



Fuel moisture and fuel state regulate CO₂–CO–CH₄ partitioning: from laboratory emission factors to a regional inventory

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10 **Abstract.** Bottom-up wildfire inventories commonly assign fixed emission factors (EFs) to vegetation classes, introducing uncertainty because EFs vary with fuel conditions. Here, we conducted laboratory burns of live-origin and litter-derived dead *Pinus massoniana* needles across a broad range of dry-basis moisture contents (MC) to quantify stable-spread-stage EFs for CO₂, CO, and CH₄ and develop fuel-condition-resolved parameterizations. Burning was smoldering-dominated, with sustained flaming observed only for litter-derived dead needles at 0.89 % MC. Increasing MC decreased EF(CO₂) and increased EF(CO)

15 for live-origin needles, whereas the opposite responses occurred for smoldering-dominated litter-derived dead needles. The moisture-response regressions for EF(CO₂) and EF(CO) explained 60.3–81.5 % of the variability in mean EFs, while EF(CH₄) showed no detectable moisture dependence and was represented by fuel-state-specific means of 15.7 ± 4.3 and 8.0 ± 2.1 g kg⁻¹ for live and dead fuels, respectively. Applying these parameterizations in a bottom-up wildfire emission framework showed that similar total gaseous carbon emissions can mask substantial shifts in species-level carbon partitioning. Over 2012–2021,

20 cumulative gaseous carbon emissions differed by only 4.3% from a fixed-EF baseline, whereas CO₂-C fell by 14.0 % and CO-C and CH₄-C rose by 154.6 % and 344.1 %, respectively. These shifts translated into an approximately 65.63 % greater 20-year global warming potential-based near-term climate impact. These findings highlight the importance of fuel-condition-resolved EFs for better representing wildfire emission composition and its atmospheric and climate implications.

25 **Keywords:**

Wildfire emissions; Fuel moisture content; Fuel state; Emission factors; Smoldering combustion; Emission inventory



1 Introduction

30 Wildfires are major episodic sources of greenhouse gases and air pollutants, affecting atmospheric chemistry, regional air quality, human health, and the terrestrial carbon balance (Andreae, 2019; Jones et al., 2024; Lei et al., 2024). During biomass burning, fuel carbon is primarily released as CO₂, CO, CH₄, nonmethane organic gases (NMOGs) and particulate carbon (Akagi et al., 2011). The partitioning of fuel carbon among these species depends strongly on combustion efficiency and burning conditions (Gkatzelis et al., 2024; Urbanski, 2013). With climate warming, increasingly frequent heat waves and
 35 prolonged droughts are expected to alter fuel moisture content and fire regimes, with consequences for both wildfire activity and emission composition (Abatzoglou and Williams, 2016; Cunningham et al., 2024; Garg et al., 2022).

Wildfire emissions are commonly estimated using bottom-up inventories that combine burned area, fuel loading, combustion completeness, and pollutant-specific emission factors (EFs) (Wiedinmyer et al., 2023). Fire INventory from NCAR (FINN), the Global Fire Emissions Database (GFED), and other widely used inventories generally assign fixed EFs based on broad
 40 vegetation or land-cover classes (Van Der Werf et al., 2017; Wiedinmyer et al., 2023). Because EFs vary with burning conditions, using fixed values may introduce substantial uncertainty into wildfire emission estimates (Garg et al., 2022; Gkatzelis et al., 2024). Fuel moisture content is a major environmental factor controlling biomass ignition, pyrolysis, fire spread, mass loss rate, combustion efficiency, and pollutant formation (Amini et al., 2019; Garg et al., 2024; Jervis and Rein, 2016; Prat-Guitart et al., 2016). Higher moisture content increases the energy required to heat and vaporize water within the
 45 fuel bed, and can promote transitions from flaming to smoldering, thereby altering the partitioning of fuel carbon among CO₂, CO, CH₄, and other products of incomplete combustion (Chen et al., 2010; Hu et al., 2019). Furthermore, the effects of moisture content also depend on fuel state (McCallister et al., 2012; Wang et al., 2024). Live and dead fuels differ in tissue structure and chemical composition and may therefore exhibit different burning modes and emission responses even at the same moisture content (Amini et al., 2019; Jervis and Rein, 2016).

50 Previous laboratory studies have shown that fuel conditions can substantially affect gaseous EFs. Hu et al. (2019) reported that increasing the dry-basis moisture content of Irish sphagnum peat from 1.5 % to 158.7 % decreased EF(CO₂) and EF(CH₄) by 48 % and 82 %, respectively, while EF(CO) increased. Wang et al. (2024) reported contrasting emission patterns between flaming and smoldering for ponderosa pine needles: recently live needles showed higher EF(CO₂) and lower EF(CO) than dead needles under smoldering, whereas the opposite pattern occurred under flaming conditions. Previous studies have
 55 documented moisture effects for individual fuels or combustion phases, but few have quantified comparable moisture-response functions for live-origin and litter-derived dead pine needles (Chen et al., 2010; Garg et al., 2024).

Evergreen coniferous forests are widely distributed across southwestern China and constitute an important component of the regional forest ecosystem (Zhan et al., 2023). Investigating the burning and emission characteristics of representative conifer fuels is important for assessing regional wildfire emissions. Pine needles occur as both live foliage and dead surface litter,
 60 representing two distinct fuel states (Jervis and Rein, 2016). Accordingly, live-origin and litter-derived dead pine needles were selected to examine the effects of fuel moisture content and fuel state on wildfire emissions. The objectives of this study were:



(1) Determine how fuel moisture content and fuel state jointly regulate burning behavior and the partitioning of emitted carbon among CO₂, CO, and CH₄.

65 (2) Develop and evaluate fuel-state-specific moisture–EF parameterizations for live-origin and litter-derived dead coniferous fuels.

(3) Quantify how fuel-condition-resolved EFs alter regional wildfire emissions and gaseous carbon partitioning relative to a conventional fixed-EF inventory.

70 This study establishes a laboratory-to-regional framework for constructing fuel-condition-resolved wildfire emission inventories by integrating moisture- and fuel-state-dependent EFs with spatiotemporally resolved fuel-moisture data, providing a transferable approach for assessing how dynamic fuel conditions affect gaseous carbon partitioning at the regional scale.

2 Materials and methods

2.1 Sample preparation

75 Live-origin and litter-derived dead needles of Masson pine (*Pinus massoniana* Lamb.) were collected in Chuxiong, Yunnan Province, China (24.6841° N, 101.3615° E) in April 2026. Live-origin needles were taken from tree branches, whereas litter-derived dead needles were collected from the forest-floor litter layer of the same location. Before the experiments, soil, twigs, bark fragments, and other debris were manually removed from the samples.

80 The elemental compositions of both fuel states were measured on a dry-mass basis using a vario MACRO cube elemental analyzer (Elementar Analysensysteme GmbH, Langenselbold, Germany). The C, H, and N mass fractions of the live-origin needles were 51.50 ± 0.33 %, 6.11 ± 0.20 %, and 1.18 ± 0.20 %, respectively. The corresponding values for the litter-derived dead needles were 51.44 ± 1.82 %, 6.25 ± 0.15 %, and 0.54 ± 0.18 %, respectively.

Fuel moisture content (MC) was expressed on a dry-mass basis in this work and calculated as follows (Norum and Miller, 1984):

$$MC = \frac{m_w - m_d}{m_d} \times 100\% \quad (1)$$

85 where MC is the dry-basis fuel moisture content (%), m_w is the wet fuel mass (g), and m_d is the oven-dry fuel mass (g). The oven-dry mass was determined on separate subsamples dried at 90 °C for 24 h to constant mass. The initial moisture contents of the live-origin and litter-derived dead needles were 101.79 ± 0.77 % and 14.99 ± 0.95 %, respectively. To obtain a broad range of moisture contents, samples of the two fuel states were treated using different procedures:

90 (i) Live-origin needle samples were directly oven-dried at 90 °C for 0–150 min to obtain different moisture contents. Because this treatment does not preserve physiological live-fuel status and may alter volatile constituents, “live-origin” refers only to the condition at collection.

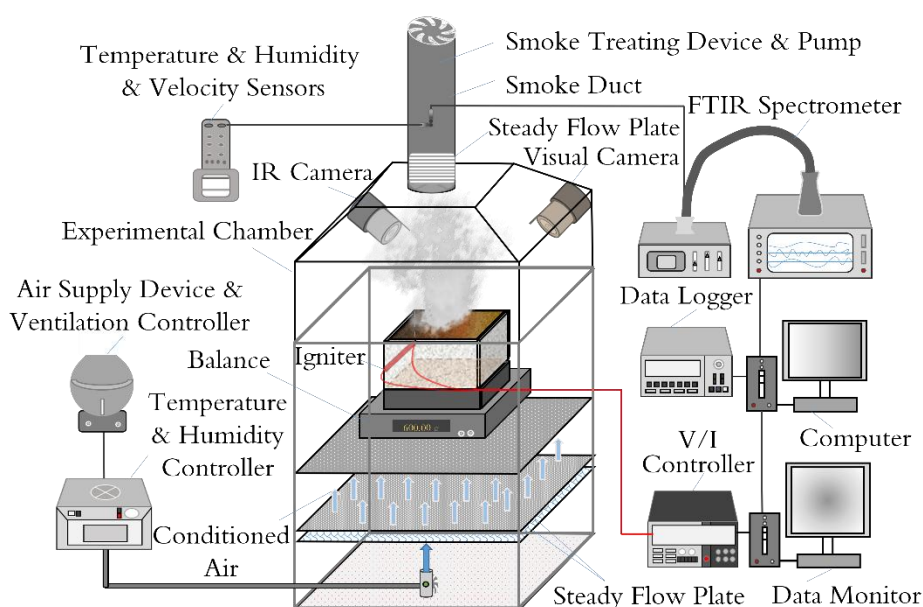


(ii) Litter-derived dead needle samples were immersed in water for 3 h and then oven-dried at 90 °C for 0–150 min to obtain different moisture contents.

Each moisture content was prepared in triplicate. The detailed moisture-content conditions are summarized in Table S1.

2.2 Experimental setup and measurement methods

95 Burning experiments were conducted using a laboratory-scale platform consisting of an environmental chamber, an open-top reactor, an electrical ignition system, a smoke collection system, and a data acquisition system (Fig. 1). This platform has previously been used for controlled forest-fuel combustion experiments to investigate ignition, self-sustained fire spread, mass loss, and gaseous emissions under different fuel and environmental conditions (Yang et al., 2024).



100 **Figure 1. Schematic of a combustion experimental platform for pine needle fire experiments.**

The reactor was constructed from aluminum silicate ceramic fiber, with internal dimensions of $0.20 \times 0.20 \times 0.10$ m and a wall thickness of 0.05 m. Pine needle samples (300 g for each experiment) were naturally accumulated in the reactor to fill the chamber and approximate natural fuel-bed arrangement, corresponding to a fuel-bed bulk density of 75 kg m^{-3} . During all experiments, the chamber temperature and relative humidity were maintained at 25 ± 1.0 °C and 40 ± 0.5 %, respectively. The
 105 fuel was ignited using a cylindrical electric heater positioned 5.0 ± 0.1 cm below the fuel surface. The heater was operated at 100 W for 30 min and then switched off (Yang et al., 2024). This configuration was selected to obtain reproducible, self-sustained burning across a wide moisture range.

Fuel mass was continuously recorded using a DJ 10K-2 electronic balance with a resolution of 0.01 g. Smoke was collected by a hood positioned 56 cm above the reactor, which fully enclosed the visible plume, and was transported through an exhaust
 110 duct at a flow rate of $0.0176 \text{ m}^3 \text{ s}^{-1}$. CO_2 , CO , and CH_4 concentrations were continuously measured using an SSCM-V2 Fourier



transform infrared (FTIR) spectrometer at a sampling flow rate of $3.0 \pm 0.2 \text{ L min}^{-1}$, with the sampling lines maintained at 180°C (Yang et al., 2024). The spectrometer was operated at a spectral resolution of 4 cm^{-1} with a 4.2 m optical path length. The FTIR was calibrated before each experimental campaign. The burning process was recorded using a visible-light camera (GoPro 11) and an NEC NS9500PRO infrared camera. Each condition was replicated three times.

115 2.3 Calculation of combustion parameters and emission factors

Based on the continuously recorded fuel-mass data and time-resolved gas concentrations, the mass loss rate (MLR), modified combustion efficiency (MCE), and EFs were calculated to characterize the burning and emission behavior of pine needles under different moisture contents and fuel states.

120 MLR quantifies the decrease in fuel mass per unit time and reflects the intensity of fuel consumption (Yang et al., 2024). A larger MLR indicates faster fuel consumption and more intense burning (Yang et al., 2024). Because the initial moisture content differed among treatments, MLR was further normalized by the initial dry-to-wet mass ratio to improve comparability among treatments (Hu et al., 2019). The dry-mass-normalized mass loss rate (MLR_{dry}) was calculated as follows:

$$\text{MLR}_{\text{dry}} = -\frac{dm}{dt} \times \frac{m_d}{m_w} \quad (2)$$

125 where MLR_{dry} is the dry-mass-normalized mass loss rate (g s^{-1}), m is the measured fuel mass (g), t is the burning time (s), and m_d and m_w are the initial dry and wet fuel masses (g), respectively.

MCE is used as an indicator of combustion completeness and the relative contributions of flaming and smoldering combustion (Akagi et al., 2011). Higher MCE values indicate more complete carbon oxidation and a greater flaming contribution, whereas lower values indicate a greater contribution from incomplete combustion (Urbanski, 2013).

$$\text{MCE} = \frac{\Delta\text{CO}_2}{\Delta\text{CO}_2 + \Delta\text{CO}} \quad (3)$$

130 where ΔCO_2 and ΔCO are the background-corrected excess mixing ratios of CO_2 and CO , respectively (ppm).

EF is defined as the mass of a given species emitted per unit mass of dry fuel consumed, which provides a quantitative measure of emission intensity and serves as a key link between laboratory measurements and wildfire emission estimates (Andreae, 2019). The EFs of CO_2 , CO , and CH_4 were calculated using the carbon balance method and expressed in g kg^{-1} (Akagi et al., 2011).

$$135 \quad \text{EF}_i = 1000 F_C \times \frac{\text{MW}_i}{\text{MW}_C} \times \frac{\Delta I_i}{\Delta I_{\text{CO}_2} + \Delta I_{\text{CO}} + \Delta I_{\text{CH}_4}} \quad (4)$$

where EF_i is the emission factor of species i (g kg^{-1} dry fuel consumed); F_C is the measured dry-basis carbon mass fraction of the fuel (dimensionless), with values of 0.5150 and 0.5144 for live-origin and litter-derived dead needles, respectively; MW_i and MW_C are the molar mass of species i and the atomic molar mass of carbon, respectively (g mol^{-1}); ΔI_i , ΔI_{CO_2} , ΔI_{CO} , and



ΔI_{CH_4} are the excess mixing ratios of species i , CO_2 , CO , and CH_4 , respectively (ppm). Although CO_2 , CO , and CH_4 have been reported to account for approximately 95 % of the carbon released from temperate conifer forest fires (Urbanski, 2014), other carbon-containing products, including NMOGs, organic carbon (OC), and black carbon (BC), were not quantified in this study. Therefore, incomplete carbon closure may introduce a positive bias of approximately 5 % in the calculated EFs (Urbanski, 2014).

Each burning experiment was divided into three stages – ignition, stable spread, and boundary-limited burning, the last defined as the period after the burning front reached the reactor wall – using synchronized visible-light and infrared images to identify the evolution and position of the burning front (Wang et al., 2025; Yang et al., 2024). The stage division for a representative experimental condition is shown in Fig. S1. The overall dominant burning mode under each experimental condition remained unchanged during the self-sustained burning period. Therefore, the stable-spread stage was selected for parameter calculations and analyses as a representative quasi-steady period, minimizing the influence of external ignition heating and reactor-boundary effects commonly existed in laboratory-scale experiments (Wang et al., 2025). The highest-MC conditions for both fuel states failed to sustain burning after the heater was switched off, they are reported only as ignition outcomes and were excluded from all subsequent calculations.

2.4 Fuel-state-specific moisture-EF parameterization

To convert the experimentally determined EFs into inputs for regional wildfire emission estimates, ordinary least-squares linear regression was used to parameterize the relationship between EF and fuel moisture content for live-origin and litter-derived dead needles. Previous biomass-burning studies have also used linear regression because of its simplicity, interpretability, and suitability for describing moisture-dependent emission responses (Svensson et al., 2026). The emission factor of species i for fuel state s was expressed as follows:

$$EF_{i,s} = a_{i,s} + b_{i,s}MC \quad (5)$$

where $EF_{i,s}$ is the emission factor of species i ($g\ kg^{-1}$ dry fuel consumed); MC is the dry-basis fuel moisture content (%); s denotes the fuel state (live or dead); $a_{i,s}$ is the intercept; and $b_{i,s}$ is the regression coefficient associated with MC . The mean EF across the three replicates was used for regression fitting, and the standard deviation was used to characterize experimental variability. The sustained-flaming condition at 0.89 % MC for litter-derived dead needles was excluded from the linear regression because it represented a distinct burning regime from the remaining smoldering-dominated conditions.

Statistical evaluations included the coefficient of determination (R^2), root-mean-square error (RMSE), and the statistical significance of the regression slope (Bennett et al., 2013). RMSE was calculated as follows (Chai and Draxler, 2014):

$$RMSE = \sqrt{\frac{1}{n} \sum_{k=1}^n (EF_{obs,k} - EF_{pred,k})^2} \quad (6)$$

where $EF_{obs,k}$ and $EF_{pred,k}$ are the observed and predicted emission factors for data point k , respectively ($g\ kg^{-1}$ dry fuel consumed), and n is the number of observations included in the statistical evaluation. Regression results were considered statistically significant at $p < 0.05$. For species without a statistically significant moisture dependence, a fuel-state-specific mean EF was used in the regional emission calculations. Parameter estimation and statistical analyses were performed using OriginPro 2024 (OriginLab Corporation, USA). The resulting fuel-state-specific EF relationships were subsequently coupled with spatially and temporally resolved fuel-moisture data to generate dynamic EFs for the regional wildfire emission inventory.

2.5 Fuel-condition-resolved regional wildfire emission estimation

Regional wildfire emissions were estimated using a bottom-up inventory framework that combines burned area, fuel loading, fraction burned, and species-specific EFs (Wiedinmyer et al., 2023). The emission of species x from grid cell i during time interval t was calculated as follows:

$$E_{x,i,t} = A_{i,t} \times B_i \times FB_i \times EF_{x,i,t} \quad (7)$$

where $E_{x,i,t}$ is the mass of species x emitted from grid cell i during time interval t (g); $A_{i,t}$ is the burned area (m^2); B_i is the total fuel loading per unit area ($kg\ m^{-2}$); FB_i is the fraction burned (dimensionless); and $EF_{x,i,t}$ is the emission factor of species x ($g\ kg^{-1}$ dry biomass). Burned area and vegetation information were derived using the FINN preprocessor based on MODIS and VIIRS active-fire detections and MCD12Q1 land-cover data (Wiedinmyer et al., 2023). Fuel loading was assigned following the regional vegetation-specific estimates of Hoelzemann et al. (2004), whereas the fraction burned was determined using a tree-cover-dependent scheme based on Ito and Penner (2004). These quantities were used as the activity and fuel-consumption inputs in the present bottom-up calculation. MCD12Q1 land-cover data were then used to identify fire grid cells classified as evergreen needleleaf forest within Yunnan, Guizhou, Sichuan, and Chongqing (Sulla-Menashe et al., 2019). To isolate the effect of EF representation, identical burned area, fuel loading, and fraction burned were used in the fixed-EF baseline and the fuel-condition-resolved inventory.

To resolve live- and dead-fuel contributions, the total fuel loading within each identified evergreen needleleaf forest fire grid cell was partitioned using a literature-derived within-stand fuel composition. A regional fuel survey of 669 *Pinus yunnanensis* plots in southwestern Sichuan reported a mean total fuel load of $75.50\ t\ ha^{-1}$ (Xian et al., 2023), comparable to the $78.65\ t\ ha^{-1}$ assigned to temperate forests in East Asia based on the regional vegetation-specific estimates of Hoelzemann et al. (2004). This agreement provided a regional consistency check on total fuel loading before the survey-derived fuel composition was used to partition, rather than replace, the total fuel loading. Within the evergreen needleleaf forest fire grid cells identified above, the reported within-stand fuel composition was then used to derive the live/dead fuel allocation. The tree, shrub, and herb layers were grouped as a live-fuel proxy (91.93 %), whereas the litter layer was treated as a dead-fuel proxy (8.07 %) (Xian et al., 2023). This allocation was held constant throughout the study period as an exploratory fuel-state scenario. The resulting live and dead fuel components were assigned their corresponding EF treatments defined in Sect. 2.4.



Daily live and dead fuel moisture contents were obtained from the Observation and ERA5-Land Derived 9 km Global Daily
 200 Fire Fuel Characteristics since 2003 dataset (European Centre for Medium-Range Weather Forecasts, 2025). High live fuel
 moisture content was assigned to the live-fuel component, whereas dead foliage fuel moisture content was assigned to the
 dead-fuel component. Both moisture variables are expressed as percentages of dry fuel mass, consistent with the dry-basis MC
 definition used in the burning experiments. The moisture content fields were resampled to the $0.1^\circ \times 0.1^\circ$ grid using nearest-
 neighbor interpolation and matched to the fire records by date and location. For CO_2 and CO , the fuel-state-specific moisture–
 205 EF relationships were evaluated for each grid cell and date, whereas the corresponding fuel-state-specific mean EFs were
 applied for CH_4 . The total emission of species x from grid cell i on date t was calculated as follows:

$$E_{x,i,t} = A_{i,t} \text{FB}_i (B_{\text{live},i} \text{EF}_{x,\text{live},i,t} + B_{\text{dead},i} \text{EF}_{x,\text{dead},i,t}) \quad (8)$$

where $B_{\text{live},i}$ and $B_{\text{dead},i}$ are the live and dead components of the fuel loading (kg m^{-2}). Regional cumulative emissions were
 calculated by summing emissions over all valid fire dates and grid cells classified as evergreen needleleaf forest:

$$E_x = 10^{-12} \sum_{t=1}^T \sum_{i=1}^N E_{x,i,t} \quad (9)$$

where E_x is the total emission of species x over the entire study region and study period (Tg); $E_{x,i,t}$ is the mass of species x
 emitted from grid cell i during time interval t (g); N is the total number of grid cells; and T is the total number of time intervals.
 Emissions were further aggregated within the administrative boundaries of Yunnan, Guizhou, Sichuan, and Chongqing. The
 study area was delineated using a GIS shapefile of provincial administrative boundaries in China.

215 Near-term climate impacts were quantified using a 20-year global warming potential (GWP_{20})-based carbon dioxide-
 equivalent ($\text{CO}_2\text{-eq}$) metric that includes the indirect climate effect of carbon monoxide (CO) (Collins et al., 2013). GWP_{20}
 represents the time-integrated radiative forcing of a pulse emission relative to carbon dioxide (CO_2) over a 20-year time horizon
 (Myhre et al., 2013). An East Asia-specific GWP_{20} of 5.4 was adopted for CO based on the Intergovernmental Panel on Climate
 Change Fifth Assessment Report (IPCC AR5) (Collins et al., 2013; Myhre et al., 2013), while a GWP_{20} of 79.7 was used for
 220 non-fossil methane (CH_4) following the IPCC Sixth Assessment Report (IPCC AR6) (Forster et al., 2021). Because the regional
 emissions were expressed as carbon mass, the corresponding CO_2 -equivalent emissions were calculated as:

$$E_{\text{CO}_2\text{-eq},20} = \frac{44}{12} E_{\text{CO}_2\text{-C}} + 5.4 \times \frac{28}{12} E_{\text{CO-C}} + 79.7 \times \frac{16}{12} E_{\text{CH}_4\text{-C}} \quad (10)$$

For independent inventory-level comparison, 2020 wildfire carbon emissions were taken directly from the native GFED5.1
 inventory for the same region and weighted by the evergreen needleleaf forest (ENF) area fraction derived from MCD12Q1
 225 (Sulla-Menashe et al., 2019; Van Der Werf et al., 2025). Grid cells intersecting the regional boundary were weighted according
 to the fractional area located within the study domain. Because GFED5.1 differs from the present inventory in vegetation
 classification, spatial resolution, fire-activity data, fuel-consumption framework, and other inventory assumptions, the
 GFED5.1 (ENF) estimate was used as an independent inventory-level benchmark rather than as independent validation.



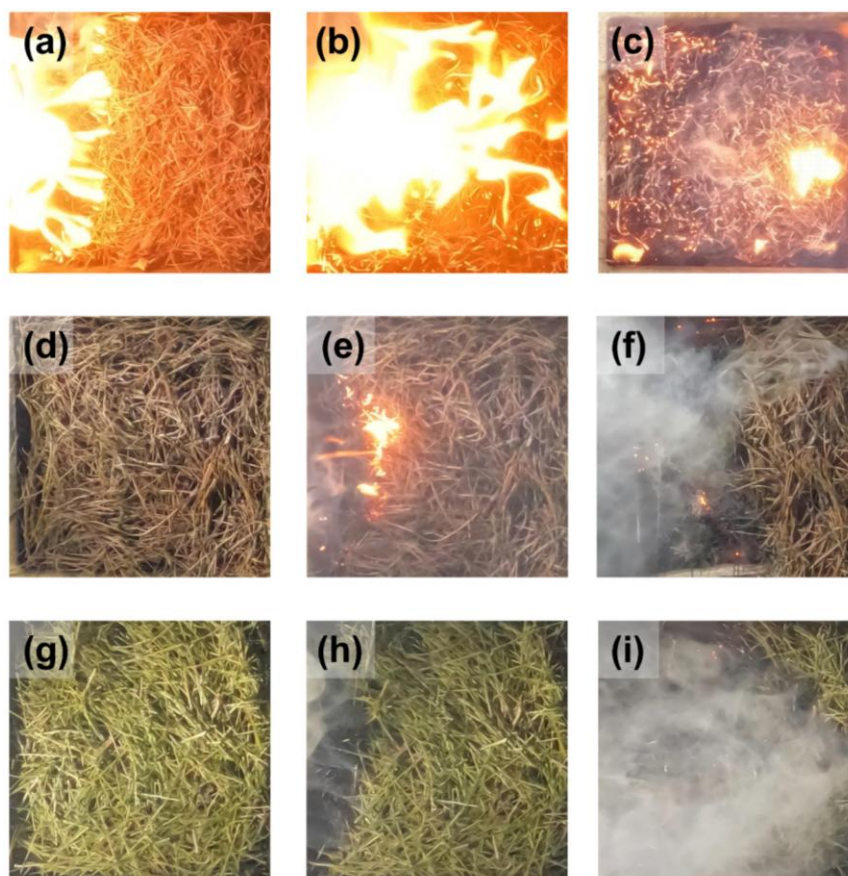
2.6 Monte Carlo analysis

230 A bootstrap-based Monte Carlo approach was used to quantify the uncertainty propagated from the experimentally derived emission factors (EFs) to the regional emission estimates (Tong et al., 2012). For each fuel-state $\times$ moisture-content condition, the replicate experiments were resampled with replacement while preserving the original sample size. For each bootstrap iteration, the moisture-dependent EF relationships for CO₂ and CO were refitted separately for live and dead fuels, and the state-specific mean EFs for CH₄ were recalculated. The resulting parameter set was then applied to the full 2012–2021 regional
 235 emission calculation using the same burned biomass, fuel-moisture data, and live/dead fuel allocation as in the main analysis. A total of 5000 bootstrap iterations were performed, and the 95 % uncertainty intervals (UIs) were defined by the 2.5th and 97.5th percentiles of the resulting emission distributions (Tong et al., 2012). The original fitted parameters were retained for the central estimates. Because other inventory inputs were held constant, the reported UIs represent uncertainty associated with the experimental EF parameterization rather than the total uncertainty of the regional emission inventory.

240 3 Results and discussion

3.1 Effects of fuel moisture content and fuel state on fire behavior

Masson pine needles with different fuel moisture contents and fuel states exhibited distinct burning behaviors. Figure 2 shows three representative burning phenomena observed during the experiments: sustained flaming, smoldering-dominated burning with localized flaming, and pure smoldering. Among conditions that sustained burning, live-origin needles at 1.33–71.11 %
 245 MC were consistently smoldering-dominated, with no visible flaming. Litter-derived dead needles exhibited sustained flaming only at 0.89 % MC, whereas those at 14.99–87.13 % MC were predominantly smoldering, with occasional localized and transient flames (Table S1). These observations are consistent with Fazeli et al. (2022) and Wang et al. (2024), who reported that burning modes of pine needles and conifer foliage vary with fuel moisture content and fuel state.



250 **Figure 2. Representative burning modes of Masson pine needles under different fuel states and moisture contents. Panels (a–c) show sustained flaming for litter-derived dead needles at 0.89 ± 0.55 % MC. Panels (d–f) show smoldering-dominated burning with localized flaming at 14.99 ± 0.95 % to 87.13 ± 0.85 % MC for litter-derived dead needles. Panels (g–i) show pure smoldering burning at 1.33 ± 0.48 % to 71.11 ± 1.58 % MC for live-origin needles.**

For litter-derived dead needles, burning at 0.89 % MC released sufficient pyrolysates to sustain gas-phase flaming. As moisture
 255 content increased, a larger fraction of the supplied heat was consumed by water heating and evaporation, reducing the energy
 available for pyrolysis and thereby suppressing the development of sustained flaming (Lai et al., 2024; Shotorban et al., 2018).
 Nonuniform drying and localized burning zones could temporarily generate sufficient pyrolysates, resulting in localized,
 transient flames. However, the burning of the litter-derived dead needles with MC > 0.89 % was dominated by smoldering.
 In contrast, all live-origin needle treatments burned predominantly by smoldering under the present experimental configuration,
 260 including the treatment dried to 1.33 % MC, indicating that fuel moisture content alone cannot explain the differences in
 burning mode between live and dead fuels. Although live-origin needles underwent pyrolysis and carbon oxidation during
 burning, the conditions required to sustain gas-phase flaming were not reached. Consequently, the burning front propagated
 predominantly through smoldering within the fuel bed.



MLR_{dry} can reflect the combined evolution of drying, pyrolysis, and oxidation within the fuel bed in real time (El Houssami et al., 2016). As shown in Fig. 3, for all moisture conditions that sustained burning, MLR_{dry} remained low during the initial heating period, increased rapidly as drying and pyrolysis progressed and oxidation intensified, and subsequently declined as the fuel was depleted. As moisture content increased, peak MLR_{dry} generally decreased and the time to peak was delayed. For live-origin needles, peak MLR_{dry} decreased from $0.171 \pm 0.013 \text{ g s}^{-1}$ at 1.33 % MC to $0.071 \pm 0.004 \text{ g s}^{-1}$ at 71.11 % MC. By comparison, litter-derived dead needles showed a smaller overall variation, with peak MLR_{dry} ranging from $0.111 \pm 0.027 \text{ g s}^{-1}$ at 0.89 % MC to $0.093 \pm 0.003 \text{ g s}^{-1}$ at 87.13 % MC (Fig. S2). These results indicate that increasing moisture content suppressed dry-fuel consumption and delayed its peak, with a stronger effect on live-origin needles than on litter-derived dead needles, highlighting the fuel-state dependence of burning dynamics.

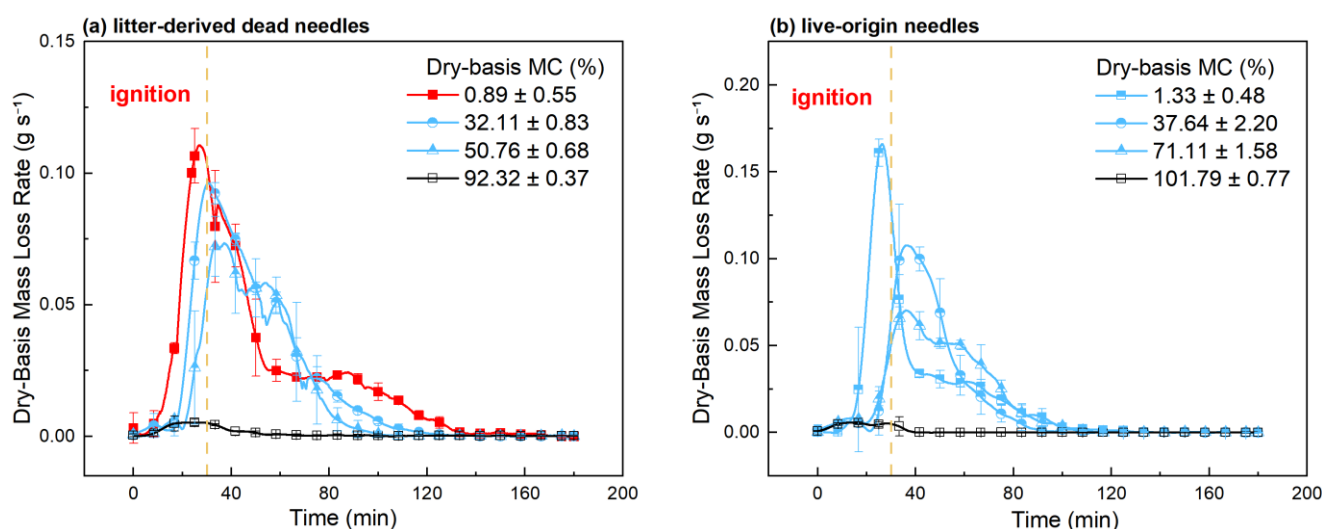


Figure 3. Time evolution of dry-basis mass loss rate for (a) litter-derived dead and (b) live-origin Masson pine needles under different dry-basis moisture contents. The vertical dashed line indicates the end of the ignition-heating period. The highest-moisture conditions for litter-derived dead ($92.32 \pm 0.37 \%$) and live-origin ($101.79 \pm 0.77 \%$) needles did not sustain burning.

3.2 Effects of moisture content and fuel state on MCE

During the stable-spread stage, mean MCE ranged from 0.792 to 0.836 for live-origin needles and from 0.690 to 0.744 for smoldering-dominated litter-derived dead needles with occasional localized flaming. As shown in Fig. 4, despite the absence of visible flaming, live-origin needles consistently exhibited higher MCE values than these litter-derived dead needles. Litter-derived dead needles at 0.89 % MC exhibited sustained flaming with the highest mean MCE of 0.872, which was below the commonly used reference threshold of 0.90 for distinguishing flaming- and smoldering-dominated burning (Akagi et al., 2011). These results indicate that MCE primarily reflects the relative partitioning of emitted carbon between CO₂ and CO and does not directly indicate the occurrence of visible flaming.

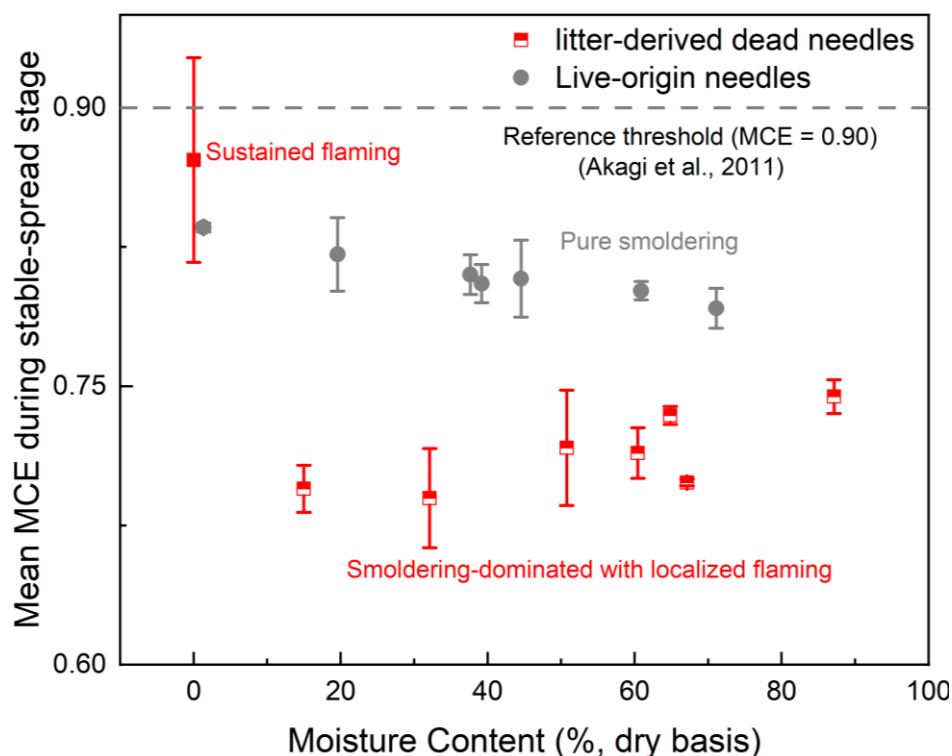


Figure 4. Mean MCE during the stable-spread stage as a function of dry-basis fuel moisture content for live-origin and litter-derived dead Masson pine needles. The dashed horizontal line at MCE = 0.90 denotes the literature-based reference threshold used to interpret flaming- versus smoldering-dominated biomass burning.

For live-origin needles, MCE decreased from 0.836 ± 0.002 at 1.33 % MC to 0.792 ± 0.011 at 71.11 % MC. This decrease may result from the additional heat consumed by water heating and evaporation, which reduced fuel-bed temperature, heat feedback, and oxidation efficiency (Chen et al., 2010; Yashwanth et al., 2016). In contrast, litter-derived dead needles showed a different response. At 0.89 % MC, litter-derived dead needles had the highest MCE of 0.872 ± 0.055 . Among the remaining conditions, MCE increased from 0.695 ± 0.013 at 14.99 % MC to 0.744 ± 0.009 at 87.13 % MC. A possible explanation for this response is that lower moisture contents promoted rapid pyrolysis and localized transient flaming, favoring incomplete oxidation and CO formation (May et al., 2019; Safdari et al., 2019). Win and Persson (2014) reported that the onset and extinction of flaming were associated with higher CO and organic-carbon emissions. Safdari et al. (2019) similarly found that rapid heating of wildland fuels favored CO production, whereas slower pyrolysis produced a larger proportion of CO₂. Increasing moisture content may have slowed pyrolysate release and reduced the intensity of transient flaming, thereby promoting more uniform oxidation during stable spread and resulting in higher MCE (Safdari et al., 2019; Yashwanth et al., 2016). The opposite MCE trends for live-origin and litter-derived dead needles indicate that moisture effects strongly depend on fuel state and burning behavior.

Although MCE is widely used to infer the relative contributions of flaming and smoldering, the use of fixed MCE thresholds alone may be unreliable for identifying burning modes under mixed or transient burning conditions. Reisen et al. (2018)

reported that MCE alone was insufficient to distinguish different combustion processes at low MCE. Hu et al. (2019) showed substantial MCE fluctuations during ignition and difficulty in identifying smoldering under high-moisture conditions. The present results further support this limitation: live-origin needles exhibited no visible flames but generally had higher MCE than litter-derived dead needles, while the occurrence of localized transient flames in litter-derived dead needles was not consistently associated with higher MCE. The mismatch between visible flaming and the conventional MCE threshold indicates that MCE should be interpreted as a carbon-oxidation metric rather than a stand-alone classifier of visual burning mode for pine needles.

3.3 Emission factors of CO₂, CO, and CH₄

Figure 5 shows the mean EF(CO₂) and EF(CO) during the stable-spread stage across the moisture-content conditions that sustained burning. Live-origin needles generally exhibited higher EF(CO₂) and lower EF(CO) than smoldering-dominated litter-derived dead needles. Wang et al. (2024) reported a similar pattern for ponderosa pine needles under smoldering conditions.

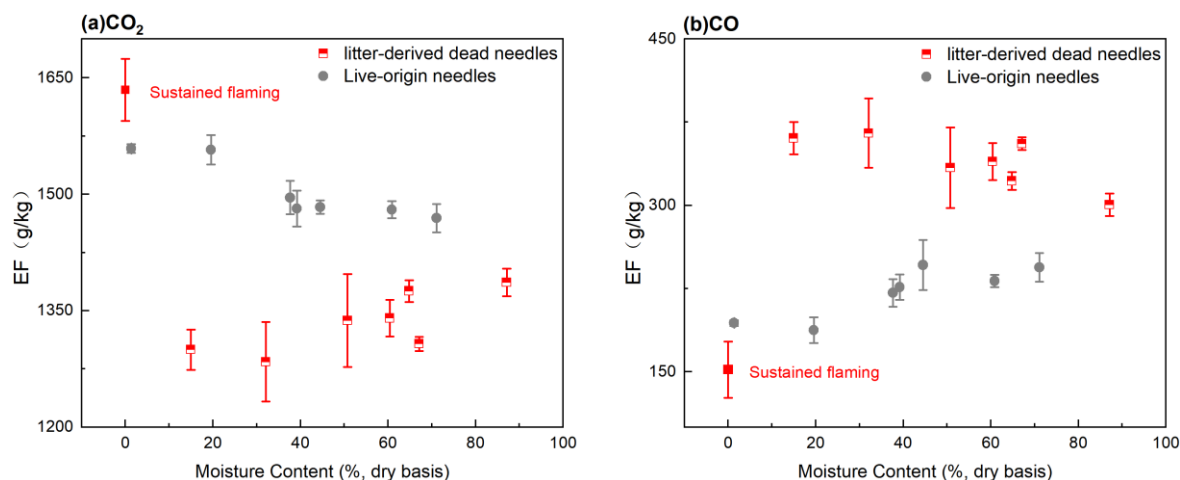


Figure 5. EFs of (a) CO₂ and (b) CO as functions of dry-basis moisture content for litter-derived dead and live-origin Masson pine needles. Symbols are means of three replicate experiments and error bars indicate one standard deviation. The dead-needle condition at 0.89 % MC sustained flaming and is shown for reference only.

For live-origin needles, EF(CO₂) decreased from 1558.9 ± 5.6 g kg⁻¹ at 1.33 % MC to 1469.3 ± 18.1 g kg⁻¹ at 71.11 % MC, whereas EF(CO) increased from 193.9 ± 2.6 to 244.0 ± 12.9 g kg⁻¹. This inverse response indicates that increasing moisture content shifted fuel carbon from CO₂ toward CO, thereby altering the partitioning of fuel carbon. Chen et al. (2010) similarly reported that increasing fuel moisture reduced combustion efficiency and substantially increased CO emissions during controlled burning of bitter brush leaves. For litter-derived dead needles, the 0.89 % MC condition exhibited the highest EF(CO₂) of 1634.5 ± 40.0 g kg⁻¹ and the lowest EF(CO) of 151.8 ± 25.4 g kg⁻¹, reflecting more complete oxidation under sustained flaming. Excluding this condition, EF(CO₂) increased from 1299.7 ± 26.0 g kg⁻¹ at 14.99 % MC to 1386.4 ± 17.9 g kg⁻¹ at 87.13 % MC, whereas EF(CO) decreased from 360.9 ± 14.4 to 300.5 ± 10.3 g kg⁻¹. This result suggests that increasing

moisture content may alter the pyrolysis and oxidation processes during stable spread, thereby shifting carbon partitioning toward CO₂ relative to CO (Shotorban et al., 2018). Rein et al. (2009) similarly reported increased CO₂ yields and decreased CO/CO₂ ratios with increasing peat moisture during smoldering of boreal peat.

As shown in Fig. 6, the mean EF(CH₄) during the stable-spread stage showed no statistically detectable dependence on fuel moisture content. Overall, EF(CH₄) was higher for live-origin needles than for litter-derived dead needles. The mean EF(CH₄) was 15.72 ± 4.33 g kg⁻¹ for live-origin needles, with values ranging from 9.18 ± 0.90 to 22.55 ± 2.66 g kg⁻¹, and 8.01 ± 2.07 g kg⁻¹ for litter-derived dead needles, with values ranging from 4.67 ± 1.30 to 10.41 ± 0.75 g kg⁻¹. Although EF(CH₄) fluctuated within a limited range across the tested moisture conditions, no consistent increasing or decreasing trend was observed. Therefore, the results did not support a moisture-dependent parameterization of EF(CH₄), and fuel-state-specific mean values were used in the subsequent regional emission calculations.

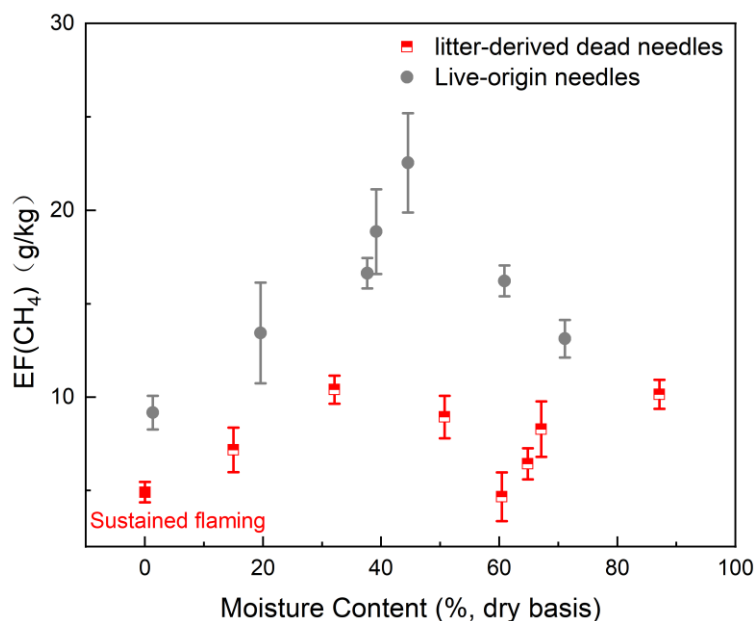


Figure 6. EFs of CH₄ as a function of dry-basis moisture content for litter-derived dead and live-origin Masson pine needles. Symbols represent the means of three replicate experiments, and error bars indicate one standard deviation.

Table 1 compares the EFs measured in this study with the FINN default values for temperate evergreen forests and previously reported EFs from other studies. The measured EF(CO₂) values broadly overlapped those reported for coniferous fuels and forest fires and were generally comparable to the FINN default of 1623 g kg⁻¹ (Wiedinmyer et al., 2023). In contrast, the measured EF(CO) and EF(CH₄) values were generally higher than previously reported values for coniferous fuels and forest fires and the FINN defaults of 112 and 3.4 g kg⁻¹, respectively. These differences were primarily attributable to the smoldering-dominated burning in the present experiments, which favored incomplete oxidation and enhanced CO and CH₄ emissions (Garg et al., 2024; Urbanski, 2013). However, the literature values were used only for order-of-magnitude comparison because fuel type, burning mode, and measurement scale differed among studies.



Table 1. Comparison of CO₂, CO, and CH₄ emission factors (g kg⁻¹ dry fuel burned) from this study with FINN defaults and previously reported values.

Source	Fuel or fire type	Burning condition	EF(CO ₂)	EF(CO)	EF(CH ₄)
This study ^a	Live-origin Masson pine needles	Smoldering-dominated	1469.3–1558.9	193.9–244.0	9.18–22.55 (mean 15.72)
This study ^a	litter-derived dead Masson pine needles	Sustained flaming at 0.89 % MC; otherwise smoldering-dominated	1299.7–1634.5	151.8–360.9	4.67–10.41 (mean 8.01)
FINN default ^b	Temperate Evergreen Forest	Fixed vegetation-class EF	1623	112	3.4
Chen et al. (2007)	Ponderosa pine needles	Smoldering phase	1596.9 ± 73.3	134.9 ± 47.0	NR
Chen et al. (2007)	White pine needles	Smoldering phase	1445.0 ± 34.5	157.4 ± 7.2	NR
Wang et al. (2024)	Dead ponderosa pine needles	Flaming; 10 % O ₂ and 50 kW m ⁻²	905.81 ± 68	36.89 ± 9.9	NR
Wang et al. (2024)	Recently live ponderosa pine needles	Flaming; 10 % O ₂ and 50 kW m ⁻²	611.88 ± 80	74.41 ± 9.5	NR
Urbanski (2013)	Mixed-conifer wildfires	Fire-integrated field measurements	1596	135	7.30
Andreae (2019)	Temperate forest fires	Literature compilation	1570 ± 130	113 ± 50	5.2 ± 2.8
Andreae (2019)	Peat fires	Smoldering-dominated compilation	1590 ± 150	260 ± 23	9.1 ± 1.5

^a Values are ranges across moisture-content conditions; parenthetical values are the fuel-state-specific mean EF(CH₄) values used in the regional calculations.

^b Fixed emission factors for temperate evergreen forests from FINN v2.5 (Wiedinmyer et al., 2023).
 Abbreviations: EF, emission factor; MC, moisture content; NR, not reported.

In summary, the sign of the moisture response of EF(CO₂) and EF(CO) reversed between fuel states, indicating that fixed EFs may not adequately capture variations in emissions across fuel states and fuel moisture contents. In contrast, EF(CH₄) showed no detectable moisture dependence and was represented by fuel-state-specific means.

3.4 Parameterization of moisture-dependent emission factors

To incorporate the effects of fuel moisture content into regional emission estimates, separate EF parameterizations were established for live-origin and litter-derived dead needles (Fig. 7 and Table 2).

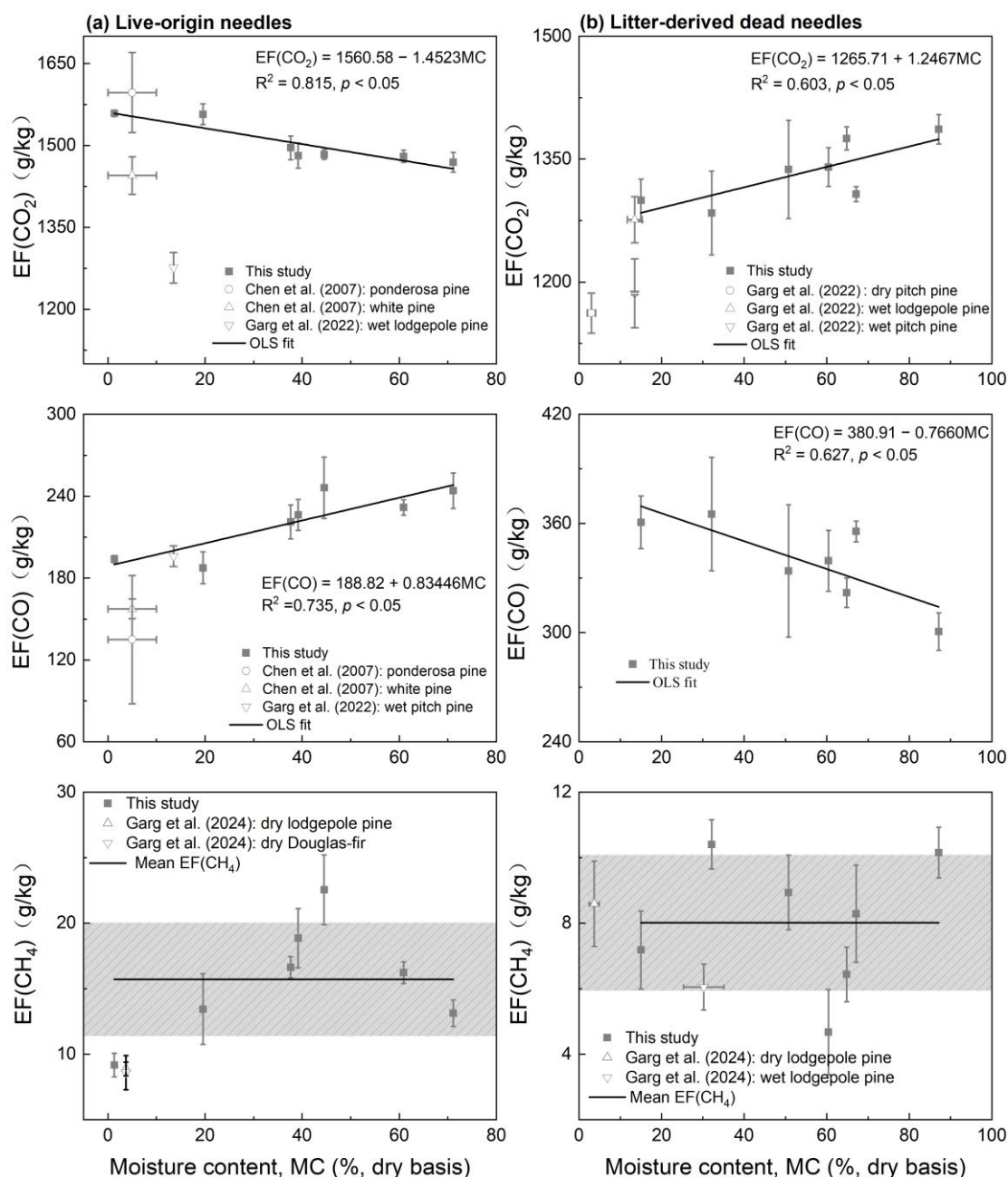


Figure 7. Moisture-dependent relationships of EF(CO₂), EF(CO), and EF(CH₄) for live-origin and dead Masson pine needles, with comparison to reported values for other coniferous fuels. Panels (a) and (b) show the moisture-dependent EFs of CO₂, CO, and CH₄ for live-origin and litter-derived dead needles, respectively. Filled squares represent the mean emission factor at each moisture content, and error bars indicate the standard deviation of three independent replicate experiments. The solid lines for EF(CO₂) and EF(CO) represent ordinary least-squares (OLS) linear fits to the data obtained in this study. For EF(CH₄), the horizontal solid lines and gray shaded areas represent mean ± standard deviation for each fuel state. Open symbols denote published values for other coniferous fuels included only for comparison of emission factor ranges and were excluded from model fitting.



370 **Table 2. Moisture-dependent emission-factor parameterizations and representative EF(CH₄) values used in the regional emission estimates.**

Fuel state	Species	Equation or representative EF (g kg ⁻¹)	R ²	RMSE (g kg ⁻¹)	<i>p</i> value	95 % CI of slope
Live	CO ₂	EF(CO ₂) = 1560.58 – 1.4523MC	0.815	15.09	0.00535	–2.247 to –0.658
Live	CO	EF(CO) = 188.82 + 0.83446MC	0.735	10.94	0.01366	0.258 to 1.411
Live	CH ₄	Mean EF(CH ₄) = 15.72 ± 4.33	—	—	—	—
Dead	CO ₂	EF(CO ₂) = 1265.71 + 1.2467MC	0.603	22.44	0.0401	0.083 to 2.410
Dead	CO	EF(CO) = 380.91 – 0.7660MC	0.627	15.50	0.0338	–1.445 to –0.087
Dead	CH ₄	Mean EF(CH ₄) = 8.01 ± 2.07	—	—	—	—

Note: Linear regressions were fitted using seven mean EF values corresponding to seven moisture-content conditions (*n* = 7). For each moisture-content condition, the EF represents the mean of three replicate experiments. The sustained-flaming condition at 0.89 % MC was excluded from the dead-fuel fits. The CO₂ and CO regressions are linked by carbon closure and do not constitute independent tests. For CH₄, fuel-state-specific mean EFs are reported because no consistent moisture-dependent relationship was observed.

For live-origin needles, EF(CO₂) decreased significantly with increasing fuel moisture content, whereas EF(CO) increased significantly. Litter-derived dead needles exhibited the opposite responses, with EF(CO₂) increasing and EF(CO) decreasing with increasing fuel moisture content. All four moisture-dependent relationships were statistically significant (*p* < 0.05), with R² values ranging from 0.603 to 0.815 and RMSE values from 10.94 to 22.44 g kg⁻¹. The opposite signs of the fitted slopes for live-origin and litter-derived dead needles indicate that moisture responses on EF(CO₂) and EF(CO) may differ between fuel origins. Therefore, separate parameterizations were used for live and dead fuels in the subsequent regional emission estimates. EF(CH₄) was not fitted as a function of fuel moisture content. Therefore, fuel-state-specific mean values of 15.72 ± 4.33 and 8.01 ± 2.07 g kg⁻¹ for live-origin and litter-derived dead needles, respectively, were used in the subsequent regional emission estimates.

385 For regional emission calculations, the EF for species *x* and fuel state *s* was expressed as follows:

$$EF_{x,s} = f_{x,s}(MC_s) \quad (11)$$

where EF_{*x,s*} is the emission factor of species *x* for fuel state *s* (g kg⁻¹ of dry fuel consumed); *x* denotes CO₂, CO, or CH₄; *s* denotes fuel state; and MC_{*s*} is the dry-basis fuel moisture content of fuel state *s* (%). For CO₂ and CO, the corresponding moisture-dependent parameterization in Table 2 was applied, whereas for CH₄, the fuel-state-specific mean EF (g kg⁻¹ of dry fuel consumed) was used. This approach retained fuel-state-specific moisture responses of live and dead fuels in the regional estimates.

3.5 Multiscale impacts of fuel-condition-resolved EFs on regional wildfire emissions

To evaluate the regional implications of moisture- and fuel-state-resolved emission factors (EFs), the parameterized EFs for CO₂, CO, and CH₄ were applied to wildfire emissions from evergreen needleleaf forests in Southwest China. In 2020, the year with the highest gaseous carbon emissions during 2012–2021, EF(CO₂) and EF(CO) showed clear monthly variations associated with changes in fuel moisture content, while remaining distinct between live and dead fuels (Fig. 8(a) and (b)). Monthly gaseous carbon emissions showed strong seasonality (Fig. 8(c)), with December, March, and April together accounting for approximately 94 % of the 2020 annual total, while little or no emissions occurred during the remaining months. Despite the monthly variation in EFs, carbon partitioning among CO₂, CO, and CH₄ remained broadly similar across the major emission months, indicating that the strong seasonal variation in total emissions was primarily driven by fire activity.

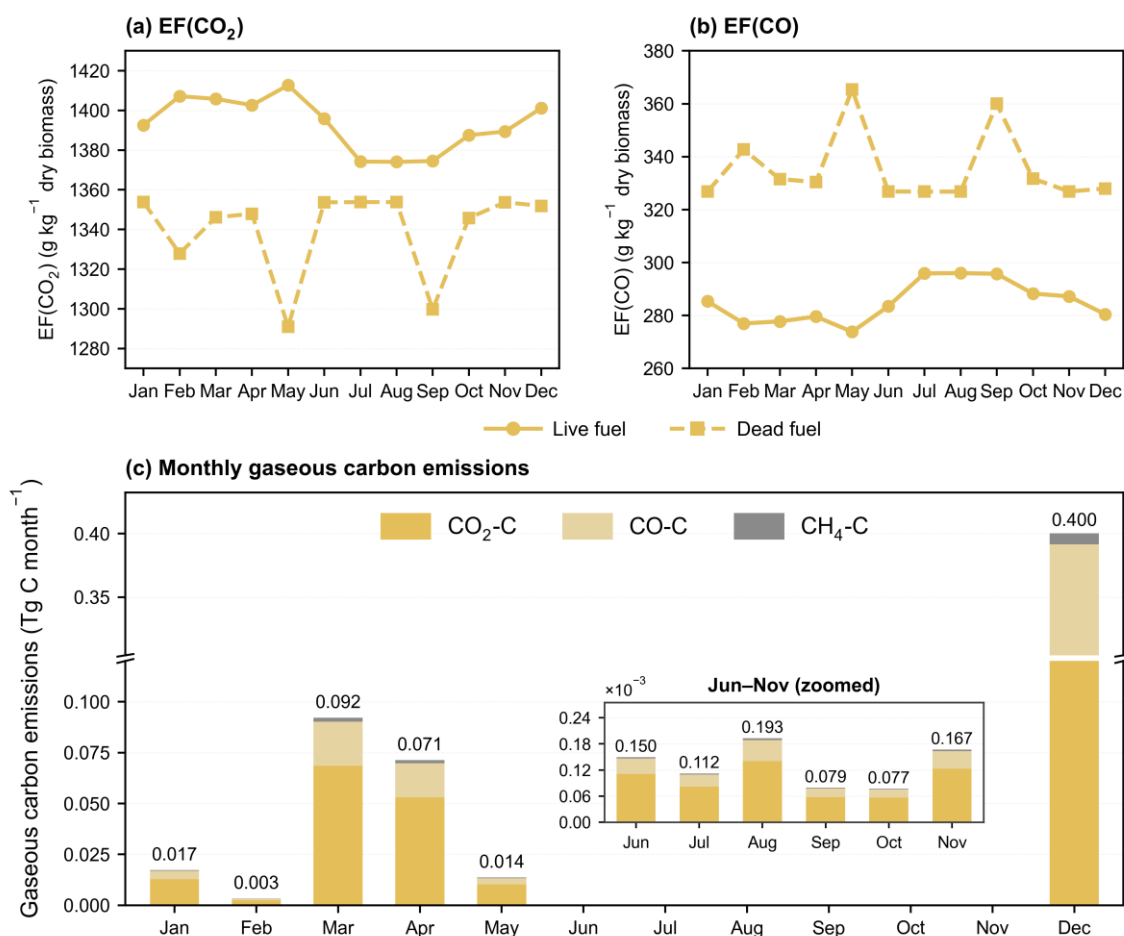


Figure 8. Monthly variations in emission factors and gaseous carbon emissions from evergreen needleleaf forest wildfires in Southwest China in 2020. (a) Emission factors of CO₂ for live and dead fuels; (b) emission factors of CO for live and dead fuels; and (c) monthly gaseous carbon emissions partitioned into CO₂-C, CO-C, and CH₄-C.



At the annual scale, gaseous carbon emissions from evergreen needleleaf forest wildfires in Southwest China were estimated at 0.599 Tg C in 2020, compared with 0.574 Tg C from the fixed-EF FINN v2.5 baseline. Emissions were spatially concentrated in north-central Yunnan and along the Yunnan–Sichuan border (Fig. 9(a)). The present estimate was also comparable in magnitude to the estimate reported by Wang et al. (2020) (0.431 Tg C) for annual mean forest-fire emissions reported for Southwest China during 2013–2017 and GFED5.1 (0.436 Tg C) for the 2020 emissions extracted for evergreen needleleaf forests (ENF) within the same four-province domain (Fig. 9(b)) (Van Der Werf et al., 2025). Total gaseous carbon emissions differed by only 4.3 % from the FINN v2.5 estimate, which follows directly from the 4.3 % difference in the implied carbon mass fraction of the two EF sets (493.5 versus 515.0 g C kg⁻¹). In contrast, the partitioning of that carbon, which is unconstrained by carbon closure, changed substantially: the contributions of CO₂-C, CO-C, and CH₄-C shifted from 89.8 %, 9.7 %, and 0.5 % to 74.1 %, 23.7 %, and 2.2 %, respectively.

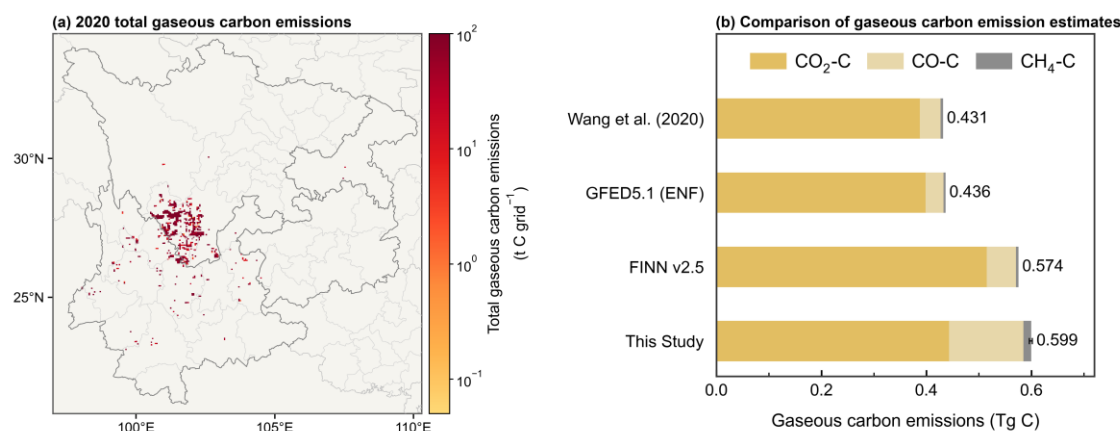


Figure 9. Spatial distribution and comparison of gaseous carbon emissions from evergreen needleleaf forest wildfires in Southwest China in 2020. (a) Spatial distribution of total gaseous carbon emissions in Southwest China in 2020. (b) Comparison of gaseous carbon emission estimates from this study, FINN v2.5, GFED5.1, and Wang et al. (2020). Estimates differ in vegetation classification, period, and fuel-consumption framework and are shown for order-of-magnitude context only. Gas emissions were converted to carbon mass as CO₂-C, CO-C, and CH₄-C.

Over the decade from 2012 to 2021, the two approaches produced similar total gaseous carbon emissions, but substantially different carbon partitioning (Fig. 10). The 10-year cumulative total increased by only 4.26 % (95 % UI: 3.74–4.72 %) relative to FINN v2.5, whereas CO₂-C decreased by 14.0 % (95 % UI: 13.0–14.9 %) and CO-C and CH₄-C increased by 154.6 % (95 % UI: 144.3–164.6 %) and 344.1 % (95 % UI: 327.1–360.7 %), respectively. These changes are environmentally important because CO₂, CO, and CH₄ have distinct atmospheric and climatic effects (Collins et al., 2013; Forster et al., 2021). Using GWP₂₀ as a screening metric for near-term climate effects, the decadal cumulative CO₂-equivalent impact was 65.63 % (95 % UI: 62.67–68.29 %) higher than that estimated using the fixed FINN v2.5 EFs. The concurrent increase in CO may further reduce atmospheric oxidizing capacity, extend CH₄ lifetime, and promote tropospheric O₃ formation (Szopa et al., 2021). These results indicate that fixed EFs can substantially alter estimates of species-specific emissions and associated atmospheric-chemistry and near-term climate implications, even when total gaseous carbon emissions remain similar.

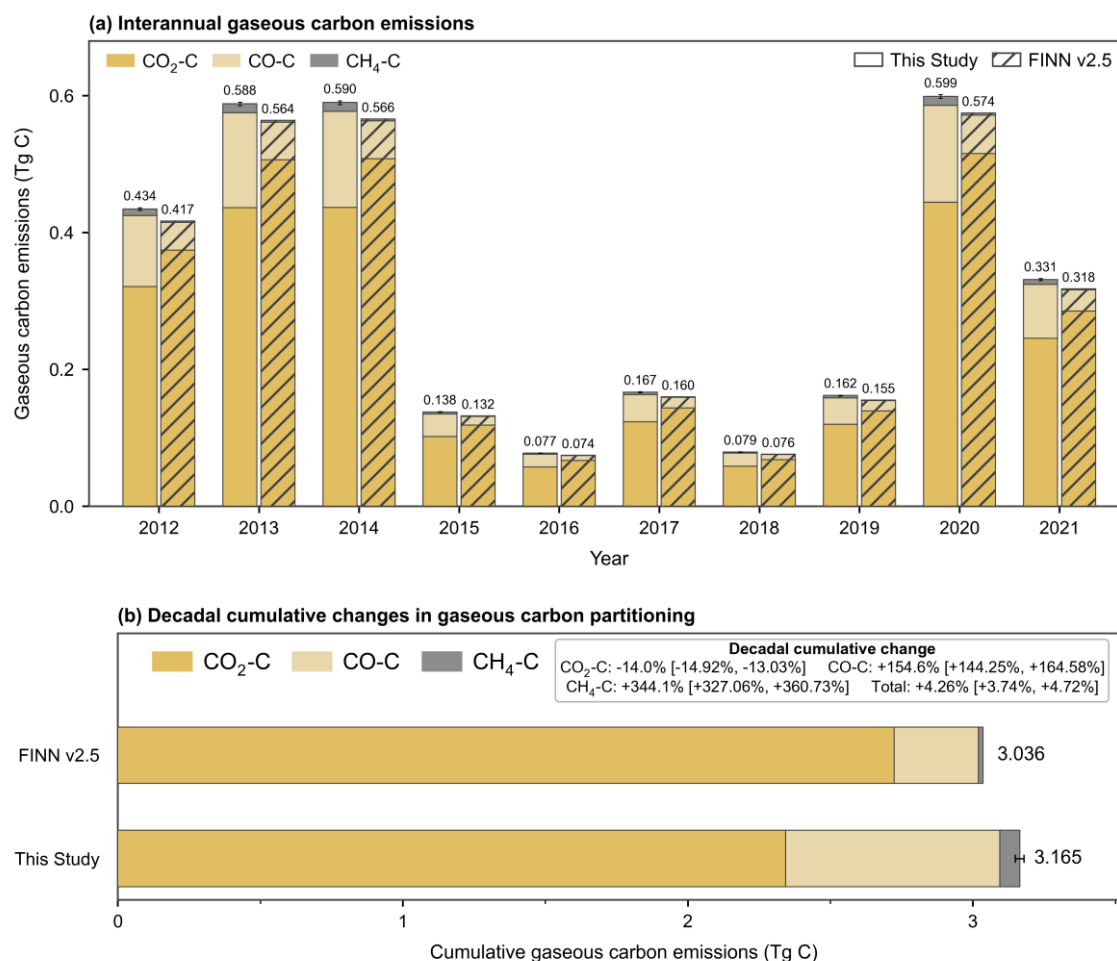


Figure 10. Interannual variations and decadal cumulative changes in gaseous carbon emissions from evergreen needleleaf forest wildfires in Southwest China during 2012–2021. Values in brackets indicate 95 % uncertainty intervals (UIs).

3.6 Uncertainty analysis

Several sources of uncertainty should be considered when interpreting the laboratory-derived EFs and their regional application. First, the absolute EFs may exhibit a modest positive bias because the carbon-balance calculation included only CO₂, CO, and CH₄, whereas carbon emitted as NMOGs, OC, and BC was not quantified (Akagi et al., 2011). Yokelson et al. (2013) estimated that omission of unmeasured carbon-containing species could increase calculated EFs by less than 5 % under prescribed-fire conditions. However, because burning in this study was predominantly smoldering, this uncertainty is likely to exceed 5 %, inflating all three EFs proportionally while leaving their relative partitioning essentially unaffected. In addition, the experiments were conducted in a small-scale reactor under controlled heating and environmental conditions. Such experiments cannot fully reproduce the heterogeneous fuel beds, airflow, oxygen supply, heat transfer, and fire feedbacks characteristic of



natural wildfires, and these scale-dependent differences may affect both burning behavior and measured EFs (El Houssami et al., 2016; Yokelson et al., 2013).

445 Burning mode is another important source of uncertainty. Fourteen of the 15 experimental conditions that sustained burning were smoldering-dominated, whereas natural wildfires contain varying contributions from flaming and smoldering (Reisen et al., 2018). This is unlikely to reflect an intrinsic propensity of *Pinus massoniana* needles to smolder. Because smoldering-dominated dead-needle burning produced substantially higher EF(CO) and lower EF(CO₂) than sustained flaming, overrepresentation of smoldering in the laboratory experiments could bias regional carbon partitioning toward incomplete-
 450 combustion products. The magnitude of this bias cannot be constrained without regional information on the relative contributions of flaming and smoldering. The regional calculation therefore quantifies how carbon partitioning responds to fuel moisture and fuel state within a smoldering-dominated regime, and the shift toward CO and CH₄ should be regarded as an upper bound of an EF inventory of evergreen needleleaf forest fires containing a substantially larger flaming contribution. The regional representativeness of the experimental conditions introduces additional uncertainty. The EFs were derived from
 455 live-origin and litter-derived dead *Pinus massoniana* needles collected at a single site and season and were used as proxies for evergreen needleleaf forest fuels across Southwest China. However, evergreen needleleaf forests also include other conifer species, and natural fires also consume branches and woody fuels with different burning characteristics, introducing uncertainty when extrapolating the laboratory-derived EFs to the regional scale. The regional live–dead partition was further represented using a fixed fuel-state allocation derived from a large-sample survey of *Pinus yunnanensis* forests (Xian et al.,
 460 2023). Although this provides a field-based regional constraint, fixed live and dead fuel fractions cannot capture spatial and temporal variability in fuel composition among forest stands.

Uncertainty also arises from parameterizing the laboratory-derived EF relationships. The moisture-dependent models explained 60.3–81.5 % of the variability in the mean EF(CO₂) and EF(CO), indicating that EF variability is also influenced by fuel properties, oxygen availability, and burning mode (Garg et al., 2024; Wang et al., 2024). The absolute regional estimates
 465 also inherit uncertainties in the activity data and fuel-consumption parameters used in the bottom-up inventory approach, including burned area, fuel loading, fraction burned, and vegetation classification (Wiedinmyer et al., 2023). The regional results are therefore most appropriately interpreted as quantifying how fuel-condition-resolved EFs alter gaseous carbon partitioning relative to fixed EFs, rather than as a definitive estimate of absolute regional emissions. The estimated 65 % difference in near-term greenhouse impact should likewise be regarded as a GWP-based screening estimate rather than a direct
 470 estimate of radiative forcing in Southwest China (Forster et al., 2021).

4 Conclusions

Wildfire emission inventories are usually evaluated in terms of total carbon release. When evaluated only by total represented gaseous carbon, the fixed-EF and fuel-condition-resolved estimates appear broadly similar. However, the environmental significance of wildfire emissions depends not only on how much carbon is released, but on the chemical form in which it is



475 released. Because carbon-balance emission factors normalize CO₂, CO, and CH₄ to measured fuel carbon, the summed carbon
 they represent is constrained by construction. The environmentally informative signal is therefore not the total represented
 gaseous carbon, but its partitioning among individual species. Fuel moisture altered this partitioning in opposite directions for
 live-origin and litter-derived *Pinus massoniana* needles under predominantly smoldering combustion: increasing moisture
 shifted carbon from CO₂ toward CO in live-origin needles, whereas the conditional relationship was reversed for litter-derived
 480 needles. CH₄ varied substantially but showed no supported monotonic moisture response. Resolving fuel condition shifted
 approximately 14 % of represented CO₂-C to CO and CH₄ over 2012–2021 and increased the GWP₂₀-weighted near-term
 burden by roughly 65 % in a regional estimation scenario in Southwest China. An inventory using fixed EFs can therefore
 appear adequate in total carbon while remaining substantially inaccurate in pollutant-specific emissions relevant to atmospheric
 oxidation, methane persistence, ozone formation, and climate effects (Szopa et al., 2021).

485 This study provides a practical framework for correcting this limitation. It retains the activity data and fuel-consumption
 structure of existing bottom-up inventories while allowing the emission-factor layer to respond to fuel origin, moisture, and
 burning regime through operational moisture fields. Increasing temperatures, more frequent heat extremes, and prolonged
 drought have already altered wildfire danger and forest-fire emissions in many regions and are expected to continue modifying
 fuel moisture and fire regimes (Jolly et al., 2015; Jones et al., 2024). Fixed emission factors assigned to vegetation classes
 490 cannot fully represent such variations across seasons, fire events, and changing climate conditions (Chen et al., 2010;
 Wiedinmyer et al., 2023). However, the relationships developed here were based on one conifer species and mainly on
 smoldering-dominated laboratory combustion. Further studies should include additional fuel components and species, cover
 the full flaming–smoldering continuum, and use field-integrated measurements. With such validation, moisture- and fuel-
 origin-dependent emission factors could improve estimates of species-specific wildfire emissions and support more reliable
 495 assessments of their atmospheric and climate effects.

Code and data availability

The experimental datasets required to reproduce the results of this study, the emission factor fitting results, and the associated
 analysis and calculation scripts will be archived together in a public repository. The repository DOI and access link will be
 provided once the archival process is completed.

500 The regional emission calculations used fire-activity and fuel-consumption information from the FINN framework
 (Wiedinmyer et al., 2023), MCD12Q1 land-cover data (Sulla-Menashe et al., 2019), and daily fuel-moisture data from the
 Observation and ERA5-Land Derived 9 km Global Daily Fire Fuel Characteristics since 2003 dataset (European Centre for
 Medium-Range Weather Forecasts, 2025). GFED5.1 data were used for the inventory-level comparison (Van Der Werf et al.,
 2025). These external datasets are available from their respective data providers.



505 Supplement link

The link to the supplement will be included by Copernicus, if applicable.

Author contributions

Heng Xie: Investigation, methodology, data curation, formal analysis, visualization, writing—original draft.

Yuqi Hu: Methodology, supervision, formal analysis, validation and resources, Writing—review & editing.

510 Yaohan Xian: Software, Data curation.

Chuan Wan: Investigation, Data curation.

Yuan Li: Data curation.

Guowei Qi: Data curation.

Fumo Yang: Review & editing, supervision, funding acquisition.

515 Nan Wang: Conceptualization, supervision, writing—review & editing, funding acquisition, and resources.

Competing interests

The authors declare that they have no conflict of interest.

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