Sentinels4Carbon (Sense4Fire)

Sentinel-based fuel, fire and emissions products to constrain the changing role of vegetation fires in the global carbon cycle

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1 Introduction

The aim of this impact assessment report is to provide an overview about significant scientific contributions to the main science gaps and major scientific challenges of the Sense4Fire project: "to constrain the changing role of vegetation fires in the global carbon cycle using ESA Sentinel satellite data".

The report is organised around the following five objectives as defined in both the ESA invitation to tender as well as in the Sense4Fire proposal.

Objective 1: Generate novel emission estimates.

A main task of the Sense4Fire project is to develop and apply innovative methods to estimate fire emissions by making use of additional and advanced satellite observations compared to what is used in state-of-the-art fire emission database – and in particular using the suite of ESA Sentinel satellites and ESA and Copernicus Earth observation products although a wide range of available Earth observation data products is used (see Table 5 in ATBDv2.1).

Objective 2: Summarise the main scientific findings and novel earth science results.

We provide a summary of the main scientific results of the different studies and analyses carried out in the Sense4Fire project. This includes a description of the science cases, the scientific methodology used and the scientific results obtained. In addition, an assessment of the suitability of the generated products for each of the science cases is reported and justified. Furthermore, part of the IAR consists of quantifying the impact and suitability of the datasets generated within the Sense4Fire project vs. equivalent products and/or model results to contribute to achieve the target scientific goals of the Sense4Fire project and advance the state of the art in carbon science.

Objective 3: Identify the potential for future operational applications.

An important outcome of the Sense4Fire project is not only to demonstrate the potential of the developed products for advancing carbon science but also to explore and identify potential future applications. This also includes an assessment of existing data availability and future data prospects since the Sentinel datasets currently still cover only a relatively short time window. In the Sense4Fire extension (contract change) the near-real-time capabilities of the developed approached was tested to explore and/or demonstrate how the approaches could be used and applied in an operational setting.

Objective 4: Implement a comprehensive research plan.

As outlined in Objective 3, the Sense4Fire project results and the datasets developed also provide directions for additional significant scientific contributions that could be made to fill key scientific gaps and address major scientific challenges in carbon science. This should be summarised in a focused proposal with a plan for how the Sense4Fire results could be further developed.

Objective 5: Submit results of science cases to suitable peer reviewed journals

Part of the project task associated with this IAR is to submit project results to suitable peer reviewed journals. As the objectives of the Sense4Fire project and in particular the impact assessment are embedded in these research papers, the IAR report has attached the current drafts of **three research papers (Forkel et al., 2025; de Laat et al., 2024, 2025**) that have been submitted, are under review or have been published at the moment of writing accompanied with a brief description of the main findings of these papers (Chapters 3, 4 and 5).

2 Impact assessment

2.1 Generation of novel emission estimates

The Sense4Fire project primarily aims to make better use of the wealth of complementary satellite-based data on fires and approaches to overcome the standard current use of a limited set of static fire emission factors to convert a small set of land use types into bottom-up fire emissions. The Sense4Fire project focuses in particular on the suite of ESA Sentinel satellite data and ESA-developed Earth observation data products such as biomass, land cover and burned area from ESA CCI datasets (see Table 5 in ATBDv2.1. To address this three main complementary approaches have been developed and applied in Sense4Fire to produce fire emissions estimates (see Algorithm Theoretical Baseline Document version 2.1 (ATBDv2.1; Forkel et al., 2023) and version 3 (ATBDv3; Forkel et al., 2024):

- **KNMI-S5p** is based on observations from Sentinel-5p, whereby fire emissions of carbon monoxide (CO) and nitrogen oxides (NO_x) or nitrogen dioxide (NO_2) are estimated using a simple top-down inversion approach (ATBD's chapter 5).
- **GFA-S4F** is based on the Global Fire Atlas (GFA) algorithm (Andela et al., 2019, 2022) and uses observations of active fires from the VIIRS and Sentinel-3 SLSTR instruments with a new fire type map to estimate fire emissions (ATBD's chapter 3).
- **TUD-S4F** is a new data-model fusion approach that combines several datasets from Sentinel-3 and other Earth observation products to estimate fuel loads, fuel moisture, fuel consumption, and fire emissions, whereby fire emissions are estimated based on dynamic emission factors (ATBD's chapter 4)

In addition, the Sense4Fire project also incorporated fire emissions from the COPERNICUS CAMS Global Fire Assimilation System (GFAS) as a benchmark wildfire emission dataset as well as CAMS anthropogenic emissions, biogenic emissions and soils NOx emissions as boundary conditions for the IFS-COMPO modem simulations.

In the Sense4Fire project these approaches have been applied to three test areas and two larger study regions were selected (

Table 1) for which fire emissions are determined as described in ATBD versions 2.1 and 3 (Forkel et al., 2023, 2024). Southern Europe /Mediterranean were added later as fourth test area. These test areas and study regions represent main fire types in the Earth system and associated land cover: a transect of tropical forest conversion to savannah (Brazil), an area with small agricultural and large savannah fires (southern Africa), to Mediterranean and temperate forests (Europe) and boreal forests and tundra (Siberia). By far most of the Sense4Fire effort has focused on the Amazon/Cerrado region, hence results for regions other than the Amazon/Cerrado will only briefly be touched in the first summary research paper .

Table 1: Overview about the study regions (large) and test areas (small).

Study region or test area	East/West extent	North/South extent
Amazon study region	40°W - 80°W	25°S - 10°N
Southern Africa study region	10°E - 30°E	5°S - 25°S
Siberia test area	132°E - 138°E	60°N - 71°N
Southern Europe test area	10°W – 30°E	34°N – 50°N

Table 2: Overview about the applied methodological approaches and related datasets in the Experimental Database version 1 (DBv1), version 2 (DBv2) and in the near-real time database (DB-NRT). Please note that the TUD-S4F approach underwent major improvements in calibration from version 0.1 to version 0.2 and hence results from v0.1 (marked with *) are not recommended to use.

Approach, version, model run and reference	Applied methods/approach	Spatial resolution and coverage	Temporal resolution and coverage	Data size and URL
GFA-S4F-FRP v0.1 ATBDv2.1/ ATBDv3, Ch. 3 PVRv2.1, Ch. 2	Fire emissions and fuel consumption derived from VIIRS and Sentinel-3 Fire Radiative Power observations based on a fire type classification	333 x 333 m 0.1 x 0.1°	Fire emissions: daily (2020, 2024) Fire types: annual (2020, 2024)	38 MB DBv01
GFA-S4F-FRP v0.2 ATBDv3, Ch. 3	Like GFA-S4F-FRP v0.1 but with revised emission factors for the Amazon	333 x 333 m 0.1 x 0.1° (Amazon-reg only)	Fire emissions: daily (2019-2024) Fire types: annual (2020, 2024)	2019-2023: 116 MB DBv02 2024: 223 MB DB-NRT
KNMI-S5p v0.1 ATBDv2.1/ ATBDv3, Ch. 5 PVRv2.1, Ch. 4	Fire NO_x emissions derived from Sentinel-5p observations using the beta-method	0.1 x 0.1°	daily 2020-08-01 - 2020-09-30	9 MB DBv01 = DBv02
TUD-S4F v0.1 **S4F-BA v0.1*** ATBDv2.1, Ch. 4.3 PVRv2.1, Ch. 3.3 **revised, refer to v0.2*	Fuel loads, fuel consumption and fire emissions derived from the S4F data-model fusion approach by using the Copernicus Proba-V/Sentinel-3 LAI and fCOVER, and ASCAT soil water index, ESA CCI land cover (v2.1.1), ESA CCI above-ground woody biomass (v3.0), and ESA CCI fire burned area maps (v5.1) as input	333 x 333 m 0.1 x 0.1°	10-daily (emissions are total emissions over the 10 days before) 2014-01-01 - 2021-10-20	3.1 TB DBv01
TUD-S4F v0.1 **S4F-BA-song v0.1*** ATBDv2.1, Ch. 4.3 PVRv2.1, Ch. 3.3 ** revised, refer to v0.2*	Like TUD-S4F-BA but with using the fractional cover of trees and short vegetation from Song et al. (2018) as input instead of the ESA CCI land cover map	333 x 333 m 0.1 x 0.1° (Amazon-reg only)	10-daily 2014-01-01 - 2021-10-21	3.1 TB DBv01

TUD-S4F v0.2 S4F.CCILC_S4Fba_dynEF v0.2 Forkel et al. (2025)	Updated version of TUD-S4F-BA including: burned area for the year 2020 from S4F (GFA-S4F-FRP approach) and from ESA CCI fire (v5.1) for the other years; recalibration based on an improved sampling of test fire events and removed biases in regional total CO emissions in comparison to KNMI-S5p v0.1	333 x 333 m 0.1 x 0.1°	10-daily 2014-01-01 - 2021-10-22	4.7 TB DBv02
TUD-S4F v0.2 S4F.CCILC_S4Fba_fixEF v0.2 Forkel et al. (2025)	Like S4F.CCILC_S4Fba_dynEF v0.2 but using fixed emission factors	333 x 333 m 0.1 x 0.1° (Amazon-reg only)	10-daily 2014-01-01 - 2021-10-23	2.6 TB DBv02
TUD-S4F v0.2 S4F.CCILC_FireCCI51 v0.2 Forkel et al. (2025)	Like S4F.CCILC_S4Fba_dynEF v0.2 but with using only burned area from ESA CCI fire (v5.1)	333 x 333 m 0.1 x 0.1° (Amazon-reg only)	10-daily 2014-01-01 - 2021-10-23	3.6 TB DBv02
TUD-S4F vNRT01 de Laat et al. (2025)	Machine learning approach applied to produce an emulator of the TUD-S4F v0.2 approach. Outputs for fuel loads, emission factors and fuel consumption for the Amazon and Cerrado for the year 2020 were taken from TUD-S4F v0.2 (experiment S4F.CCILC_S4Fba_dynEF v0.2) and the fire type map from GFA-S4F v0.2 for the year 2024 to estimate fire emissions for 2024.	333 x 333 m 0.1 x 0.1° (Amazon-reg only)	daily 2024-01-01 – 2024-09-31	504 GB DB-NRT

Fire emissions were estimated with the three main S4F approaches for each region extending beyond the common standard use of fire radiative power and burned area. The GFA-S4F approach estimates fuel consumption and uses fire emissions that depend on a new classification of fire types (Andela et al., 2022). In the TUD-S4F approach information from satellite observations about leaf area, soil moisture, land cover, above-ground biomass and canopy height are combined with fire radiative power and burned area in a fuel combustion model with dynamic emission factors to estimate trace gas and aerosol emissions from fires. The KNMI-S5P approach provides an atmospheric perspective on fire emissions.

For the application of TUD-S4F in near real time (NRT), a new approach was developed: TUD-S4F vNRT01 is a machine learning emulator of the baseline TUD-S4F approach to enable and speed up the NRT calculation of emissions via the TUD-S4F approach. The NRT application of the TUD-S4F approach is hampered by the timely availability of input data. The main limitation is caused by the Copernicus Land Service Sentinel-3 LAI product, which contains continental-scale amounts of missing data in its NRT version (RT0) and provides reliable gap-filled LAI estimates only after 60 days. This permits a use of the dataset in NRT applications. In addition, the need to download, pre-process and integrate all input datasets (e.g. several 100s of GBs for the Amazon region) for a NRT application of TUD-S4F requires the implementation of more performant processing workflows and the access to more performant computing infrastructure (currently up to four machines with each 16 cores and 256 MB RAM are used at TUD for the processing of data and application of TUD-S4F).

An overview about the different datasets that are currently produced in Sense4Fire is provided in Table 2.

In order to explore and compare the Sense4Fire emission approaches with each other and with other established or state-of the art emission inventories, the Amazon study region (including large other parts of South America such as the Cerrado) was selected first for advanced analyses during the period August-October 2020 which had the largest burned area in the South America since 2010 prior to 2024, only to be exceeded by the August-September 2024 period. For the Amazon and Cerrado region also different factorial experiments with TUD S4F approach (version 0.2) have been conducted to assess the impact of different burned area datasets and of dynamics and fixed emission factors on estimated fire emissions (Table 2).

2.2 Main scientific findings and novel Earth science results

The focus of the Sense4Fire research efforts has been on two main topics: (a) evaluation and inter-comparison of the approaches used in Sense4Fire by using additional satellite observations and by benchmarking against other state-of-the-art emission inventories and (b) use of IFS atmospheric composition model simulations for comparison with Sentinel-5p observations as an independent means of verification and to assess the realism, correspondence and differences of the fire emission databases. By conducting those comparisons, we develop and describe new scientific findings that help to better parametrise top-down and bottom-up fire emission inventories and that help to better understand the role of fire dynamics on the carbon cycle and the Earth system.

2.2.1 Woody debris dominate regional total fire emissions

The Sense4Fire emission approaches reveal that regional total fire CO emissions in the Amazon and Cerrado biomes are dominated by forest and deforestation fires (Figure 1). Those emissions originate according to the TUD-S4F approach mostly from the burning woody debris (~70%), while the burning of live wood has only a small contribution to fire emissions. Across all Sense4Fire approaches, the highest fire emissions in the Amazon/Cerrado occur in forest fires, followed by deforestation fires, small land clearing and savannah fires (fire type classification following (Andela et al., 2022)). Further results are summarised in Chapter 4 and in (Forkel et al., 2025)

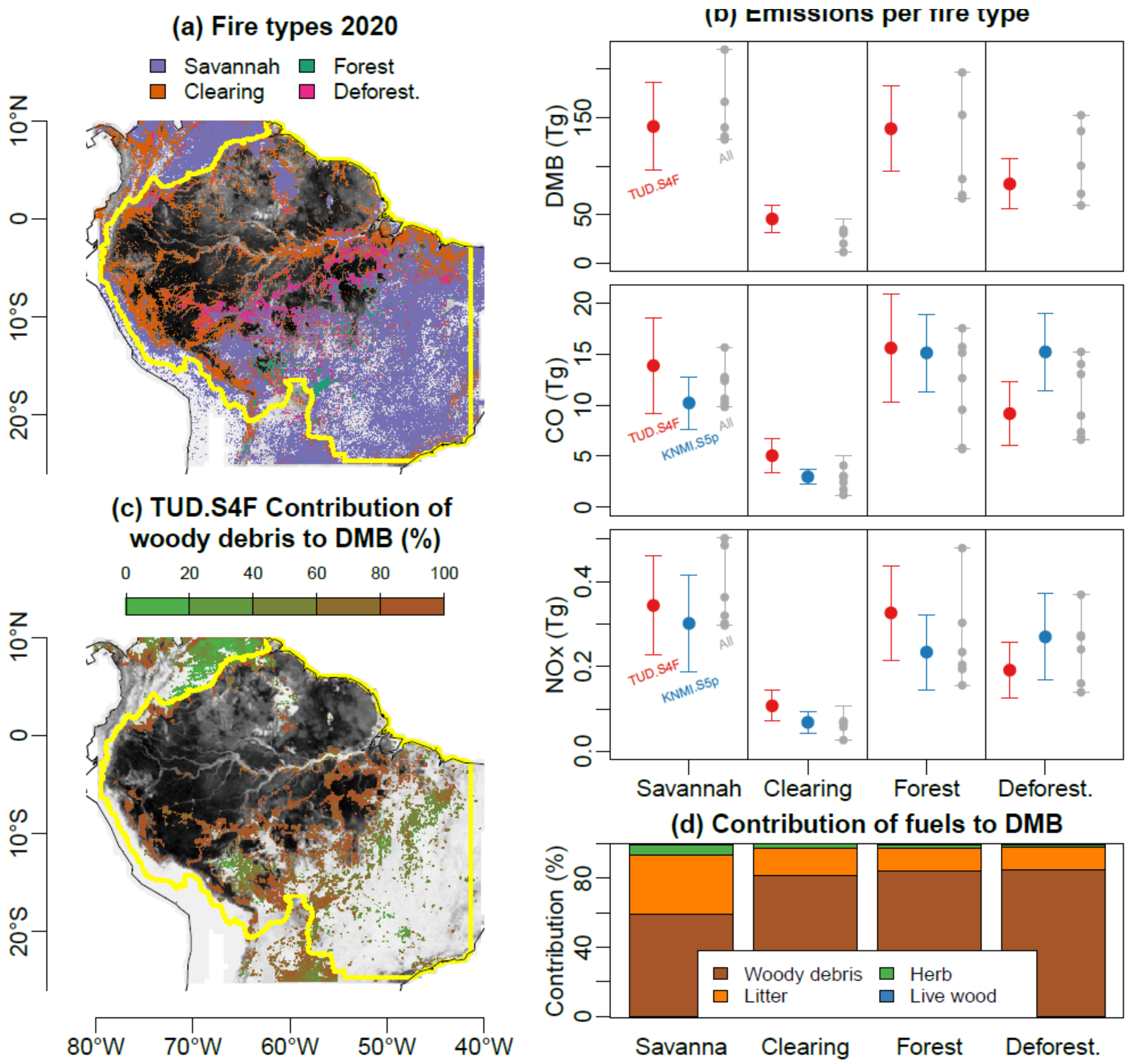

Figure 1: Fire emissions for different fire types and fuels in the Amazon and the Cerrado in the period 1st August to 31st October 2020. (a) Map of fire types in 2020 GFA.S4F approach. (b) Regional emissions by fire type. "all" EO approaches display ranges across five (for DMB) and six (for CO and NOx) methods. (c) Contribution of woody debris to dry matter burnt via TUD.S4F. (d) Contribution of woody debris, litter, herbaceous vegetation, and live biomass to DMB by fire type. Results from (Forkel et al., 2025).

2.2.2 Emission factors vary by fire and fuel type

The TUD-S4F approach is the first bottom-up fire emission approach that uses dynamic emission factors for carbon-related species by accounting for the combustion of different fuel types (leaves, grass, live wood, woody debris, litter), their chemical composition (lignin, cellulose, volatiles) and fuel moisture content. Generally, the results reveal more incomplete combustion (lower combustion efficiency and higher emission factor for CO or more smouldering combustion) over forested areas than over savannahs and grasslands (Figure 2). The highest emission factors for CO occur over small land clearing fires and deforestation fires. The obtained distributions of emission factors for CO and of the modified combustion efficiency agree well with the observed values for tropical forests and savannahs reported by (Andreae, 2019). Hence, this presents one of the first successful attempts to move beyond the use of fixed emission factors in fire emission inventories.

However, there is a tendency to underestimate extreme emission factor values for particulate matter and for methane. As those emission factors are mainly driven by the amount of volatile hydrocarbonates in a fuel, those results indicate the need to better quantify the chemical composition of different fuel types at large scales.

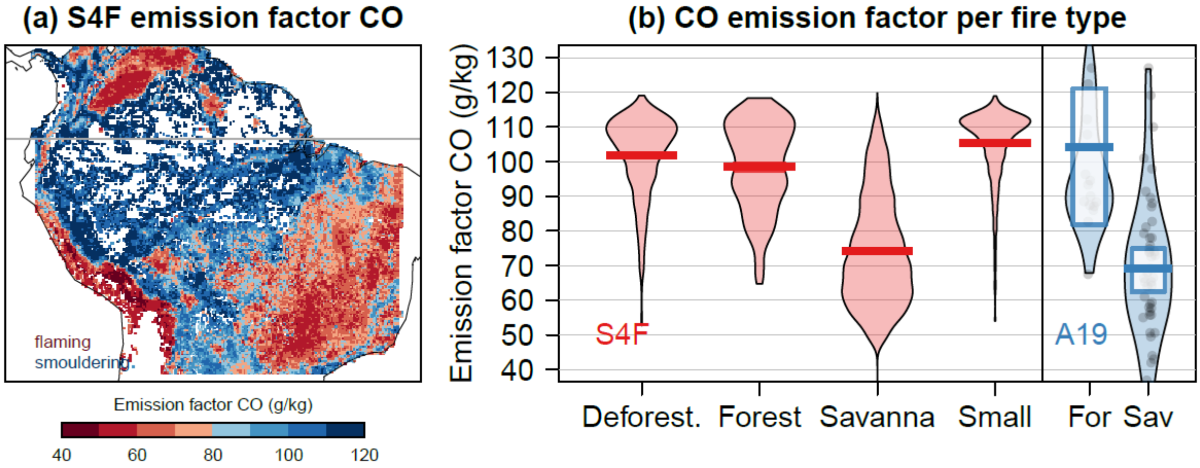

Figure 2: Spatial variability of the emission factor for carbon monoxide (CO) as derived from the TUD S4F approach in the Amazon and Cerrado (a) and (b) distribution of the emission factor across different fire types and in comparison, to the values reported for tropical forests and savannahs by Andreae (2019) [A19]. Results from (Forkel et al., 2025).

2.2.3 Sentinel-5p observations provide constraints on total fire emissions

Comparison with IFS model simulations further reveals that the GFA-S4F emissions lead to better agreement (smaller negative bias) with Sentinel-5p CO than the GFAS emissions (large negative bias). This was the case for 2020 and was further proven for the 2024 NRT results for the Amazon/Cerrado region.

Figure 3 shows CO emissions from different emission databases (GFAS, GFA-S4F, TUD-S4F-vNRT01) and IFS-COMPO simulations using those emissions evaluated against Sentinel-5p CO observations on a daily basis for the 2024 Amazon/Cerrado fire season. Spatial correlations are comparable regardless of emission database, in indicating that all emission databases capture the spatial variability of CO emissions. Differences grow over time while consistently values of regression coefficients (linear fit to the data) decrease over time. Difference between Sentinel-5p and GFAS were larger than differences between Sentinel-5p and GFA-S4F or TUD-S4F-vNRT01 the latter two yielding comparable results although both nevertheless also underestimate observed CO.

A simple optimization procedure applied to GFA-S4F emissions (GFA-OPT), which essentially increased GFA-S4F emissions by 50%; optimization based on August 2024, resulted in a fair comparison for August 2024. Differences nevertheless emerged – and grew - in September 2024. Following the same basic optimization approach indicated that another 50-100% increase would be warranted in order to match Sentinel-5p CO observations.

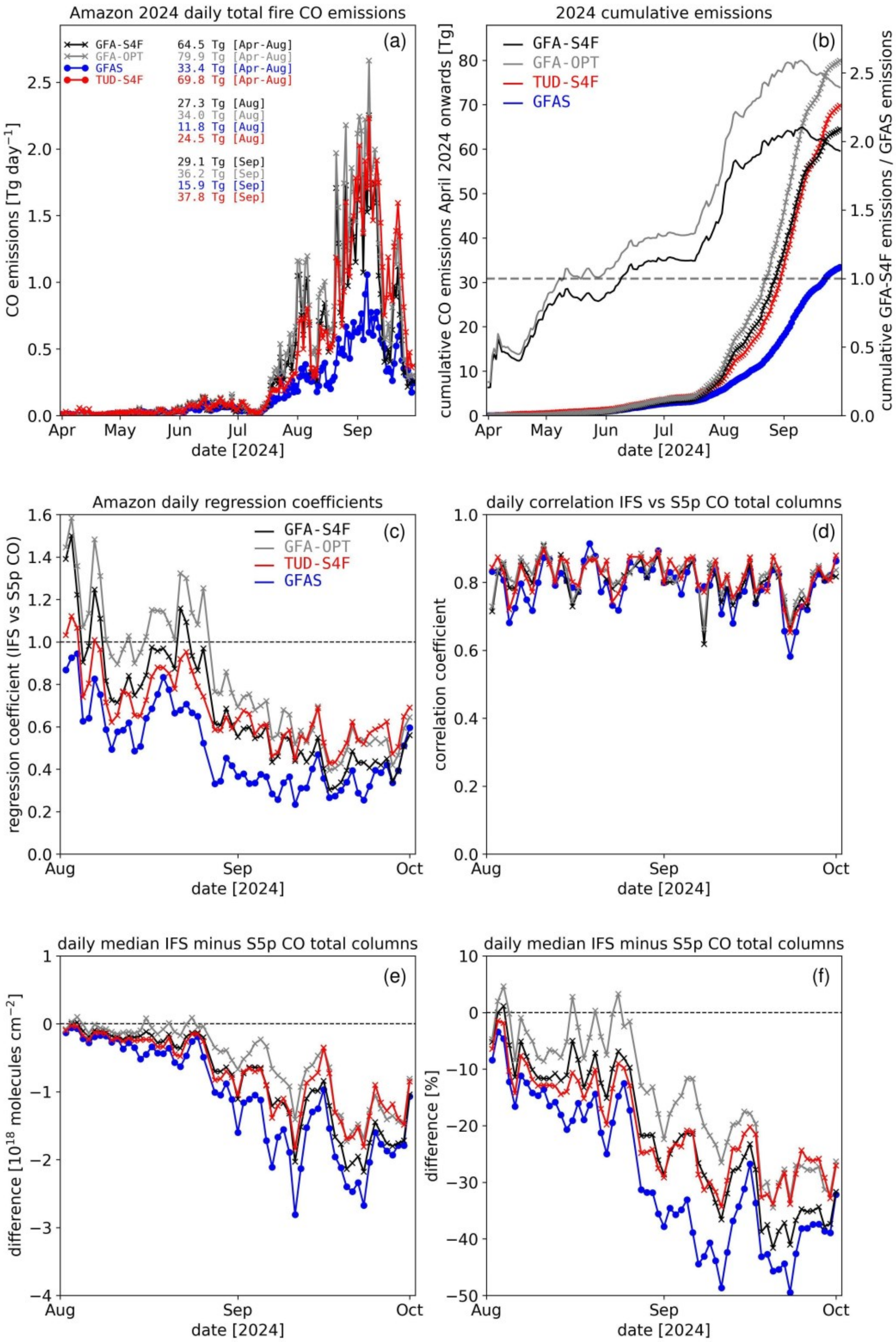

Figure 3: Daily emissions and regression statistics of the comparison between IFS and S5p CO total columns for the four IFS simulations with different bottom-up emission databases. (a) Daily CO emissions for the period April to August 2024 in Tg day-1. (b) Cumulative emissions in Tg for the period for the period April to August 2024 (lines with markers) and cumulative GFA emissions as fraction of cumulative GFAS emissions (solid lines without markers). (c) Daily regression coefficient of IFS and S5p columns. (d) Daily Pearson correlation coefficients of the regression. (e) Absolute differences in IFS - S5p daily CO-TC. (f) Relative differences in IFS - S5p CO-TC.

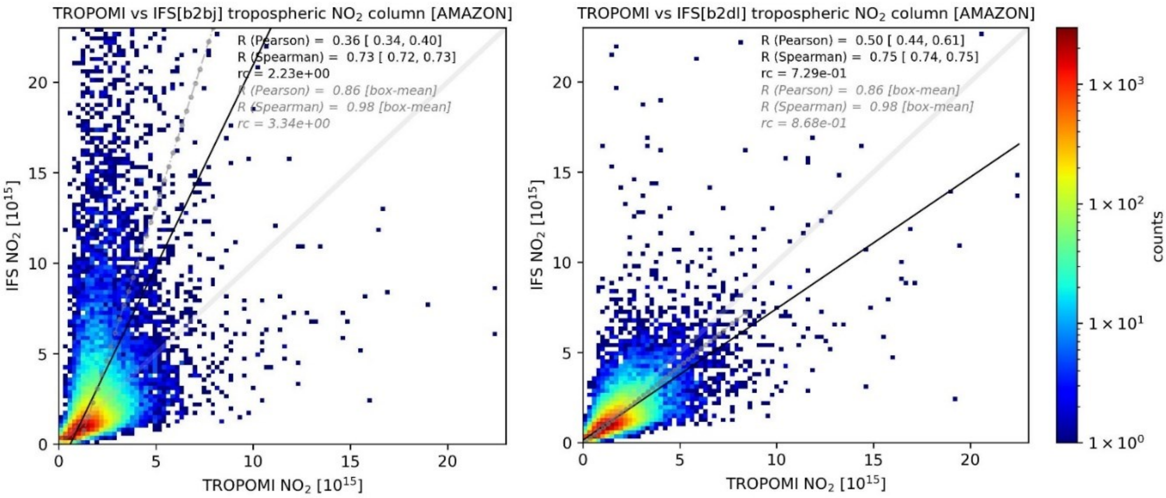

Figure 4: 2D histogram of Sentinel-5p observed and IFS-CAMPO simulated tropospheric NO_2 columns for daily August and September 2020 data for the Amazon region. The IFS-CAMPO B2BJ simulation uses emissions from GFA-S4F, for the IFS-CAMPO B2DL simulation Sentinel-5p -optimised GFAS emissions are used. The black line indicates the regression coefficient for all data, the grey line ("box-mean") when IFS-CAMPO data are averaged within twenty (20) Sentinel-5p bins (only with more than ten data points in a particular Sentinel-5p bin).

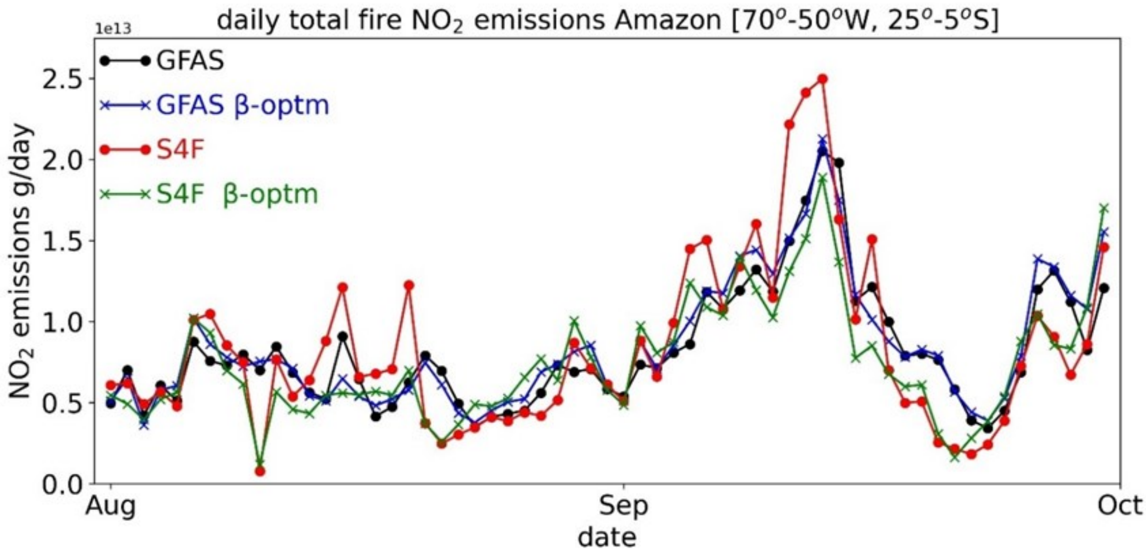

Figure 5. Daily total NO_2 emissions over the larger Amazon region for August and September 2020. GFAS emissions in black, β-optimised GFAS emissions in blue, S4F-GFA emissions in red, β-optimised S4F-GFA emissions in green.

On the other hand, evaluation of NO_x emissions for 2020, simulations and observations uncover the presence of a "large fire NO_2 bias" in both GFAS and GFA-S4F emissions (Figure 4). Using either of these bottom-up emissions in IFS-CAMPO simulations results in a strong overestimation of simulated tropospheric NO_2 columns compared to Sentinel-5p observations. Although the contribution of this bias to total NO_x emissions is relatively small (Figure 5) emissions derived for Sense4Fire did not improve the comparison relative to GFAS emissions. Note that 2024 yield similar results for NO_2.

Application of a novel technique to *a posteriori* correct fire NO_x emissions from for example GFAS or Sense4Fire using Sentinel-5p NO_2 data results in a large reduction in the "large fire NO_2 bias" and better agreement between IFS-COMPO simulations and Sentinel-5p observations. Although the results from this so-called β-method are not unexpected it shows that even in a relatively simple *a posteriori* approach Sentinel-5p observations contain additional information for reducing the overestimation in NO_x emissions.

Most of the effort in the Sense4Fire project has been aimed at the Amazon/Cerrado region as for those regions the GFA data was easily accessible. Additionally, computationally intensive data processing, particularly the TUD approach, limited data provision for many other regions over longer periods of time. Nevertheless, some analyses and intercomparison for the other regions were performed. Note that the number of fires and amount of emissions for Siberia (tundra and steppe) as well as for Europe were much smaller than for the Amazon/Cerrado and to some extend also the south-equatorial Africa region, limiting the amount of data to be analysed. Nevertheless, insofar as was analysed and/or could be concluded, similar results were found: the bottom-up emission tend to significantly underestimate CO emissions while for NO2, indications of a large-fire-NO2 bias in the bottom-up fire emission databases were also found in other regions.

Overall, these results clearly indicate that the use of a limited set of static emission factors combined with only information for a limited set of land use types, fire radiative power and burned area introduces significant biases in fire emissions.

The Sense4Fire project demonstrates the added value of using more information from satellites relevant for fires like leaf area, soil moisture, land cover, above-ground biomass, and canopy height. This could include other data from Sentinel missions (for example fluorescence from Sentinel-5p), successors of the current Sentinel missions, upcoming ESA satellite missions like Earth Explorers BIOMASS and FLEX, essentially all Sentinel Expansion missions and even partner satellite missions like EUMETSAT's MTG-FCI, to just name a few.

2.3 Testing Sense4Fire near-real-time capabilities

Because of the importance of wildfire monitoring and estimating wildfire emissions, a demonstration of "near-real-time" capacity test of the Sense4Fire approach was conducted summer 2024. For the test a particular wildfire case would be selected in summer 2024 after which the S4F team would derive emissions, run the IFS-COMPO model, and assessed the results using Sentinel-5p data (see Figure 3).

For the test, the Amazon 2024 biomass burning season in August and September was selected as the region was subject to significantly more than usual larger fires and deterioration of air quality was reported. The main reason was a severe drought that started in 2023 by an El Niñoevent that persisted well in to 2024.

The Sense4Fire team started their efforts on 1 September 2024. Within two weeks GFAS and GFA emissions were available which were fed into the IFS-COMPO model and simulation results were compared to Sentinel-5p CO and NO_2 data.

The Amazon fire season persisted well into September 2024 with the strongest emissions in the period middle of August 2024 to the middle of September 2024 (Figure 3). Hence by October 2024 the analysis was extended with emissions for the September 2024 month.. By that time, also emissions from TUD-S4F had become available as a machine learning algorithm had been developed for rapidly assessing emissions (TUD-S4F vNRT01).

In summary, the test of the Sense4Fire near-real-time capabilities showed that with dedicated effort emissions, IFS model simulations and first analysis of results could be provided within a four-week time window. This paves the road towards an operational fire emission monitoring applications of the Sense4Fire suite of tools.

2.4 Sense4Fire results for the Amazon for August-September 2024

The analysis of the Sense4Fire assessment of the uncovered a significant underestimation of observed Sentinel-5p CO total columns (CO-TC). Depending on the emission database used, differences between IFS-COMPO modelled and Sentinel-5p observed CO-TC values ranged from 5-15% (August 2024) to 20-40% (September 2024).

Differences between emission estimates thereby vary by up to a factor of three between the lowest and highest emissions. The much larger differences in emissions reflect the long atmospheric lifetime of CO (~2 months in most of the tropics but up to 4 months over the Amazon (Lichtig et al., 2024)) which leads to accumulation of CO in the atmosphere. CO-TC's thus represent atmospheric accumulation over time of CO emissions. On shorter timescales of weeks differences in estimated emissions can be even larger (factor four or more).

The GFAS emissions were lowest and resulted in the largest differences when used in the IFS-COMPO simulations and compared to S5p CO-TC values. Emissions for GFA and TUD were larger (approximately a factor two) and to first order comparable resulting in more comparable biases in the evaluation against S5p CO-TCs. Nevertheless, using both emission databases resulted in a significant underestimation of S5p CO-TC values of 5-10% (August 2024) and 25-30% (September 2024).

A test with a simple optimization of GFA emissions based on August 2024 results indicated that GFA emissions should be increased by another 50% to match S5p CO-TC observations, which indeed was the case as for those emissions the August 2024 bias was eradicated. Still, applying this 50% increase did not result in a similar disappearance of the September bias which remained high at more than 20%.

Following the same optimization approach as for August 2024 indicated that another increase of 50-100% of GFA emissions would be warranted, but this was not tested. It is hypothesized that this underestimation of 2024 wildfire CO emissions could be related to missing small fires and low-burning-intensity fires, a well known issue in estimating wildfire emissions using satellite observations of fires and vegetation characteristics. Overall, it was assessed that current state-of-the-art and widely used bottom-up fire emission databases significantly underestimated 2024 Amazon CO (and thus carbon) emissions by a factor of 1.5 to 3 for the entire fire season, but for shorter periods of time even more.

Finally, analysis of the GFA emissions also revealed that for the Amazon region wildfire emissions in 2024 were dominated by burning of natural vegetation (forest) rather than deforestation as was typically the case for the years 2019-2023 and with 2024 deforestation fire carbon emissions comparable to those from 2019-2023 (deforestation as defined in Andela et al. (2019, 2022)). This can be explained by the exceptional 2024 Amazon drought which likely dried out natural vegetation more, making it susceptible to fires.

Results have been summarized a submitted scientific journal article for Geophysical Research Letters (de Laat et al., 2025; see also paper 3 below)

2.5 Potential for future operational applications

The scientific analyses in Sense4Fire so far have focused on generic characteristics of fires over a main wildfire area in South America and during a limited period of time. Future efforts should focus on similar characteristics for the other chosen study regions and test areas as well as potentially new regions and for other years or longer periods of time. Regions of interest could be north equatorial Africa (seasonal savannah burning), India/Ganghes valley (seasonal crop burning), Indonesia (deforestation and peat fires) and Australia (severe bush fires in the south and seasonal bush fires in the north). This does, however, require more computation resources as deriving/calculating bottom-up fire emissions is computationally intensive. For example, for the formal KNMI DECSO NOx inversion algorithm, deriving emissions for a 40°×20° lon/lat region at 0.2° spatial resolution, one year of emissions based on daily Sentinel-5p NO_2 data a "cloud" (HPC) virtual machine with 16 CPU's takes approximately two weeks. This does open the possibility for developing AI/ML emission emulators trained on actual bottom-up fire emission data, an approach that was developed and demonstrated for the near-real-time activities. However, such methods would still require deriving emissions for other regions and training of algorithms for those regions. The latter being a computationally intensive effort in itself, albeit only once. That would nevertheless be worth exploring in particular for an operational application.

Given the current development level of the Sense4Fire approaches, operational fire emission products are feasible from all approaches for the Amazon study region. The test with near-real time has demonstrated the capacity of the Sense4Fire approaches to provide data and analyses within a four weeks after an event of episode. This does provide a path towards an operational application with frequent updates for the Amazon study region but in principle worldwide. For example, it is thus in principle possible to update wildfire emission estimates using the Sense4Fire approaches every month, season or year, depending on user needs and wishes. However, operational applications of the Sense4Fire approaches for other regions of the world require first more detailed benchmarking and testing analyses (see Chapters 2.1-2.3) as already conducted for the Amazon study region.

Another important potential long-term development area is operationalisation of the Sense4Fire fire emission methodologies to allow for constantly updating fire emission estimates (towards a system similar to the Copernicus Atmosphere Monitoring System (CAMS) Global Fire Assimilation System (GFAS)). Note that "operational" here would not necessarily mean on a daily basis in near-real time (NRT), but nevertheless with an update frequency (weekly-monthly) that would make it valuable for monitoring purposes. In addition, an automated evaluation against Sentinel-5p data as developed and demonstrated in the Sense4Fire would be beneficial to users. That should include IFS-COMPO model simulation results against Sentinel-5p data (CO, NO_2). Additional satellite data could be incorporated as well, such as CO observations from other satellites, or aerosol optical depth, to name a few. An example of such a dashboard is the automated Sentinel-5p data validation server (https://mpc-vdaf-server.tropomi.eu/) that provides continuously extensive validation data, figures, statistics and reports about the comparison of Sentinel-5p data products and ground-based observations.

Furthermore, the project team aims to transfer the scientific findings and developments of the Sense4Fire approach to the developers of the Copernicus GFAS system. Sense4Fire can help to provide constraints on operational fire emission estimates and forecasts like CAMS GFAS by e.g. reducing regional bias for NO_x and CO emissions (using the KNMI-S5p approach); by new parametrisations for combustion efficiency and emission factors in relation to fuel types, fire types and fuel moisture (TUD-S4F and GFA-S4F approaches), and to better constrain conversion factors from fire radiative power to combustion rates (TUD-S4F and GFA-S4F approaches). Note that efforts are underway towards a project for updating the COPERNICUS CAMS GFAS approach to which Sense4Fire results could contribute. GFAS is currently based on MODIS fire radiative power and a limited set of vegetation types. At minimum an GFAS upgrade should include burned area, more up-to-date and extensive land use data, and VIIRS FRP replacing MODIS FRP. Further down the line, also Sense4Fire approaches might be of interest, for example a merger with the GFA dynamical fire polygons and TUD dynamical emission factors.

The Sense4Fire partners are currently exploring the possibility for a proposal to the upcoming 2025 EU HORIZON Space call (HORIZON-CL4-SPACE-2025-01-43) on “Copernicus Anthropogenic CO_2 Emissions Monitoring & Verification Support (CO2MVS) capacity: new and innovative methods to estimate the impact of fires on vegetation and related carbon fluxes”. The call specifically asks for contributions to the following themes:

- Enable accounting for the interaction between droughts, fires and vegetation in the CO2 Monitoring and Verification Support (CO2MVS) capacity
- Improve the estimation of fire emissions in the Copernicus Atmosphere Monitoring Service (CAMS)
- Improve the fire risk forecasting in the Copernicus Emergency Management Service (CEMS)
- Improve the assimilation of Copernicus Land Monitoring Service (CLMS) products in vegetation fire impact and carbon fluxes assessments.

The Sense4Fire project does contribute to each of these themes – if not already with project partners being part of the aforementioned activities.

Estimating fire carbon emissions, assessing them and improving those estimates are a key input for the CO2MVS. As noted, efforts are underway towards a project for updating the COPERNICUS CAMS GFAS approach and Sense4Fire outcomes would contribute to the CO2MVS capacity.

The bottom-up approaches in the Sense4Fire project used to estimate wildfire emissions could be explored for integration in the CAMS fire emission estimation.

The system used to assess those bottom-up fire emission estimates via the IFS-COMPO modelling and comparison with S5p observations supports the post-production assessment of these emissions, something currently lacking operationally in bottom-up fire emission fire emission estimates.

Land cover and vegetation products based on ESA Sentinel data (in part derived from the Copernicus LMS) is already incorporated in the bottom-up emission estimates used in Sense4Fire. Their use as input for IFS-COMPO modelling and verification with Sentinel-5p data supports the use of associated carbon fluxes and identifying biases in carbon flux assessments.

Note that this call specifically also asks for “the transfer of research results to operations … to strengthen the readiness for an operational deployment in the future”. The near-real time demonstration of the Sense4Fire approaches thus contribute to this particular request as it shows an appreciable readiness level has been reached with the Sense4Fire project.

2.6 Submissions to peer reviewed journals

So far, two research papers with the main results of the Sense4Fire project were submitted to peer reviewed scientific journals while a third paper has been submitted. Draft versions of two submitted papers were attached to the first IAR report.

After the review comments on the first paper (de Laat et al. 2024), it was decided that the paper would need a major revision. Given the long (planned) absence of the lead author during the summer of 2024 in combination with the need to shift activities to the Sense4Fire extension (CCN) it was decided to put the activities on hold with the aim to resubmit a revision as a new paper in 2025.

The second paper (Forkel et al. 2025) has been published in Nature Geoscience.

The third paper (de Laat et al., 2025) has been submitted to Geophysical Research letters, a preprint is available online, see the reference.

Chapters 3, 4 and 5 provide a brief description of these three papers (de Laat et al., 2024; Forkel et al., 2025; de Laat et al., 2025) and a summary of their main findings.

3 Summary of research paper 1

Assessment of satellite observation-based fire emissions using Sentinel-5p data and CAMS-CIFS-COMPO model simulations: results from the ESA Sense4Fire project.

The publication was submitted to Atmos. Chem. Phys. (2024) and major revisions are needed. In the light of the NRT results (research paper 3), we plan to fully revise the paper and submit as a new paper to ACP but referring to the submitted original version, review comments, and request for the same referees:

de Laat, A., Huijnen, V., Andela, N., and Forkel, M.: Assessment of satellite observation-based wildfire emissions inventories using TROPOMI data and IFS-COMPO model simulations, EGUsphere, 1–81, https://doi.org/10.5194/egusphere-2024-732, 2024.

Sentinel-5p observations of tropospheric NO_2, CO and the absorbing aerosol index are used to assess the accuracy and precision of a new fire emission database based on Global Fire Atlas (GFA) results that combines multiple ESA sentinel broad-band high resolution satellite observations as well as burned area and fire radiative power-based fire emissions from the Copernicus Atmosphere Monitoring Service (CAMS) GFAS system. Note that no emissions from the Technical University Dresden were used in the paper nor that there is any reference to TUD emissions.

The main focus region is the Amazon and Cerrado biomes during August-September 2020. This region is one of the two major biomass burning regions worldwide (together with equatorial Africa). Furthermore, GFA activities and associated had until S4F mostly been focusing on this region, so emissions - in particular the year 2020 - are already available at the start of the S4F project. Because of the large volume of data to work with it was decided to focus on the core fire months of August and September 2020. Obtaining emissions elsewhere and/or for other months would require more effort and computational time and such emissions were not available at the start of the S4F project. However, analyses are also made for a region in sub-Saharan Africa as well as two regions in Siberia (steppe and boreal forests/tundra) in 2020 using GFAS data.

These emissions are used as input for global atmospheric composition model simulations based on IFS-COMPO, i.e. an extension of ECMWF's Integrated Forecasting System (IFS) for simulation atmospheric composition. Comparing the model output with the Sentinel-5p observations of CO and NO_2 emission plumes over the same regions and same days allows for an indirect but detailed check on the realism of the emission estimates.

The results reveal that for small fires NO_x emission estimates are realistic on average albeit with a large spread, i.e. for individual fires emission can be significantly underestimated or overestimated – and regardless of emission database. However, for large fires NO_x emissions are systematically and largely overestimated in all four regions. The overestimation can be an order of magnitude or even more. For area total NO_x emissions this "large fire bias" is of minor importance, *i.e.* total NO_2 emissions are dominated by small fires. Use of more satellite information in the GFA-based approach actually worsened this "large fire bias" in NO_x emissions relative to the GFAS emissions.

The source of this bias is not well understood and despite multiple sensitivity tests with the IFS model no straight forward recipe could be found to reduce this "large fire bias". Updating the NO_x emissions by direct adjustment of emissions using Sentinel-5p NO_2 observations or "topping off" NO_x emissions does reduce this "large fire bias". Combined with an update of soil NO_x emissions – that had been causing modelled background NO_x levels that were too low – a fairly good agreement between IFS with Sentinel-5p NO_2 was reached with correlations of 0.41 (Pearson) and 0.75 (Spearmon) and a regression coefficient of 0.74. When binning and averaging NO_2 data the correlations improve to 0.98 (Pearson) and 0.99 (Spearmon) with a similar regression coefficient of 0.75. As the data is not normally distributed and there are outliers, both the Pearson and Spearmon correlation coefficients were calculated. Spearmon being less sensitive to outliers and less biased for non-Gaussian data distributions. A high Spearmon correlation coefficient reflects a monotonic relation between two variables even with outliers and a non-Gaussian data distribution.

CO overall was underestimated using GFAS emissions (~50% on average for the selected regions) regardless of region and the size of fires. Updating CO emissions over the Amazon by incorporating more Sentinel satellite data (GFA) did reduce this fire CO bias significantly (to ~25% on average).

An innovative application of the IFS model was introduced for directly updating NO_2 emissions using Sentinel-5p measurements. Although local emissions may be uncertain and/or inaccurate - resulting in differences between the IFS model and Sentinel-5p measurements, the IFS model results can be used to calculate the local relationship between emissions and tropospheric NO_2 columns. This is determined by performing an IFS baseline simulation and an IFS simulation with a 20% change in emissions. This allows for calculating a ratio factor of the 20% emission change over the difference in tropospheric NO_2 columns between both simulations and for every model grid. This local relationship then can be multiplied with the differences in observed and modelled tropospheric NO_2 columns yielding a local emission update. The results show that this method eliminates the observed NO_2 "large fire bias" even if differences between observed and modelled baseline tropospheric NO_2 columns were large.

Overall, the results show that Sentinel-5p data allows for systematically identifying uncertainties and errors in Sentinel-5p based emissions. The results also provide strong indications that fire emissions are much more complex than the current representation in fire emission algorithms and that in particular emission factors may be (much) more variable than used in those algorithms. In addition, the results highlight that the use of Sentinel-5p data could be expanded, more detailed and extended over longer time periods while also assessing individual fires on a daily basis for better understanding fire dynamics and to improve and diversify fire emission factors. Finally, with several upcoming missions providing observational capacities similar to Sentinel-5p – or even better than in case of spatial resolution – the Sense4Fire project has laid out the start of a generic foundation for the use of Sentinel-5p-like satellite observations for bottom-up fire emission "truthing".

4 Summary of research paper 2

Burning of woody debris dominates fire emissions in the Amazon and Cerrado

The paper is published as:

Forkel, M., Wessollek, C., Huijnen, V., Andela, N., de Laat, A., Kinalczyk, D., Marrs, C., van Wees, D., Bastos, A., Ciais, P., Fawcett, D., Kaiser, J. W., Klauberg, C., Kutchartt, E., Leite, R., Li, W., Silva, C., Sitch, S., Goncalves De Souza, J., Zaehle, S., and Plummer, S.: Burning of woody debris dominates fire emissions in the Amazon and Cerrado, Nat. Geosci., 1–8, https://doi.org/10.1038/s41561-024-01637-5, 2025.

Fires in the Amazon are of great concern because they threaten the tropical forest biome, the carbon cycle and air quality. Fire emissions depends on the burning behaviour of vegetation biomass, woody debris and litter. However, the effects of fuels on the combustion process and on the composition of fire emissions are simplified in current fire emission inventories.

By introducing and applying the TUD-S4F approach that integrates various satellite observations of vegetation, fire and atmospheric composition with a fuel combustion model it is estimated that increasing loads of woody debris cause a decline in combustion efficiency and hence a relative increase in CO emissions. By comparing five novel satellite-based fire emission approaches for the fire season 2020 the mean and range of total CO emissions and nitrogen oxides are estimated.

Analysis of satellite -based fire characteristics shows that understorey forest fires and deforestation fires contribute to the majority of fuel consumption and fire emissions. Total fire emissions in the Amazon and Cerrado biomes are dominated by smouldering combustion of woody debris in the most extreme fire events.

Despite some convergence in different fire emission approaches there still is a large uncertainty in estimates of total fuel consumption estimates stemming mostly from forest and deforestation fires. A better understanding of fuel consumption for such fires is required for better constraining emission estimates. More field campaigns like the planned ESA Amazon Campaign 2024 and novel remote sensing approaches beyond above-ground total biomass are necessary to quantify pre- and post-fire woody debris and litter, which can support development of novel approaches to map surface fuel dynamics and fire emissions.

The importance of woody debris and the effect of woody debris on emission factors highlight potential directions to further develop fire-enabled vegetation and Earth system models. Global models cannot well represent the inter-annual variability of global fire emissions because they misrepresent among other processes deforestation fires.

The results demonstrate the need for new satellite observations and in situ measurements of surface fuels and emission factors in individual extreme fire events to better quantify the role of wildfire combustion on atmospheric composition and the carbon cycle.

5 Summary of research paper 3

Sentinel-5p reveals unexplained large wildfire carbon emissions in the Amazon in 2024

The paper is submitted to Geophysical Research Letters and has been published as pre-print:

de Laat, A. T. J., Andela, N., Forkel, M., Huijnen, V., Kinalzcyzk, D., and van Wees, D.: Sentinel-5p reveals unexplained large wildfire carbon emissions in the Amazon in 2024, ESS Open Archive, https://doi.org/10.22541/essoar.173869416.69575859/v1, 2025.

In 2024, the Amazon basin experienced severe wildfires related to drought associated with a persistent La Nina. Advanced fire emission models estimated Amazon carbon monoxide (CO) emissions between 28–56 Tg during the main August-September Amazon fire season.

The majority of the 2024 CO emissions came from (understory) forest fires, unlike the past five years for which deforestation fires were the dominant CO source. The atypical dominance of natural vegetation as main Amazon wildfire emission source – 2024 forest fire emissions were double to triple those of 2019-2023 - reflects the La Nina impact.

Comparison with observed atmospheric Sentinel-5p CO levels indicates nevertheless that the advanced fire emission models underestimate CO emissions by a factor of 1.5-3. This is likely due to prolonged smouldering of fires after their detection in satellite active fire data. This suggest that also Amazon 2024 wildfire carbon emissions are also underestimated in advanced fire emission models.

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