia and 82% for USA. With our simple definition approach, it is possible to decrease our area of managed lands (by excluding larger values of the Global Human Influence Index), as would be needed in the case of Brazil, but not to increase it (since we have excluded the lowest values of the Global Human Influence Index only), as would be needed for Russia. We are not trying to resolve the inconsistency in the definition of managed land, as it varies between parties and also taking into account the other inconsistencies discussed below. For the same reason, we do not account for the lateral fluxes of soil and biomass carbon stocks through trade (outside harvested wood products that are normally reported to UNFCCC, see Section 2d) or rivers. These lateral fluxes may be significant relative to net atmosphere-land fluxes, even without contributing much to the year-to-year variability, but they are very uncertain: Foodstuff international trade, for example, may be well documented but not their carbon fraction.

Figures 1 and 2 show, for the 10 parties, the time series of the vegetation and soil fluxes in managed areas estimated by the two CAMS inversions with their 1-σ uncertainty envelope, and of the AFOLU CO_2 fluxes reported to UNFCCC. The abscissa covers the full period of the CAMS surface inversion (1979–2019). The satellite inversion only covers the last five years, the Annex-I inventory numbers are for the period 1990–2018, while the non-Annex-I inventory numbers are for various years, depending on the party.

The two CAMS inversions, in blue and orange, agree with each other within their respective uncertainty envelope. Interannual variations show interesting similarity: The Pearson's correlation coefficient between the surface inversion results and the satellite inversion results for the five common years and the 10 parties (i.e., 50 values in total) is 0.61, and the ratio of the standard deviations of the two series is 0.8 (the larger variability is for the satellite inversion). This similarity is remarkable given the spatial scale studied here and given the very different nature of the assimilated data that drive this interannual variability (remembering that the prior vegetation fluxes over land are just a climatology, see Section 2a): Column retrievals from a polar-orbiting satellite outside the high latitudes of the winter hemisphere and in cloud-free areas versus pointwise measurements near surface at 156 sites over the globe. The remaining differences between the

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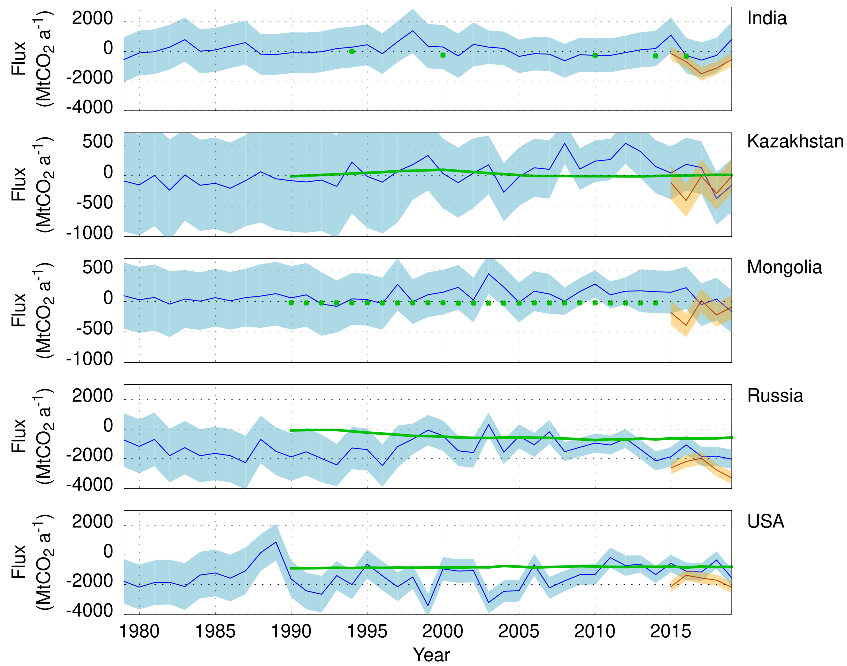

Figure 2. Same as Figure 1 for the other five parties.

two inversions seem to be fairly explained by the error bars, which strengthens our confidence in the realism of the CAMS statistical models: when assuming that the two inversions are independent, the reduced chi-squared statistics of the series of 50 differences between the two inversions is 0.84, without any new tuning. We note that the 1-σ posterior uncertainty of each product is about half the spread of a series of about 10 inversions (that includes an older version of the CAMS surface inversion) for EU27+UK, where almost all land is considered as managed, shown by Petrescu et al. (2021). However, this spread of an ad hoc set of existing inversions is not directly comparable to Bayesian uncertainties and does not necessarily represent the uncertainty of any of its members.

In comparison with the two inversions, the inventory values look flat in time, although less so for Brazil and China. The surface inversion time series may display some artifacts linked to discontinuities in the measurement time series, not only when new measurement sites are activated or existing ones are stopped, but also when some site routine operations are interrupted for a few months because of technical issues, lack of funding or manpower. Correspondingly, the v20r1 inversion uncertainty usually decreases with time, as surface network observations become denser. However, the correlation with the satellite inversion, their similar amplitude, previous analyses of the link between the inversion times series and climate variations (e.g., Bastos et al., 2016) suggest good realism in these variations, challenging the comparatively small uncertainty declared by the inventories (see Section 2d). Two reasons may explain the small amount of variability of the inventories. The first reason is practical. Inventories for the LULUCF sector rely on detailed field measurements that cannot be repeated every year: The goal is to sample all plots usually within 5–10 years with interpolations and models to get the missing data (see, e.g., Annex 3 of USA, 2020), but this slow process removes some of the temporal variations in a less straightforward way than a running mean for which the inversion statistics exist (see Section 2c). The second reason is conceptual. As mentioned above, Canada temporarily excludes managed stands dominated by natural emissions and removals that potentially drive the large variations of the LULUCF fluxes from one year to the next, in order to reveal the flux changes that are due to management decisions. In that case, a similar processing should be done on the inversion fluxes for a comparison of the same quantity, but this challenging task has not been attempted yet.

These methodological warnings relativize the differences between inversions and inventories. However, the inventory values are often within the 1-σ envelope of the two inversions for eight parties: Brazil, China, DR Congo, India, Kazakhstan, Mongolia, Russia (except for the first and last years of this inventory), USA (at least for the last decade when inversions show less temporal variability). Note that the two inversions often cannot identify whether parties are sources or sinks of CO_2 with high degree of confidence. Canada's inventory values are much less negative than the inversions over most of the study period, despite a larger area of managed lands (see above), likely for the conceptual reason that we discussed in the previous paragraph and for the export of crops that is included in the figure. The other outlier is EU27+UK, although this party does not attempt to remove the natural component of LULUCF fluxes in its reporting (European Union, 2020). There is no ambiguity in the definition of managed land for EU27+UK since both the inventory and our study classify almost all of the party area as managed. However, the magnitude of the carbon sink in geographic Europe remains debated (Reuter et al., 2017). Indeed, Europe is a subcontinent with an unusually large entanglement of different land uses, land use practices and carbon processes, making it difficult to upscale local above-ground and below-ground measurements. Crop export also likely plays a role in the difference.

4. Discussion

Encouraged by the UNFCCC reporting guidelines on annual inventories (IPCC, 2006, 2019), we attempted to compare two CO_2 atmospheric inversions with AFOLU values reported by 10 large parties to the UNFCCC. From the design of the study to the results, significant practical difficulties were encountered. The first is the absence of a mask that unambiguously defines the plots considered by each party as managed from year to year, while some of the NIRs describe very sophisticated approaches involving, for example, manual photo-interpretation or the collection of details about the local administration. The second is the lack of exhaustiveness of the CRFs, despite their 72 spreadsheet pages: The evolution of the carbon stocks is unevenly reported among the parties, in particular for less accessible or not dominant pools (soil carbon, below-ground biomass, smaller or understory vegetation, mixed land uses). The lateral fluxes of carbon through rivers and international trade, which are outside the scope of the UNFCCC reports, further complicate the comparison with atmospheric measurements. Finally, the temporal support of the values reported for a given year, blurred by interpolations between infrequent plot measurements, sometimes separated in time by large natural disturbances, is another important issue. For all these reasons, we recommend that functional operators (i.e., computer programs with corresponding ancillary data, like detailed maps of areas involved) that allow conversion between inventory flux categories and the way they are seen by the atmosphere in the real world are designed and made available by the parties. This translation approach would respect the specific responsibility of each party to design its own inventory strategy within the 10 volumes now of general guidelines, to engage its administration, to enhance its own data, and to acquire expertize in the complex interaction between its *national circumstances* and the carbon cycle, while strengthening the efforts of UNFCCC to ensure accurate, consistent and relevant reporting and improving the possibility to discuss the reported values widely.

In the meantime, the large international ETF process may develop several types of CO_2 flux accounting in parallel, with different political statuses and different main users. Atmospheric inversions can serve both the scientific debate and the general public with products generated in quasi-near-real time (i.e., weeks compared to more than a year for the UNFCCC Annex-I reports) and in a consistent manner between countries (or groups of countries), in particular through the use of remote sensing and standardized processing, but with less detailed process attribution than inventories. We expect its role to grow further due to the pressure for "net zero" emissions targets, which will increase the importance of effective carbon offsets, primarily from the AFOLU sector, for the most difficult to eliminate emissions (European Union, 2018).

In particular, we illustrated here with the CAMS CO_2 inversions the applicability of the full uncertainty covariance matrix which links uncertainty at all spatio-temporal scales and which has been rarely exploited. We argue that it may be a more comprehensive quality indicator than the spread of heterogeneous inversion products (which has other important scientific virtues not touched here), in that it explores the uncertainty space more rigorously, based on the Bayesian framework, provided the underlying statistical models are the subject of dedicated development efforts. There is also potential for improvement in global inversions like CAMS with higher resolution transport models to process satellite and surface CO_2 observations, for example, through the use of graphics processing units. The increase in resolution, together with the extension of the observation systems, would also allow studying smaller countries or groups of countries. Finally, satellite imagery, for example, on vegetation activity, could help interpret the results of inverse modeling and form the basis of a better mask to identify managed lands than the one used here.

Data Availability Statement

The CAMS data, the global terrestrial human footprint maps, and the UNFCCC Annex-I data are publicly available from https://ads.atmosphere.copernicus.eu/cdsapp#!/dataset/cams-global-greenhouse-gas-inversion, https://sedac.ciesin.columbia.edu/data/collection/wildareas-v3/, and https://unfccc.int/ghg-inventories-annex-i-parties/2020/, respectively.

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