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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Final Report (FR)

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Summary

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.

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, biomass burning, composition of emissions) and the effect of fire emissions on atmospheric composition (smoke plumes, atmospheric gas composition, aerosols).

The Sense4Fire project provides estimates of fire emissions, emission factors, dry matter burnt, fuel loads and live fuel moisture content using three complementary approaches:

- **GFA-S4F** is based on the Global Fire Atlas (GFA) algorithm (Andela et al., 2022a) and uses observations of active fires from the VIIRS sensors with a new fire type map to estimate fire emissions.
- **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. Emission factors are computed dynamically depending on fuel type and fuel composition. The approach was developed within the project (Forkel et al., 2025).
- **KNMI-S5p** is based on observations from Sentinel-5p, whereby fire emissions of CO and NOx are estimated using simulations of the IFS-COMPO atmosphere model in a top-down approach. Alternatively, the IFS-COMPO model has been used to simulate how fire emissions from the GFA-S4F and TUD-S4F estimates distribute in the atmosphere in order to enable a direct validation with observations from Sentinel-5p. The approach serves as a constraint on regional total fire emissions.

Deliverables and datasets produced under the project are available at https://sense4fire.eu/. Additionally, the datasets for the Amazon and Cerrado regions that were scientifically investigated in Forkel et al. (2025) are also available in a long-term data repository at https://doi.org/10.25532/OPARA-688.

The project resulted in a series of scientific publications and preprints (Andela et al., 2022a; Forkel et al., 2025; de Laat et al., 2024, 2025), was presented at several conferences and workshops (section 8.2) and in an ESA webstory with an associated video on Youtube: https://www.esa.int/Applications/Observing_the_Earth/FutureEO/Smouldering_woody_debris_fuels_air_pollution_over_the_Amazon

This **Final Report (FR)** is a technical description of all the work done during the project, it includes an introduction of the context, a description of the program of work and report on the activities performed and the main results achieved by describing all deliverables. The FR is structured according to the work packages (WP1-9). The accompanying **Summary Report (SR)** provides a concise scientific summary of the key findings and all outputs of the project such as publications, datasets, and the scientific roadmap.

The Sense4Fire project was funded under the European Space Agencies' (ESA) Earth Observation Science for Society programme and is part of the ESA Carbon Science Cluster. The project has been

initially funded for two years (August 2021 – July 2023) and has been prolonged until January 2025 based on a Contract Change Notice.

1 Overview of the project

1.1 Overview of the Sense4Fire work packages and deliverables

The Sense4Fire project was organised into nine work packages. The work packages and associated deliverables in Sense4Fire were:

- WP1 Consolidation of Open Scientific Questions (Chapter 1.2), which included a review of scientific requirements as described in deliverable RBRv1.1.
- WP2 Dataset Collection (Chapter 2), which included the preparation of an internal database for all project partners and the Database Description (DBDv1).
- WP3 Development and validation of innovative products (Chapter 3) included the development and validation of the methods. Methods are described in the Algorithm Theoretical Baseline Document (ATBDv1.1 and ATBDv2.1) and validation results are presented in the Product Validation Report (PVRv1.1 and PVRv2.1). Those documents were later updated within WP9 (ATBDv3 and PVRv3).
- WP4 Development and inter-comparison of 4D-fire products (Chapter 4) included the generation of all products at large scale, the inter-comparison of products, and the release in the Experimental Database (DBv1 and DBv2).
- WP9 Developing near-real time fire emissions products (Chapter 5): This was an additional work package that was later added to the project under the Contract Change Notice. The aim was to develop the Sense4Fire approaches to allow for near-real time estimates of fire emissions, i.e. with only a few weeks delay. The activity resulted in the Experimental NRT Database (DBv3). Part of this activity was also an update of the methods and validation results which were then presented in ATBDv3 and PVRv3, respectively.
- WP5 Scientific Analysis, Impact Assessment and Comparison (Chapter 6) included the comparison of 4D-fire products with other approaches and a quantification of fire effects on the global carbon cycle. WP5 resulted in two consecutive versions of an Impact Assessment Report (IARv1 and IARv2).
- WP6 Scientific Roadmap
- WP7 Promotion and Coordination
- WP8 Management

A summary of the deliverables is presented in Table 1. Deliverables are accessible at the Sense4Fire website: https://sense4fire.eu/index.php/deliverables

Table 1: List of deliverables produced in Sense4Fire.

Deliverable and version	Description	Date of the final revised version
D1.1 Requirement Baseline Review Document version 1.1 (RBRv1.1)	Review, assessment and analysis of the main scientific challenges, knowledge gaps and scientific problems to be addressed in the Sense4Fire	06.12.2021

D2.1 Database for project partners	Internal database of input datasets accessible on-line to the project team, located at network drives at TUD	07.11.2021
D2.2 Database Description version (DBDv1)	Overview and technical specifications about input and validation datasets to be used in the project	07.11.2021
D3.1 Algorithm Theoretical Baseline Document version 1 (ATBDv1.1)	(superseded by ATBDv2.1)	11.11.2022
D3.2 Product Validation Report version 1 (PVRv1.1)	(superseded by PVRv2.1)	11.11.2022
D3.3 Algorithm Theoretical Baseline Document version 2 (ATBDv2.1)	Description of methods to develop and generate novel and advanced geo-information products on fuel conditions, fire behaviour and fire emission estimates	05.05.2023
D3.4 Product Validation Report version 2 (PVRv2.1)	Description of the strategy and results for product calibration and validation for methods and products	07.05.2023
D9.1 Algorithm Theoretical Baseline Document version 3 (ATBDv3)	Update of ATBDv2.1 with description of setups and experiments for all study regions as presented in PVRv3.	03.05.2024
D9.2 Product Validation Report version 3 (PVRv3)	Update of PVRv2.1 with results for all approaches and all study regions	03.05.2024
D4.1 Experimental Database version 1 (DBv1) D4.2 Experimental Database Description version 1 (DBDv1)	Products for the Amazon, southern Africa, and Siberian study regions from GFA-S4F, TUD-S4F v01, and KNMI-S5p https://sense4fire.eu/database/ TUD-S4F v01 was superseded by TUD-S4F v02 published in DBv2	May 2023
D4.3 Experimental Database version 2 (DBv2) D4.4 Experimental Database Description version 2 (DBDv2)	Revised products for the Amazon, southern Africa, Siberian study, and southern Europe regions from GFA-S4F, TUD-S4F v02, and KNMI-S5p https://sense4fire.eu/database/	October 2023
D5.1 Impact Assessment Report version 1 (IARv1) D5.2 Impact Assessment Report version 2 (IARv2.1)	Overview about significant scientific contributions to the main science gaps and major scientific challenges of the project. IARv1 was a preliminary version and was superseded by IARv2.	30.10.2023 18.03.2025
D9.3 Experimental NRT Database (DBv3) D9.4 Experimental NRT Database Description (DBDv3)	Datasets of fire emissions for the Amazon and Cerrado in 2024 as part of a near-real time demonstration of the methods https://sense4fire.eu/database/2024_nrt/	Released and updated during September-November 2024
D6.1 Scientific Roadmap	Recommendations for further scientific support activities, scientific agenda addressing the main scientific and observational gaps in potential improvement of fire emission estimates	31.01.2025
D7.1 Promotional graphic material D7.2 Project Website	A project logo, website and presentation templates were made available after the second month of the project: https://sense4fire.eu	September 2021
D8.1 Final Report (FR)	This document.	31.01.2025

D8.2 Summary Report (SR)	Concise scientific summary of the key findings and all outputs of the project such as publications, datasets, and the scientific roadmap	31.01.2025
D3.5 Drafts for publication D5.3 Scientific publications	Four publications were prepared or published (Andela et al., 2022a; Forkel et al., 2025; de Laat et al., 2024, 2025).	

1.2 Requirement baseline and consolidation of scientific questions (WP1)

The scientific questions were consolidated within the **requirement baseline review (RBRv1.1)**, which provides a review, assessment and analysis of the main scientific challenges, knowledge gaps and scientific problems to be addressed in the Sense4Fire project. The RBR represents the basis for all the activities that were carried out during the project. This document provides a concise review of the state of the art and of the objectives, identifies the candidate test areas, provides a survey of datasets and methods to be used in development and validation including the associated risks, consolidates the technical specifications of the target products, and consolidates the science cases and scientific studies to be carried out. Finally, the document provides an overview about related European and international projects and activities and defines the publication plan.

In short, the following objectives were identified for Sense4Fire:

Objective 1: 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. Specific developments include:

- Fuel loads and combustion completeness: Estimation through an innovative framework integrating satellite-derived surface reflectance, vegetation data, soil moisture, and biomass information.
- Fire behaviour and burned areas: Advanced mapping of fires using thermal anomalies and diurnal fire cycles (Sentinel-3) alongside burned area data (Sentinel-2). These will inform fire type identification and bottom-up fire emission estimates.
- Fire effects on atmospheric composition: Comparison of Sentinel-5p observations of trace gases and aerosols with Copernicus Atmosphere Monitoring Service (CAMS) models to refine emission factors and top-down fire emission estimates.

Objective 2: 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 three research questions:

- How do ecosystem changes influence fuel dynamics and fire behaviour?
- How do fires contribute to short- and long-term carbon emissions?
- What role do uncertainties (emission factors, injection parameters, tracer lifetimes) play in estimating total fire-related carbon emissions?

The activity initially identified three smaller test areas of 5° latitude x 5° longitude that were later enlarged to larger study regions (Amazon/Cerrado, southern Africa, Siberia) and supplemented by a fourth region (southern Europe) during the project (Table 2).

Table 2: Overview of the study regions (large) and test areas (small).

Study region or test area	East/West extent	North/South extent
South America (Amazon/ Cerrado) study region	40°W - 80°W	25°S - 10°N
Southern Europe study region	10°W – 29.5°E	34.5°N - 49°N
Southern Africa study region	10°E - 30°E	5°S - 25°S
Siberia test area	132°E - 138°E	60°N - 71°N

Furthermore, the activity identified a list of **Earth observation datasets** to be explored in the project that can assist to quantify fuel properties, fire behaviour, fire emissions and their effects on the atmosphere. The activity also identified a list of minimum and optimum **technical specifications of the Sense4Fire target products**. The technical specifications of the generated products in Sense4Fire exceeded those minimum specifications in terms of spatial and temporal resolution (Table 3).

Finally, the requirement baseline review identified the following **scientific analyses** of fire dynamics and their effects on ecosystems and the carbon cycle:

1. Fuel Changes and Fire Behaviour: The study explores how variations in tree, herbaceous, and litter fuel loads and moisture affect fire spread, size, and severity. The influence of specific fuel properties will be investigated. Results will enhance understanding of vegetation-fire interactions and inform global fire models, leveraging newly available fuel datasets.

2. Fires and Carbon Emissions: Fires directly emit carbon through biomass combustion and indirectly through long-term ecosystem changes, particularly tree mortality. Fire-adapted ecosystems, like savannahs, recover quickly, while non-adapted ecosystems, such as tropical forests, suffer long-term carbon loss. A novel fire database to differentiate emissions from various fire types, enabling assessment of direct and indirect impacts on carbon cycles is needed to improve fire-enabled vegetation models and quantify fire emissions' influence on global carbon sink capacity.

3. Fire Emission Estimates: Emission estimates should be compared with existing systems (GFED, GFAS) to understand discrepancies and refine models. Atmospheric simulations, combined with Sentinel-5p satellite data, will identify uncertainties and validate improved emission estimates.

Table 3: Comparison of minimum technical specifications of the target products as defined in the RBRv1.1 with the achieved technical specifications of the Sense4Fire products at the end of the project.

Name	Description	Minimum spatial and temporal resolution / Temporal coverage (RBRv1.1)	Achieved at the end of the project
Fuel loads (FL) BM_tree_[leaves, wood] BM_herb	Biomass in different tree compartments and herbaceous vegetation Unit: kg/m^2	Calibration of the approach at 0.25 x 0.25° Application to 1 x 1 km Monthly time step for canopy and herbaceous fuels, annual time steps for woody fuels	Biomass in leaves, branches, stems and herbaceous vegetation, Surface fuel loads of fine and coarse woody debris and litter 300 x 300 m spatial resolution, 10-daily time step
FL_[dead]_x	Mass of dead fuels, debris and organic material, Unit: kg/m^2	Annual time step for surface dead fuels	
Fuel moisture (FM) LFMC_[tree, herb]	Live-fuel moisture content of tree leaves and herbaceous vegetation, Unit: %	Estimation at 1 x 1 km Monthly time step	LFMC of tree leaves and herbaceous vegetation 300 x 300 m spatial resolution, 10-daily time step
DFMC	Dead-fuel moisture content Unit: %	Estimation at 10 x 10 km Monthly time step	
Fire objects Fire perimeters	Each fire perimeter includes attributes about fire type, burned area (ha) and emissions (g m^{-2}day^{-1}) estimates.	per fire object, daily to multi-day burning fire objects with start and end date	Monthly updates of fire objects were achieved during the near-real time demonstration in WP9.
Active fires from S3 and VIIRS	Active fire detections with attributes, including unique fire identifying number, time, location, type of carbon emissions, and other relevant fire characteristics.	Active fire detections per fire object (minimum spatial accuracy 1 km, temporal: 10 am, 1:30 pm, 10 pm, and 1:30 am).	
Fire emissions Trace gases	Emissions of key trace gases and aerosol. Unit: g m^{-2}day^{-1}	Per-fire object (minimum object size about 30ha), temporal: 10 am, 1:30 pm, 10 pm, and 1:30 am.	Emission estimates possible in near-real time (demonstrated with monthly updates) from two approaches

2 Dataset collection (WP2)

Several datasets were collected internally at the beginning of the project to develop, validate and inter-compare innovative Earth observation products in WP3 (Development and validation of innovative products). All input datasets and project products were made available to the project partners through an internal data repository, hosted by the lead partner, TUD. The deliverable **Database Description Document version 1 (DBDv1)** provides a full description of all candidate input datasets.

In summary, the following were the main input datasets used in the project:

- Vegetation data, including FAPAR, LAI, and fCOVER from the Ocean and Land Colour Instrument (OLCI) on Sentinel-3 and Proba-V have been generated since 2014 (Fuster et al., 2020). These products, processed using neural networks and with advanced temporal smoothing and gap-filling were used to estimate canopy and herbaceous fuel load dynamics and live fuel moisture content (LFMC) in the TUD-S4F approach. The data was obtained from the Copernicus Land Monitoring Service https://land.copernicus.eu/global/products/lai

- The soil water index (SWI) from Metop/ASCAT is a proxy for soil moisture at various soil depths. Soil depths are represented by different layers that represent different time lags of soil moisture change relative to surface soil moisture. The layers do not correspond to specific depths. The SWI of the top layer was used as proxy for surface fuel moisture content in the TUD-S4F approach. However, given a strong influence of vegetation on the C-band backscatter of ASCAT, the soil moisture dataset might be affected by the moisture of the canopy especially in dense tropical forest. The dataset is available at a resolution of 0.1° for the period since 2007 (Bauer-Marschallinger et al., 2018). https://land.copernicus.eu/global/products/swi
- The Biomass CCI dataset provides Above Ground Biomass (AGB) at 100 m resolution for 2010, 2017, and 2018, representing total woody components (stem, bark, branches, twigs) with uncertainty estimates (Santoro et al., 2021) was used to constrain total woody AGB in fuel load estimations in the TUD-S4F approach. http://dx.doi.org/10.5285/bedc59f37c9545c981a839eb552e4084
- Canopy height from the GEDI space-borne Lidar sensor was used to constrain estimates of total above-ground biomass in the TUD-S4F approach. We took the level 3 gridded relative height 100 product (https://doi.org/10.3334/ORNLDAAC/1952).
- Land cover maps from ESA CCI (used for 2014-2021) at 300 m were used to provide information on vegetation types to finally estimate fuel loads by detailing herbaceous and tree cover, tree types, and masking water bodies and wetlands in the TUD-S4F approach. https://www.esa-landcover-cci.org/?q=node/164
- The VIIRS instruments on NOAA-20 and S-NPP provide 375 m thermal resolution, enabling detection of low-intensity fires with reduced off-nadir pixel distortion. The 375 m active fire product is available via NASA FIRMS (https://firms.modaps.eosdis.nasa.gov/). The data was used to detect fires in near-real time and to provide estimates of fire size and to estimate fire emissions in both the GFA-S4F and TUD-S4F approaches.
- Burnt area for the period 2014-2019 was used from the Fire CCI dataset version 51 (Lizundia-Loiola et al., 2020). https://dx.doi.org/10.5285/58f00d8814064b79a0c49662ad3af537
- Sentinel-2a and 2b offer 20 m spatial and 5-day temporal resolution, enabling detailed burned area mapping, especially in cloudy regions and transitional fire seasons. This study uses Sentinel-2 based burnt area data for Africa (FireCCISFD20 dataset) (Roteta et al., 2019) and the corresponding Burnt Area Mapping Tool to obtain local Sentinel-2 based burned area maps for South America in order to calibrate and validate active fire-based burned area estimates. The Sentinel-2 BAMT tool has been accessed through the Google Earth Engine.
- Sentinel-5p provides observations of atmospheric carbon monoxide (CO) and nitrogen dioxide (NO_2). CO is derived from shortwave infrared wavelengths (7×7 km resolution, improved to 7×5.5 km from 2019), providing insights on combustion efficiency. NO_2 is estimated at visible wavelengths (3.5×7 km resolution, refined to 3.5×5.5 km), distinguishing tropospheric NO_2 columns. Data from Sentinel-5p was used to provide top-

down constraints on fire emissions by making use of the IFS-COMPO atmospheric transport model. Sentinel-5P data was first obtained from the ESA Sentinel-5P data hub (https://s5phub.copernicus.eu/) and later from the Copernicus Data Space Ecosystem: https://documentation.dataspace.copernicus.eu/APIs/S3.html

While the Sentinel-5p data was used internally available at KNMI, all other datasets have been downloaded to the internal data repository at TUD.

3 Development and validation of innovative products (WP3)

Three main approaches were developed in Sense4Fire to estimate fire emissions. Each approach aims to estimate fire emissions by considering properties of individual fires:

- **GFA-S4F** is based on the Global Fire Atlas (GFA) algorithm (Andela et al., 2019, 2022b) and uses observations of active fires from the VIIRS instruments with a new fire type map to estimate fire emissions.
- **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.
- **KNMI-S5p** is based on observation from Sentinel-5p, whereby fire emissions of CO and NOx are estimated using a top-down approach.

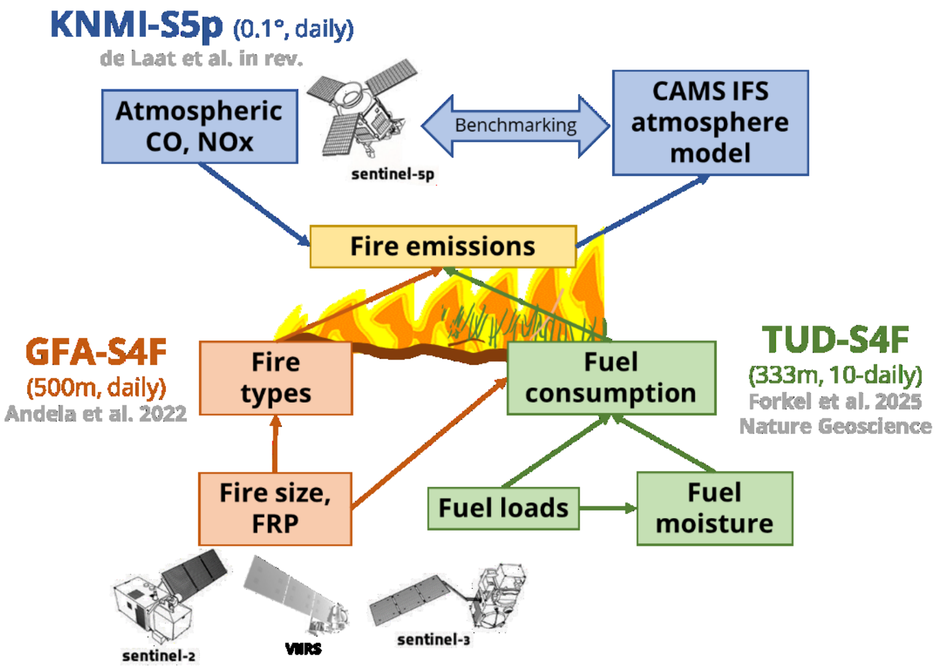


Figure 1: Overview about the three approaches developed in Sense4Fire.

Those three approaches were described in detail in the **Algorithm Theoretical Baseline Document (ATBD)**, first in version 1.1., which has been later superseded by version 2.1 (ATBDv2.1). Each approach has been first individually validated against specific datasets. Validation results of each approach were described in the **Product Validation Report** (PVRv1.1, superseded by **PVRv2.1**). Those validation activities are here summarised in the following for each approach. A final inter-comparison of the three approaches was conducted in the third version of the Product Validation Report (**PVRv3**), which was accompanied by a description of small updates in the algorithms (ATBDv3). Those inter-comparison results are described in Chapter 4.2.

3.1 GFA-S4F: Fire emissions from fire types

Global fire emissions datasets traditionally rely on gridded burned area estimates or active fire detections to calculate carbon and trace gas emissions. However, these approaches do not fully account for variations in fuel type and fire intensity. The GFA-S4F approach introduces an object-based methodology, building on the Global Fire Atlas and Amazon Dashboard (Andela et al., 2019, 2022b), to track individual fires and their characteristics (Figure 2).

Fire Event Monitoring: The integration of VIIRS data provides daily active fire detection with a high spatial resolution (originally at 375 m, here analysed at 550 m), optimal for forest fire spread rates. Active fire detections are clustered into fire events using the Fire Atlas algorithm, which improves upon the MCD64A1 burned area product by addressing its time delays and limited resolution. A key innovation is the separation of adjacent fires through a temporal threshold of five consecutive fire-free days, distinguishing closely located fires burning at different times. Fire Radiative Energy (FRE) is derived from Fire Radiative Power (FRP) by computing the average FRP over fire duration (i.e. FRP density) and by multiplying with fire duration, providing detailed insights into fire duration and energy release.

Fire Type Classification: The classification of fire types is crucial for estimating combustion completeness and emissions. Fires are clustered into broad categories like cropland, grassland, savannah, and forest fires, with forested regions undergoing detailed analysis. Using Sentinel-2 data and land cover information, specific fire types in Brazil include: savannah and grassland fires, deforestation fires, forest fires, and small agricultural clearing fires. For Russia and Europe, we distinguished between cropland, grassland, ground and crown forest fires. For Africa, woodland, cropland and grassland/savannah fires were distinguished (details can be found in ATBDv2.1).

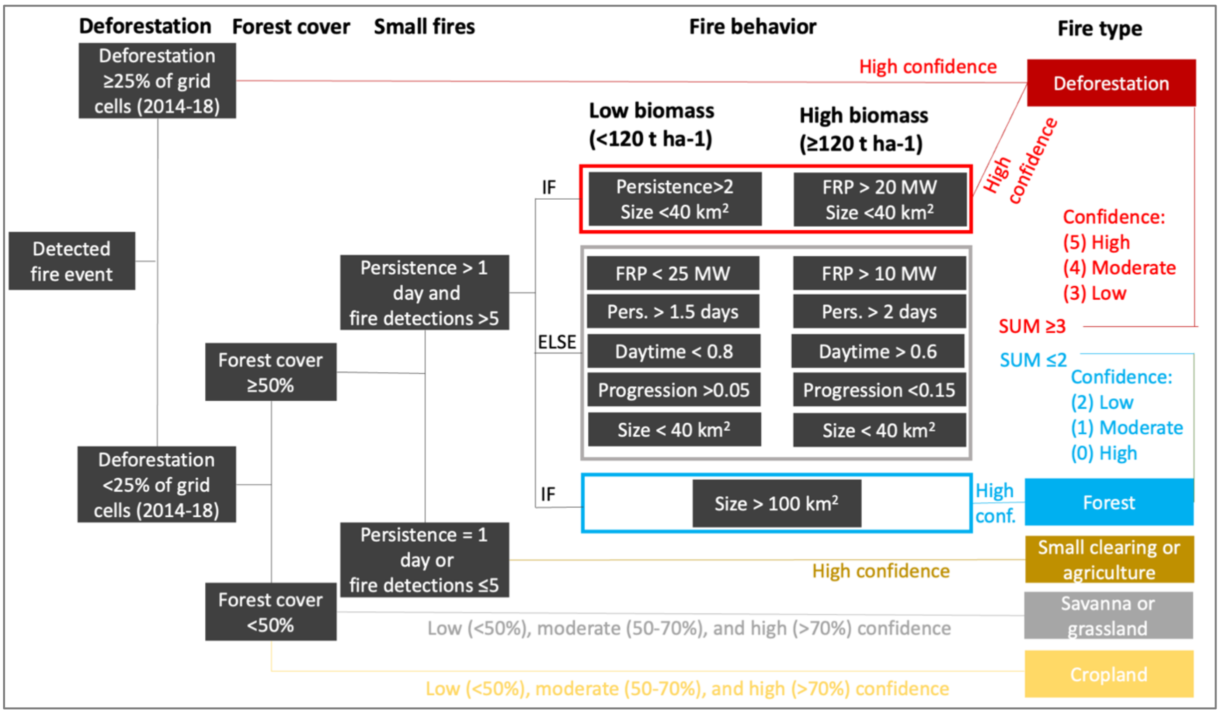


Figure 2: Flow diagram of the fire type classification system used in GFA-S4F and confidence level assessment for the Amazon and Cerrado.
Fires are separated into deforestation, forest, small clearing and agricultural, savannah and grassland, and cropland fires using metrics of fire behaviour and land cover information. The initial separation between high-confidence deforestation fires and non-forest fires uses historic deforestation data (2014 – 2018), fractional tree cover (2014) and land cover information. For all forest fire types, with ≥50% tree cover, we first isolate small clearing and agricultural fires based on low fire persistence and number of fire detections. To further separate deforestation fires from forest fires we use a separate classification for low biomass (left column, <120 t ha^{-1}) and high biomass (right column, ≥120 t ha^{-1}) systems based on observed differences in fire behaviour in moist and dry forests, respectively (see Figure. 5).

In Brazil, deforestation fires are identified by historic data (e.g., PRODES) and behavioural characteristics such as fire persistence, size and FRP (Figure 2). Deforestation fires typically show higher FRP and persistence compared to forest fires, which are larger and exhibit circular progression. Fires are classified into high-confidence categories based on metrics like fire size, persistence, and FRP thresholds.

In Russia and Europe, boreal wildfires are separated into ground and crown fires using pre- and post-fire Sentinel-2 imagery. A set of Sentinel-2 imagery was used to train an approach to predict crown or ground fires from fire behaviour characteristics. The diverse landscape and prolonged fire durations necessitate detailed classification. African fires are grouped into woodland, cropland, and savannah categories based on land cover information and aggregated forest cover information from WorldCover V2 (Zanaga et al., 2022) data.

The fire type classification in GFA-S4F has been validated based on a quality assessment of the fire types for the Amazon/Cerrado region with pre- and post-fire Sentinel-2 pairs. The overall accuracy was 66% for fire events and 92% for active fire detections (large fires include more active fire detections). The largest difference in accuracy was observed for forest fires, with 55% User's accuracy (reflecting commission error) for fire events increasing to 93% User's accuracy for fire detections, likely indicating a more skewed distribution of fire size and associated fire detections compared to deforestation fires. Deforestation fire classification was more stable, with 78% User's and 63% Producer's accuracy for fire events, and 87% User's and 71% Producer's accuracy for fire detections.

Burned Area Mapping and Scaling: Burned area estimation combines fire perimeters with scaling factors to derive accurate measurements of burned regions. The study employs the Sentinel-2 Burned Area Mapping Tools (BAMT) and MCD64A1 products to validate and scale burned area estimates. For forest fires in tropical and boreal regions, fire perimeters directly correspond to burned areas. However, open cover types like grasslands and savannahs require scaling factors to address biases in burned area estimates. High-quality burned area data, such as Sentinel-2 FireCCI, are used for training and validation. In Africa and Russia, BAMT outputs achieve approximately 90% accuracy. For South America, burned area estimates for deforestation fires are refined using MCD64A1 data. The VIIRS-derived burned area was validated against a Sentinel-2 based reference burned area dataset for 2020 using the BAMT approach developed by Roteta et al. (2021). Across all regions the burned area estimates showed good agreement ($R^2 > 0.9$) with the Sentinel-based reference datasets.

3.2 TUD-S4F: Fire emissions from novel estimates of fuel loads, fuel moisture content and combustion

Datasets derived from satellite observations provide indirect information on fuel loads, fuel moisture content (FMC), and fuel consumption, which are essential for estimating fire emissions using emission factors (EFs). Current fire emission inventories rely on fixed average EFs for biomes, which limits their accuracy. The aim of the TU Dresden Satellite data-model fusion approach for Fuel loads, Fuel moisture, Fuel consumption and Fire emissions (S4F) is to combine the wealth of satellite datasets to estimate fuel loads and fuel moisture and by computing EFs dynamically based on FMC and for various fuel types, such as live leaves, wood, litter, and woody debris. The approach is described in detail in the Supplement of Forkel et al. (2025).

TUD-S4F makes use of satellite time-series data of vegetation indices (e.g., LAI, FAPAR) and vegetation optical depth (VOD) to estimate temporal dynamics of canopy fuels and from this to derive surface dead fuels such as litter and woody debris. Spatial information on AGB and canopy height is used to constrain absolute values and spatial patterns of biomass/fuel loads. Key features of TUD-S4F include (Figure 3):

- Estimation of tree height dynamics using fractional tree cover and LAI.
- Biomass allocation to tree stems, branches, and leaves through allometric equations.
- Herbaceous biomass and surface fuel dynamics derived from LAI changes.
- Turnover and decomposition rates to estimate surface fuels such as litter, FWD, and CWD.
- Estimation of LFMC based on LAI and SWI and calibration against the Globe-LFMC database (Yebra et al., 2019) and the VOD2LFMC dataset (Forkel et al., 2022).
- Combustion completeness computed dependent on LFMC for live fuels and on SWI for surface dead fuels.
- Fuel consumption and emissions estimated via combustion model that allows dynamic EF computation of emission factors based on fuel composition and moisture.

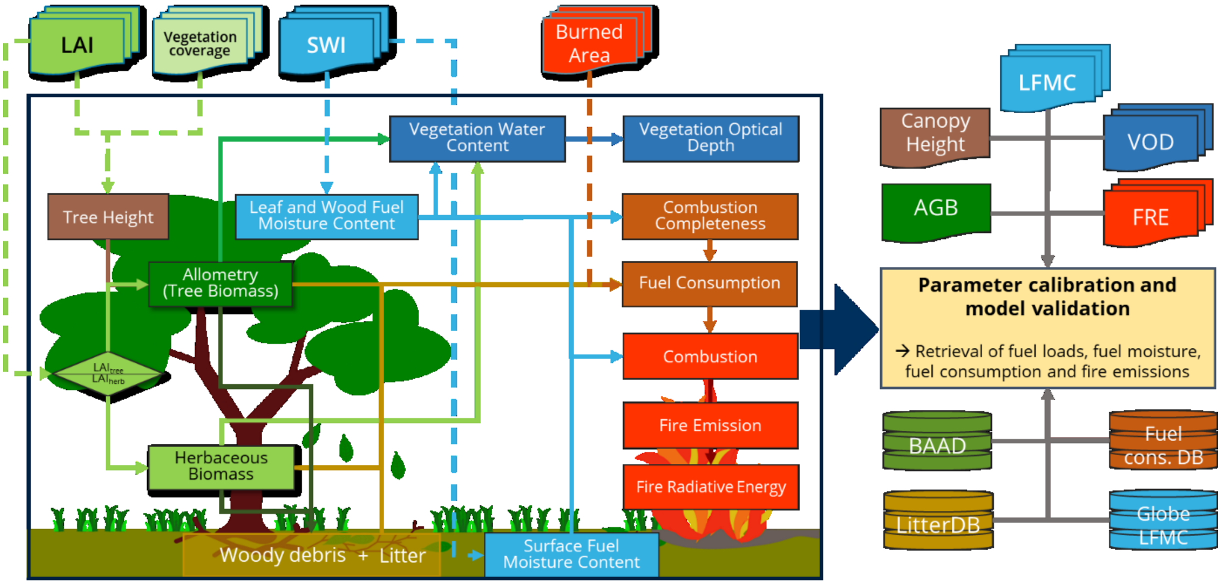


Figure 3: Simplified structure of the TUD-S4F model with forcing data (top) and data used for local calibration and model validation (right).

The TUD-S4F model combines literature-derived parameters with those that need calibration, achieved by optimising model performance against observations. Therefore specific model components were first calibrated against databases (such as for LFMC). Then the full TUD-S4F approach has been calibrated independently for each study region for selected fire events by using datasets such as GEDI canopy height, ESA CCI AGB, LFMC from VOD2LFMC, VODCA Ku- and X-VOD, SMOS L-VOD, and fire radiative energy (FRE) derived from VIIRS. Combustion completeness and emission factors were also calibrated against relevant databases (Andreae, 2019). Surface fuel loads (litter, FWD, CWD) were validated against datasets described below.

For the various modules of TUD-S4F calibration and validation tests were performed for the estimation of canopy height, tree biomass components, surface litter and woody debris, fuel moisture and vegetation water content, vegetation optical depth, fuel loads, combustion completeness and fuel consumption, and of emission factors.

The validation of estimated canopy heights from TUD-S4F revealed that validation results largely depend on the reference product used. Three products were used for validation (GEDI L3 Gridded Land Surface Metrics product, and two spatially interpolated canopy height products that combine GEDI with satellite imagery: GLAD product from Potapov et al. (2021), and ETH product from Lang et al. (2022)). These validations have shown that the GLAD and ETH products are not reliable in the study regions and therefore the original but spatially not continuous GEDI product was used for calibration. Different regression models were tested to estimate canopy height. For the best model, the error between the estimated forest canopy height and GEDI canopy height is on average 0.1 m.

Estimated biomass compartments were calibrated and validated against the Biomass And Allometry Database (BAAD) (Falster et al., 2015). The TUD-S4F allometry model provides an acceptable fit to all biomass components with medium to high correlations and low to medium RMSE. The lowest performance was achieved in the estimation of leaf biomass. The calibration against BAAD is however limited because most measurements in the BAAD database originate from rather small trees with low biomass (majority of trees < 25 m and < 20 kg/m²), hence the allometric relationships are poorly constrained for high-biomass trees.

The estimated fuel loads were validated against measurements from the global database of litter fall mass and litter pool sizes (Holland et al., 2014) and against the updated fuel database (van Wees et al., 2022). For the Amazon and Cerrado regions, surface woody debris was further validated against measurements reported in the literature (Leite et al., 2022; Scaranello et al., 2019). Especially in the Amazon region, estimated fuel loads agree well with the statistical distribution and spatial patterns from the datasets. In southern Africa, the TUD-S4F model tends to overestimate fuel loads. However, this needs further investigation as most of the field observations come from the more drier southern part of the study region while the TUD-S4F model was mostly calibrated for the wetter central and northern parts. Total fuel loads and litter agree are comparable with the databases in Siberia but CWD is overestimated.

The estimated combustion completeness and fuel consumption from TUD-S4F model were also validated against measurements from the updated fuel consumption database (van Leeuwen et al., 2014; van Wees et al., 2022). In the Amazon and Siberia study regions, total fuel consumption agrees well with the database. In southern Africa, total fuel consumption seems to be over-estimated, which however might be related to higher fuel loads in the wetter parts of the study region which are not represented by the field measurements from the drier regions.

Emission factors and the Modified Combustion Efficiency (MCE) from TUD-S4F were then compared against the statistical distribution obtained from the compilation of emission factors by Andreae (2019). TUD-S4F reproduces the observed statistical distributions of emission factors. Only in Siberia, lower median MCE was estimated, resulting in a higher median emission factor for CO.

3.3 KNMI-S5p: Top-down constraints on fire emissions

Sentinel-5p satellite data, specifically measurements of atmospheric trace gases, play a critical role in independently validating bottom-up fire emission estimates, making full use of the Sentinel satellite constellation. The top-down assessment method used to evaluate fire emissions does not constitute an algorithm itself; it serves more as an evaluation and validation activity.

In the KNMI-S5p approach, a mass-balance approach has been applied to all study regions constrain seasonal and regional total carbon monoxide (CO) emissions from fires. This involves performing dedicated reference and baseline experiments with the IFS-COMPO atmospheric model, whereby CO enhancements simulated by models are scaled to match satellite observations, optimising the emission estimates on regional and seasonal scales. This method, often referred to as a 'poor-man's inversion', involves iterative model simulations that update input emissions, combined with detailed uncertainty analysis. Unlike formal inversion methods, this approach serves as a model evaluation and verification activity, rather than a formal algorithm. Specifically, the IFS/CAMS reference configuration is run with different variants of the emission estimates based on fire type classifications (from GFA-S4F) or based on the results from TUD-S4F and analysed to identify the best-performing configuration with respect to Sentinel-5p data, taking observation operators into account. Disagreement is further explored by tracing the disagreement back to specific fires and/or fire locations.

In addition, these results are also evaluated against limitations of the sensitivity analysis. Certain sensitivities may be difficult to capture and/or constrained with the existing IFS-CAMS model setup up. Certain processes may not be captured or resolved at the desired scales, may be difficult to constrain due to limited or missing information and data, or may be difficult to tailor as a whole (*e.g.* optimise an entire atmospheric chemistry scheme). Finally, other uncertainties are explored and characterised on a best-effort-basis, for example assumptions about parameters and parameter values *(e.g*. emission factors), observations and methods. This is by no means a simple and straightforward exercise and may result in an incomplete analysis but it is important to identify how fire emission estimates can be further improved.

Overall, this method provides an effective way to bridge the gap between satellite-derived observations and model-based emissions. It leverages the rich information from Sentinel 1-2-3 observations in conjunction with Sentinel-5p trace gas measurements. The approach, while not formalised as an algorithm, enables a robust evaluation and verification process for fire emissions.

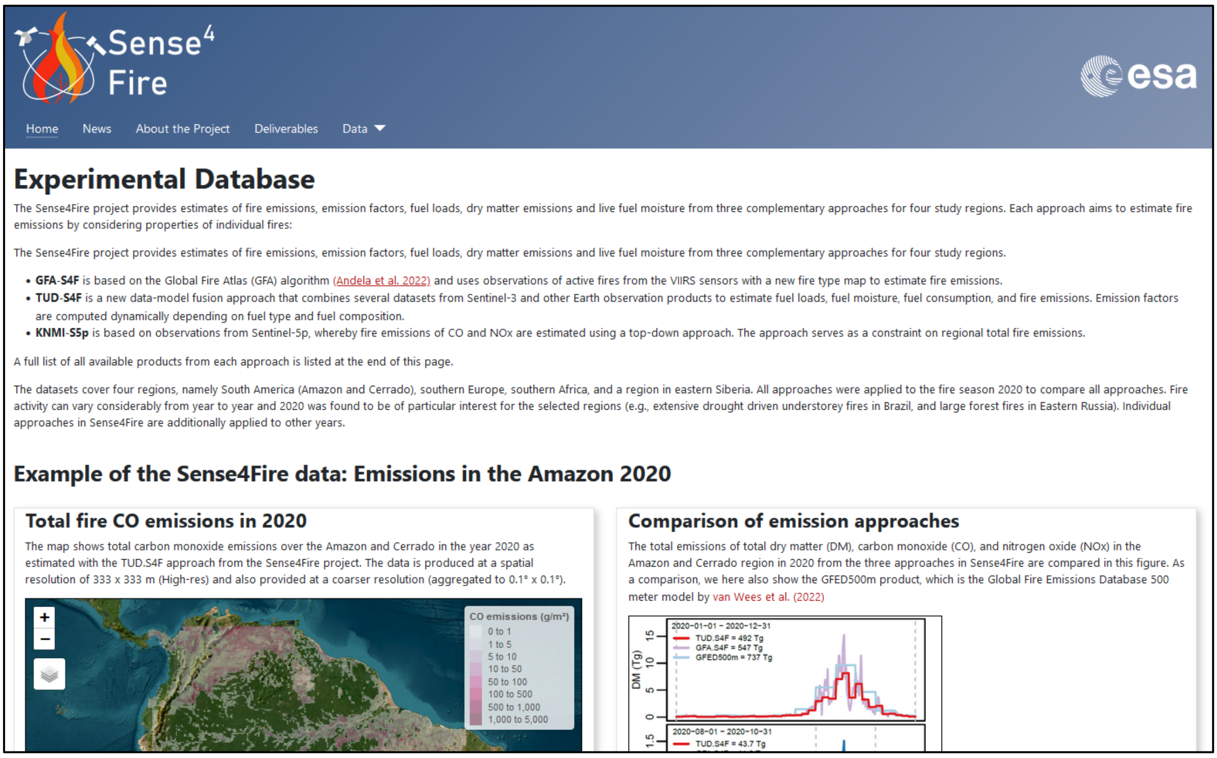
4 Development and inter-comparison of 4D-fire products (WP4)

4.1 Large-scale product generation (version 1 and 2)

The Sense4Fire products were produced, validated and released in two cycles of product generation (Task 4.2), integration and comparison of products (Task 4.3), product assessment and re-calibration (Task 4.4) and production of updates products at large scales (Task 4.5). This development cycle resulted in the release of two version of datasets:

- The first version of the Sense4Fire **Experimental Database (DBv1**) was made available in May 2023 and provided the first products for the Amazon, southern Africa, and Siberian study regions. This was followed by an inter-comparison and scientific analysis of the products. Based on those analyses, several modifications were made to the TUD-S4F approach. The highly experimental TUD-S4F datasets in version 01 of the Experimental Database are deprecated.
- The second version of the Sense4Fire **Experimental Database (DBv2)** was published in October 2023 with results for the Amazon/Cerrado, southern Africa, and Siberian study regions and extended in May 2024 with results for southern Europe (Figure 4).

The GFA-S4F datasets for southern Africa, Siberia and Europe remain the same in version 02 of the database. The GFA-S4F results for the Amazon/Cerrado have been updated for version 02. TUD-S4F results have been completely revised for version 02 of the database and the use of version v01 for TUD-S4F is not recommended. The KNMI.S5p dataset remains the same in versions 01 and 02 of the Experimental Database.



Experimental Database

The Sense4Fire project provides estimates of fire emissions, emission factors, fuel loads, dry matter emissions and live fuel moisture from three complementary approaches for four study regions. Each approach aims to estimate fire emissions by considering properties of individual fires:

The Sense4Fire project provides estimates of fire emissions, emission factors, fuel loads, dry matter emissions and live fuel moisture from three complementary approaches for four study regions.

- **GFA-S4F** is based on the Global Fire Atlas (GFA) algorithm (Andela et al. 2022) and uses observations of active fires from the VIIRS sensors with a new fire type map to estimate fire emissions.
- **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. Emission factors are computed dynamically depending on fuel type and fuel composition.
- **KNMI-S5p** is based on observations from Sentinel-5p, whereby fire emissions of CO and NOx are estimated using a top-down approach. The approach serves as a constraint on regional total fire emissions.

A full list of all available products from each approach is listed at the end of this page.

The datasets cover four regions, namely South America (Amazon and Cerrado), southern Europe, southern Africa, and a region in eastern Siberia. All approaches were applied to the fire season 2020 to compare all approaches. Fire activity can vary considerably from year to year and 2020 was found to be of particular interest for the selected regions (e.g., extensive drought driven understorey fires in Brazil, and large forest fires in Eastern Russia). Individual approaches in Sense4Fire are additionally applied to other years.

Example of the Sense4Fire data: Emissions in the Amazon 2020

Total fire CO emissions in 2020

The map shows total carbon monoxide emissions over the Amazon and Cerrado in the year 2020 as estimated with the TUD.S4F approach from the Sense4Fire project. The data is produced at a spatial resolution of 333 x 333 m (High-res) and also provided at a coarser resolution (aggregated to 0.1° x 0.1°).

Comparison of emission approaches

The total emissions of total dry matter (DM), carbon monoxide (CO), and nitrogen oxide (NOx) in the Amazon and Cerrado region in 2020 from the three approaches in Sense4Fire are compared in this figure. As a comparison, we here also show the GFED500m product, which is the Global Fire Emissions Database 500 meter model by van Wees et al. (2022)

Figure 4: Sense4Fire website with the Description of the Experimental Database and the corresponding data access. https://sense4fire.eu/database/

The **Experimental Database version 2 (DBv2)** provides the following datasets:

TUD-S4F v0.2: TUD-S4F provides fuel loads, fuel consumption and fire emissions. The data is provided at a spatial resolution of 333 x 333 m and aggregated to 0.1 x 0.1° for Amazon, Europe, southern Africa, and Siberia. It covers the period 2014-01-01 to 2021-10-20 at 10-daily time step.

- S4F.CCILC_S4Fba_dynEF: The TUD-S4F default experiment computes dynamic emission factors and uses as input burned area data for the year 2020 from the GFA-S4F approach and for the other years from the ESA CCI fire (v5.1) dataset.
- S4F.CCILC_S4Fba_fixEF: This experiment differs from S4F.CCILC_S4Fba_dynEF in the estimated emissions because it is based on fixed emission factors for forests and grasslands. Estimated fuel loads and fuel consumption are identical to S4F.CCILC_S4Fba_dynEF. The experiment is available for the Amazon region only.
- S4F.CCILC_FireCCI51: This experiment uses burned area from ESA's CCI fire (v5.1) dataset only and dynamic emission factors.

KNMI-S5p v0.1: KNMI-S5p provides fire emission for carbon monoxide (CO) and nitrogen oxides (NO_x) derived from Sentinel-5p observations. The data is provided for all regions at 0.1 x 0.1° and at daily time step for the year 2020.

- KNMI-S5p provides CO and NO_x emissions for all regions for 2020.

GFA-S4F v0.1 and v0.2: GFA-S4F provides fire emissions and fuel consumption derived from VIIRS Fire Radiative Power observations based on a fire type classification. The method is based on Andela et al. (2022). The fire type map is provided at a resampled resolution of 333 x 333 m and emissions aggregated to 0.1 x 0.1° for all regions and covers the year 2020 for all regions and for 2019-2024 for the Amazon/Cerrado region. Fire emission are provided daily. The fire type map is an annual map.

- GFA-S4F v0.1: Results for all regions for 2020. Results for the Amazon/Cerrado region are superseded by version 0.2.
- GFA-S4F v0.2: Like GFA-S4F v0.1 but with improved parametrisation for NO_x emissions and prolonged time series (2019-2024) for the Amazon/Cerrado study region.

Each approach provides a different set of output variables with a focus on fire properties and emissions in GFA-S4F, fuel properties and fire emission in TUD-S4F, and top-down fire emission estimates of CO and NO_x from KNMI-S5p for validation purposes (Table 4).

Table 4: Description of Sense4Fire output variables.

Variable	Description	Unit	Methods
e_co	fire emissions of carbon monoxide	g/m^2	GFA-S4F-FRP, KNMI-S5p, TUD-S4F
e_co2	fire emissions of carbon dioxide	g/m^2	GFA-S4F-FRP, TUD-S4F
e_ch4	fire emissions of methane	g/m^2	GFA-S4F-FRP, TUD-S4F
e_pm25	fire emissions of particulate matter < 2.5 µm	g/m^2	GFA-S4F-FRP, TUD-S4F
e_nox	fire emissions of nitrogen oxides	g/m^2	GFA-S4F-FRP, KNMI-S5p, TUD-S4F
ef_co	emission factor carbon monoxide	g/kg	TUD-S4F
ef_co2	emission factor carbon dioxide	g/kg	TUD-S4F
ef_ch4	emission factor methane	g/kg	TUD-S4F
ef_pm25	emission factor particulate matter < 2.5 µm	g/kg	TUD-S4F
ef_nox	emission factor nitrogen oxides	g/kg	TUD-S4F
mce	modified combustion efficiency	No units	TUD-S4F
bm_wood	woody biomass of trees/shrubs	kg/m^2	TUD-S4F
bm_leaf	leaf biomass of trees/shrubs	kg/m^2	TUD-S4F
bm_herb	herbaceous biomass (incl. crops)	kg/m^2	TUD-S4F
fwd	fine woody debris (diameter < 7.62 cm)	kg/m^2	TUD-S4F
cwd	coarse woody debris (diameter > 7.62 cm)	kg/m^2	TUD-S4F
litter	litter (dead herbaceous and leaf material)	kg/m^2	TUD-S4F
fc_total	total fuel consumption	kg/m^2	GFA-S4F-FRP, TUD-S4F
fc_stem	stem biomass fuel consumption	kg/m^2	TUD-S4F
fc_branches	branches biomass fuel consumption	kg/m^2	TUD-S4F
fc_leaf	leaf biomass fuel consumption	kg/m^2	TUD-S4F
fc_herb	herbaceous biomass fuel consumption	kg/m^2	TUD-S4F
fc_fwd	fine woody debris fuel consumption	kg/m^2	TUD-S4F
fc_cwd	coarse woody debris fuel consumption	kg/m^2	TUD-S4F
fc_litter	litter fuel consumption	kg/m^2	TUD-S4F
fmc_live	live fuel moisture content	%	TUD-S4F
fre	fire radiative energy	MJ/m^2	GFA-S4F-FRP
fire_type	fire types	classes	GFA-S4F-FRP
ba_scale	burned area scaling factor	No units	GFA-S4F-FRP

4.2 Comparison of fuel, fire and atmosphere prototype products at the test sites

A comparison of the three fire emission products was first conducted for the Amazon/Cerrado study region and the southern Africa test areas in the product validation report version 2.1 (PVRv2.1) and then completed for all study regions, products and an entire year (2020) in the product validation report version 3 (PVRv3). This report also included a comparison of the products with fire emission estimates from the operational Global Fire Assimilation System (GFAS) (Kaiser et al., 2012).

4.2.1 Amazon region (including Cerrado)

Fuel loads: Estimated fuel loads from TUD-S4F were compared with two other satellite based estimates, namely from the GFED500m model (van Wees et al., 2022) and with the estimates by Leite et al. (2022) (L22). Spatial patterns and absolute values of estimated surface fuel loads are different between the three approaches (Figure 5). TUD-S4F shows similar spatial patterns and absolute values of leaf and woody biomass with GFED500m but differs in comparison with L22. The magnitude of woody debris in TUD-S4F is similar to GFED500m and L22 but spatial gradients are especially different with L22. *In situ* measurements from the Amazon show a range of CWD from 2.2 to 9.3 kg/m^2 (Scaranello et al., 2019), which corresponds to the range in the TUD.S4F approach. Those comparisons of surface fuels indicate that TUD-S4F produces estimates within plausible ranges, however, a proper validation of surface fuel loads requires more field observations or a coordinated effort to compile such measurements in a global database.

NOx emissions: The time series of daily emissions shows consistent variations for GFAS, GFA-S4F and TUD-S4F with a strong peak in September 2020 (day of year 250-270) (Figure 6). The total NO_x emission estimates for 2020 are quite comparable, although somewhat lower for GFAS (77 Gg) than GFA-S4F (109 Gg). Results using the GFAS emissions (Figure 6, left panel) show in general a fair agreement between observed and modelled tropospheric NO_2 columns although the regression indicates an underestimation which is dominated by the distribution and dominance of smaller tropospheric NO_2 columns (5 < 1015 molecules cm-2). When optimising the NOx emissions with respect to TROPOMI NO_2 observations using the KNMI-S5p β-method nearly identical values independent of the a-priori emissions are reached (91 Gg yr^{-1} for optimising against GFAS and 88 Gg yr^{-1} for optimising against GFA-S4F, 75 Gg yr^{-1} for TUD-S4F without optimisation against S-5p, Figure 6). These results reveal a rather consistent picture for the Amazon/Cerrado region for all available databases and approaches and provide confidences in the NO_x emission estimates.

CO emissions: For CO there similarly is a good agreement between TROPOMI observations and IFS-COMPO model results. There are some indications that GFAS underestimates CO emissions GFA-S4F and TUD-S4F show better agreement with IFS-COMPO than GFAS.

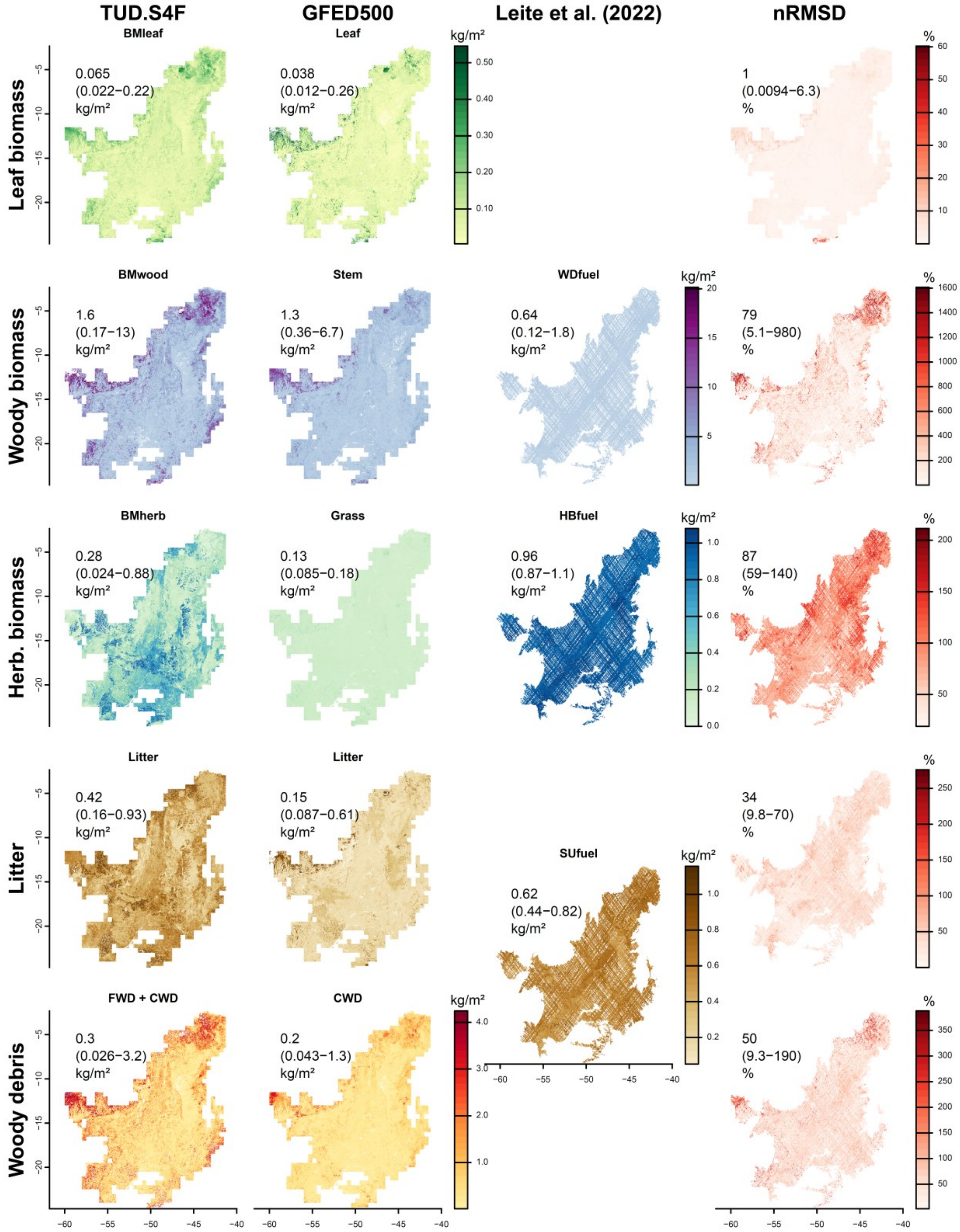


Figure 5: Comparison of different fuel components for the Cerrado biome from three different satellite-based approaches.
Please note that WDfuel in L22 includes woody biomass for trees with diameter at breast height > 10 cm while TUD.S4F treats shrubs as small trees. SUfuels in L22 includes all dead herbaceous and woody plant material at the surface and hence a direct assignment of SUfuel to the litter or woody debris classes in TUD.S4F and GFED500m is not possible. nRMSD is the normalised root mean squared difference relative to the mean value

of the three approaches. The numbers in each map represent the median value and percentiles 5% and 95% of the values in each map.

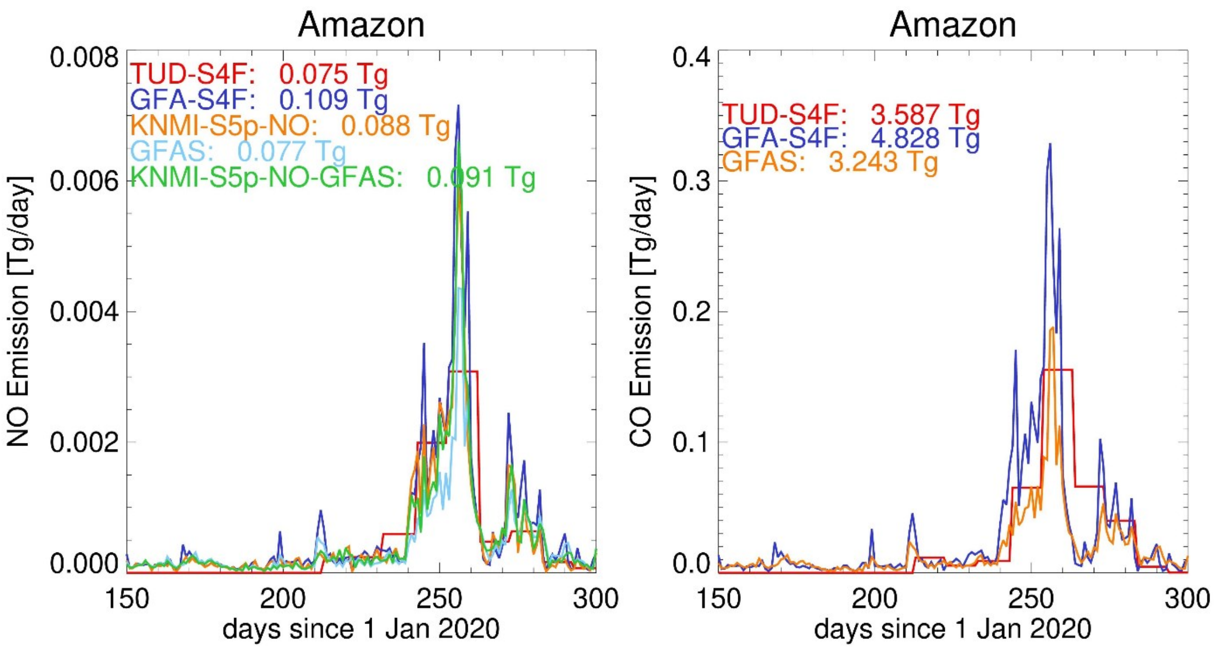


Figure 6: Time series of June-October 2020 daily NO_x emissions (left panel) and daily CO emissions (right panel) for the Amazon region. The emissions are displayed for both the GFAS and GFA-S4F emissions as well as for NOx the associated β-optimised emissions.

4.2.2 Southern Africa

Fuel loads: Estimated fuel load, fuel consumption and combustion completeness from TUD-S4F were compared with statistical distributions from field samples as compiled in van Wees et al. (2022) and by Holland et al. (2014). TUD-S4F reproduces the distribution of herbaceous fuel loads but tends to overestimate the fuel load of litter and FWD. Median total fuel consumption matches the observed median but TUD-S4F shows many fires with higher values of fuel consumption than included in the field data. The range of herbaceous fuel consumption agrees with field data but the median tends to be underestimated. However, from the field data it is not clear if herbaceous fuels contain dry or dead grass which would be included in the litter fuels in TUD-S4F.

Fire emissions: The time series for CO and NO_x emissions for southern Africa show consistent temporal variability amongst all emission databases, but also large differences (Figure 7). Both findings are similar to what was reported for the Amazon. GFAS total CO emissions for this region for the year 2020 amount to 48 Tg, whereas GFA-S4F CO emissions are more than four times larger (213 Tg). The TUD-S4F emissions are in-between (102 Tg). For NO_x the 2020 total GFAS emissions amount for 1.6 Tg NO yr^{-1} whereas the equivalent GFA-S4F emissions are approximately three times larger (4.9 Tg yr^{-1}). Again, TUD-S4F is in-between (3.2 Tg yr^{-1}).

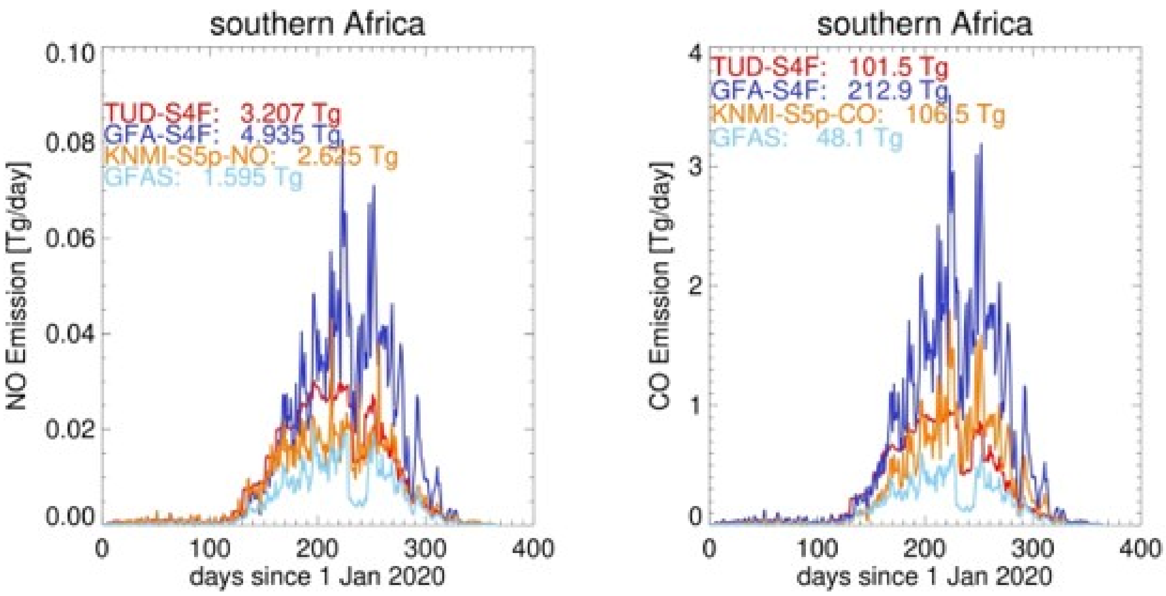


Figure 7: Daily NO_x (as NO, left) and CO (right) emission estimates for southern Africa in 2020 for the various products.

Evaluation of IFS-COMPO using the GFAS against TROPOMI NO_2 observations emissions show in general a fair agreement between observed and modelled tropospheric NO_2 columns. For the IFS-COMPO simulations using the GFA-S4F emissions the results for southern Africa are significantly different from those reported for the Amazon. The large-fire NO_x bias is evident (Figure 7). The KNMI-S5p optimised NO_x emissions are larger than the GFAS emissions and much smaller than the GFA-S4F emissions: 2.6 Tg NO yr^{-1}.

For CO the there is a good correlation between observations and model results. However, both GFAS and GFA-S4F show clear biases with GFAS underestimating CO – as also reported for southern Africa in de Laat et al. (2024) and with GFA-S4F largely overestimating CO.

The consistent overestimation of southern African fire emissions in GFA-S4F indicate problems with the conversion of satellite information (Fire Radiative Power) to emission rates. This is unsurprising, as the GFA-S4F algorithm has not been tuned with known emission factors for woodland and forests in Africa. An update of those emission factors (van der Velde et al., 2024) could help to reduce the overestimation of fire emissions in the GFA-S4F approach.

4.2.3 Siberia

Fuel loads: Estimated fuel load, fuel consumption and combustion completeness from TUD-S4F were compared with statistical distributions from field samples as compiled in van Wees et al. (2022). TUD-S4F tends to underestimate the fuel load of living vegetation (wood, leaves) but corresponds well to the observed distribution of woody debris and litter and fine woody debris. The differences in fuel loads translate into similar differences in fuel consumption. TUD-S4F tends to underestimate total fuel consumption but agrees with the fuel consumption of woody debris and litter.

Fire emissions: The time series of emissions show that fire emissions occur much more sporadic resulting in a more stochastic time series, with fires found mostly in the months July-September (Figure 8). The total 2020 NO_x emissions for GFAS (74 Gg) are higher than for TUD-S4F (55 Gg) and

GFA-S4F (15 Gg). Note that for these boreal fires the default GFAS NO_x emissions have been already scaled down for this comparison by a factor 0.34, because of a known outdated emission factor specifically for NO_x. This however still results in much higher NO_x emissions. The corresponding CO emissions are more similar (2.29 Tg for GFAS, 2.17 for GFA-S4F, 2.03 for TUD-S4F), with GFA-S4F showing higher peak emission values in combination with lower values in case of smaller fires, compared to GFAS.

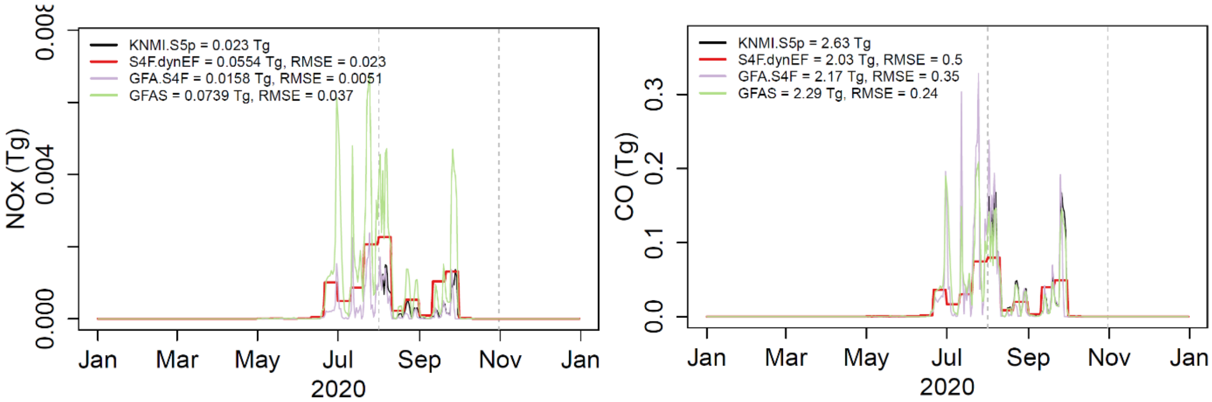


Figure 8: Daily NOx (as NO, left) and CO (right) emission estimates for the Siberia Taiga/Tundra region in 2020 for the various products.

Evaluation results of IFS-COMPO versus TROPOMI observations for the Siberia region are more difficult to interpret than those for the Amazon/Cerrado and sub-equatorial Africa regions due to many fewer fires occurring. However, the results also suggest here a large-fire NO_x bias particularly in the GFA-S4F dataset. The KNMI-S5p β-optimisation cannot resolve this discrepancy likely due to fewer fires and greater cloudiness, which limited the possibility for using TROPOMI measurements for the post-hoc emission adjustment.

For CO, the results are similar to those of NO_x. Both GFAS and GFA-S4F appear to underestimate fire CO emissions, although the GFA-S4F emissions appear to capture slightly better the large fire events, indicated by a better slope in the regression line, and improved correlation.

4.2.4 Europe

Fuel loads: Validation of fuel load and fuel consumption from TUD-S4F over Europe is challenging than in the other regions because the fuel consumption database by van Wees et al. (2022) contains only a few measurements. Hence for the comparison over Europe, we mainly take observations from the Database of Litter Fall Masses and Litter carbon (Holland et al., 2014). The comparison of litter and the combined litter and FWD show that TUD-S4F reproduces plausible ranges but has a tendency to overestimate litter loads over Europe.

Fire emissions: For the southern Europe region the months August and September 2020 were analysed. The emissions time series shows large differences between 2020 total GFAS NO_x emissions (33 Gg) and GFA-S4F emissions (105 Tg). Also the GFA-S4F CO emissions are much larger (4.4 Tg CO yr^{-1}) than those estimated by GFAS (1.0 Tg CO yr^{-1}).

Despite the limited number of fires there is a clear indication of also here large-fire NO_x bias in GFA-S4F, not present in GFAS. For CO there clearly is a large positive bias in GFA-S4F fire emissions. This is consistent with the results for NO_x and similar to that seen for southern Africa.

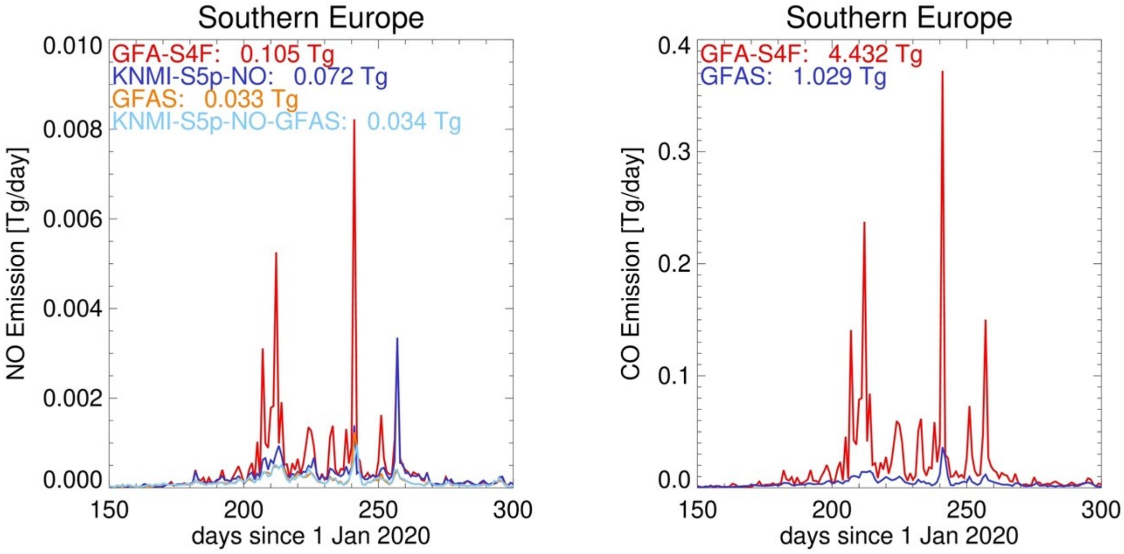


Figure 9: Daily NO_x (as NO, left) and CO (right) emission estimates for Southern Europe in June-October 2020 for the various products.

5 Developing near-real time fire emissions products (WP9)

Because of the importance of wildfire monitoring and estimating wildfire emissions, a demonstration of "near-real-time" (NRT) capacity test of the Sense4Fire approaches was conducted in summer and autumn 2024. For the test, the Amazon 2024 biomass burning season in August and September 2024 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 a strong La Nina the persisted well in to 2024.

The Sense4Fire team started their efforts on 1 September 2024. Within two weeks GFAS and TUD-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 10). Hence by October 2024 the analysis was extended with emissions for the September 2024 month and within a few weeks results were available. 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).

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 emissions monitoring applications of the Sense4Fire suite of tools.

The setup of the approaches and results of the near-real time demonstration are currently prepared for a manuscript (de Laat et al., 2025)

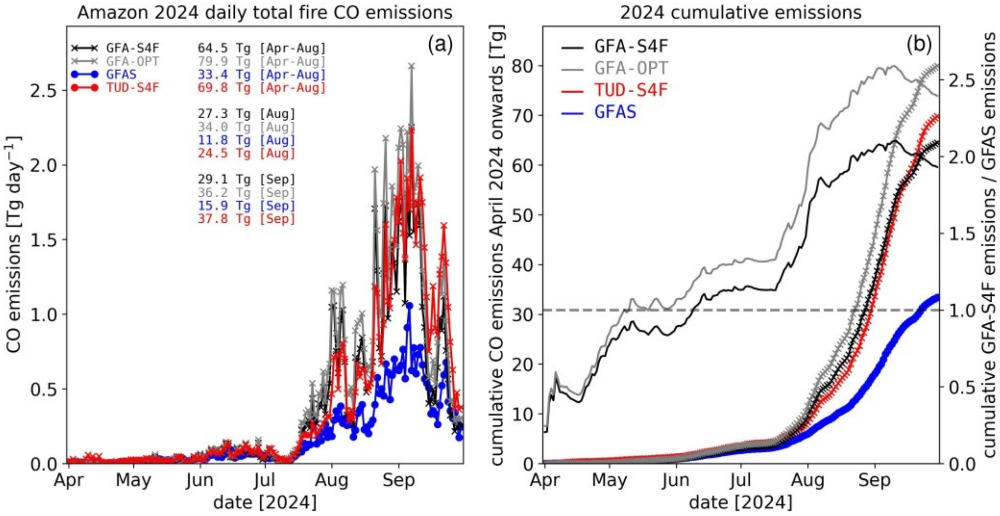


Figure 10: (a) Daily CO emissions for the Amazon/Cerrado for the period April to August 2024. (b) Cumulative emissions in Tg for the period for the period April to August 2024 (lines with markers) and cumulative GFA-S4F emissions as fraction of cumulative GFAS emissions (solid lines without markers).

5.1 Towards developing of prototype NRT emission products

Three approaches were used to obtain fire emission in near-real time and to validate them against Sentinel-5p observations by using the IFS-COMPO atmospheric model:

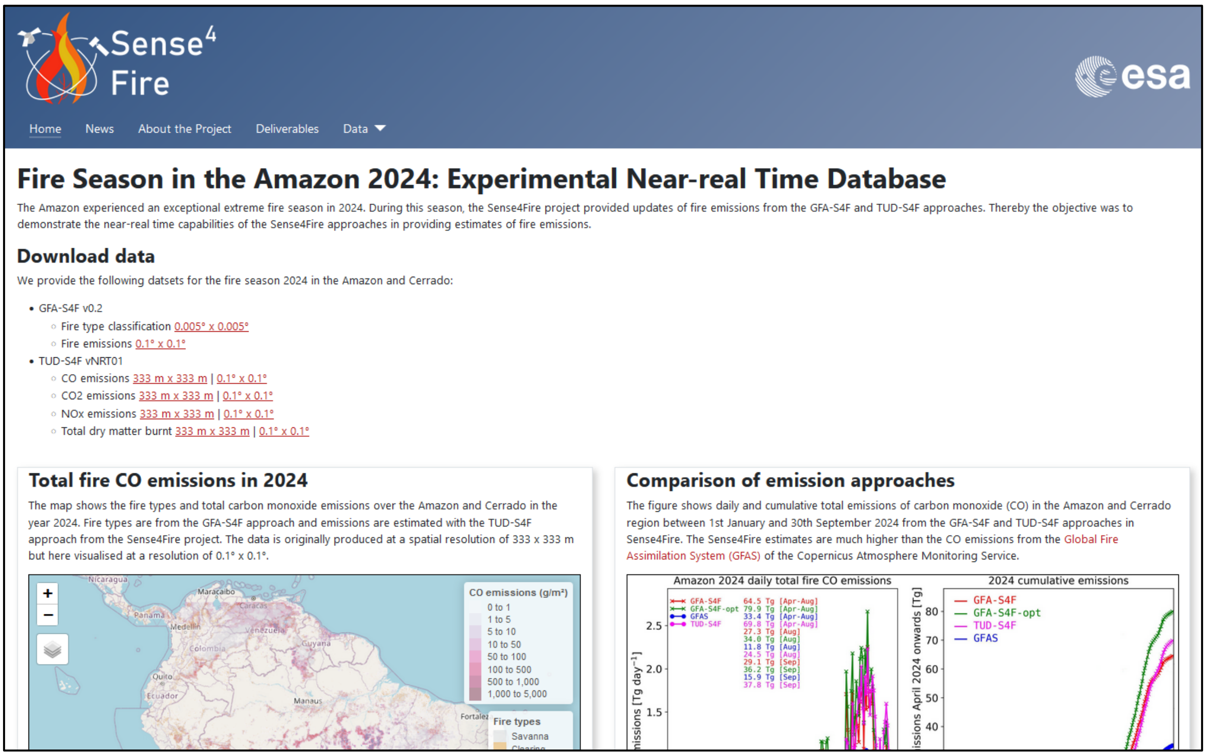
- **GFAS:** Emissions from the operational Copernicus Atmosphere Monitoring Service GFAS system.
- **GFA-S4F** was applied to the Amazon/Cerrado for the full period 2019-2024. The method was applied as previously described in ATBv2.1.
- **TUD-S4F** needed a refinement in order to allow a NRT application as many input datasets to TUD-S4F are available only with a long temporal delay. 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 limits the 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). Therefore, a machine learning emulator was developed to estimate fire emissions in NRT. This TUD-S4F-vNRT01 approach applies a series of random forest models to predict dry matter burned and emission factors from the near-real time fire type map from GFA-S4F for the year 2024 and from spatial patterns of fuel loads from a previous TUD-S4F model run (year 2020) as predictors.

In addition, the IFS-COMPO GFA-S4F model results and comparison with Sentinel-5p data for August 2024 were used to create a so-called “optimised” GFA-S4F emission database (GFA-OPT). Based on the observed CO column bias for GFAS and GFA-S4F compared to IFS-COMPO results and differences in total August emissions it was estimated that an increase of GFA-S4F emissions by a factor 1.5 (north of 10°S) should obtain IFS-COMPO results close to Sentinel-5p observations.

5.2 Demonstration of prototype NRT emission products

The Sense4Fire project provided near-real time estimates of fire emissions for the Amazon/Cerrado at the end of July, end of August and end of September 2024. The resulting datasets were produced and made available at the NRT database at the Sense4Fire website (Figure 11, https://sense4fire.eu/database/2024_nrt/):

- GFA-S4F v0.2
    - Fire type classification 0.005° x 0.005°
    - Fire emissions 0.1° x 0.1°
- TUD-S4F vNRT01
    - CO emissions 333 m x 333 m | 0.1° x 0.1°
    - CO2 emissions 333 m x 333 m | 0.1° x 0.1°
    - NOx emissions 333 m x 333 m | 0.1° x 0.1°
    - Total dry matter burnt 333 m x 333 m | 0.1° x 0.1°



Fire Season in the Amazon 2024: Experimental Near-real Time Database

The Amazon experienced an exceptional extreme fire season in 2024. During this season, the Sense4Fire project provided updates of fire emissions from the GFA-S4F and TUD-S4F approaches. Thereby the objective was to demonstrate the near-real time capabilities of the Sense4Fire approaches in providing estimates of fire emissions.

Download data

We provide the following datsets for the fire season 2024 in the Amazon and Cerrado:

- GFA-S4F v0.2
    - Fire type classification 0.005° x 0.005°
    - Fire emissions 0.1° x 0.1°
- TUD-S4F vNRT01
    - CO emissions 333 m x 333 m | 0.1° x 0.1°
    - CO2 emissions 333 m x 333 m | 0.1° x 0.1°
    - NOx emissions 333 m x 333 m | 0.1° x 0.1°
    - Total dry matter burnt 333 m x 333 m | 0.1° x 0.1°

Total fire CO emissions in 2024

The map shows the fire types and total carbon monoxide emissions over the Amazon and Cerrado in the year 2024. Fire types are from the GFA-S4F approach and emissions are estimated with the TUD-S4F approach from the Sense4Fire project. The data is originally produced at a spatial resolution of 333 x 333 m but here visualised at a resolution of 0.1° x 0.1°.

Comparison of emission approaches

The figure shows daily and cumulative total emissions of carbon monoxide (CO) in the Amazon and Cerrado region between 1st January and 30th September 2024 from the GFA-S4F and TUD-S4F approaches in Sense4Fire. The Sense4Fire estimates are much higher than the CO emissions from the Global Fire Assimilation System (GFAS) of the Copernicus Atmosphere Monitoring Service.

Figure 11: Sense4Fire website with the Description of the Experimental Near-real time Database and the corresponding data access. https://sense4fire.eu/database/2024_nrt/

The output products demonstrates the near-real time capabilities of the GFA-S4F and TUD-S4F approaches. The near-real time results of the fire emissions in 2024 have been presented and discussed with the scientific community at various scientific events:

- Fire Modelling Development Brainstorming Workshop; Leverhulme Centre for Wildfire, Science and Society; 16-18 September 2024, Dartington Hall, UK
- 13th EARSeL Forest Fires Special Interest Group Workshop; 19-20 September 2024, Milano, Italy | [Book of Abstracts]

- Future Focus Wildfires. Community forum on Earth Observation for wildfires monitoring; EUMETSAT; 26-28 November 2024, Darmstadt, Germany | [Presentation PDF] | Event website including Final Report

6 Scientific analysis, impact assessment and comparison (WP5)

The scientific analyses of the Sense4Fire project are described in the Impact Assessment Report, in a first version (IARv1) which has been superseded by its second version (**IARv2.1**). In addition, the main scientific developments and findings have been submitted (de Laat et al., 2025), published as preprints (de Laat et al., 2024) or as scientific publications (Andela et al., 2022a; Forkel et al., 2025).

6.1 Comparison of 4D-fire products with other approaches

The approaches and products developed in Sense4Fire were across four regions and in the near-real time demonstration compared with the operational fire emission estimates from GFAS (see Chapter 4.2). In addition, a comprehensive comparison of fire emissions has been conducted with estimates from GFED500m (van Wees et al., 2022), REFIT.AC (Fawcett et al., 2023) and three dynamic global vegetation models for the Amazon and Cerrado region. Results of this analysis are included in (Forkel et al., 2025). Generally, the three Sense4Fire approaches show comparable fire emission estimates, whereas GFAS tends to underestimate, GFED500m overestimates, and the DGVMs show a large spread (Figure 12).

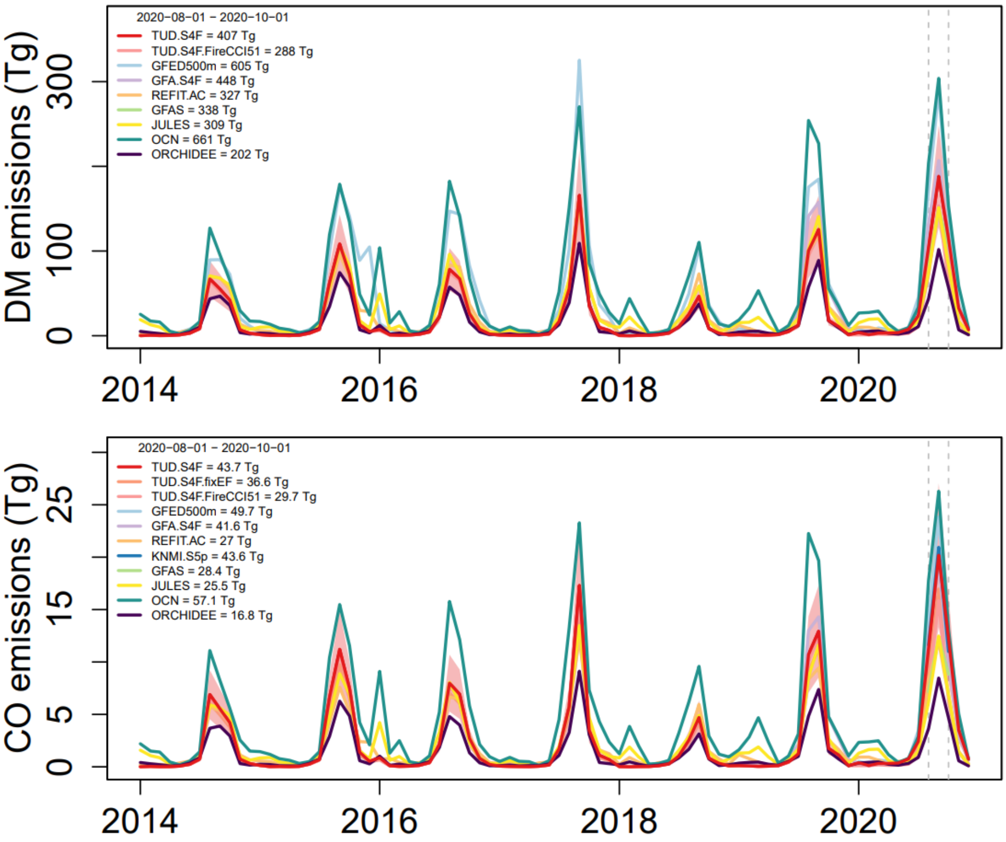


Figure 12: Comparison of dry matter burnt and CO emissions for the Amazon and Cerrado from the Sense4Fire approaches (TUD-S4F, GFA-S4F, KNMI-S5p), with three other bottom-up estimates (GFAS, GFED500m, REFIT.AC) and three dynamic global vegetation models (JULES, OCN, ORCHIDEE).

6.2 Comparison of NRT fire emission approaches

The analysis of the Sense4Fire emission products (GFA-S4F and TUD-S4F) in near-real time for the fire season 2024 in the Amazon and Cerrado uncovered a significant underestimation of total columns (CO-TC) as observed by Sentinel-5p. 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 the tropics) which leads to accumulation of CO in the atmosphere. The GFAS emissions were lowest (Figure 10) 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 a more comparable evaluation against S5p CO-TCs.

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. This can be explained by the exceptional 2024 Amazon drought which likely dried out natural vegetation more than normal, making it susceptible to fires.

This analysis has been summarised in a manuscript which has been submitted to Geophysical Research Letters (27. January 2025).

6.3 Fire effects on the carbon cycle

In short, we provide the following answers to the initial research questions from Objective 2 of Sense4Fire:

How do ecosystem changes influence fuel dynamics and fire behaviour?

Changes in land cover and ecosystem structure increase the availability of surface fuels such as litter and woody debris. Those surface fuels decrease combustion efficiency and hence increase the shouldering combustion and production of CO emissions. This has been shown by using the TUD-S4F data model fusion approach which allowed to quantify the effect of surface fuels on fire emission factors. The effect is a dominant source of fire emissions caused by forest and deforestation fires in the Amazon and Cerrado regions. Those results have been published in Nature Geoscience (Forkel et al., 2025).

How do fires contribute to short- and long-term carbon emissions?

The Sense4Fire products have not been specifically analysed to investigate long-term fire emissions and hence to answer this question. However, the results from GFA-S4F and TUD-S4F were used to quantify direct short-term fire emissions (Forkel et al., 2025; de Laat et al., 2025). In addition, the estimates of temporal dynamics in vegetation biomass and surface fuel loads from TUD-S4F provide information to derive the development of ecosystem carbon stocks and to analyse as a temporal derivative the long-term development of respiration from previously fire-affected fuels. Hence, the methodological developments and products from Sense4Fire provide information to investigate post-fire emissions in future studies.

What role do uncertainties play in estimating total fire-related carbon emissions?

A detailed uncertainty analysis was conducted for the 2020 fire season in the Amazon and Cerrado (Forkel et al., 2025) from which the following text is taken: Across several EO-based approaches, median total dry matter burnt (DMB) is 372 Tg ranging from 288 to 605 Tg DMB (6 estimates, Figure 13). The TUD.S4F approach estimates total DMB of 407_{277}^{537} Tg with a parameter uncertainty 32%. CO emissions are $39.1_{27.0}^{49.7}$ Tg across all EO approaches and $43.7_{28.8}^{58.6}$ Tg in TUD.S4F, aligning with the S5p.KNMI top-down validation estimate of $43.6_{32.7}^{54.5}$ Tg, which includes an uncertainty of 25%. The estimated DMB vary significantly at local to regional scales, with uncertainties up to 60%.

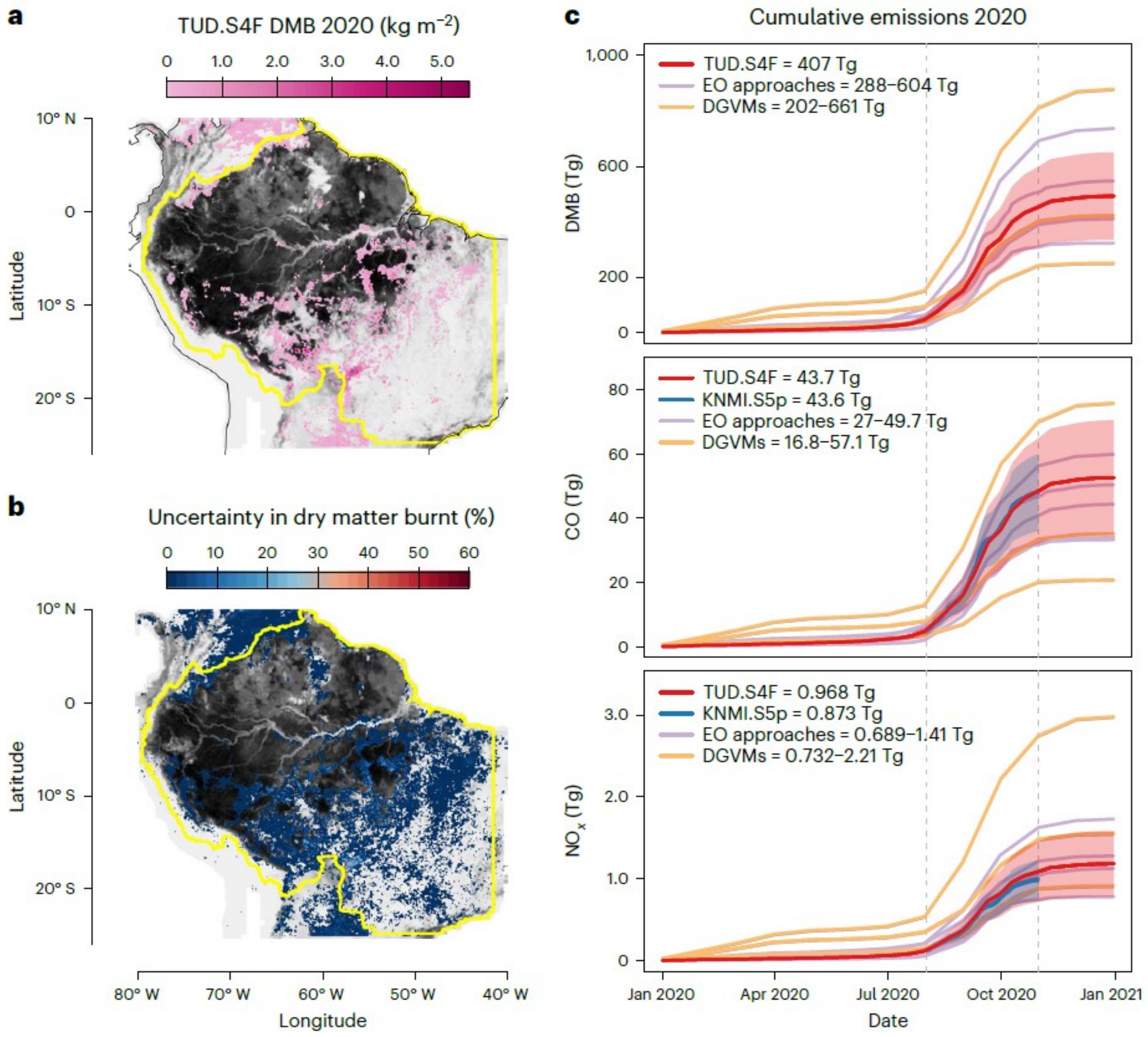


Figure 13: Fire emissions and uncertainties in the Amazon and the Cerrado in 2020 (from Forkel et al. 2025). (a) Total dry matter burnt (DMB) in 2020 and above-ground biomass (background map from grey = 0 to black = 40 kg m^{-2}) from the TUD.S4F approach. The yellow polygon indicates the extent of the 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 NO$_x$ 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. From Forkel et al. (2025).

Uncertainties in total fire emissions in EO products originate from the approach and used fire data (e.g., burnt area or FRP). EO approaches that exclude small fires show 27% lower DMB than those accounting for small fires. Multi-model uncertainties in fire emissions from DGVMs (N = 3) are much higher than for EO-based estimates. Regionally, uncertainties reach up to 140% in the Amazon forest and deforestation regions.

The KNMI.S5p approach constrains model uncertainties in regional total fire emissions by providing an integrated atmospheric view of total CO and NO concentrations without relying on burnt area or FRP data. For example, the KNMI.S5p top-down CO emissions estimate (32.7-54.5

Tg) reduces uncertainty by 46% compared to DGVMs. However, because of the rather coarse spatial resolution of Sentinel-5p relative to the size of fires, the KNMI.S5p approach does not capture local differences in fire emissions or constrain local estimates effectively.

7 Scientific roadmap (WP6)

The Scientific Roadmap provides recommendations for further scientific support activities within the context of the ESA Earth Observation (EO) programme and in the context of ESA's Carbon Cluster. Specifically, we worked together with the group from ESA's RECCAP-2 and NRT-Extreme project, which resulted in their contribution to Forkel et al. (2025). The roadmap is based on the experience obtained in the Sense4Fire project complemented with wider scientific knowledge including conferences and workshop participation of Sense4Fire members. Discussions products at those workshops enabled identifying early adopters of the Sense4Fire products, which are for example research from ECMWF and fire-carbon cycle science that are using the datasets for the development and benchmarking of fire models (e.g. SPARKY model at ECMWF), to assess fire impacts on the carbon cycle or to investigate impacts of the fire season 2024 in the Amazon on oceans. All early adopters highlighted the innovative new approaches and the possibility for near-real time updates as advantages of the Sense4Fire products and were asking about if those products will be maintained and further developed.

The scientific roadmap in particular defines a scientific agenda addressing the main scientific and observational gaps in this specific domain of science. The roadmap focuses on potential improvement of fire emission estimates, reconciliation of model approaches, the generation of EO products needed, and the instruments/missions required. It identifies the potential for exploitation and evolution of the fire characterisation database. It provides considerations for new data products to include in the future (with an associated justification) and the potential for linkage to tools already developed by ESA (and wider where relevant) and interfaces required. It also includes a discussion of existing and future satellite instruments/missions that could add value to suite of methods and products used and developed in the Sense4Fire project. The roadmap also provides recommendations to ESA to advance in the use of EO technology to address the main knowledge gaps and scientific challenges associated to fires and their impacts on society.

8 Promotion and coordination (WP7)

8.1 Publications

A project logo, PowerPoint template and project website were developed within the first project months. The project website and the project website on ESA's EO4Society Portal (https://eo4society.esa.int/projects/sense4fire/) were kept up-to-date with the latest news and scientific papers being released and linked into that website.

As a part of promotion and outreach, an ESA WebStory and a Youtube video were created to promote and highlight the results on woody debris fuels air pollution over the Amazon, published in Nature Geoscience on 25/01/2025:

- https://www.esa.int/Applications/Observing_the_Earth/FutureEO/Smouldering_woody_debris_fuels_air_pollution_over_the_Amazon.

- https://www.youtube.com/watch?v=1q_iPFTuh1o&embeds_referring_euri=https%3A%2F%2Fwww.esa.int%2F&source_ve_path=OTY3MTQ

The following publications were published based on (partial) funding from Sense4Fire:

Andela, N., Morton, D. C., Schroeder, W., Chen, Y., Brando, P. M., and Randerson, J. T.: Tracking and classifying Amazon fire events in near real time, Science Advances, 8, eabd2713, https://doi.org/doi:10.1126/sciadv.abd2713, 2022.

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.

The following two manuscripts are available as pre-prints or have been submitted:

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.

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.

8.2 Presentations at scientific conferences and coordination with the community

Developments and results from Sense4Fire were presented and discussed at various scientific conferences and workshops (Table 5). During those events, the developments where discussed and coordinated with several communities such as from atmosphere monitoring, remote sensing of fires, fire emission estimation, and global vegetation-fire modelling. Those coordinating discussions shaped the developments of the project as well as the content of the scientific roadmap.

Table 5: Overview about scientific conferences and events where Sense4Fire results have been presented.

Date and event	Presenter	Title and link
23-27 May 2022 | ESA Living Planet Symposium 2022, Bonn, Germany	Jos de Laat	On the use of daily Sentinel-5p trace gas and aerosol observations for characterising small-scale localised wildfires (Presentation)
	Vincent Huijnen	Using Sentinel-5p trace gas and aerosol observations of fire plumes to constrain a global composition model: a critical assessment (Poster)
	Matthias Forkel	Integrating the Sentinels for novel fuel, fire and emissions products to constrain the changing role of vegetation fires in the global carbon cycle (Presentation) (Poster)
	Christine Wessollek	Estimating vegetation fuel loads for the quantification of fire emissions by integrating various Earth observation data (Poster)
	Niels Andela	Understanding Earth Systems - Tracking Amazon fires in near-real time (Presentation)
23-28 April 2023 | EGU General Assembly 2023, Vienna, Austria	Matthias Forkel	Effects of land use, fuel loads and fuel moisture on fire intensity and fire emissions in South America derived by reconciling bottom-up and top-down satellite observations (Abstract) (Presentation)
	Christine Wessollek	Estimating biomass compartments and surface fuel loads by integrating various satellite products with a data-model fusion approach (Abstract) (Presentation)
14-19 April 2024 | EGU General Assembly 2024, Vienna, Austria	Matthias Forkel	Multiple approaches for quantifying fuels, combustion dynamics, and regional fire emissions in the Amazon and Cerrado (Abstract) (Presentation)
	Niels Andela	New insights on global fire extremes from object-based fire inventories (Abstract) (Presentation)
	Dave van Wees	Comparison and validation of state-of-the-art fire emissions models for the Amazon (Abstract) (Presentation)
16-18 Sep 2024 | Fire Modelling Workshop; Leverhulme Centre for Wildfire, Science and Society; Dartington Hall, UK	Matthias Forkel	Vegetation-fire interactions: Role of dead wood
19-20 Sep 2024 | 13th EARSeL Forest Fires Special Interest Group Workshop, Milano, Italy	Matthias Forkel	Complementary Earth Observation Approaches to Advance Fire Emission Estimation (Book of abstracts)
26-28 Nov 2024 | Future Focus Wildfires. Community forum; EUMETSAT; Darmstadt, Germany	Matthias Forkel	Sense4Fire – novel fuel, fire and emission products (Presentation)
23-27 Jun 2025 | ESA Living Planet Symposium 2025, Bonn, Germany	Matthias Forkel	Novel Earth observation data-model fusion approaches reveal dominant role of woody debris in fire emissions in the Amazon and Cerrado

8.3 Promotion of early-career scientists

Finally, the Sense4Fire project also promoted early-career researchers at TU Dresden. Four Master students at TU Dresden made their final thesis in topics that were closely related to the project and were supervised by project members:

- Felix Schneider (MSc Geodesy): Identifying hotspots of changes in vegetation biomass - focusing on the Amazon region, defended 5 September 2024, supervised by Christine Wessollek
- Daniel Kinalczyk (MSc Geodesy): Wildfire Plume Detection and Investigation with Sentinel-5p, defended 13 December 2023, supervised by Matthias Forkel and Jos de Laat
- David Schleehahn (MSc Geodesy): Classification of fire types in savannahs of southern Africa using Sentinel data, defended 20 January 2023, supervised by Christine Wessollek
- Johanna Kranz (MSc Geoinformation technologies): Model-based estimation of Live Fuel Moisture Content with Sentinel-1 radar data, defended 4 April 2022, supervised by Matthias Forkel

Daniel Kinalczyk and Johanna Kranz joined the Environmental Remote Sensing group as PhD candidates and Daniel Kinalczyk will further develop and use the TUD-S4F approach as part of his PhD thesis.

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