D 2.2 Datasets on fire emissions estimates

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Executive summary

This deliverable presents a spatially explicit workflow to estimate CO_2 emissions from wildfires in Italy within the FIRE-BOX project for 2007–2022. The method combines the harmonized FIRE-BOX fire-perimeter database with regional fuel maps, national fuel-load data, biomass allocation rules, moisture proxies from fire-weather indices, and a crown-burn proxy derived from NDVI and canopy-cover data. These inputs are assembled into a FOFEM batch table and used to simulate fuel consumption and CO_2 emissions, which are then converted to metric units and aggregated by year, region, vegetation type, and bioclimatic zone.

The final simulation-ready dataset contained 322,614 burned-pixel rows, 170,957 unique cells, and 66,905 reburned cells. Area-weighted fuel summaries showed that herbaceous biomass, duff, and canopy fuels were major components of the modeled fuel complex. Moisture conditions were driest in summer, while the NDVI-based crown-burn module remained limited by extensive missing NDVI support. Even so, the selected canopy-cover model provided a workable non-linear proxy for crown involvement, and crown consumption showed a highly skewed distribution, with many pixels showing no canopy involvement but a substantial fraction showing moderate to high crown loss.

The final modeled total was 54.47 Mt CO_2 over 2007–2022, corresponding to 3.40 Mt CO_2 yr^{-1} on average. Emissions were highly variable among years, with maxima in 2007, 2017, and 2021, and were concentrated geographically in southern and insular Italy, especially Sicily, Calabria, and Sardinia. A key result is that explicit crown consumption contributed 10.18 Mt CO_2, or 18.7% of the total, showing that excluding canopy fuels can substantially underestimate emissions in severe fire years. Compared with previous national estimates, the FIRE-BOX series is generally higher, mainly because it uses a more complete perimeter basis and explicitly includes canopy consumption.

Overall, the workflow represents a substantial advance in national fire-emission assessment by making fuels, canopy involvement, and spatial variability explicit in a reproducible modeling chain. The main limitations remain incomplete NDVI support, use of a static biomass layer, empirical moisture conversions, and the lack of dynamic fuel updating after reburns. Despite these constraints, the present framework already provides a robust basis for improving the consistency, ecological realism, and policy relevance of fire-emission accounting in Italy.

Keywords

Wildfire; CO_2 emissions; FOFEM; Italy; fire severity; fuel moisture; FIRE-BOX.

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1. Introduction

Vegetation fires are a relevant source of greenhouse gases, particulate matter, and climate-active aerosols. Their role is especially important in the Mediterranean region, where strong interannual variability, recurrent drought, heat extremes, and the concentration of fire activity in summer produce marked year-to-year swings in burned area and emissions. Recent regional syntheses show that, despite their importance for carbon dioxide, methane, nitrous oxide, black carbon, climate forcing, air quality, and human health, Mediterranean fire emissions are still less consistently characterized than many other anthropogenic sources (Hundal et al., 2024).

State-of-the-art fire-emission workflows generally combine four core components: burned area, biomass available to burn, combustion completeness or fuel consumption, and emission factors. The final estimate depends on several variables that change simultaneously in space and time: fire perimeters, fuel type, fuel load, fuel moisture, combustion completeness, and emission factors. Uncertainty in any one of these terms can propagate directly to the final emissions inventory. Among them, fuel consumption is the core process linking fire behaviour, biomass loss, carbon transfer, and atmospheric emissions. This is why apparently small errors in burned fraction, fuel characterization, or burning efficiency can produce large discrepancies among products and inventories (Ottmar, 2014; Balde et al., 2023).

Within this common architecture, current approaches differ substantially in the way each term is estimated. Some workflows rely mainly on global satellite products, where burned area and productivity are derived from remote sensing and emissions are estimated at coarse spatial and temporal resolution. Others use national or regional bottom-up approaches, in which georeferenced fire perimeters, vegetation maps, fuel-type classifications, field-based fuel loads, weather-derived moisture indices, and fuel-consumption models are integrated explicitly. A key conceptual distinction is that emissions depend on **fuel actually consumed**, not simply on burned area or spectral change. This is why fire intensity, fire severity, and burn severity cannot be treated as interchangeable proxies – they are related, but they are not equivalent. Fire intensity refers to energy release, whereas fire or burn severity refers to the loss or transformation of organic matter aboveground and belowground. This distinction matters because emissions are generated by combustion and fuel consumption, while remote-sensing products often capture spectral change, canopy loss, or post-fire effects rather than direct oxidation of biomass. For this reason, translating remotely sensed indicators into fire emissions always requires explicit assumptions, calibration choices, and a clear statement of what is actually being represented (Keeley, 2009; De Santis and Chuvieco, 2007).

Recent advances in fire-emission assessment can be grouped into three main development lines. The first concerns the architecture of emission inventories themselves, that is, how burned area, fuel load, combustion completeness, and emission factors are combined. The main frontiers in current workflows lies in improving the spatial accuracy of burned-area data, representing fuel heterogeneity more realistically, accounting for combustion phases, and incorporating canopy consumption where crown fire or severe canopy damage occurs

(Hundal et al., 2024; Ottmar, 2014). The second line concerns fuel-consumption modelling, with the need to separate fuel classes, moisture conditions, combustion phases, and crown involvement, thus allowing emissions to be estimated from explicit assumptions rather than from aggregated emission coefficients alone. The third line concerns the use of remotely sensed severity proxies to inform biomass consumption. Here the literature shows both promise and caution. Severity metrics can improve the estimation of burning efficiency, including live canopy components, but their relation to consumed biomass is vegetation-dependent and not automatically transferable across regions or fuel types (Balde et al., 2023; De Santis and Chuvieco, 2007; Guérette et al., 2025).

The Italian National Inventory Report on Greenhouse Gases (NIR) includes emissions from forest, cropland, and grassland fires within IPCC land-use categories. In that framework, grassland also includes grazing land, natural grassland, and other wooded land that does not meet the forest definition, including shrublands. In the NIR method (Annex 12), fire damage and related biomass loss depend mainly on forest vegetation type and fire intensity, with scorch height measured in the field are used as a proxy for intensity. All variables are estimated as national-scale aggregates. This makes the NIR a necessary benchmark for national comparison, but also highlights a difference in modelling philosophy relative to more spatially explicit bottom-up approaches. FIRE-BOX in fact aims to reconstruct event-level and pixel-level variability in fuels, moisture, and consumption, with greater spatial detail and a more explicit treatment of within-country heterogeneity. In Italy, the most important recent benchmark in bottom-up fire emission accounts is the integrated modelling framework developed by Scarpa et al. (2024) for the period 2007 to 2017. That workflow combined daily georeferenced fire perimeters, fuel-type assignment, fuel moisture scenarios derived from FFMC, and FOFEM-based fuel-consumption modelling. It represented a major step forward because it assembled a coherent national estimate from spatially explicit fire activity, vegetation, and weather information, and showed good agreement with national and global inventories. At the same time, it also documented the main operational limits of previous national applications, especially concerning canopy fuels. Scarpa et al. (2024) did not use a spatial severity analysis but parameterized consumption based on the FWI associated with each event, which derived the fuel moisture content to be used as input in FOFEM. This value was constant for each individual fire. They also used the Corine Land Cover as an information layer to spatialize fuelbeds. Finally, they explicitly excluded canopy fuel consumption because the available nationwide inputs did not allow a reliable estimate of crown-fire occurrence or canopy biomass consumption. In their framework, this limitation was non-trivial, because crown fire in Italy is concentrated in Mediterranean and montane pine systems and, although not dominant in total burned area, can be relevant for total emissions where stand-replacing fire occurs (Scarpa et al., 2024).

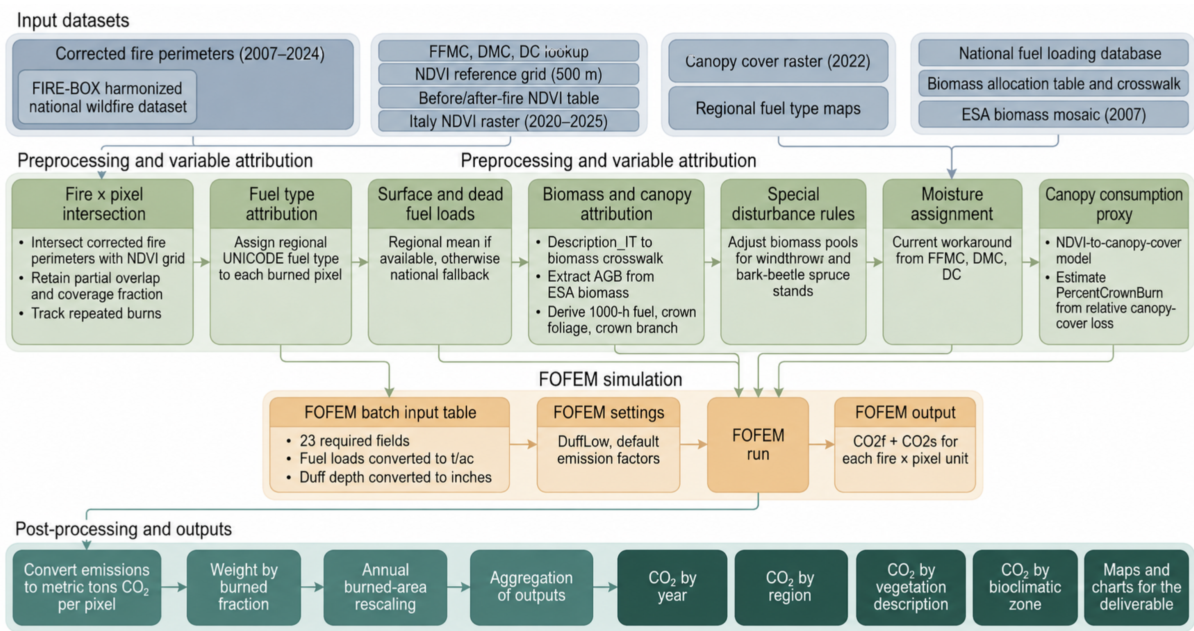
This is the main point where the present FIRE-BOX workflow advances beyond the previous state of the art. The current script intersects corrected fire perimeters (see Deliverable 2.) with a 500 m NDVI grid, preserves repeated burns, intersect the fuel types map (see Deliverable 1.2 and 1.3) and assigns surface and dead fuel loads from national fuel databases (see Deliverable 2.1), derives coarse woody debris and canopy biomass from national and European datasets, and estimates crown involvement through a canopy-cover proxy calibrated against external raster information. In operational terms, this means that canopy consumption is no longer treated as a negligible or external component, but as an explicit term in the modelling chain through PercentCrownBurn. This is methodologically consistent with the FOFEM framework, which does not infer crown fire automatically from spectral indices but requires an estimate of percent crown burn and then applies it to canopy foliage and part of canopy branch biomass (Lutes, 2020). The rationale is straightforward. If national estimates aim to represent the full fuel complex more realistically, canopy consumption cannot remain outside the accounting framework wherever crown-affected fire is substantial (Scarpa et al., 2024; Lutes, 2020).

Against this background, one of the main opportunities for methodological improvement comes from the FIRE-BOX harmonized fire-perimeter dataset described by Moris et al., (2024). That dataset was built specifically to address the long-standing lack of a complete and coherent multiannual national fire database for Italy. It merges wildfire records from national and regional agencies, standardizes attributes and geometry, applies both automatic and manual quality control, updates the earlier 2007 to 2017 dataset, and extends coverage to 2022. Importantly, it includes regions and autonomous provinces that were unavailable in the earlier national application, i.e., Valle d'Aosta and the provinces of Trento and Bolzano. The resulting harmonized product contains 106,978 fire records and a total burned area of 1,356,851 ha, and was explicitly developed as a basis for geospatial analyses of fire severity, fire weather, fire emissions, ecosystem impacts, and other applications. This is not a marginal improvement. A more consistent perimeter layer directly improves the burned-area term in the emissions equation and reduces the need to rely on heterogeneous regional inputs with variable geometry, attributes, and quality standards (Moris et al., 2024).

The FIRE-BOX workflow also opens other opportunities for improvement over existing approaches. First, it enables a more explicit integration between harmonized fire perimeters, regional fuel maps, and fuel-loading databases. Second, it creates the conditions for a nationwide treatment of repeated burns at pixel level, something that is still only partly implemented in the current version of the script but is essential for representing post-fire structural change and altered fuel availability. Third, it allows canopy biomass and crown involvement to be represented explicitly through a dedicated proxy rather than being omitted altogether. Fourth, it is structured in a modular way, separating preprocessing, FOFEM input-table construction, and post-processing of emissions outputs, which improves reproducibility and debugging. The purpose of this deliverable is therefore not only to provide updated fire emission estimates, but also to test how much these methodological improvements can strengthen the consistency, spatial detail, and interpretability of national fire-emission accounting.

2. Methods

Figure 1 summarizes the workflow implemented in the current FIRE-BOX scripts. The process is organized into four main blocks: construction of the event-by-pixel database, attribution of fuels and moisture, preparation and execution of the FOFEM batch simulation, and post-processing of model outputs into annual and spatially aggregated CO_2 estimates.



Workflow used to estimate CO_2 emissions from Italian fires in the FIRE-BOX project

The starting point is the FIRE-BOX national fire-perimeter database (Moris et al., 2024), which is intersected with a fixed reference grid to generate the basic computational unit of the analysis, namely a 500x500 m fire-event grid-cell. Each unit is then attributed a fuel type, a set of fuel loads, moisture values, and a canopy-consumption estimate. These variables are assembled into a batch input table for FOFEM 6.7. The model output is then converted into metric tons of CO_2 emitted per fire-event pixel and finally aggregated by year, region, vegetation description, and bioclimatic zone. Despite fire perimeters being available for the period 2007 to 2024, the analysis was run on the subset for 2007 to 2022, i.e., the period of availability of remotely-sensed fire severity estimates (used to assess crown consumption) and of Fire Weather Index (FWI) and sub-indices for each fire perimeter, allowing estimation of percent fuel moisture.

2.1 Fire activity data and construction of the fire-by-pixel table

The primary event layer is the corrected **national fire-perimeter** dataset developed by FIREBOX WP1. The shapefile dataset stores the administrative region, fire year and fire date, as well weather-derived fire-danger codes, specifically FWI, FFMC, DMC, and DC, currently used for fuel moisture assignment. The first major preprocessing phase is the **spatial discretization** of each fire perimeter onto a 500 m reference grid. The grid is based on fire severity assessments by remote sensing produced by FIREBOX partner University of Bari (see Deliverable 2.1). One the two layers have been aligned over the same coordinate reference system (CRS), fire perimeters are intersected with the grid returning, for each fire-polygon intersection, a cell identifier, the cell centroid coordinates, and the `coverage_fraction`, that is, the fraction of each 500 × 500 m cell actually covered by each fire polygon. As a consequence, edge cells are kept in the analysis, but their contribution can later be weighted by the fraction of area actually burned.

At this stage, the script also records **repeated burns**. Rows are ordered by cell and fire date, and each cell receives a sequence number over time. Any cell affected by a second or later fire is flagged. In the current implementation, reburned cells are tracked but their fuels are not yet dynamically updated after the first fire. This is a recognized limitation and an explicitly planned future improvement. At present, repeated burns are preserved in the event table, but they still inherit fuels from the static attribution rules described below.

Season of fire is assigned directly from the fire date using a month-based classification into spring (March to May), summer (June to August), fall (September to November), and winter (December to February). When fire dates were missing, the script assigns a **default season of summer**.

2.2 Fuel-type attribution and fuel loads

Fuel type is assigned to each burned pixel from a set of regional **fuel-type raster maps** developed by FIREBOX partner University of Turin, starting from the 2020 national forest map ad Corine Land Cover map (see Deliverable 1.2 and 1.3). For each row of the fire-by-pixel table, the script reads the raster corresponding to the administrative region and extracts the value at the cell centroid. The extracted value is converted to a numeric `id`, which becomes the key used for linking fuel loads and biomass attributes. Trentino-Alto Adige is treated as a special case because separate rasters are used for Trento and Bolzano, and the script retains the non-missing value across the two extractions. This avoids losing observations from that region due to file partitioning.

Fuel-type attribution therefore rests on two assumptions. The first is that **centroid sampling is an acceptable representation of fuel type for each 500 m fire pixel unit**. In an improved version of the emission algorithm, this could be replaced by calculating the mean fuel loading for every fire pixel, weighted on the portion of the pixel occupied by each fuel type. The second is that regional fuel maps are thematically consistent enough to be linked through a common id system. Errors in fuel-code assignment propagate directly into fuel loads, biomass allocation, and ultimately emissions; further improvement might include e.g. using a majority filter to assign the prevailing fuel type for each cell.

Surface and dead fuel loads were derived by averaging values for each fuel type id included in the national fuel database developed by FIREBOX (see Deliverable 2.1). The script calculates loads for the following fuel components: duff (`Wduff`), fine surface dead fuel (`W1h`), 10-hour fuel (`W10h`), 100-hour fuel (`W100h`), herbaceous biomass (`WGr`), shrub biomass (`WShTot`), and dead-fuel depth (`Ddead`), which is entirely assigned to duff depth and converted from centimeters to inches by dividing by 2.54. One-hour fuel is then split into litter and one-hour woody fuel using a fixed 60:40 partition.

Regional mean fuel loads are used whenever available; if a regional value is missing, the script falls back to the national mean for the same fuel code. Three agricultural burnable classes, 1701, 1702, and 1703, were present in the fuel maps but absent from the original national fuel database. The script therefore creates them in memory by copying mean values from source id classes 101, 201, and 301, respectively. In addition, all fuel codes with no duff are forced to `DuffDepth = 0` to comply with FOFEM constraints.

Beyond surface and fine dead fuels, the workflow has to assign 1000-hour dead woody fuel and canopy biomass divided into branch and foliage components. Coarse woody debris (CWD) was obtained as the mean of raw plot-level CWD biomass values per hectare reported by the Italian National Forest Inventory **2015** (INFC) for all plots belonging to the same forest category. Foliage and branch biomass were estimated through category-specific biomass-allocation percent coefficients. To derive these coefficients, allometric equations for total aboveground biomass (AGB) and for canopy components were applied, separately for each forest category, to a synthetic population of virtual trees covering diameters from **1 to 100 cm** and heights from **2 to 50 m**. For each diameter-height combination, the ratios foliage/AGB and branch/AGB were computed, and the mean ratio across all simulated trees was then calculated for each component. CWD and AGB partitioning coefficients values were then attributed to each fuel type after building a AI-assisted crosswalk table of 17 INFC forest categories to 123 national fuel types. When more than one association was possible, the most probable category was retained based on frequency and crosswalk flags. For unmapped or non-forest descriptions, 1000-hour fuel, crown foliage, and crown branch biomass were set to zero.

To calculate actual branch (diameter <5 cm) and foliage biomass, we extracted AGB at the location of each burned pixel from the ESA Copernicus biomass mosaic for 2007, i.e., at the start of the study period. This meant that subsequent biomass changed are currently unaccounted for in the estimates, both for increasing (i.e., forest growth) and decreasing biomass (i.e., natural disturbances or harvest). For fires occurring long after 2007, this choice can bias both total canopy biomass and coarse woody debris attribution. Subsequent improvements might integrate with the script biomass maps with yearly resolution, if available, over the entire analysis period. Foliage and branch fractions were then applied to total aboveground biomass to obtain pixel-level `CrownFoliage` and `CrownBranch` loadings. All loadings were then converted from t/ha to t/acre as per FOFEM requirements (x 0.4047).

Finally, the workflow contains special redistribution rules for two disturbance classes affecting **spruce-dominated stands affected by storm and bark beetle damage**, under the expectation that disturbances would redistribute part of the canopy biomass into dead woody pools before fire.. For storm damage, crown foliage and crown branches were set to zero, and all canopy biomass was transferred additively to 10-hour, 100-hour, and 1000-hour fuels in the proportions 10%, 20%, and 70%, respectively. For bark beetle damage, crown foliage was set to zero and canopy biomass was redistributed additively across 10-hour, 100-hour, 1000-hour, and crown branch pools in the proportions 5%, 10%, 70%, and 15%. These expert-based adjustments were intended to improve realism where current fuel structure is known to depart substantially from undisturbed stand conditions. In an improved version of the algorithm, fuel loadings for damaged spruce forests will be inputed directly from field-surveyed data already present in the FIREBOX national fuel database (33 plots, see Deliverable 1.1).

2.3 Crown-burn and fuel moisture proxies

A central innovation of the present workflow relative to earlier Italian applications is the explicit approximation of canopy consumption during crown fire. This step uses a two-stage approach. First, a canopy-cover model was calibrated using an Italy-wide NDVI raster, filtered for months of May to September and averaged over 2020 to 2025 to smooth out phenological differences, and a country-wide Copernicus canopy-cover raster for 2022. Training points were sampled from non-burned areas, and several candidate models were compared, including a linear model, a quadratic model, a spline-based generalized additive model, and, when available, a random-forest model. Model selection was based on cross-validated predictive accuracy. Second, the selected model was applied to the before-fire and after-fire NDVI values stored in the fire severity assessment provided by University of Bari. This yielded predicted canopy cover before and after each fire. The difference between these two predictions was then interpreted as the fraction of canopy cover lost because of the fire. To make this quantity compatible with FOFEM, the loss was expressed relative to the estimated pre-fire canopy cover, so that the final metric represented the **fraction of the original canopy cover lost because of fire**. This relative canopy-cover loss was used as a proxy for `PercentCrownBurn`. If NDVI was missing for some pixels (as was often the case for small fires) the script imputed the missing crown-burn value using the mean observed among other rows of the same fire. If all NDVI values were missing within a fire, `PercentCrownBurn` was set to zero. Hence, crown burn was approximated from relative canopy-cover loss, not measured directly as consumed crown biomass. Such proxy remains indirect and depends on the transferability of the NDVI-to-canopy relation across vegetation types and fire conditions. In the current version of the algorithm, canopy emissions are computed for all forest types, including broadleaved forests that do not sustain crown fire (i.e., all broadleaves excelt eucalypts, holm oak, and cork oak). However, even if leaf mortality and fall is an indirect and delayed consequence of burning (e.g. due to crown scorch or overheating), damaged and shed leaves are considered to decay and eventually emit their carbon content in the atmosphere, so this should not determine any large overestimation of emissions.

The intended long-term design of the workflow is to derive fuel-moisture classes from historical CEMS fire-danger reanalysis, but this part has not yet been fully implemented in the current consolidated script. Instead, the active version uses FFMC, DMC, and DC values stored in the fire perimeter database as follows. Ten-hour fuel moisture was assigned by reclassifying FFMC classes: FFMC ≤ 70 corresponded to a moisture of 13%, 71 to 80 to 10%, 81 to 88 to 7%, and values above 88 to 4%. Thousand-hour moisture was assigned from DC classes: DC ≤ 100 gives 15%, 101 to 200 gives 12%, 201 to 300 gives 9%, and values above 300 give 6%. Duff moisture was calculated using an exponential function of DMC, 20 + exp(5.6348 - DMC / 43.43), and then constrained to FOFEM limits (i.e., a maximum of 197.2%). The present moisture assignment is therefore more refined than using a single national default, but less rigorous than the fully planned workflow. Because fuel moisture strongly affects combustion completeness, this simplification is one of the main sources of uncertainty.

2.4 FOFEM batch-table construction and settings

Once fuel type, fuel loads, biomass, canopy variables, and moisture values are assembled, we built a FOFEM input table with the 23 required fields. Each row corresponds to one fire × pixel unit. The table includes litter, one-hour, ten-hour, hundred-hour, thousand-hour, duff, herbaceous, shrub, crown foliage, crown branch, moisture values, percent crown burn, season, and fuel category. `RegionFOFEM` was currently set to `NorthEast` for all rows as the default US region used for compatibility, and `FuelCategory` was set to `Natural`. `CoverGroup` was left blank. `ThousandHourDist` was fixed to `Even`, and `ThousandHourPctRotten` was fixed to zero because no decay-state information was available for large coarse woody debris. Missing moisture values (i.e., fire weather subindices not availble in the fire database) were replaced with the mean of the corresponding column.

The current script specifies `DuffLow` as the duff heat-production source and uses the `Default` emission-factor option in FOFEM: 1778.01 g kg^{-1} for the flaming phase and 1228.11 g kg^{-1} for the smoldering phase, applied to all fuel components. Further improvements might ecplore using the expanded-emission-factor framework available in FOFEM, where fuel-component-specific factors are used for duff and coarse woody debris. In the present workflow, the default factors prioritize consistency and operational simplicity over a more differentiated factor structure.

2.5 Output analysis

For each row in the FOFEM output table, the output variables `co2f` and `co2s` were summed to obtain total CO_2 release. Because FOFEM reports emissions in lb ac^{-1}, we converted them to metric units using a coefficient of 0.00112085 to obtain tons per hectare, then multiplies by 25 ha, the area of a 500 × 500 m pixel, and by `coverage_fraction`, the burned fraction of that pixel.

A further post-processing correction was necessary at annual scale. Since the aggregated burned area from the FOFEM output analysis was not always equal to the cumulative burned area calculated from the FIREBOX fire database, we computed a yearly ratio between official annual burned area and FOFEM-derived annual burned area, and used it to rescale total CO_2 release in each row year by year. This is an explicit correction for mismatch between the discretized pixel representation and the polygon-based annual area total. The need for this correction likely arises from partial overlaps, spatial discretization effects, and other small inconsistencies between polygon area and rasterized representation. Since the correction is applied multiplicatively to all rows within a year, it preserves spatial allocation patterns within that year while matching the annual total burned area.

After row-level conversion and annual rescaling, CO_2 emissions were computed for the full study period, and aggregated into annual totals, totals by region, totals by fuel type code, totals by vegetation type, and totals by bioclimatic zone extracted from a dedicated raster. This aggregation phase is not a secondary add-on, but the final interpretive layer of the workflow. It allows CO_2 to be analyzed not only as a national annual total, but also as a function of geography, vegetation type, and ecological context. In this way, the workflow connects event-level simulation with the kinds of summary patterns needed for inventory comparison, fire-risk interpretation, and policy discussion. Aggregated emissions were also recalculated after excluding all crown fires, to check for consistency with the time series provided by Scarpa et al. (2024). Emissions were finally aggregated for each fire perimeter and added to the FIREBOX fire database.

2.6 Main assumptions and current limitations

The current workflow rests on several assumptions that should be made explicit:

- The spatial unit is the fire × NDVI-pixel intersection, not the original fire polygon. This improves spatial explicitness but introduces dependence on a fixed 500 m reference grid. Also, fuel types were assigned using the centroid of each cell, and not yet according to a majority rule.
- Canopy biomass was estimated with a fixed 2007 ESA static biomass layer.
- Crown burn was approximated from modeled canopy-cover loss rather than measured directly. The model was based on canopy cover provided for year 2022 and summer NDVI averaged across years 2020-2025. The model was built by pooling all fuel types, but in the future it might be made fuel type-specific.
- Moisture assignment was based on empirical reclassification of FFMC, DMC, and DC values.
- Repeated burns are tracked but not yet associated with dynamic post-fire fuel updating.
- The crosswalk between INFC forest categories and fuel types might introduce some thematic approximation.
- Thousand hour loadings were averaged nationwide across all INFC forest categories rather than for each category and/or each region separately.

- Small fires assumed no crown consumption due to lack of remotely sensed fire severity.

These limitations do not necessarily invalidate the workflow, but introduce a number of uncertainties. Relative to earlier national applications, the main advances already achieved are the use of a corrected national fire-perimeter framework, explicit treatment of partial pixel overlap, integration of regional fuel maps and national fuel databases, incorporation of canopy biomass and a crown-burn proxy, and a reproducible post-processing chain that converts FOFEM outputs to annual and spatially explicit CO_2 estimates.

3. Results

The final simulation-ready table used to analyze the properties of the FOFEM input dataset contained **322 614 burned pixel rows**, **170 957 unique cells** and **66 905 reburned cells**. The fact that mpre than one third of all burned cells were associated with reburning confirms that repeated fire is not an exceptional case in the national rasterized dataset and that future dynamic updating of fuels in reburned cells will likely be an important improvement for later versions of the workflow.

3.1. Fuel loadings and moistures

Because the fire-perimeter intersection with a 500 m grid produces many partially burned cells, the most meaningful national summaries of fuel loadings are those weighted by `coverage_fraction`, which better represent the actually burned area rather than the mere number of simulation rows. Under this weighting, the largest average fuel pools in the input table were **crown foliage** (**5.74 t/ha**), **herbaceous biomass** (**4.46**), **crown branch biomass** (**2.74**), and **duff** (**2.24**). All other pools had weighted means below 1 t/ha, with **litter = 0.65**, **1-Hour fuel = 0.43**, **10-Hour fuel = 0.62**, **100-Hour fuel = 0.59**, **1000-Hour fuel = 0.62**, and **shrub biomass = 1.89**. These values show that the modeled burned area was not dominated only by surface dead fuels, but by a mixed fuel complex in which herbaceous, duff, and canopy pools all contribute materially. **Crown foliage alone accounted for 28.7%** of the total weighted fuel mass represented by the ten main pools, followed by **herbaceous biomass (22.3%)**, **crown branches (13.7%)**, **duff (11.2%)**, and **shrubs (9.5%)**. Each of the woody surface and dead fuel components contributed between roughly 2% and 3% of the total.

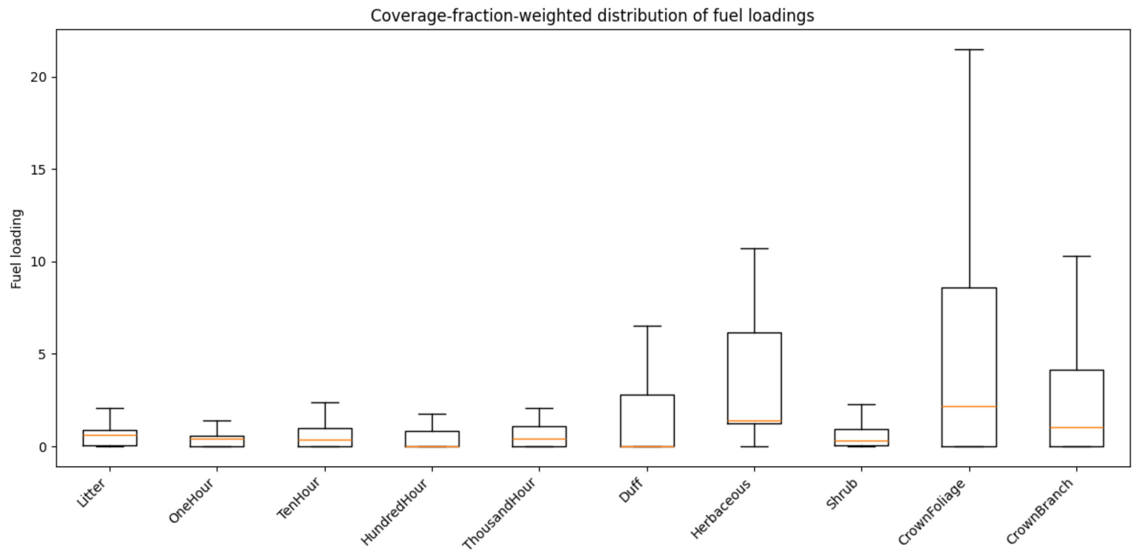


Figure 2. Fuel loadings (t/ha) for each fuel component, weighted on burned area per pixel.

Fuel-moisture conditions are most meaningfully interpreted at **fire level**, because in the current implementation the moisture values are assigned through event-level FFMC, DMC, and DC information and then repeated for all pixel rows belonging to the same fire. At fire level, **10-Hour Moisture** had a mean of **5.46%**, **1000-Hour Moisture** showed a mean of **7.61%**, **Duff Moisture** and had a mean of **82.8**%. These statistics suggest that most fires in the dataset occurred under relatively dry fine-fuel conditions and low coarse-fuel moisture, whereas duff moisture retained much greater variability across the fire archive.

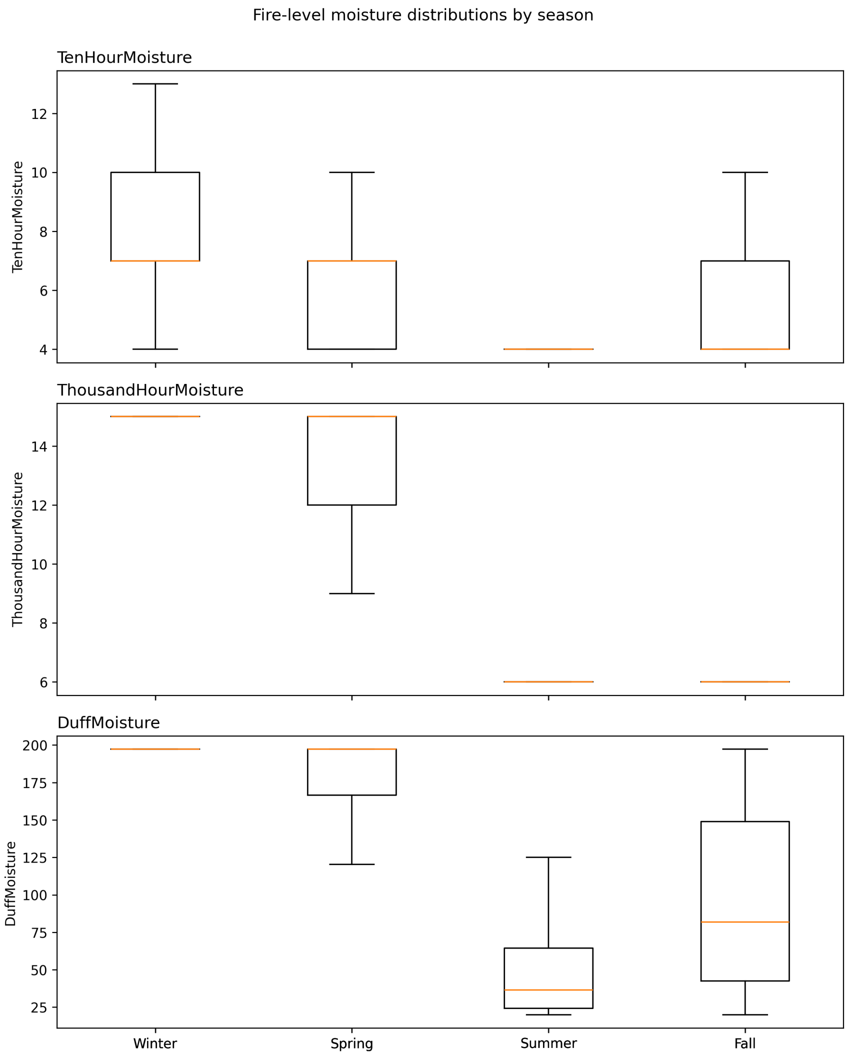


Figure 3. Fire-level fuel moisture distribution by season

Seasonal patterns further clarify this structure. At fire level, **summer** dominated the national fire archive, with **65,230 fires**, followed by **fall (20,257)**, **spring (12,371)**, and **winter (4,867)**. Summer fires had the driest conditions, with average **10-Hour Moisture = 4.8%**, **1000-Hour Moisture = 6.3%**, and **Duff Moisture = 52.6%**. Spring and winter fires were much wetter, with 10-Hour Moisture means of **7.03%** and **8.24%**, 1000-Hour Moisture means of **13.7%** and **14.5%**, and Duff Moisture means of **174.1%** and **196.7%**, respectively. Fall occupied an intermediate position. These seasonal differences are large enough to confirm that the current moisture-assignment scheme captures meaningful fire-weather contrasts across the annual cycle, even if it remains a provisional workaround compared with the fully planned CEMS-based percentile workflow.

3.2. NDVI-based crown consumption

Across the full 2007–2022 period, **94,714 fires** had all cells missing NDVI (92%), and only **6,928 fires** had partial NDVI support, meaning that at least some of their cells retained usable pre-fire and post-fire NDVI information. At the pixel level, the percentage of missing NDVI exceeded **50% in every year** and ranged from about **54.5% in 2007** to more than **72% in 2010** and **2011**. This means that the current canopy-consumption layer is affected by a structural support limitation that is temporally persistent across the national fire archive. In many fires, crown-burn estimates would therefore not directly informed by observed before-fire and short time after-fire NDVI contrasts, but instead rely on imputation or on the default zero assignment used when no NDVI data are available for any cell of the fire. The availability of partial support in some years and some events, and the fact that most fires with missing NDVI were small events, still allows the proxy to capture spatial heterogeneity in canopy loss, but the large prevalence of complete NDVI absence means that the current implementation should be considered an important intermediate step rather than the final solution. An improved version of the algorithm will have to rely on a finer resolution for the NDVI assessment before and after each fire.

The candidate NDVI–canopy cover models differed substantially in predictive performance. The **GAM spline** model performed best, with a cross-validated **RMSE of 15.75%**. This ranking indicates that the relationship between NDVI and canopy cover is clearly non-linear and is better captured by a flexible smooth model than by a straight linear approximation. The superiority of the GAM is also ecologically plausible. Canopy cover does not increase linearly with NDVI across the full range of open, semi-open, and dense vegetation. At low NDVI values, a large proportion of points correspond to sparse or non-forest conditions, while at higher NDVI the relation steepens and then saturates. The observed-versus-predicted plot reflects this structure. Agreement is strongest in the upper part of the canopy-cover distribution, especially for dense canopies around 70–90%, whereas dispersion increases markedly at low and intermediate observed canopy cover. A large vertical concentration of points near very low observed canopy values also indicates that the training data contain many open or weakly wooded pixels, which likely contributes to heteroscedasticity and to the difficulty of distinguishing low canopy cover from sparse woody vegetation using NDVI alone.

Table 1. Performance of candidate NDVI-canopy cover models

Model	RMSE	MAE	R^2
GAM spline	15.75	11.24	0.745
Quadratic linear model	16.61	12.15	0.716
Random forest	18.21	12.70	0.658
Linear model	20.35	16.88	0.573

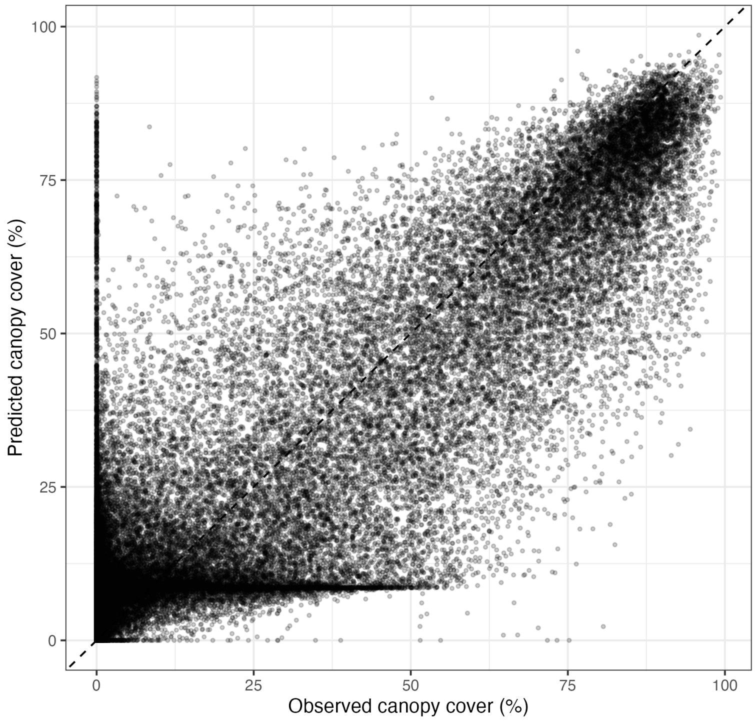


Figure 4. Predicted vs observed percent canopy cover using the GAM spline model.

Modeled crown consumption showed a strongly skewed and clearly bimodal-like national distribution when summarized over burned area. The **coverage-fraction-weighted mean** was **29.4%**, but the **weighted median** was only **3%.** This indicates that a large fraction of the burned area was modeled with little or no crown involvement, while another substantial fraction experienced moderate to high canopy loss. About **48.0%** of the burned area had `PercentCrownBurn = 0`, meaning no modeled crown involvement. By contrast, **40.0%** of the burned area exceeded **25% crown burn**, **29.6%** exceeded **50%**, and **17.8%** exceeded **75%**. These proportions indicate that once explicit canopy attribution is included in the modeling chain, a non-negligible fraction of the national burned area falls into classes where crown involvement could materially influence total biomass consumption and thus emissions. This result is one of the clearest differences between the present workflow and earlier Italian applications that did not explicitly propagate canopy fuels through the national simulation chain.

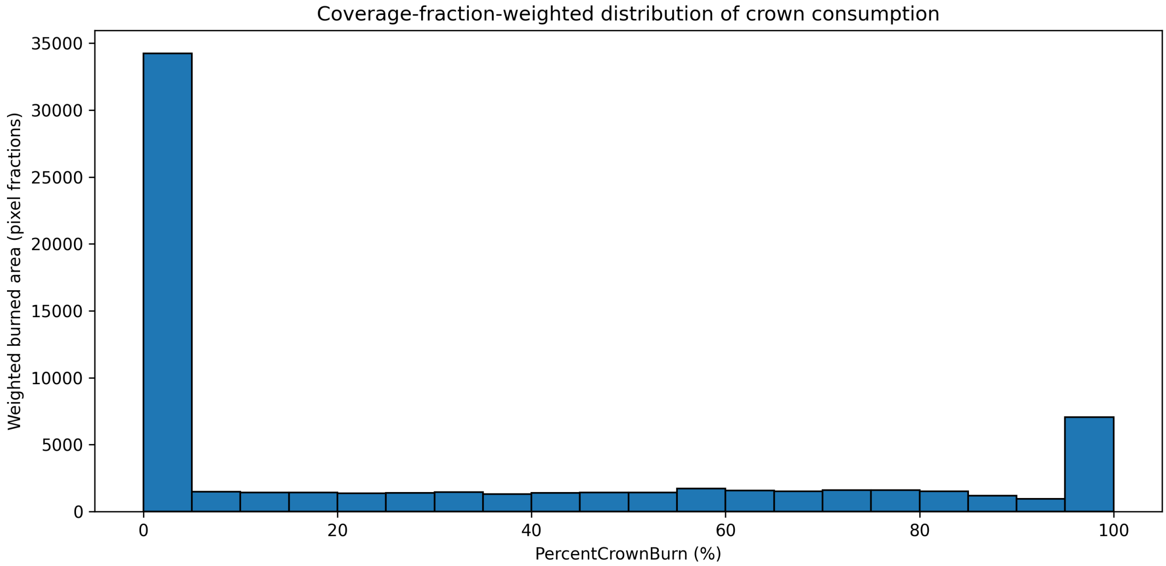


Figure 5. Coverage-fraction-weighted histogram of percent crown consumption

Crown consumption was also highly structured by vegetation description. When summarized as area-weighted means, the highest crown-burn values occurred in **Prateria in via di imboschimento spontaneo**, **Pineta di pino d'Aleppo**, **Pineta di pino marittimo**, and **Latifoglie di invasione miste**. In these classes, the weighted mean crown burn exceeded or approached 40%, and the share of burned area above **50% crown burn** ranged from roughly **0.33** to **0.39**. This was especially true for Mediterranean pine forests, which is consistent with their structural predisposition to canopy involvement and with previous ecological understanding of crown fire in these conifer systems.

At the same time, the classes contributing most to the total burned area did not always coincide with the classes showing the highest average crown involvement. The largest burned-area classes included **Latifoglie di invasione miste**, **Agricoltura**, **Cerreta termofila**, **Querceto sempreverde, Castagneto**, and **Prateria continua**. Among these, only few classes, such as **Latifoglie di invasione miste** and **Querceti sempreverdi** showed quite high average crown consumption.

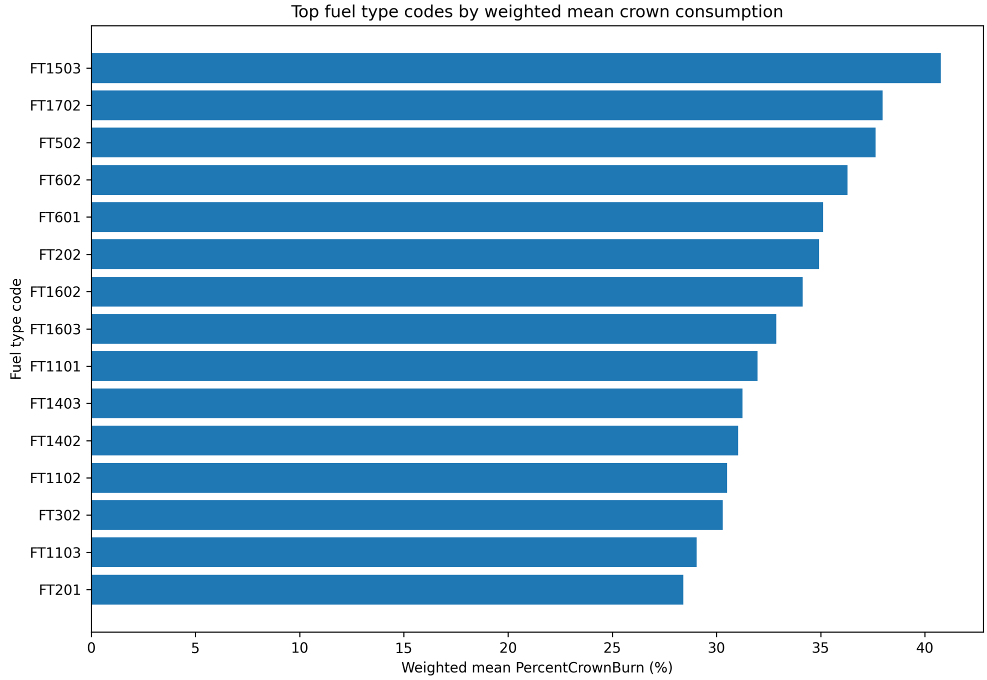


Figure 6. Top fuel type codes by weighted mean crown consumption

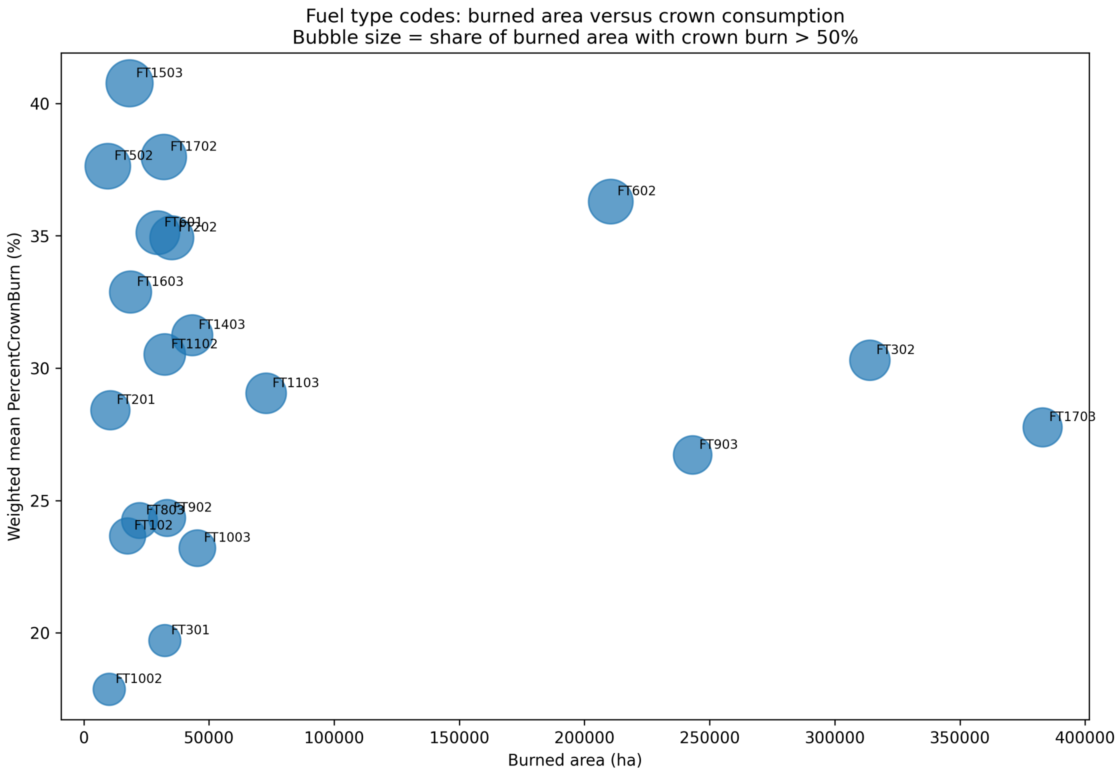


Figure 7. Burned area versus crown consumption by fuel type code

3.3. CO_2 emissions

The final modeled total for the study period was **54.47 Mt CO_2** corresponding to a mean of **3.40 Mt CO_2 yr^{-1}** over 2007–2022. The annual series showed strong interannual variability, with a maximum in **2007** (**10.32 Mt CO_2**), followed by **2017** (**8.82 Mt**), **2021** (**6.73 Mt**), and **2012** (**4.92 Mt**). The lowest values occurred in **2018** (**0.89 Mt**) and **2013** (**1.01 Mt**). Emissions per unit burned area were also highly variable: the highest values in the current output were **45.5 t ha^{-1}** in 2007, **43.6 t ha^{-1}** in 2017, and **40.1 t ha^{-1}** in 2021, whereas the lowest occurred in **2018** (**29.2 t ha^{-1}**) and **2015** (**29.9 t ha^{-1}**). This indicates that interannual variability was driven not only by the extent of burned area, but also by differences in the composition and combustion of the affected fuels.

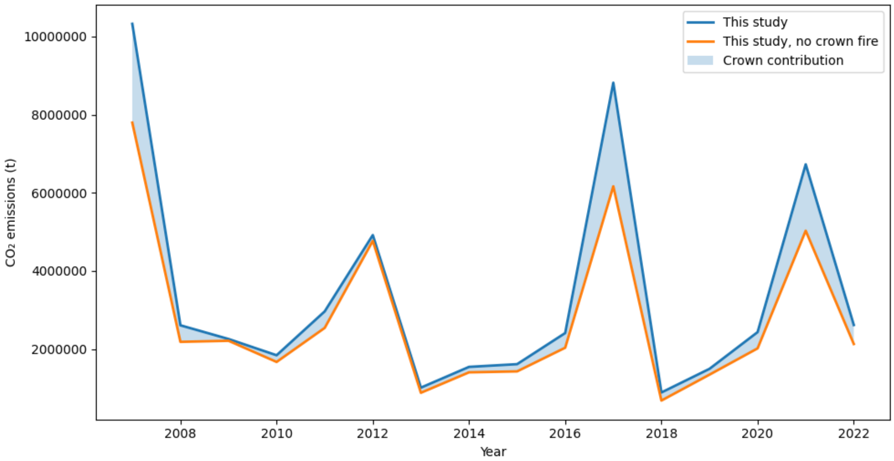


Figure 8. Time series of fire emissions in Italy 2007-2022, with and without crown fire

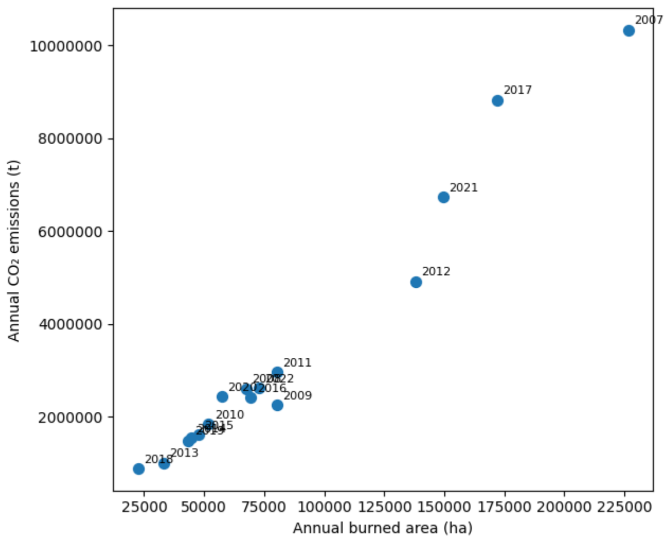


Figure 9. Annual CO_2 emissions versus burned area. According to bthe best fit linear regression, every hectare burned emits about 42 t CO_2 (R^2 =0.95).

The explicit inclusion of crown burn contributed substantially to total emissions. Summing the annual difference between the full run and the no-crown-fire run gave **10.18 Mt CO_2**, equivalent to **18.7%** of the total modeled emissions over 2007–2022. The importance of canopy consumption varied strongly by year. The absolute contribution of crown fire was highest in **2017** (**2.65 Mt CO_2**), **2007** (**2.53 Mt**), and **2021** (**1.70 Mt**). In relative terms, the largest contributions occurred in **2017** (**30.1% of annual total**), **2021** (**25.3%**), **2007** (**24.5%**), and **2018** (**23.3%**). By contrast, canopy consumption had only a minor influence in **2009** (**2.0%**) and **2012** (**3.0%**). These differences indicate that the contribution of crown fuels is episodic rather than constant, becoming especially important in years characterized by high-severity or canopy-affected fire regimes.

Table 2. Annual CO_2 emissions from Italian fires, 2007–2022

Year	This study (t)	CO_2 per burned area unit (t ha^{-1})	No crown fire (t)	Crown contribution (t)	Crown contribution (%)
2007	10,323,420	45.55	7,793,705.8	2,529,714.2	24.5
2008	2,608,420	38.60	2,184,417.0	424,003.0	16.3
2009	2,257,902	28.10	2,212,562.0	45,340.0	2.0
2010	1,841,495	35.58	1,670,492.0	171,003.0	9.3
2011	2,964,036	36.90	2,541,342.0	422,694.0	14.3
2012	4,917,444	37.60	4,769,537.0	147,907.0	3.0
2013	1,012,606	34.83	880,990.0	131,616.0	13.0
2014	1,543,794	42.73	1,404,355.0	139,439.0	9.0
2015	1,613,705	29.86	1,428,811.0	184,894.0	11.5
2016	2,409,896	36.79	2,034,127.0	375,769.0	15.6
2017	8,816,589	43.60	6,164,750.0	2,651,839.0	30.1
2018	888,668	29.21	681,964.0	206,704.0	23.3
2019	1,494,231	41.46	1,345,294.0	148,937.0	10.0
2020	2,433,712	43.72	2,017,785.0	415,927.0	17.1
2021	6,727,053	44.27	5,028,151.0	1,698,902.0	25.3
2022	2,616,184	36.49	2,129,571.0	486,613.0	18.6

At regional scale, emissions were strongly concentrated in the southern and insular regions. **Sicilia** was the largest source, with **17.27 Mt CO_2**, followed by **Calabria** (**11.33 Mt**), **Sardegna** (**6.14 Mt**), **Campania** (**4.68 Mt**), and **Lazio** (**4.32 Mt**). Together, these five regions accounted for **43.73 Mt CO_2**, or about **80.3%** of the national total. At the opposite end of the distribution, the smallest regional totals were found in **Valle d'Aosta**, **Provincia Autonoma di Bolzano**, **Provincia Autonoma di Trento**, **Molise**, and **Friuli Venezia Giulia**. This ranking confirms that the national geography of emissions is dominated by the Mediterranean and Tyrrhenian fire-prone regions, especially the large islands and the southern peninsula.

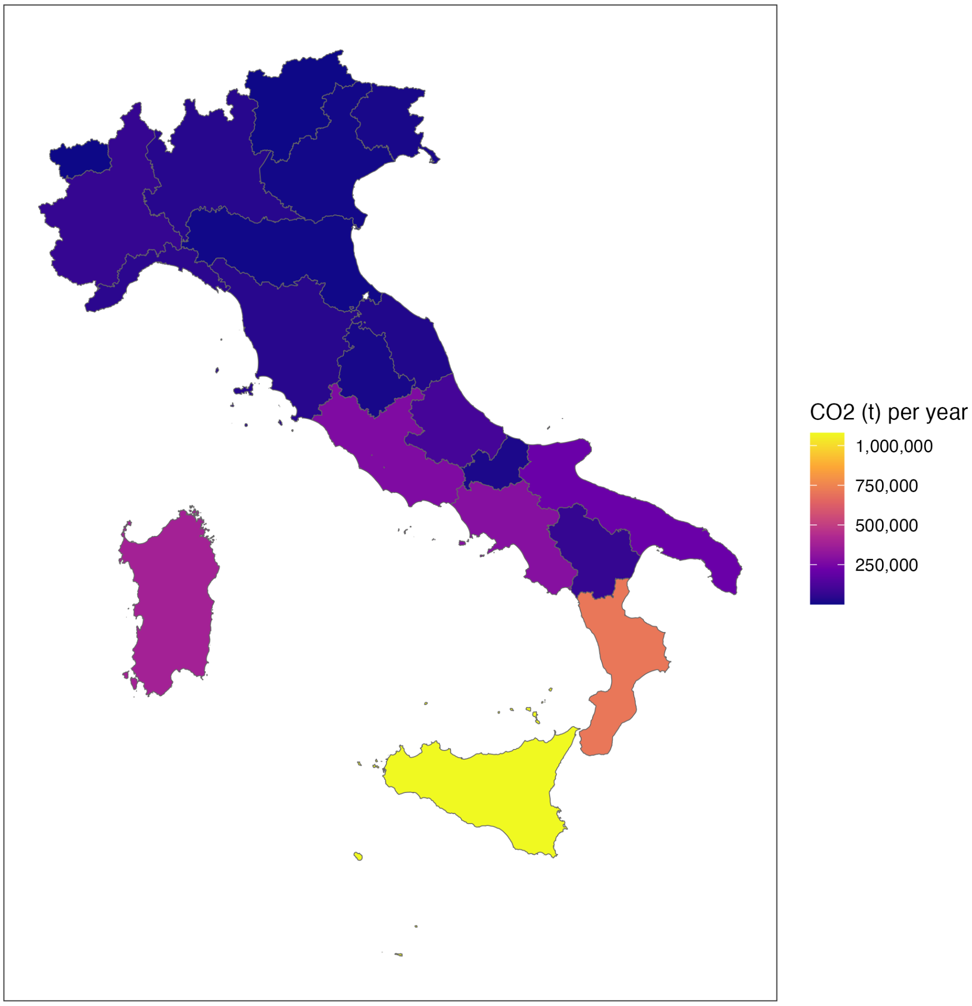


Figure 10. Average annual CO_2 emissions for Italian regions

When aggregated by vegetation description, emissions were dominated by a relatively small number of fuel and cover types. The largest contributor was **Latifoglie di invasione miste**, with **26.15 Mt CO_2**, corresponding on its own to nearly **48%** of the national total. It was followed by **Cerreta termofila** (**9.56 Mt**), **Querceto sempreverde** (**3.90 Mt**), **Pineta di pino silvestre** (**2.89 Mt**), and **Castagneto** (**2.60 Mt**). The first five vegetation descriptions together accounted for **45.12 Mt CO_2**, or about **82.8%** of the total. This very strong concentration suggests that the national emission burden is produced by a limited set of structurally and geographically dominant vegetation systems, rather than being evenly distributed across all mapped classes.

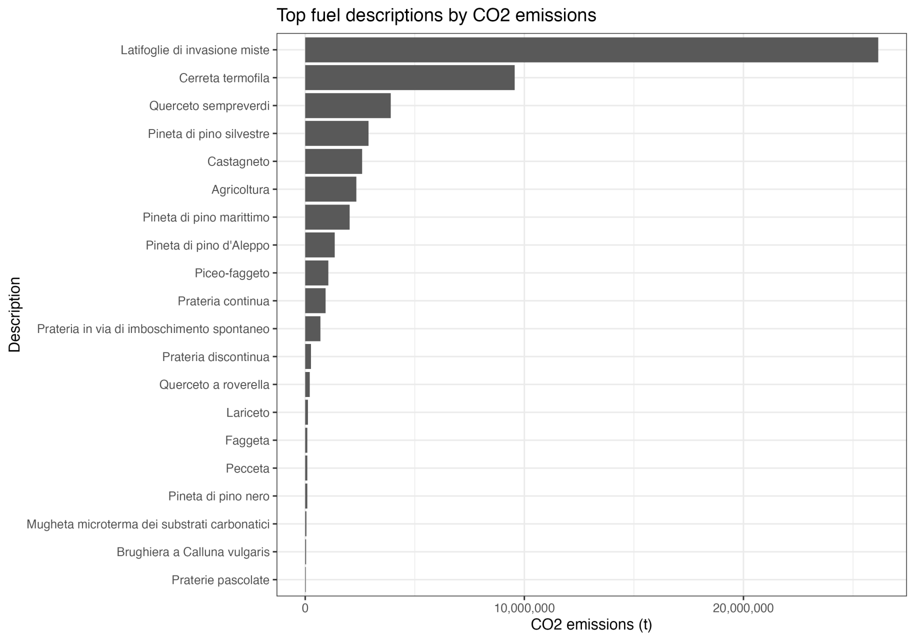


Figure 11. Top vegetation descriptions by total CO_2 emissions

The classification by bioclimatic zone showed an even stronger concentration. **Bioclimatic zone 3 (Mediterranean)** accounted for **47.05 Mt CO_2**, equivalent to **86.4%** of the total. Zone 2 (Temperate) contributed **5.57 Mt (10.2%)**, while zone 1 (Alpine) contributed only **1.85 Mt (3.4%)**. This result indicates that the national fire-emission burden is overwhelmingly concentrated in the warmest and most fire-prone bioclimatic domain represented in the current raster classification. It also suggests that any future effort to reduce emissions or refine national modeling should prioritize the fuel complexes and climatic settings corresponding to zone 3, since that is where the vast majority of both burned rows and emissions are located.

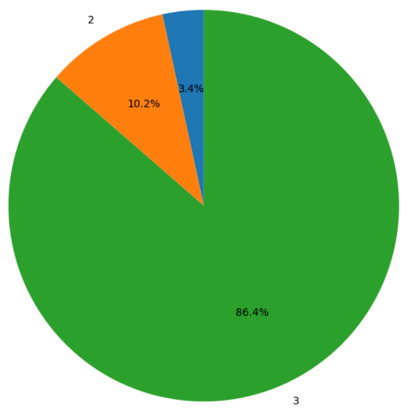


Figure 12. Share of fire emissions by bioclimatic zone
(1 = Alpine, 2 = Temperate, 3= Mediterranean)

4. Discussion

The present assessment confirms that fire-related CO_2 emissions in Italy are both **large** and **highly variable in time and space**. The modeled total of **54.5 Mt CO_2** over 2007–2022, corresponding to **3.40 Mt CO_2 yr^{-1}** on average, places wildfire emissions among the most important intermittent carbon-loss processes affecting Italian terrestrial systems. The temporal pattern is dominated by a small number of severe years, especially 2007, 2017, and 2021, while the spatial pattern is concentrated in southern and insular Italy, with Sicilia, Calabria, and Sardegna alone accounting for a very large share of the national total. This means that the national fire-emission burden is not diffuse. It is concentrated in specific climatic, ecological, and territorial contexts, and this has direct consequences for both interpretation and management.

A first key result is the **strong role of canopy consumption**, either as a direct immediate or as indirect and delayed damage. In the present workflow, the explicit crown-burn term contributed about **18.7%** of total modeled CO_2 emissions over the study period, with much larger contributions in some years, such as 2017 and 2021. This is not a minor adjustment. It changes the order of magnitude of annual totals in the most severe fire seasons and confirms that excluding canopy fuels can lead to a substantial underestimation of emissions whenever crown-affected fire is widespread. This is also the main point of departure from the benchmark study by Scarpa et al. (2024), who explicitly excluded canopy fuels because reliable national information on crown involvement was not available. The present workflow does not eliminate that uncertainty, because `PercentCrownBurn` remains a proxy derived from canopy-cover loss, but it moves the problem from omission to explicit representation. That is an important methodological step, because it allows the effect of canopy involvement to be quantified, tested, and improved over time rather than left outside the model chain altogether.

Ecologically, this result matters because it suggests that the Italian fire-emission signal is not controlled only by burned area, but also by **fuel structure and vertical fuel continuity**. The largest emission totals were concentrated in vegetation descriptions such as mixed invading broadleaves, thermophilous oak woods, evergreen oak systems, and pine forests. These differ in canopy biomass, shrub layers, duff, and coarse woody fractions, and therefore in the amount of biomass available for combustion and in the probability that fire affects canopy layers. The fact that bioclimatic zone 3 (Mediterranean) accounted for most of the national total reinforces this interpretation. The dominant fire-emission signal in Italy is generated where fire-prone climate, recurrent summer drought, and fuel complexes capable of substantial aboveground combustion overlap. In practical terms, this means that future mitigation strategies cannot rely only on reducing burned area. They also need to account for **which vegetation types burn, under which moisture conditions, and with which degree of crown involvement**.

A second major implication concerns the relationship between **burned area and emissions**. The strong correlation between annual burned area and annual CO_2 indicates that area remains a first-order driver, but the scatterplot of annual CO_2 against annual burned area also shows that the relationship is not one-to-one. Some years emitted more CO_2 per hectare than others. This reflects differences in fuel composition, crown involvement, and probably moisture and combustion completeness. In other words, burned area alone is not sufficient to explain the interannual fire-emission signal. This is a central reason why bottom-up workflows such as the present one are useful. They make it possible to distinguish between years dominated by extensive but relatively low-intensity burning and years in which a comparable or smaller burned area produces much higher emissions because the affected fuels are denser, drier, or more vertically continuous. The practical consequence is that fire-emission forecasting and mitigation planning should not be based on burned area alone, but should integrate fuels, canopy condition, and weather-derived moisture.

The spatial concentration of emissions in southern and insular Italy also has direct policy relevance. Sicilia, Calabria, Sardegna, Campania, and Lazio dominate the regional totals. This implies that actions aimed at reducing national fire-related CO_2 emissions will be more efficient if they prioritize these regions. At the same time, the vegetation-level results show that broad mixed woody systems, thermophilous oak forests, evergreen oak systems, and pine forests are disproportionately important. This provides a more operational basis for mitigation than a national average. It points toward region-by-fuel combinations where prevention, fuel treatment, suppression readiness, or post-fire restoration may have the highest climate benefit. In this sense, the outputs are potentially useful not only for scientific reporting, but also for targeting interventions where emissions are most likely to be reduced.

Compared with **Scarpa et al. (2024)**, the present series is clearly higher in absolute magnitude. Over the common 2007–2016 period, the present workflow gives an average of about **3.15 Mt CO_2 yr^{-1}**, compared with about **2.07 Mt** in the Scarpa time series, **2.20 Mt** in GFASv1.3, and **2.99 Mt** in GFED4s. The year-to-year pattern remains highly coherent, especially with Scarpa and GFAS, but the level is shifted upward. The current workflow adds an explicit canopy term, includes a different fire-perimeter basis, uses a corrected and harmonized national event layer, and applies annual rescaling of rasterized burned area to the polygon-based annual totals. When canopy is disabled, the difference decreases, but it does not disappear. This suggests that canopy consumption is a substantial part of the gap, but not the only one. Part of the increase likely also comes from the updated perimeter base, from the treatment of overlap fractions and rescaling, and from differences in fuel allocation, especially in categories where crown, coarse woody debris, herbaceous biomass, and shrubs now enter the same FOFEM framework.

The comparison with **GFASv1.3** and **GFED4s** is also informative. Scarpa et al. reported that their ITDB series was in good agreement with GFAS and lower than GFED on average, with a mean relative percentage difference of **−7%** against GFAS and **−37%** against GFED over 2007–2016. In the current results, the full workflow is on average **higher than GFAS** and much closer to **GFED4s**. This shift is meaningful. GFAS and GFED are based on very different architectures: global gridded products, satellite-driven activity estimates, broad land-cover classes, and generalized biomass and emission-factor assumptions. When a national bottom-up workflow begins to move upward toward or beyond those global products, it suggests that the additional structure in fuels and canopy is having a large effect.

This does not prove that the current estimates are more accurate, but it does indicate that the missing terms in simpler national approaches may have been important. It also means that future validation should focus especially on the fuel pools most likely to drive this upward shift, namely canopy biomass, duff, and coarse woody debris.

The relationship with the **Italian National Inventory Report (NIR)** is different, because the NIR is not built as an event-by-pixel fire-emission model. NIR includes emissions from forest, cropland, and grassland fires under IPCC land-use categories, and uses a methodology based on vegetation type and fire intensity proxies such as scorch height. That makes it a robust official inventory framework, but one with a different modeling philosophy. The FIRE-BOX approach is more explicit in representing within-country spatial variability in fuels, canopy biomass, and combustion conditions. The two approaches should therefore not be seen as competitors in a narrow sense. The NIR is needed for official reporting consistency, whereas the present workflow is better suited to exploring the ecological and spatial mechanisms that generate the emissions. The practical value of FIRE-BOX is precisely that it can help identify which parts of the national total are most sensitive to improved data on burned area, fuels, and canopy damage.

Several **limitations** remain and should be stated clearly. The first is the resolution of the **NDVI analysis**. A large fraction of fires had all cells missing NDVI, and many crown-burn values were therefore either imputed or set to zero. This is probably the single most important weakness of the present canopy module. It means that the crown-burn term is explicit, but still partly constrained by missing support data. The second limitation is that `PercentCrownBurn` is derived from relative canopy-cover loss, not from direct observation of consumed canopy biomass. This is a defensible operational approximation because FOFEM requires crown burn as input, but it does not directly measure combustion. The third limitation is the use of a **fixed 2007 biomass raster** for all years. This is practical, but it can bias canopy and woody-fuel loads in later years, especially after major disturbances, management changes, or long growth intervals. The fourth limitation is the current **moisture assignment workaround**, which uses FFMC, DMC, and DC values from the legacy fire database rather than the intended pixel-level percentile workflow from CEMS reanalysis. The fifth is that reburned cells are tracked but their fuels are not yet updated dynamically after the first fire.

These limitations also imply likely **bias directions**. Missing NDVI support may lead to underestimation of crown consumption where all values are set to zero, but in other cases imputation from fire-level means may smooth real heterogeneity and produce either under- or overestimation locally. The fixed 2007 biomass raster may overestimate loads in areas later affected by prior disturbance and underestimate them in areas that accumulated biomass afterward. National 1000-hour loads may obscure meaningful regional differences in coarse woody fuels. Finally, leaving `CoverGroup` blank delegates some consumption behavior to the general FOFEM algorithm rather than to explicitly assigned cover classes. None of these issues invalidate the workflow, but together they define the uncertainty envelope that should accompany interpretation of the current estimates.

At the same time, the present study also demonstrates **clear improvements over previous approaches**. It uses a corrected and harmonized national fire-perimeter framework, works at the fire-event by pixel level, preserves partial burned fractions, integrates regional fuel maps and national fuel-load data, introduces inventory-based canopy and coarse-woody components, and keeps the entire chain reproducible from batch-table construction to final CO_2 aggregation. This is a substantial step forward relative to workflows that treat burned area and vegetation more coarsely or exclude canopy entirely. Even where uncertainty remains high, the current implementation has one major advantage: it makes those uncertain components explicit and therefore improvable. That is a stronger position than one in which canopy, reburns, or woody-fuel dynamics are simply absent from the accounting chain.

The most important **next improvements** are therefore also clear. First, NDVI support should be strengthened by reconstructing missing pre-fire and post-fire values, or by switching to a more robust multi-temporal spectral framework. Second, annual biomass products should replace the fixed 2007 raster. Third, the intended moisture assignment from pixel-level percentile classes should be completed using CEMS historical fire-danger reanalysis. Fourth, fuels in reburned cells should be updated dynamically after the first fire, including both fuel type and load. Fifth, the NDVI–canopy model should probably be fit separately by broad forest type, eco-region, or structural class, rather than nationally as a single relationship. Sixth, 1000-hour loads should be differentiated by region as well as forest category. Together, these improvements would address almost all of the largest uncertainties identified in the present workflow.

Our results suggest three broad conclusions. First, fire-related CO_2 emissions in Italy are large, strongly concentrated in specific years, regions, and vegetation systems, and therefore relevant both ecologically and for carbon accounting. Second, explicit canopy representation materially changes national emission totals and should not be neglected in future assessments. Third, the current FIRE-BOX workflow should be seen as an **advanced intermediate stage**: already much more spatially explicit and mechanistic than previous national implementations, but still with clear avenues for improvement in canopy support, biomass dynamics, fuel updating, and moisture assignment. From a scientific point of view, this means that the workflow is already informative enough to change the interpretation of Italian fire emissions. From a practical point of view, it provides a concrete platform for progressively reducing uncertainty and improving the realism of future national fire-emission inventories.

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