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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Summary Report (SR)

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Contents

Abstract

Vegetation fires are an important component of the global climate system and an integral part of many ecosystems where periodic fires are essential for vegetation health and regeneration. Changing environments, practices and climatic conditions have caused fires to have more impact on ecosystems and society while attention has been increasing from a political, societal and scientific perspective. For the latter, the impact of fires on the carbon cycle has become an important research area.

Over the past two decades – with increasing earth observation capacities – various approaches have been developed for estimating carbon emissions using satellite data. The most widely used approach is to assign fire regions and fire activity to a regularly space geographical grid and calculate emissions for each grid where active fires are detected or where burnt area was mapped, using conversion and emission factors to convert that information into emissions. However, the conversion and emission factors that the calculations rely on are generally static in space and time and available only for a limited set of biomes.

However, it has recently also become more evident that there are limitations to these approaches. Fires are dynamic in nature and change location and behaviour over time. Thus emission factors are also dynamic as they depend on vegetation characteristics that also change in space and over time. Furthermore, opportunities to evaluate and validate fire emission data using *in situ* data from field campaigns have been limited, so novel and more representative approaches for evaluation and validation are needed.

Consequently, there is a growing need to develop and/or expand contemporary approaches that derive fire emissions from satellite observations whilst at the same time employing new types of satellite observations to provide the much needed information and evaluate and validate those fire emissions.

The Sense4Fire project addressed these issues by making use of new state-of-the-art fire emission approaches that calculate dynamic fire emissions based on vegetation characteristics and characterise fires as dynamic systems. The project developed approaches to use satellite observations of atmospheric composition to evaluate and validate fire emissions.

Results reveal that indeed fire emissions are much more variable if the evolution over time and changes in vegetation characteristics are taken into account. The use of satellite observations of atmospheric composition allowed for an improved constraining of those fire emissions and identification of issues and shortcomings.

Finally, the Sense4Fire project also demonstrated the operational readiness of the approaches, which in part was achieved by use of artificial intelligence/machine learning to speed up certain parts of the data processing chains.

1 Introduction

This Summary Report provides a concise and informative overview of the main findings of the ESA Sense4Fire project that ran from August 2021 to January 2025. The summary report builds on the associated Sense4Fire Final Report (FR) and the Scientific Roadmap as well as associated research papers and pre-prints (Andela et al., 2022; Forkel et al., 2025; de Laat et al., 2024, 2025). In addition, links and references are provided to repositories and web-portals where data produced by the Sense4Fire project is located.

Summary of Activities

The Sense4Fire project consisted of three main activities: (1) develop and/or expand state-of-the-art approaches for estimating fire emissions based on earth observation data, (2) assess and evaluate those fire emissions using other types of earth observation data as well as inter-comparison of the estimated fire emissions with other fire emissions data products, and (3) explore the "operational readiness" of the approaches used and/or developed in Sense4Fire.

Two state-of-the-art approaches were developed and used: a satellite data-model fusion approach for fuel loads, fuel moisture, fuel consumption and fire emissions (TUD-S4F approach by Technical University Dresden) and the Global Fire Atlas (GFA-S4F approach by BeZero Carbon Ltd, formerly Cardiff University). In addition, a post-hoc fire emission adjustment approach based on Sentinel-5p observations has been applied for fire CO and NOx emissions (KNMI-S5p approach by the Royal Netherlands Meteorological Institute).

Each of the three main activities are documented in research papers, the results of which are summarised in Sections 3, 4 and 5. In addition, results have been presented at various conferences, meetings and workshops (see Final Report Section 8.2).

Aims and objectives

The aim of the Sense4Fire project was to increase the scientific understanding of fire dynamics and their role in the carbon cycle by integrating observations from the Sentinels into new Earth observation products.

The first **Objective 1** was to develop advanced geo-information products to analyse spatial-temporal variations in fuel conditions, fire behaviour, and emissions across three regions. Sentinel-3 and -5p observations will be central, supplemented by Sentinel-1, -2, and other European Earth observation datasets. The second **Objective 2** was to integrate Sentinel data with advanced modelling frameworks to provide critical insights into fire dynamics and their broader environmental impacts and demonstrate the utility of these products by addressing research questions on the impacts of ecosystem changes on fuels dynamics and fire behaviour, the impact of fires on short- and long-term carbon emissions, and the role of uncertainties in fire-related carbon emissions.

Fire dynamics are understood as all processes that contribute to pre-fire conditions of the land surface (i.e. fuel loads and fuel moisture), fire behaviour (fire ignitions, spread, speed, size, burned area, thermal emissions and radiative power), combustion and production of fire emissions (combustion completeness and emissions, fuel consumption, composition of emissions) and the effect of fire emissions on atmospheric composition (smoke plumes, atmospheric gas composition, aerosols).

The Sense4Fire project provided estimates of fire emissions, emission factors, dry matter burnt, fuel loads and live fuel moisture content from three complementary approaches: GFA-S4F, TUD-S4F and KNMI.S5P. Datasets have been produced and an assessment of their application was performed for South America (Amazon and Cerrado region), southern Africa, a region in eastern Siberia and southern Europe (Mediterranean). The main focus of the scientific analyses and publications were the Amazon and Cerrado region (Andela et al., 2022; Forkel et al., 2025; de Laat et al., 2025).

The Sense4Fire project was extended in 2024 for 18 months to explore the "operational readiness" of the approaches used and/or developed in Sense4Fire, so-called "near-real-time" (NRT) aiming at the timely provision of fire emissions data, which was set at two to four weeks.

2 Approaches developed in Sense4Fire

Estimates of fire emissions and fire properties were estimated with three main approaches in Sense4Fire (Table 1).

Table 1: Overview about approaches and datasets developed in Sense4Fire.

Approach, description and reference	Main input data	Datasets
GFA-S4F is based on the Global Fire Atlas (GFA) algorithm and uses observations of active fires from the VIIRS sensors with a new fire type map to estimate fire emissions (Andela et al. 2022)	VIIRS active fire detections, land cover and deforestation maps	GFA-S4F v0.1: Results for all regions for 2020. GFA-S4F v0.2: Improved parametrisation for NOx emissions and prolonged time series (2019-2024) for the Amazon/Cerrado study region.
TUD-S4F is a data-model fusion approach that combines several Earth observation products to estimate fuel loads, fuel moisture, fuel consumption, and fire emissions. The approach is described in Forkel et al. (2025)	Proba-V/Sentinel-3 leaf area index and vegetation cover, ASCAT soil water index, ESA CCI land cover, burnt area (from FireCCI51 dataset or alternatively from VIIRS-derived fire objects), further datasets used for calibration: ESA CCI biomass, GEDI canopy height, VIIRS-derived fire radiative power, VOD2LFMC live fuel moisture content and various databases of in situ observations	**TUD-S4F v0.2** with three setups: S4F.CCILC_S4Fba_dynEF: default dataset with dynamic emission factors for all regions for 2014-2021 S4F.CCILC_S4Fba_fixEF: Setup with fixed emission factors, available for the Amazon region. S4F.CCILC_FireCCI51: burnt area is taken from ESA's CCI fire (v5.1) dataset for all years **TUD-S4F-vNRT01:** near-real time estimates of fire emissions for the Amazon/Cerrado region in 2024 by training a machine learning algorithm against TUD-S4F v0.2
KNMI-S5p is based on observations from Sentinel-5p, whereby fire emissions of CO and NO_x are estimated using a top-down approach (de Laat et al. 2024).	Sentinel-5p observations of CO and NOx	KNMI-S5p v0.1 KNMI-S5p provides CO and NO emissions for all regions for 2020.

2.1 GFA-S4F

Summary

GFA-S4F is based on the Global Fire Atlas (GFA) which is an approach to treat a fire event as an object with associated properties and fire emissions based on satellite observations (Andela et al., 2019, 2022). The approach differs to past methods that use satellite observations to derive emission assigned to a pre-defined regular spatial grid. Such objects thus can changes over time in extend and locations.

For each fire event, information was collected about land cover (tree cover, biomass, historic deforestation rates) within the fire perimeter and fire characteristics (e.g., fire radiative power, persistence, progression, day-time detection fraction, and size) based on all satellite fire detections within the larger perimeter. The combination of these data provides a unique signature of each fire type that allows for classification using three confidence intervals (low, moderate, and high).

Input data

GFA-S4F is based on the Global Fire Atlas (GFA) algorithm and uses observations of active fires from the VIIRS instruments onboard the Suomi NPP and NOAA20 satellites to classify fire types.

Approach

GFA-S4F uses observations of active fires from the VIIRS instruments onboard the Suomi NPP and NOAA20 satellites to classify fire types for the Amazon and Cerrado to estimate fire carbon emissions. The active fire detections are spatially clustered to derive a fire perimeter. These fire perimeters are then regressed against burnt area estimates from MCD64A1 collection 6 to derive scaling factors for savannah and grassland fires and deforestation fires to convert fire perimeters to burnt area. For understorey forest fires, the estimated burnt area equals the full extent of the fire perimeters. For small land clearings and agricultural fires, the approach assumes that burnt area equals 10% of the VIIRS pixel area. Here we refer to these burnt area estimates from the active fire observations as GFA-S4F burnt area. Those burnt area estimates are then combined with information on fuel consumption and emissions factors for each fire type to estimate fire emissions. For the GFA-S4F approach, fuel consumption is estimated based on relationships between satellite FRP and field observations of fuel consumption as compiled in van Wees et al. (2022), and emissions factors were based on selected emissions factors from Andreae (2019) per fire type. GFA-S4F provides daily estimates of fire emissions at 500 m spatial resolution.

2.2 TUD-S4F

Summary

TUD-S4F fire emissions are estimated with a satellite-based data-model fusion approach. It is solely driven by satellite products, and in addition, parameters are constrained by various satellite and ground observations. The main inputs to the model are satellite products of land cover, leaf area index, soil moisture and burnt area to estimate fuel loads, fuel moisture, fuel consumption, and fire emissions. Thereby, emissions factors are computed dynamically based on the chemical composition of each fuel component (i.e. woody debris, litter, grass and woody biomass). The approach has been applied to all study regions to estimate dry matter burnt and fire emissions at a spatial resolution of 333 m x 333 m for the period 2014-2021 (Forkel et al., 2025). The code is available at https://doi.org/10.1038/s41561-024-01637-5.

Input data

The TUD-S4F data–model fusion approach takes Earth observation-based time series of the fractional coverage of trees and herbaceous vegetation (from ESA CCI land cover maps), leaf area index (LAI), fractional vegetation cover (fCover), soil water index (SWI) and burnt area as input and estimates the temporal dynamics of fuel loads and fuel moisture, combustion completeness, fuel consumption, combustion efficiency, emission factors and fire emissions. Details of which dataset used for a particular parameter can be found in Forkel et al. (2025; Supplementary Information, Section 1.2, Table S1).

Approach

The model represents different fuel components such as tree leaves, branches and stems, herbaceous vegetation, surface herbaceous litter and fine and coarse woody debris (FWD, CWD). Fuel loads are derived from canopy height and LAI to estimate the biomass in tree stems, branches and leaves using allometric equations that are calibrated based on GEDI observations of canopy height and the ESA CCI biomass map. The accumulation of surface fuels is then estimated from changes in land cover and from seasonal and long-term temporal changes in LAI, which affect the turnover of herbaceous and leaf biomass to litter and of branches and stems to FWD and CWD, respectively. Fuel moisture content (FMC) is estimated from SWI and LAI for tree leaves and herbaceous biomass (that is, live-fuel moisture content) and for woody biomass from SWI. Additionally, SWI is used as a proxy for the dead fuel moisture content of surface fuels. The estimated FMC is then used to estimate combustion completeness. The model also estimates vegetation water content from FMC and biomass compartments, which allows for the comparison and calibration of vegetation water and biomass dynamics against satellite observations of vegetation optical depth (L-band VOD from SMOS and Ku/C-VOD from VODCA datasets).

Unlike other fire emissions inventories, TUD-S4F estimates emission factors dynamically dependent on the fuel components and fuel moisture by using a chemical-based combustion model that is calibrated against the emission factor database from Andreae (2019) and against satellite observations of fire radiative energy derived from VIIRS.

The TUD-S4F approach has also been refined to allow for near-real time estimates of fire emissions. The original approach is lacking near-real time capabilities because of the delayed availability of input data (e.g. Copernicus LAI product) and is computationally intensive and unsuitable to provide emission estimates on the relatively short notice of days to weeks. Hence a near-real-time version was developed (**TUD-S4F-vNRT01**) for which a machine learning emulator was trained to a previous full TUD-S4F model run while using the fire type map from GFA-S4F. This approach was applied for the year 2024 to estimate fire emissions for 2024 in the Amazon/Cerrado.

Although the TUD-S4F-vNRT01 approach is a simplification of the full complexity of the TUD-S4F v0.2 approach by assuming that the spatial configuration and amount of fuels in 2024 still corresponds to the conditions in 2020, it still makes use of the dynamic emission factors which is a key advancement of TUD-S4F in comparison to other fire emission approaches.

2.3 KNMI.S5p

Summary

The KNMI.S5p approach is based on using perturbed atmospheric composition model simulations to derive the sensitivity of local NO_2 tropospheric columns to local NO_2 emissions. Tropospheric NO_2 is short-lived, thus reflecting mostly local conditions, but its chemistry can be (highly) non-linear so variations in observed local NO_2 tropospheric columns do not automatically reflect similar variations in local NO_2 emissions.

Input data

The KNMI.S5p approach uses IFS-COMPO model simulations of the actual atmospheric chemistry, taking actual meteorological conditions into account (insofar as represented in the IFS model). The atmospheric conditions are provided by the ECMWF CAMS reanalysis. The model output takes Sentinel-5p NO_2 observations into account by applying a resampling the Sentinel-5p observations onto the model grid via an area-weighted approach, requiring at least a 50% Sentinel-5p coverage of the model grids.

Approach

For the so-called β-approach the IFS-COMPO model is run for the particular time period under considering. Two simulations are performed: a base run and a run with perturbed NO_x emissions, typically differing 20% to 30% compared to the baseline NO_x emissions. The change in simulated NO_2 tropospheric columns between both runs is then related to the change in NO_x emissions providing the so-called β-factor. This factor can then be multiplied with the differences between modelled and observed NO_2 tropospheric columns to provide an approximate number for how the emissions in the model should change to arrive at a simulated NO_2 tropospheric columns that is comparable to what is observed by Sentinel-5p. The β-approach was developed for – and has been successfully applied to updating anthropogenic NO_x emissions based on satellite observations (Castellanos et al., 2014; Lamsal et al., 2011) but has never been applied to wildfire NO_x emissions before. The approach works best for short-lived trace gases where local changes in trace gas amounts are mostly associated with local changes in emissions but whose relations are non-linear (if the relation were linear no advanced approach would be needed). It is an intuitive fast approach that requires less computation effort and tuning than a more traditional formal emission inversion approach and thus serves as an alternative for the latter.

3 Assessment of satellite observation-based wildfire emissions inventories using TROPOMI data and IFS-COMPO model simulations

The results presented here are largely based on the following pre-print:

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.

Main research question

An important goal of the first phase of the Sense4Fire project was to compare Sentinel-5p data (NO_2, CO) with IFS-COMPO model simulations fed with data from bottom-up emission databases such as GFAS and GFA-S4F. Sentinel-5p data had never been used with such an approach for assessing and evaluating bottom-up fire emissions. Hence, there was a need to explore methods for making such comparisons and determine which approaches would be most effective for use in the next phases of the project.

The Sentinel-5p satellite provides atmospheric composition observations of unprecedented quality and unprecedented spatial resolution. These capabilities are highly valuable for monitoring and characterizing wildfires and enable deriving emissions directly from atmospheric composition data, rather than relying on surface properties such as burned area or fire radiative power."

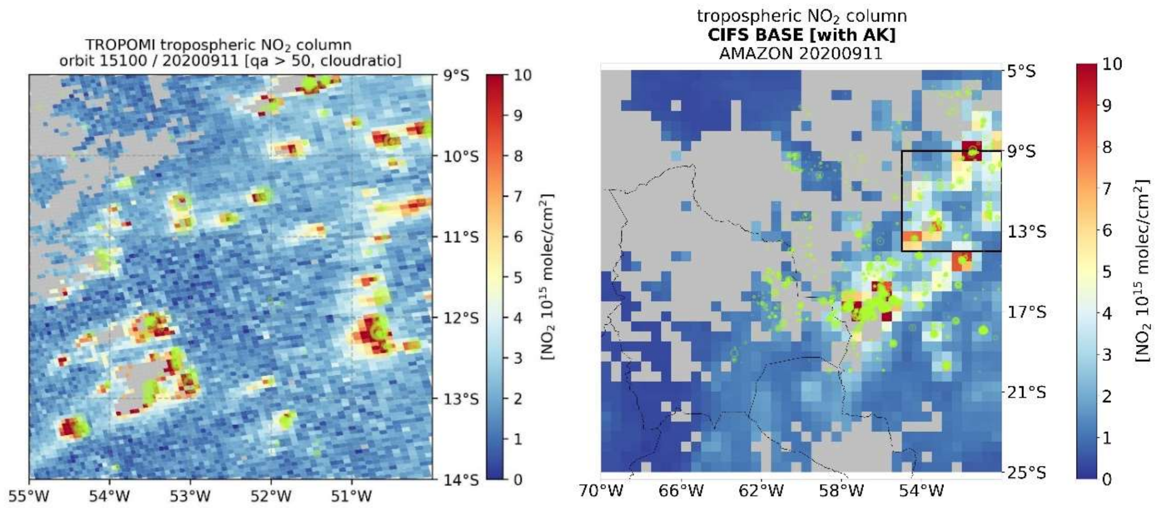

Figure 1: Left panel: TROPOMI measurements of tropospheric NO_2 column on 11th September 2020 for the Sense4Fire Amazon test area. The open green circles depict coincident NPP-VIIRS FRP measurements with the radius of the circles representing the magnitude of the FRP (arbitrary unit). Only measurements with Sentinel-5p quality flag values > 0.5 are shown. Sentinel-5p pixels in which the cloud pressure was within 4% of the surface pressure were also included to display pixels with enhanced NO_2 over low altitude smoke. Right panel: IFS-COMPO ("CIFS") modelled tropospheric NO_2 columns also on 11th September 2020 for a large Amazon region using GFAS emissions and applying the corresponding TROPOMI NO_2 averaging kernel. The black box indicates the small region shown in the left panel.

Main results

An important aspect for this assessment of approaches were the different spatial resolutions and representations of the data that was used. The bottom-up GFAS emissions are available at 0.1° spatial resolution. GFA data is provided in a shapefile format, therefore for appropriate use in models or for intercomparison it must be converted first to a gridded dataset. Sentinel-5p provides observations with a resolution – at best – of 3.5 × 5.5 km, which allows to discern larger mission plumes. However, data was regridded and studied at 0.1° resolution, which is the same order of magnitude of the 0.1° resolution from GFAS. IFS-COMPO, on the other hand, is only available at a spatial resolution of 0.5° (~ 50 km). As a consequence, a comparison at the IFS-COMPO model level requires the aggregating of data – be it Sentinel-5p data or bottom-up emission data. Hence this only allows for the analysis of cumulative emission effects on average conditions within the 0.5° area.

Despite the limitations discussed above there still was a tremendous amount of data available for further exploration. Below follows a short list of main findings and results.

- There is a clear correspondence between Sentinel-5p CO, NO_2 and AAI (Absorbing Aerosol Index; essentially smoke in this region) data and detected fire hot spots by the VIIRS satellite (Figure 1, left panel).
- Analysis of Sentinel-5p data revealed that CO and AAI correlate well in space, less so with NO_2. At the spatiotemporal scales considered, both CO and smoke are inert and their emission plumes are primarily governed by dispersion and turbulence. NO_2 has a much shorter lifetime of hours and is photochemically converted in the emission plume into other trace gases. It thus more rapidly decays away from its fire sources.
- When the smoke becomes sufficiently thick, Sentinel-5p measurements of CO and NO_2 become less reliable as the smoke prevents detection of air pollution below the smoke. This can be seen in for certain fires in Figure 1 (left panel) where enhanced NO_2 is only seen at the edges of plumes. The greys in Figure 1 reflect mostly clouds and thick smoke is "seen" by the algorithms as a cloud.
- Comparison of observed and modelled trace gases uncovered that there was a good agreement for NO_2 between Sentinel-5p and bottom-up estimates from GFA-S4F (for an example see Figure 2). However, there was some bias for very large fires in the bottom-up fire emissions from GFAS and even more so for GFA (and later shown to also exist in emission data from the TUD-S4F). The bottom-up emission data suggest very large NO_2 emissions for very large fires that are not observed by Sentinel-5p. For total NO_2 emissions this bias is small but it stands out in the visualisations. While reasons could be the choice of NO_2 emission factors for flaming fires in bottom-up fire emission inventories, a further hypothesised reason might be the inability of Sentinel-5p to accurately quantify NO_2 in case of thick smoke plumes. Both potential reasons require further analysis.
- The Sense4Fire project also explored use of the so-called β-approach in which the IFS-COMPO model was used to derive the local sensitivity of NO_2 columns to local NO_2 emissions. This allows for a post-hoc Sentinel-5p based correction of NO_2 emissions used in IFS-COMPO. The approach was developed and successfully applied for anthropogenic NO_2 emissions but never applied to fire NO_2 emissions. Results showed that post-hoc β-approach corrected NO_2 emissions indeed – and not unexpectedly – resulted a reduction of this "large fire bias".
- Results for CO revealed a large underestimation of Sentinel-5p observed CO total columns for the Amazon region that was also observed over southern Africa, Siberia and Europe. The bias

is larger with GFAS than with GFA – unlike the "large fire bias" in NO_2 which was worse for GFA than for GFAS - and could also be reduced by applying a simple scaling of CO emissions. A likely reason would be an underestimation of CO emissions by small and smouldering fires that remain undetected in satellite observations of Fire Radiative Power (de Laat et al., 2024, 2025).

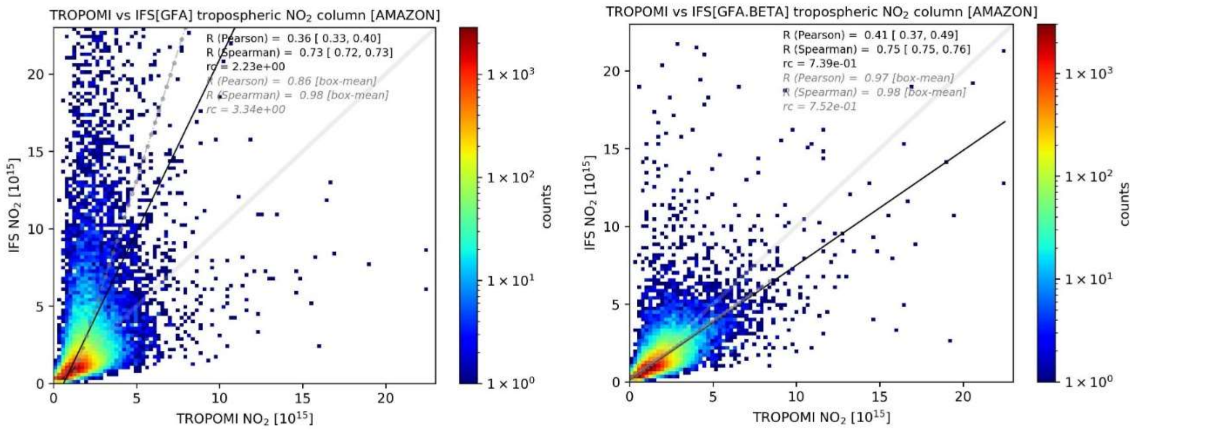

Figure 2: 2D-histograms of TROPOMI observed and IFS-COMPO simulated tropospheric NO_2 columns for daily observations throughout August and September 2020 for the Amazon region. The black line indicates the regression coefficient for all data, the grey line ("box-mean") when IFS-COMPO data are averaged within 20 TROPOMI bins (only with more than ten data points in a particular TROPOMI bin). The left panel shows the average GFA NO_2 emission for the distribution in the upper panel. The right panel shows the same results but after applying the post-hoc β-approach-based correction to GFA NO_2 emission.

Conclusions

The results have demonstrated the significant added value of using Sentinel-5p data for verification and validation of bottom-up wildfire emission databases at large spatial scales. Lack of ground-based observations and/or field campaigns in the major wildfire regions around the world hampers verification and validation of these emission databases. The quality of Sentinel-5p data in terms of accuracy, spatial resolution and recurrence thus provides an excellent alternative to *in situ* data from field campaigns.

The innovative use of a state-of-the-art atmospheric composition model IFS-COMPO as "interface" unlocks the richness of the Sentinel-5p data for the purpose of verification and validation of the bottom-up wildfire emission databases. In addition, use of the IFS-COMPO model also allowed for exploring a fast innovative method (β-approach) for post-hoc correcting bottom-up emission databases rather than relying on – or as an alternative to – formal but computationally expensive formal emission inversions.

The Sense4Fire results reveal several shortcomings of the bottom-up emission databases. For NO_2, the bottom-up emission databases generally do a fair job but there is a very specific "large fire" NO_2 bias where the bottom-up approaches produce high emissions where Sentinel-5p clearly indicates there are none. Using newer state-of-the-art bottom-up approaches – designed for improving wildfire emissions - nevertheless worsened this particular "large fire bias", even though it had little impact on total NO_2 emissions. Applying the post-hoc β-approach could eradicate the "very large fire bias" but more research is needed to identify the root cause(s).

At the other end, the bottom-up approaches GFA-S4F and GFAS significantly underestimated wildfire CO emissions, not only over the Amazon but also over southern Africa, Siberia, and Europe.

As wildfire CO emissions are a good proxy for wildfire CO_2 and total carbon emissions, this suggests that wildfire carbon emissions are also significantly underestimated. However, it still needs to be further explored if this underestimation originates from an under-detection of small or low-temperature smouldering fires or if it is caused by a wrong choice of conversion and emission factors to relate FRP to emissions. The bias was partly ameliorated by the newer state-of-the-art wildfire emission approaches (e.g. TUD-S4F, chapter 4) but not fully eradicated. During the later stages of the Sense4Fire project this "problem" was explored as part of efforts to test the operational readiness of the Sense4Fire approaches (chapter 5).

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

The findings presented here are published in:

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.

Main research question

The Amazon forest is a fire sensitive region where fires used to be uncommon as a natural disturbance. However, deforestation and drought are accelerating fire occurrences, which threaten the integrity of the tropical forest, the carbon cycle and air quality. Fire emissions depend on fuel amount and type, moisture conditions and burning behaviour. Higher-resolution satellite data have helped more accurately map global burnt areas and fire activity. However, the effects of vegetation conditions and fuel properties on the combustion process and on the composition of fire emissions remain uncertain in current fire emissions inventories.

The effects of fuel properties on combustion and fire emissions tend to be oversimplified in regional and global Earth observation (EO)-based emissions inventories. State-of-the-art approaches use time-independent (static) emissions factors linking fuel consumption to trace gas emissions such as CO or NO_x, whereby emission factors are typically averaged values per biome. In reality, emission factors actually vary spatially and temporally with fuel type, chemistry and moisture.

Recent analyses of atmospheric Sentinel-5p observations have provided empirical evidence in support of the notion of missing processes in these state-of-the-art fire emission approaches. It is hypothesised that the burning of woody debris dominates fire emissions in the Amazon but that overall higher amounts of woody debris result in lower combustion efficiency and hence higher CO emissions in tropical forest and deforestation fires in the Amazon than in savannah fires in the Cerrado. However, a direct link between fuels and CO emissions has not yet been established. Such an analysis requires reconciling top-down estimates of regional emissions with bottom-up estimates accounting for fuel type, composition and combustion efficiency.

Here, the question of sensitivity of emissions to vegetation conditions is investigated by exploring the effects that dynamical emission factors have on emissions.

Main results

To overcome the limitations using average (static) emission factors per biome, a satellite data–model fusion approach for fuel loads, moisture, and combustion and fire emissions has been developed at the Technical University of Dresden (TUD-S4F). This approach (1) offers higher spatial resolution (333 × 333 m) than existing methods; (2) estimates local surface fuel accumulation from observed vegetation (LAI) and land cover changes; (3) incorporates fuel moisture derived from satellite data and (4) dynamically computes emission factors and combustion efficiency based on fuel moisture, composition and type.

In addition, the estimated fire emissions have been evaluated with a top-down approach based on Sentinel-5p observations and benchmark against seven other EO-based estimates. Additionally, simulations from three fire-enabled dynamic global vegetation model runs (DGVM) are compared with observed burnt area against our emission estimates to assess the reliability of current fuel consumption models.

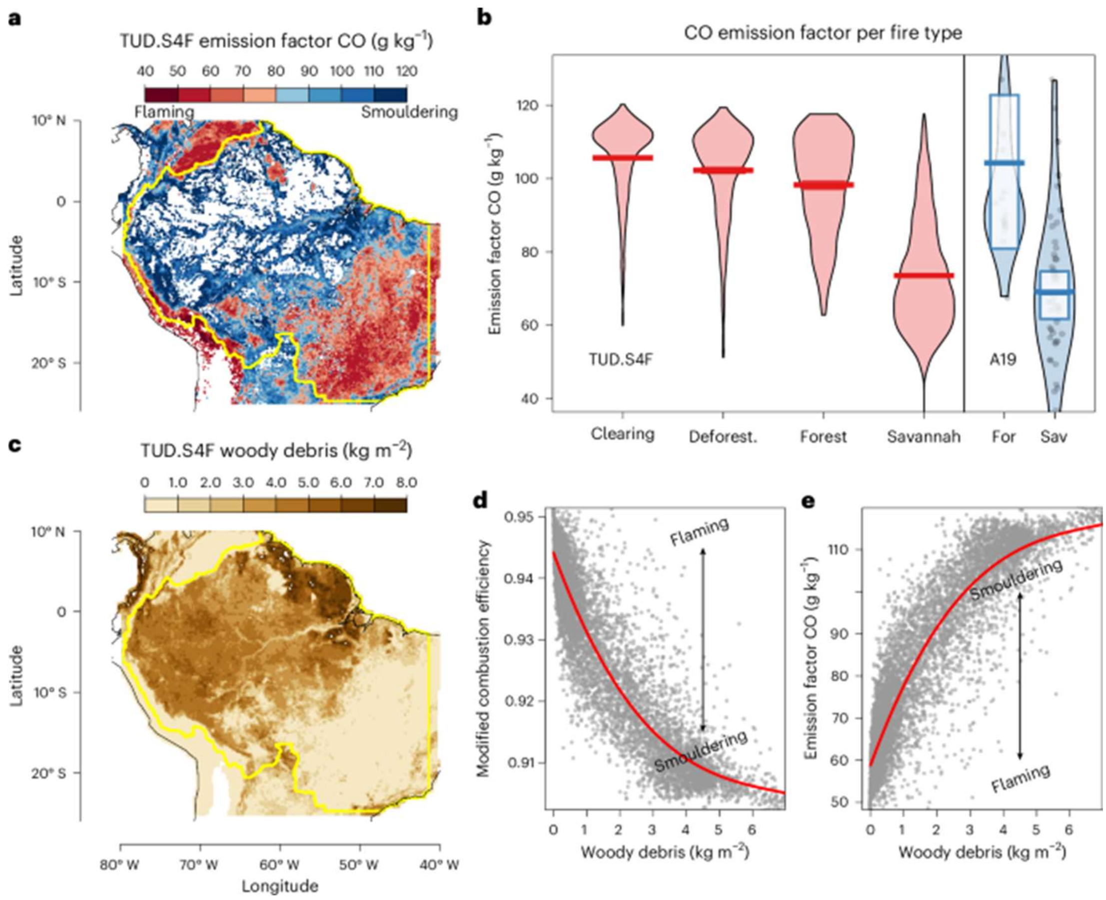

Figure 3: Variation of the CO emission factor (EF_{CO}) and of combustion efficiency with fire types and woody debris. (a) Map of EF_{CO} averaged for the year 2020 from the TUD-S4F with dynamic emission factors. A high EF_{CO} indicates incomplete burning (smouldering combustion); whereas a low value indicates more complete burning (flaming combustion). (b) Variability of EF_{CO} for different fire types from the TUD-S4F approach and in comparison with field and laboratory values reported for tropical forests (For) and savannahs and grasslands (Sav) by A19 (Andreae, 2019). Horizontal lines are mean values, boxes are highest density intervals, and grey points in A19 are individual reported values. (c) Spatial patterns of woody debris from TUD-S4F for 2020. (d)

and (e) emerging relationships between woody debris and the modified combustion efficiency (MCE) and EF_{CO}, respectively.

Figure 3 (a) shows an example of the spatial variability in estimated emission factors, in this case for CO (EF_{CO}), revealing spatial gradients from 40 g kg^{-1} in the arid highlands of the Andes to 120 g kg^{-1} in the Amazon rainforest, indicating more complete combustion in flaming fires in sparse vegetation and savannahs and incomplete combustion in smouldering forest fires (Figure 3a,b). The median EF_{CO} is 71 g kg^{-1} in savannah fires and between 100 and 109 g kg^{-1} in forest, deforestation, and small land-clearing and agricultural fires. Those values align with the mean and variability of EF_{CO} from field and laboratory observations. However, they also reveal much more variable emission factors in space and time, supporting the hypothesis that static and biome-averaged emission factors do not represent the dynamical nature of fuel conditions and thus the spatial-temporal variability of real emission factors.

The results further show that the spatial variations of EF_{CO} are mainly driven by availability of woody debris (Figure 3c–e). Ecosystems with high loads of woody debris (>3 kg m^{-2}) typically show smouldering combustion with EF_{CO} > 100 g kg^{-1}. Thus, higher CO emissions from deforestation and forest fires result not only from higher fuel load and consumption but also from more smouldering combustion of woody debris. The results clearly support the notion that CO emissions are larger for more incomplete combustion. However, despite the mean EF_{CO} being consistent with the most frequently used fixed EF_{CO} from literature, it is clear that there is a large spatial variability in EFs that is not represented by static EFs.

As a consequence, the range of estimated CO emissions vary significantly between emission databases and between different Earth Observation approaches. Figure 4 shows the estimated dry matter burned (DMB) over the Amazon in 2020 for different approaches. Across EO-based approaches, median total dry matter burnt is 372 Tg ranging from 288 to 605 Tg DMB (six estimates). Fire emissions inventories agree in terms of the temporal development of fire emissions and show similar continental-scale spatial distributions. Although not discussed here in detail, a similar large range in NO_x emissions is found.

Conclusions

Fire emissions in the Amazon and Cerrado biomes are dominated by smouldering combustion of woody debris. The higher CO emissions over the Amazon compared to the Cerrado are due to the greater proportion of smouldering combustion in understorey forest and deforestation fires, which are fuelled by high loads of woody debris.

These results complement previous research on fire emissions by introducing a satellite data–model fusion approach that integrates Earth observation datasets to assess the role of fuels in combustion and fire emissions. It is demonstrated that this approach aligns with field observations and local studies on woody debris and its effects on dry matter burnt and agrees with top-down estimates of fire emissions from Sentinel-5p. Hence, the approach provides necessary information for a best estimate of fuel combustion dynamics and fire emissions. However, more field observations are needed on woody debris loads, its decay, density and chemistry to refine estimates of fuels, fuel combustion, emission factors and emissions and their large-scale effects on the atmosphere.

The results also highlight large uncertainties in fire emissions in global vegetation–fire models driven by variations in fuel loads and combustion, particularly in deforestation fires. Our data helps evaluate and reformulate global models for deforestation and the associated dynamics of fuel accumulation and decay and to overcome inaccurate model estimates of global fire emissions.

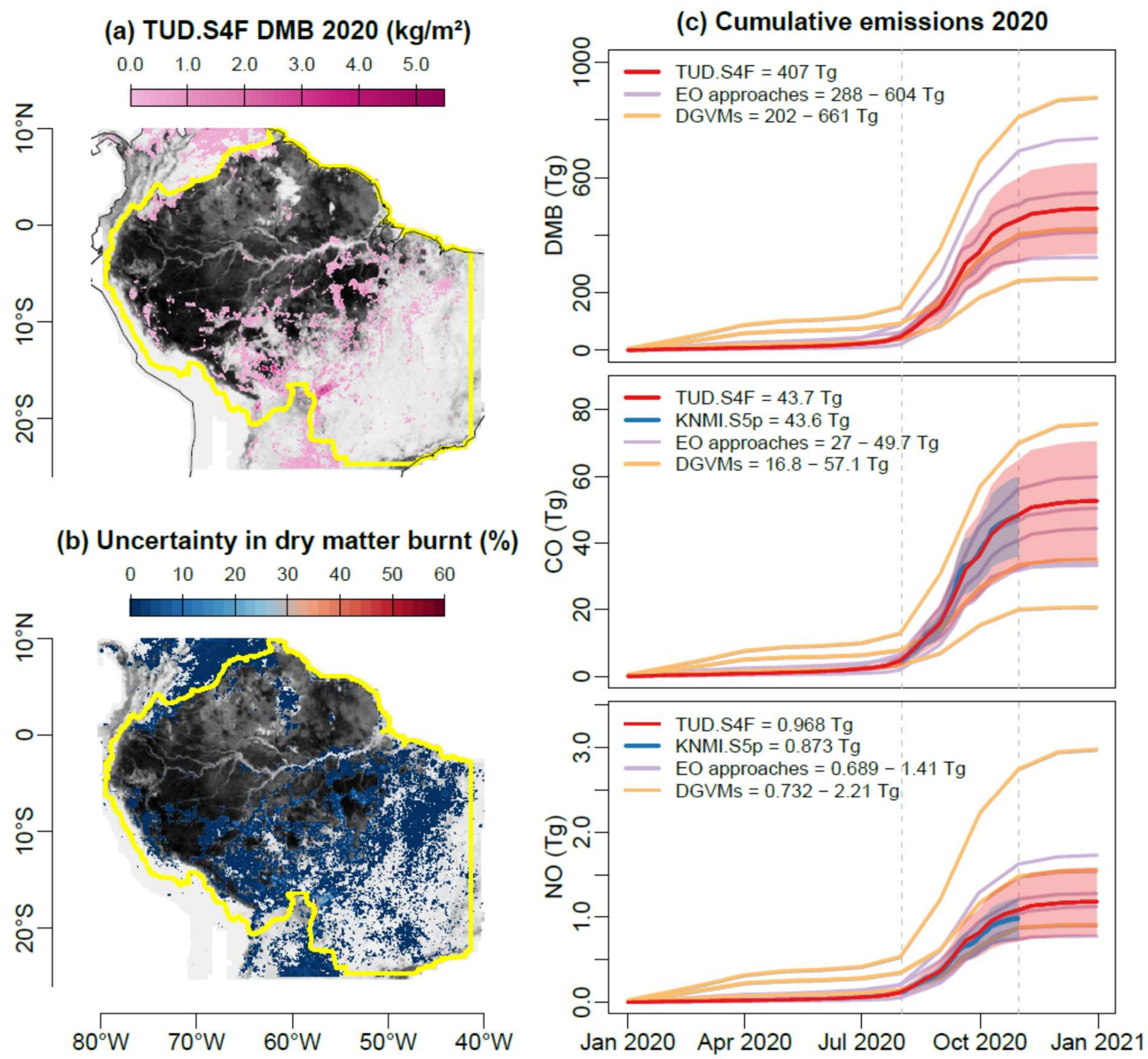

Figure 4: Fire emissions in the Amazon and the Cerrado in 2020. (a) Total dry matter burnt (DMB) in 2020 and above-ground biomass (background map from grey = 0 to black = 40 kg m^{-2}) from the TUD-S4F approach. The yellow polygon indicates the extent of the Amazon and Cerrado biomes, which was used to create the time series and aggregated statistics in (c) and in the text. (b) Uncertainty in DMB is defined as the normalised root mean squared difference across six Earth observation-based estimates for the period August-October 2020. (c) Time series of regional total cumulative DMB, CO and NOx emissions from different Earth observation approaches (violet lines), three dynamic global vegetation-fire models (yellow), the TUD-S4F satellite-data model fusion approach (red line, default model run) and the top-down constraint from KNMI.S5p (blue, default estimate). Red and blue bands show uncertainties for the TUD-S4F and KNMI-S5p approaches, respectively.

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

The findings presented here are based on a manuscript submitted (January 2025) to Geophysical Research Letters (2025GL115123):

de Laat, A. T. J., Andela, N., Forkel, M., Huijnen, V., Kinalczyk, 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.

Main research question

Wildfires impact the climate system through the emission of greenhouse gases and air pollutants. In addition, wildfires in tropical forests such as the Amazon convert those ecosystems from carbon sinks into carbon sources. There is growing need for timely information about the magnitude of wildfire emissions.

The Amazon basin experienced extremely large wildfires in 2024, centred near Bolivia, with record level regional fire carbon emissions. The region was struck by exceptional drought due to a persistent La Nina that started in 2023. Anecdotal evidence and local reports and news items suggested that emissions were significantly larger than typically observed, and air quality was much worse than many local communities could remember. Here, the Sense4Fire consortium put in a dedicated effort to rapidly assess those 2024 emissions.

The Sense4Fire efforts were in part designed to assess the capacity of their data processing chains to provide data in near-real-time. At the same time, obtaining accurate emission estimates of extreme events are critical for understanding their impact on ecosystems and society. Conditions like those experienced in the Amazon in late summer and autumn 2024 could be considered an "out of sample test" of algorithms that use satellite data to estimate fire emissions. Do algorithms still provide reasonable amounts of wildfire emissions, and how did emissions differ compared to more typical seasons?

Main results

The comparison between Sentinel-5p CO-TC with IFS-COMPO simulated CO-TC for the different fire emission approaches over South America for September 2024 is shown in Figure 5. Overall, modelled CO-TCs are smaller than observed with the largest differences found for September 2024. The largest emission amounts – regardless of emission database – occurred during the four week period from middle of August 2024 to the middle of September 2024. CO accumulates in the atmosphere over longer periods of time due to its lifetime of approximately two months. Hence, in case of low CO emissions, CO-TC biases will also increase over time. This causes differences in CO-TC between models and Sentinel-5p to be larger in September 2024 than in August 2024.

The CO-TC bias also extends over the Atlantic Ocean towards Africa. These differences change in line with differences in emissions with smaller differences for larger emissions (GFA-OPT) and larger differences for smaller emissions (GFAS). However, some influence of CO advected from equatorial Africa cannot be excluded. Although not the scope of this paper, it is well established that African equatorial biomass burning pollution is advected onto the equatorial Atlantic Ocean.

The South American biomass burning plume similarly extends in a westerly direction into the equatorial Pacific Ocean, which is clearly visible in Sentinel-5p data, in particular during September 2024. The differences between IFS-COMPO and Sentinel-5p illustrate this advective process by the gradual decreasing differences further away from the equatorial South American west coast into the Pacific Ocean, reflecting CO-TCs decaying to background values. Furthermore, the difference plots (Figs. 5f-1i) also show that pollution is transported over/through the Andes region. For the databases with higher emissions like GFA-OPT the differences between IFS-COMPO and Sentinel-5p become negligible. This likely indicates that there are other biases in simulated CO not related to biomass burning emissions.

The differences between August and September 2024 were also reflected in the time evolution of regression values that deviate over time from the preferred value of one. It was found that the fire emission estimates adopted in IFS-COMPO were increasingly underestimating Sentinel-5p CO-TC through August and September 2024 going from a 0-10% bias at the beginning of August 2024 to a 20-40% bias at the end of September 2024, depending on the fire emission dataset used. Regression coefficients between daily observed and modelled column values similarly changed from hovering around 1.0 the beginning of August 2024 and declining to around 0.5 at the end of September 2024. Daily spatial correlations, on the other hand, were constant over time and varying between 0.7 and 0.9, indicating that all bottom-up emission databases were representative of the spatial variability of CO emissions. There were considerable day-to-day variations in statistics which for an important part were related to clouds and smoke in daily Sentinel-5p observations.

Quantitatively, GFAS CO emissions (11.8 Tg and 15.9 Tg for August and September 2024, respectively) are much lower than either GFA-S4F (27.3 and 29.1 Tg) and TUD-S4F (24.5 and 37.8 Tg) (Table 1). Regression coefficients are similarly smaller for GFAS (0.50 and 0.33) compared to GFA-S4F (0.75 and 0.46) and TUD-S4F (0.68 and 0.54). Biases for GFAS are also larger (-15.4 and -39.4 %) compared to GFA-S4F (-6.6 and -31.6 %) and TUD-S4F (-10.0 and -27.4 %). For the optimised GFA, the performance improves with larger emissions (34.0 and 36.2 Tg), better regression values (0.92 and 0.56) and smaller biases (0.5 and -23.6 %).

The GFA-S4F optimisation factor of 1.5 based on August 2024 results expectedly reduced the August 2024 bias to 0.5% while the associated regression value (0.92) of modelled against observed CO-TCs is close to the preferred value of one. However, for September 2024 GFA-OPT still results in a large bias (-23.6 %) and low regression values. Differences increase fastest during late August 2024 and early September 2024. This likely reflects stronger accumulation of CO during periods with higher emissions.

Compared to GFAS, the cumulative emissions for the core Amazon/Cerrado region by the end of September 2024 are more than two times greater for GFA-S4F and TUD-S4F and more than 2.5 times greater for GFA-OPT, the latter of which still results in too low September 2024 CO-TC values in comparison to Sentinel-5p.

It is hypothesised that these differences reflect missing emissions from (widespread) small fires. Satellites like MODIS and VIIRS used for deriving especially FRP are limited to large(r) fires. Several recent research papers have identified and analysed this particular problem. Smouldering fires are more likely to be small not only in size (spatial coverage) but also in emitted infrared radiation, for example because they are more easily covered by material, making them more difficult to detect with remote sensors.

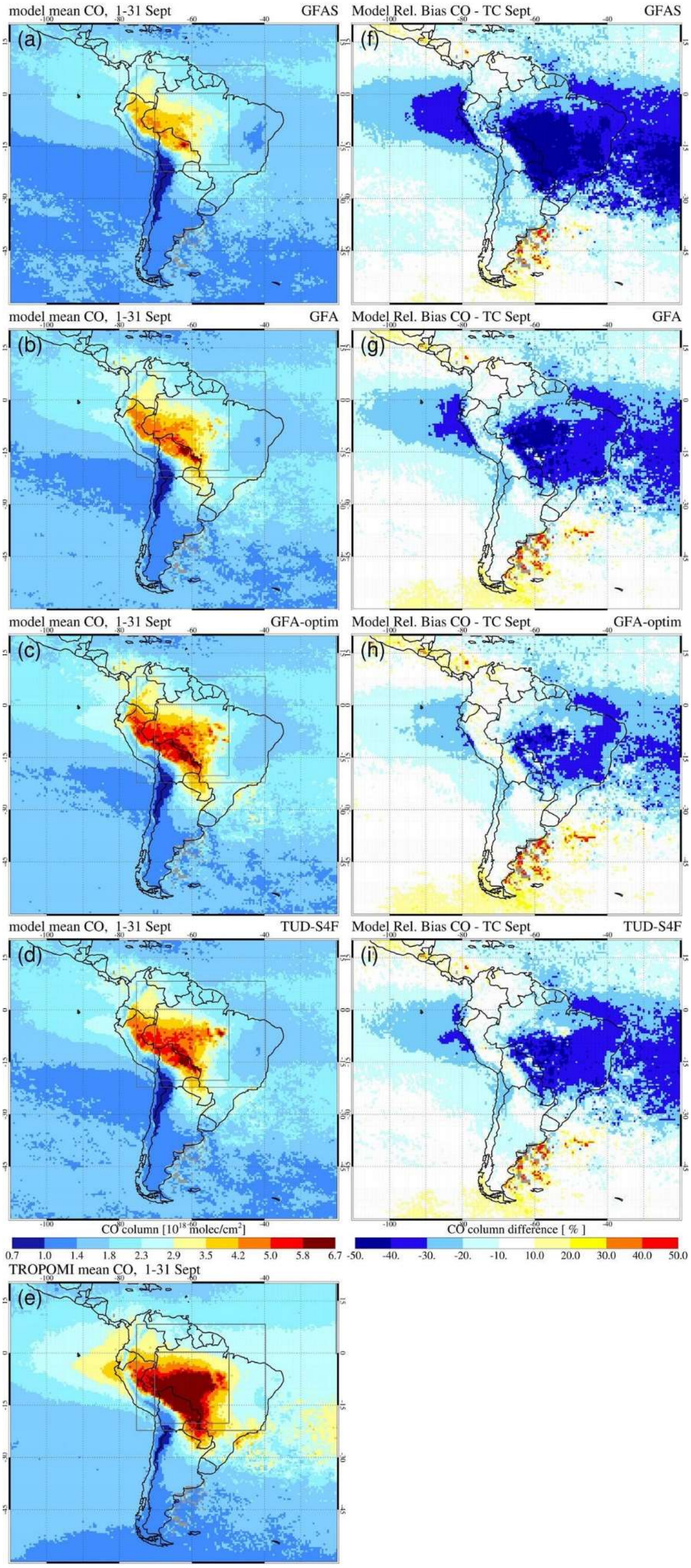

Figure 5: Average IFS-COMPO modelled CO total columns (CO-TC) over South America for September 2024 by using bottom-up emissions from GFAS (a) GFA-S4F (b), optimised GFA-S4F (c) and TUD-S4F (d). (e) Average CO-TC from Sentinel-5p. (f-i) Bias (% relative to Sentinel-5p CO-TC) of each modelled average CO-TC. CO column values in 10^{18} molecules cm^{-2}.

Table 2: Total CO and CO_2 emissions and evaluation statistics over the region 70°W-50°W, 25°S-5°S for the wildfire emission databases used in this study for August 2024 and September 2024. Evaluation statistics are regression coefficients (REG, slope), bias (B), and Pearson correlation coefficients (R) between IFS-COMPO simulations using one emission inventory and Sentinel-5p observations.

	August 2024					September 2024				
Emissions	**CO (Tg)**	**CO2 (Tg)**	**REG**	**B (%)**	**R**	**CO (Tg)**	**CO2 (Tg)**	**REG**	**B (%)**	**R**
GFAS	11.8		0.50	-15.4	0.75	15.9		0.33	-39.4	0.77
GFA-S4F	27.3	473	0.75	-6.6	0.78	29.1	572	0.46	-31.6	0.77
GFA-OPT	34.0		0.92	0.5	0.81	36.2		0.56	-23.6	0.78
TUD-S4F	24.5	385	0.68	-10.0	0.81	37.8	605	0.54	-27.4	0.80

Conclusions

The Amazon basin experienced extremely large fires in 2024, centred near Bolivia, with record level regional fire carbon emissions. August and September 2024 Amazon fire carbon emissions were quantified and evaluated. Sentinel-5p satellite carbon monoxide observations, an atmospheric transport model, one operational and two state-of-the-art bottom-up fire emission models were used to quantify and assess emissions of carbon monoxide – a proxy for carbon emissions. Total CO emissions were estimated at 28-62 Tg accumulated over the main fire season in August and September 2024. The increased emissions originate mainly from understorey forest fires and were 2-4 times larger than for the same months in 2019-2023. Comparison with Sentinel-5p CO observations revealed that CO emissions were nevertheless still underestimated by a factor of 1.5-3. It is hypothesised that the missing emissions originate from smouldering fires not captured by satellite observations of active fires. Overall, carbon emissions from the Amazon forest fires in 2024 were much higher than what can currently be explained with state-of-the-art fire emissions bottom-up approaches.

6 Scientific roadmap

The Sense4Fire deliverable 6.1 provides a detailed Scientific Roadmap. It provides an overview and discussion of Sense4Fire findings that warrant additional research or that provide a perspective for future developments and exploitation of current and upcoming satellite systems. Here, we suffice by providing the list of recommendations as provided in the Scientific Roadmap (D6.1).

6.1 Assessment of required *in situ* observations for development and validation of the fire characterisation database

Support to improve and expand *in situ* observations and campaigns and the coordinated collection and/or harmonisation of existing in situ data in global databases of fuel properties and fire smoke plumes. This could be achieved through ESA funding initiatives (e.g. similar to activities like https://data.geo-trees.org) or by advocating for funding from other organizations, both at national levels, and through pan-European institutions and organizations.

6.2 Possibilities for operationalisation of the fire characterisation database for near-real time monitoring

- Exploration and assessment of computational resources needed for global operationalisation of the innovative tools used and developed within the Sense4Fire project with in particular a focus on the ESA Earth Code facilities. For example, the database and the tools could be transferred to ESA platforms such as APEX (for operationalisation) and EarthCODE (for data, code and workflow) sharing.
- Exploration and assessment of the Sense4fire tools (or their likes) identify innovations needed to provide timely global near-real-time fire emission data. This includes the development and use of learning algorithms (AI/ML) as emulators.
- Establish links with the emission monitoring community – for example the Copernicus CO_2 Monitoring and Validation Service (CO2MVS) – to jointly start adopting developments from Sense4Fire in the CO2MVS tools. For example, emissions and conversion factors used in GFAS could be updated based on findings in Sense4Fire.
- Assess user needs for which timeliness is needed or preferred for various data products on fuels and fire. This could be part of activities from the recommendation above.

6.3 Recommendations for the development and integration of the Sentinel expansion, evolution and future earth explorers for characterisation of fire dynamics

- Continue support for efforts to explore measurements from existing and upcoming satellites for their added value for, and use in, characterising fire dynamics
- Continue support for integration of valuable data from new satellites into fire characterisation and fire emission databases.
- Provide support to harvest the potential of passive and active microwave satellite to quantify fuel loads and fuel moisture by developing appropriate methodologies.
- Support for refining atmospheric composition modelling. This involves both modelling the global atmospheric composition like the IFS-COMPO model at higher spatial resolution as well as exploring and developing the use of large eddy model simulations of atmospheric composition that includes fire dynamics.
- Develop and establish detailed fire emission databases based on assessment of individual fires for validation, evaluation and benchmarking purposes. Such a database should include – if available – information about the pre- and post-fire fuelbed, fuel loads, individual fuel components, combustion efficiency and measured emissions. This includes the use of such a database for learning algorithms (AI/ML) which require well established and benchmarked datasets to be trained on.

6.4 Recommendations for the use of fire databases for the development of global vegetation/fire models and earth system model

- Expand existing validation and benchmarking protocols for fire models to fuel properties, which includes to output fuel loads and fuel moisture from models by default.
- Strengthen connections between remote sensing and climate modelling communities in the field of fire science for evaluating the model representation of fires, for example within the Fire Model Intercomparison Project (FireMIP)
- Assist fire modelling teams to make satellite products more easily available by e.g. providing re-gridding tools, data cubes (e.g. as provided in EarthCODE) or by already providing re-gridded products.
- Evaluate historical CMIP model simulations over fire prone regions with satellite observations of atmospheric composition – like Sentinel-5p – as done within Sense4Fire with IFS-COMPO
- Use observation-based fuel or fire emission estimates such as developed within Sense4Fire as input for historical DGVM or CMIP model simulations to assess the effect of an improved representation of fire dynamics and emissions on the estimated impacts on vegetation and the carbon cycle. Earth observation time series of ~10 years could already be informative to diagnose model behaviour and deficiencies.
- Continue to work on - and expand - the framework for assessing and evaluating fire emissions based on earth observation data.
- Develop approaches to make use and integrate the "richness" and detailed information about fire dynamics and fire conditions that can be derived from current and future satellite instruments
- Explore the use of high(er) resolution models – from regional vegetation and climate models at kilometre-scale all the way to large eddy simulations at metre-scale to resolve fire-smoke-atmosphere interactions – so that all relevant scales are covered by these models and fire effects can be appropriately assessed.
- Explore the integration of the suite of numerical models and how to scale high resolution information about fire dynamics and vegetation conditions to the global vegetation/fire models and earth system models.
- Establish connections with emission monitoring activities, for example the Copernicus CO_2 monitoring and verification system (CO2VMS)

7 Data availability

All datasets that have been produced within Sense4Fire are available at https://sense4fire.eu/.

- The second version of the Sense4Fire **Experimental Database (DBv2)** provides results from GFA-S4F, TUD-S4F and KNMI-S5p for the Amazon/Cerrado, southern Africa, the Siberian study regions and southern Europe: https://sense4fire.eu/database/
- The near-real time database provided fire emissions for the Amazon/Cerrado for the year 2024: https://sense4fire.eu/database/2024_nrt/

The website will be maintained at least until January 2028.

The following datasets have been additionally archived in long-term data repositories:

- GFA-S4F data for 2018-2024: https://doi.org/10.5281/zenodo.14338495 (CC-BY licence)
- TUD-S4F (2014-2021), KNMI-S5p (2020) and GFA-S4F (2019-2020) for the Amazon/Cerrado region (corresponding to the data from DBv2): https://doi.org/10.25532/OPARA-688 (CC-BY-NC licence)
- IFS-COMPO CO and resampled and re-gridded Sentinel-5p CO data for August and September 2024 are available at https://doi.org/10.5281/zenodo.14770767 (CC-BY licence)

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