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Reviews and syntheses: Spatiotemporal Dynamics, Drivers, and Uncertainties of Global Wildfire Carbon Dioxide Emissions

Yu Liang[1], Tianxiao Ma[1], Bo Liu[1], Zhihua Liu[1*], Hong S. He[2*], Jian Yang[3], Yude Pan[4], Chao Yue[5], Xianli Wang[6], Mia M. Wu[1], Wenru Xu[1], Jiaojun Zhu[1]

[1]CAS Key Laboratory of Forest Ecology and Silviculture, Institute of Applied Ecology, Chinese Academy of Sciences, Shenyang 110016, China
[2]School of Natural Resources, University of Missouri, Columbia, MO 65211, USA
3Department of Forestry and Natural Resources, University of Kentucky, Lexington, KY, 40546-0073, USA
[4]USDA Forest Service, Durham, NH 03824, USA
[5]State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Northwest A & F University, Yangling 712100, China
[6]Natural Resources Canada, Canadian Forest Service, Northern Forestry Centre, Edmonton, Alberta T6H 3S5, Canada

Correspondence to : Zhihua Liu (liuzh@iae.ac.cn), Hong S. He (heh@missouri.edu)

Abstract. Wildfire carbon dioxide emissions (WCEs) are increasingly recognized as a major and highly uncertain component of the global biogeochemical carbon cycle, reflecting limitations in constraining their historical evolution, future trajectories, and controlling mechanisms. This review synthesizes evidence from satellite-based emission products, fire-enabled model reconstructions and scenario projections, and paleoenvironmental archives (charcoal and ice-core black carbon) to evaluate global WCE dynamics from 1700 to 2100. Historical reconstructions indicate relatively stable global WCEs during 1700–1850, whereas pronounced divergence emerges during 1851–2000 due to differing representations of land-use change and industrialization. Contemporary satellite observations show declining WCEs over 2001–2020 (8.72 ± 0.67 Pg CO_2 yr^{-1}), with 83% originating from tropical ecosystems because of large burned area and high combustion efficiency. Importantly, these fluxes represent a critical shift in the net carbon balance of tropical and boreal biomes. Multi-model projections suggest increases through the 2040s, followed by growing divergence under alternative socioeconomic pathways. Across datasets and models, annual WCE estimates differ by up to 40%, driven by uncertainties in fire detection, combustion completeness, emission factors, and fire–climate–human interactions. Despite regional heterogeneity, climate change emerges as the primary regulator of interannual variability in WCEs. Approximately 43% of global vegetated areas have experienced increasing extreme wildfire seasons, particularly in northern high-latitude forests where recurrent burning amplifies carbon losses and weakens ecosystem carbon sinks. We conclude by identifying priorities for reducing uncertainty through tighter integration of multi-source observations with fire-enabled process models, improved representation of coupled fire–climate–carbon feedback and post-fire recovery, and the application of artificial intelligence to better constrain WCE spatiotemporal variability and enhance predictive capability under increasingly nonlinear fire–climate interactions.

1 Introduction

Wildfires are a fundamental component of the Earth system and exert a pivotal influence in shaping terrestrial ecosystem structures and functions. Since the Silurian period, wildfires have released carbon dioxide (CO_2) and other trace gases to the atmosphere, modulating atmospheric composition and climate (Bowman et al., 2009). Anthropogenic emissions, primarily from fossil fuel combustion, have become the dominant source of the atmospheric CO_2 in the postindustrial era, 40.19 ± 3.30 Pg CO_2 yr^{-1} from 2000 to 2020. Meanwhile, satellite observations from this period suggest that wildfires annually burned 3.8–4.8% of global vegetated land and wildfire carbon dioxide emissions (WCEs) emitted approximately 20% of CO_2 released from fossil fuel combustion (Jones et al., 2022; Van Der Werf et al., 2017; Zheng et al., 2021). Between 2013 and 2022, WCEs accounted for 35–52% of the net annual atmospheric CO_2 increase (19.08 ± 0.07 Pg CO_2 yr^{-1}) (Friedlingstein et al., 2023; Zheng et al., 2023). Despite this evident importance, estimates of the magnitude and spatiotemporal dynamics of WCEs remain highly uncertain, reflecting pronounced heterogeneity across regions and biomes. This persistent uncertainty underscores the need for systematic synthesis and mechanistic understanding.

WCEs are regulated by multiple interacting drivers that operate across various spatial and temporal scales (Moritz et al., 2005; Parisien and Moritz, 2009). At broad scales, climate and atmospheric conditions exert dominant control, whereas finer-scale variability is shaped by vegetation structure, fuel availability, topography, ignition sources, and human land-use practices (Parisien and Moritz, 2009; Bowman et al., 2009). Interannual variability in WCEs often mirrors climate anomalies such as ENSO events, while regional signatures arise from local biophysical and anthropogenic influences (Chen et al., 2017; Van Der Velde et al., 2021). This multiscale interplay generates pronounced spatial and temporal heterogeneity, complicating efforts to comprehensively quantify and predict global WCEs. Although advances in satellite remote sensing, process-based modeling, and paleoenvironmental reconstructions have greatly enhanced the characterization of wildfire activity and associated emissions (Luo et al., 2024; Marlon et al., 2012; Van Der Werf et al., 2017; Zheng et al., 2021), it is still challenging to adequately capture the full range of processes and drivers underlying WCEs. Future progress will likely rely on integrating multiple observational and modeling frameworks to constrain WCEs variability and improve attribution of underlying drivers (Forkel et al., 2019; Hantson et al., 2020; Kelley et al., 2014).

Climate warming and intensified human activities are expected to amplify wildfire activity, giving rise to extreme wildfire seasons (EWS) characterized by unprecedented intensity, rapid spread, and extensive burned area (Bowman et al., 2017; Tedim et al., 2018). These events lead to disproportionate increases in WCEs, reduce terrestrial carbon sequestration, and trigger long-lasting ecosystem transformations that favor fire-adapted species and alter vegetation structure and composition (Senande-Rivera et al., 2022; Jones et al., 2022; Walker et al., 2019). Individual extreme wildfire events can contribute a substantial fraction of annual WCEs, intensifying climate–carbon feedback and highlighting the growing ecological and biogeochemical consequences of EWS (Bowman et al., 2020; Coop et al., 2020; Zheng et al., 2023).

This Review synthesizes the spatiotemporal dynamics of global wildfire carbon dioxide emissions (WCEs) across historical (1700–2000), contemporary (2001–2020), and future (2021–2100) periods by integrating evidence from satellite-based products, process-based models, and scenario projections. We evaluate the major drivers regulating WCEs across spatial and temporal scales and examine recent extreme wildfire seasons (EWS), which have become increasingly important contributors to interannual variability in global WCEs. Building on this synthesis, we delineate research priorities for reducing uncertainty and improving predictability, including methodological integration across observations and models, improved representation of climate–wildfire feedback in fire-enabled Earth system models, and mechanistic constraints on post-fire carbon recovery. Collectively, these advances provide an integrated framework to support more robust projections and to inform wildfire management and climate mitigation strategies.

2 Spatiotemporal Dynamics and Uncertainties of WCEs

Global WCEs exhibit substantial spatial and temporal variability due to differences in burned area, fuel availability, combustion completeness, and climate conditions across ecosystems. These estimates remain highly uncertain because satellite products, model structures, fire parameterizations, fuel consumption estimates, and emission factors differ substantially across datasets and modelling frameworks. Evaluating these spatial patterns and temporal trajectories therefore requires explicit consideration of the uncertainties embedded in both observational products and model-based estimates.

2.1 Spatial pattern of WCEs from 2001 to 2022

The ensemble mean of four fire emission datasets (Table 1), including the Global Fire Emissions Dataset with small fires (GFEDv4s), the Global Fire Assimilation System Dataset (GFASv1.2), the Quick Fire Emissions Dataset (QFEDv2.6r1), and the Fire Energetics and Emissions Research Dataset (FEER), indicates that the global burned area averaged 440 ± 50 Mha yr^{-1} from 2001 to 2020 (Bowman et al., 2020), corresponding to 8.72 ± 0.67 Pg CO$_2$ yr^{-1} of WCEs. Spatially, pronounced variations in WCEs are observed across continents and biomes, with tropical and subtropical ecosystems dominating global WCEs because extensive burned areas and high combustion completeness promote large carbon releases, particularly across African savannas and tropical dry forests. Africa contributed the most to WCEs (45.33 ± 8.40 %), followed by Asia (20.44 ± 3.42 %), South America (17.01 ± 4.43 %), North America (7.78 ± 1.74 %), Oceania (7.46 ± 3.25 %), and Europe (1.98 ± 0.53 %). Tropical fires, primarily within 20°S-15° N, account for approximately 83% of global WCEs (Fig. 1), largely due to tropical dry forests in Amazonia. In addition, tropical forest fire occurrence has marked spatial and temporal heterogeneity, especially in Southeast Asia (0.77 ± 0.33 Pg CO$_2$ yr^{-1}) which contributes more than 1/3 of total Asian WCEs. Temperate and boreal regions above 45°N contribute approximately 12% of global WCEs (Fig. 1) and have experienced increasing wildfire activity and carbon emissions in recent decades, especially during EWSs associated with climate warming. (De Groot et al., 2013).

Table 1. Summary of four fire emission datasets used in this analysis.

Dataset	Methods	Spatial resolution	Time frame/ Frequency	Used fire product	Emission factor	Biome types	References
GFED v4s	Burn area-based	0.25°×0.25°	2000–2015/3-hourly, daily, monthly	Daily MCD64A1 product in Collection 5.1 at 500m spatial resolution; L3 MOD14A1 and MYD14A1; fire location	Mainly from Akagi et al. (2011), supplemented by Andreae and Merlet (2001) and others	Agricultural waste burning; Boreal forest fires; Tropical forest fires; Savanna, grassland, and shrubland fires; Temperate forest fires; Peat fires	Van Der Werf et al. (2017)

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				product MCD14ML			
GFAS 1.2	FRP (Fire radiative power)-based	0.1°×0.1°	2003–present/daily	Assimilation of level 2 MOD14 and MYD14 FRP; Statistical regression of the output when assimilating only Aqua or Terra observations	Mainly from Andreae and Merlet (2001) with updates from literatures through 2009	Agricultural waste burning; Tropical forest fires; Savanna, grassland, and shrubland fires; Extratropical forest fires; Peat fires	Kaiser et al. (2012)
FEER 1.0	FRP-based	0.1°×0.1°	2003–present/daily, monthly	From GFASv1.2 (Kaiser et al., 2012)	Andreae and Merlet (2001) with updates provided by Andreae (2019)	Agricultural waste burning; Tropical forest fires; Savanna, grassland, and shrubland fires; Extratropical forest fires; Peat fires	Ichoku and Ellison (2014)
QFED 2.6	FRP-based	0.1°×0.1°	2000–present/daily, monthly	Level 2 fire products MOD14/MYD14	Andreae and Merlet (2001)	Tropical forest fires; Savanna, grassland, and shrubland fires; Extratropical forest fires	Darmenov and Da Silva (2015)

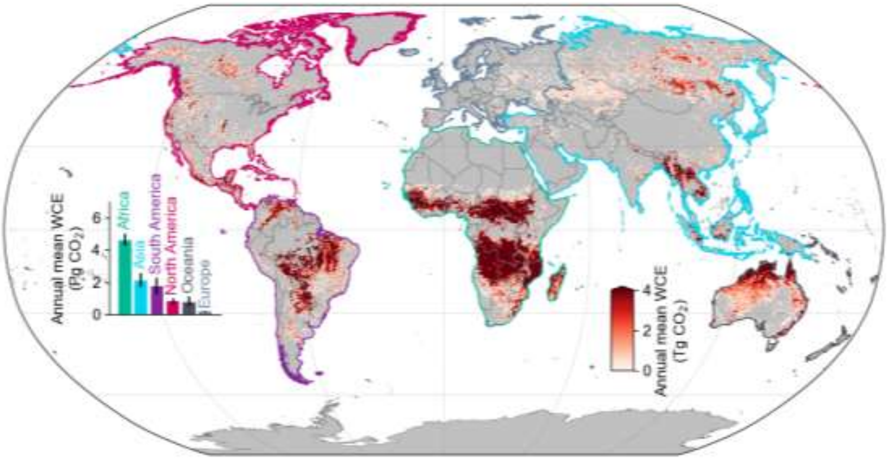

Figure 1. The global pattern of annual mean WCEs from 2001 to 2022 averaged based on four fire emission datasets (GFED, GFAS, QFED and FEER), gridded at 0.1° resolution.

The change rates of annual WCEs show distinct global patterns, quantified using the Theil–Sen slope estimator and Mann–Kendall test (95% confidence interval; Fig. 2). At the continental scale, North America (+19.72 Tg CO_2 yr^{-1}, significant), South America (+14.92 Tg CO_2 yr^{-1}), and Asia (+8.95 Tg CO_2 yr^{-1}) exhibit increasing trends, whereas Africa (–32.92 Tg CO_2 yr^{-1}, significant), Oceania (–11.64 Tg CO_2 yr^{-1}), and Europe (–3.25 Tg CO_2 yr^{-1}) exhibit decreasing trends. Using density-based spatial clustering algorithm (DBSCAN), we identified seven major positive hotspots (red boxes) in the Canadian

Boreal Forest (+8.45 Tg CO_2 yr^{-1}), Pacific Coast of the United States (+7.44 Tg CO_2 yr^{-1}), Central America (+11.16 Tg CO_2 yr^{-1}), northern South America (+17.96 Tg CO_2 yr^{-1}), Madagascar (+4.44 Tg CO_2 yr^{-1}), Southeast Asia (+6.25 Tg CO_2 yr^{-1}), and eastern Siberia (+6.75 Tg CO_2 yr^{-1}). Six negative hotspots (blue boxes) are located in Alaska (–4.72 Tg CO_2 yr^{-1}), the Amazon Rainforest (–10.06 Tg CO_2 yr^{-1}), sub-Saharan Africa (–6.85 Tg CO_2 yr^{-1}), northern Australia (–2.98 Tg CO_2 yr^{-1}), and the eastern (–6.30 Tg CO_2 yr^{-1}) and western (–2.98 Tg CO_2 yr^{-1}) Eurasian steppes. Strongest increases occur in boreal and temperate forests, reflecting enhanced fuel accumulation and fire activity under warming (Jones et al. 2024). In contrast, negative hotspots in tropical forests and grass-dominated ecosystems (–3 to –11 Tg CO_2 yr^{-1}) are linked to land-use change, fire suppression, and climatic variability (Jones et al., 2024), and show higher uncertainties (black lines in Fig. 2). Together, these contrasting regional patterns underscore the combined influence of climate, ecosystems, and human activity on the dynamics of global WCEs.

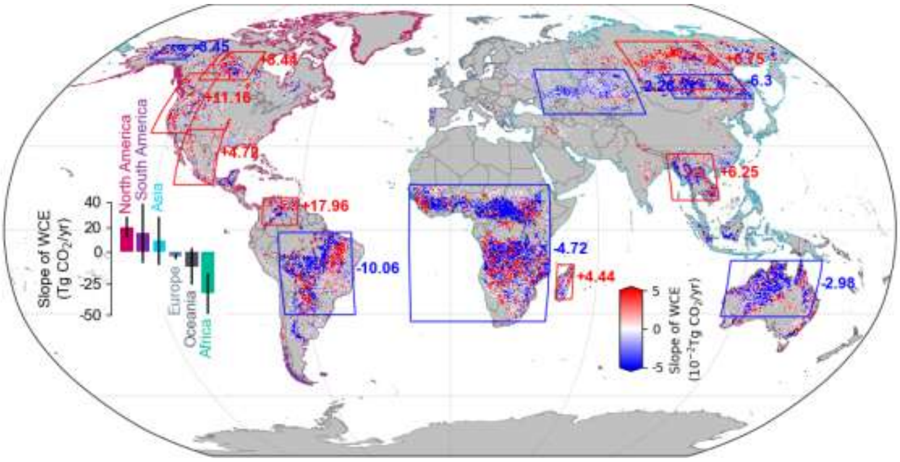

Figure 2. The global pattern of changes rates (Theil-Sen slope) in annual WCEs from 2001 to 2022 based on four fire emission datasets, gridded at 0.1° resolution. Hotspots of increasing and decreasing WCEs are indicated by red and blue boxes, respectively.

Trends in WCEs and burned area exhibited divergent spatial patterns (Bowman et al., 2020; Zheng et al., 2021). Increases in burned area do not necessarily result in increasing WCEs (e.g. in Africa and Oceania), since vegetation flammability and biomass density critically mediate carbon release efficiency (Bowman et al., 2020). In herbaceous-dominated ecosystems (e.g., grasslands and savannas), the expansion of burned areas typically amplifies CO_2 emissions. This pattern likely reflects their low aboveground biomass density (<5 t/ha) and spatially homogeneous fuel loads, which promote combustion completeness (>90%) (Andela et al. 2019). Conversely, in high-biomass ecosystems like boreal forests (>150 t·C·ha^{-1}) or tropical forests, elevated moisture content (vegetation >30%, soil >25%) suppresses flammability and limits the deep ignition of soil organic carbon (SOC) pools. Consequently, when critical moisture thresholds are exceeded, larger burned areas in these systems may release less CO_2 than theoretical models predict (Chen et al., 2010; Walker et al., 2020).

2.2 Temporal dynamics of global WCEs

Since systematic global fire emission monitoring has only been available since 2000, reconstructions of long-term WCEs have relied on an ensemble of Earth System Models (ESMs), Dynamic Global Vegetation Models (DGVMs), machine-learning (ML) surrogates, and paleoenvironmental proxies such as charcoal and ice-core black carbon records. A central initiative in this field is the Fire Model Intercomparison Project (FireMIP), which harmonized input datasets (e.g., CRU TS climate forcing, historical land-use change) and designed standardized experimental protocols to benchmark model performance against satellite products (e.g., MODIS burned area, GFED emissions) and paleo-archives (e.g., charcoal, ice-core black carbon) (Rabin et al., 2017). Ensemble means from FireMIP, aggregating outputs from multiple fire-enabled DGVMs, have been widely employed to quantify historical trajectories and project future pathways of WCEs under Shared Socioeconomic Pathways (SSPs) (Li et al., 2024). FireMIP simulations revealed a shift from precipitation-dominated fire regimes in the pre-industrial era to anthropogenic-dominated regimes post-1850 (Burton et al., 2019), with an impending transition to temperature-driven regimes by 2100. These efforts are increasingly complemented by ML frameworks that integrate satellite observations with process-based models, thereby reducing emission uncertainties, particularly in human-dominated landscapes such as agricultural frontiers and urban wildland interfaces (Burton et al., 2019; Li et al., 2019; Rabin et al., 2017; Yu et al., 2022).

Historical WCEs (1700–2000) in this study were derived from DGVMs participating in FireMIP (Fig. 3). Although global emissions remained relatively stable prior to 1850 (±0.1% yr^{-1}), reflecting predominantly natural climate variability, the post-1850 period exhibits strong divergence among models. These differences are largely attributable to accelerating land-use change (e.g., tropical deforestation for agriculture) and industrial-era landscape fragmentation (Van Marle et al., 2017; Li et al., 2024). Models that explicitly incorporate anthropogenic ignitions (e.g., LPJ-GUESS-SIMFIRE-BLAZE) or Bayesian optimization (FINAL) simulate declining WCEs, consistent with CMIP6 projections emphasizing fire suppression in converted landscapes. In contrast, process-based models such as ORCHIDEE-SPITFIRE and paleo reconstructions from ice-core black carbon and sedimentary charcoal point to marked increases in fire emissions (Ferretti et al., 2005; Wang et al., 2010). This divergence underscores a key uncertainty: many DGVMs underestimate the extent of human–fire interactions, whereas empirical reconstructions suggest enhanced burning linked to deforestation, peatland drainage, vegetation feedback, and land-use intensification (Marlon et al., 2008; Li et al., 2024).

Moving from model-based reconstructions to the satellite era, contemporary satellite-derived fire emission datasets capture consistent magnitudes and interannual variability of WCEs, with pronounced peaks during El Niño–induced droughts and reductions in La Niña years (Van Der Werf et al., 2017). Between 2001 and 2020, the four widely used datasets (GFED, QFED, CAMS, and FEER) reveal broadly comparable global averages but exhibit substantial discrepancies in interannual dynamics and long-term trends (Fig. 3). Several products suggest a modest decline in global fire emissions during the early 21st century, largely linked to reductions in burned area across savanna regions of Africa and South America (Andela et al., 2017; Zheng et al., 2021), whereas others indicate relatively stable emissions, underscoring their strong dependence on dataset choice and the continuing uncertainties associated with satellite retrievals and emission modeling.

Extending beyond the observational record, future projections of WCEs (2021–2100) draw on fire-enabled DGVMs (e.g., CLM4.5, ModelE2-YIBs), ESMs from CMIP5 and CMIP6, and ML-based ensembles (Kloster and Lasslop, 2017; Park et al., 2023; Yu et al., 2022). Multi-scenario simulations consistently suggest a near-term increase of 0.3-0.8% yr^{-1} through the 2040s (Richardson et al., 2022), largely driven by climate warming that extends fire seasons and intensifies compound drought–heatwave extremes. After mid-century, projections diverge across socioeconomic pathways: high-emission scenarios (e.g., SSP5-8.5) amplify boreal fire–carbon feedbacks through permafrost thaw and peatland drying, leading to up to 40% greater cumulative carbon loss in Canadian boreal forests by 2060 than under low-emission pathways (e.g., SSP1-2.6) (Mccarty et al., 2020; Turetsky et al., 2015). Under low-emission scenarios (e.g., SSP1-2.6 and SSP2-4.5), projected fire carbon emissions increase more modestly, with part of the increase potentially buffered by enhanced vegetation regrowth and strengthened fire-suppression policies (Bowman et al., 2020; Park et al., 2023; Zhao et al., 2025).

Collectively, these scenarios underscore the central role of climate–fire–carbon feedbacks in shaping the future global carbon budget, while emphasizing the urgent need to better represent human influences in fire-enabled Earth system models.

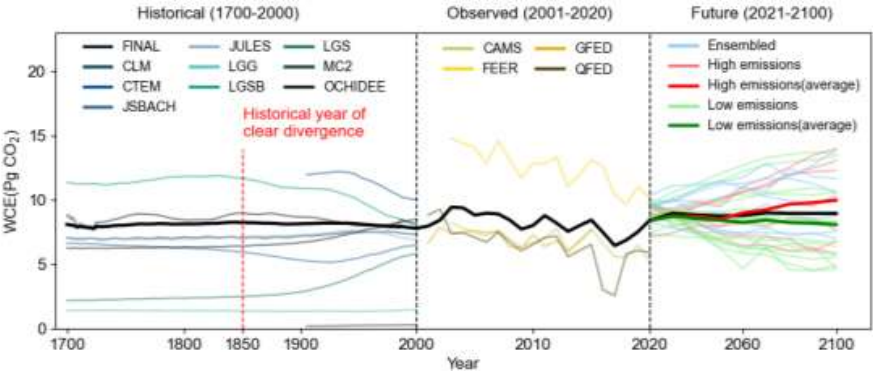

Figure 3. Trends of global WCEs from 1700 to 2100. Historical estimates (1700–2000) are derived from DGVMs participating in the FireMIP, including CLM4.5/CLM5 (Li et al., 2012), ORCHIDEE-SPITFIRE (Yue et al., 2015), LPJ-GUESS-SPITFIRE (Spessa and Fisher, 2010), MC2 (Bachelet et al., 2015), CTEM (Melton and Arora, 2016), LPJ-GUESS-GlobFIRM (Rabin et al., 2017), JULES-INFERNO (Burton et al., 2019), FINAL (Ward et al., 2018), LPJ-GUESS-SIMFIRE-BLAZE (Lehsten et al., 2009), and JSBACH-SPITFIRE (Lasslop et al., 2018). Contemporary estimates (2001–2020) are constrained by four fire emission datasets (GFED, GFAS, QFED and FEER). Future projections (2021–2100) are based on fire-enabled DGVMs (e.g., CLM4.5 and ModelE2-YIBs; Park et al. (2023)), ESMs from CMIP5 (e.g., IPSL-CM5A-MR, CCSM4; Kloster and Lasslop (2017)), and machine-learning ensembles of 13 CMIP6 ESMs (e.g., NorESM2-LM, MRI-ESM2-0; Yu et al. (2022)). Future projections are categorized into low-emission (SSP1-2.6 “Sustainability” and SSP2-4.5 “Middle of the road”) and high-emission (SSP3-7.0 “Regional rivalry”, SSP4-6.0 “Inequality”, and SSP5-8.5 “Fossil-fueled development”) scenarios, as well as an ensemble mean across scenarios.

National-scale trends in WCEs differ substantially across countries and territories, reflecting contrasting interactions among climate warming, vegetation characteristics, land-use change, and fire management. Several representative countries are shown to illustrate these divergent trajectories across major regions and biome types (Fig. 4). Russia, Canada, and the USA show substantial rises in WCEs (Fig. 4b, d, e). As vegetation types are also relevant to WCEs, increased WCEs in Russia (0.41 ± 0.19 Pg CO_2 yr^{-1}) and Canada (0.12 ± 0.07 Pg CO_2 yr^{-1}), mainly from increased forest fires linked to elevated regional temperature (Drobyshev et al., 2021; Flannigan et al., 2016; Jain et al., 2017), while in the USA (0.16 ± 0.08 Pg CO_2 yr^{-1}) the increase was mainly from increased grassland fires due to extensive droughts (Bowman et al., 2017; Sutanto et al., 2020). Conversely, Brazil (0.85 ± 0.35 Pg CO_2 yr^{-1}), China (0.06 ± 0.02 Pg CO_2 yr^{-1}), the Democratic Republic of Congo (0.88 ± 0.07 Pg CO_2 yr^{-1}), Australia (0.64

± 0.29 Pg CO_2 yr^{-1}), and Indonesia (0.24 ± 0.25 Pg CO_2 yr^{-1}) exhibit declines in WCEs (Fig. 4c, f, g, h, i), attributed to effective policies and management practices promoting fire prevention and forest conservation (e.g., New Forest Code in Brazil, REDD+ in Congo, Bushfire Management Policy in Australia) (Andela et al., 2017; Jiang et al., 2020; Nepstad et al., 2014; Volkova et al., 2014).

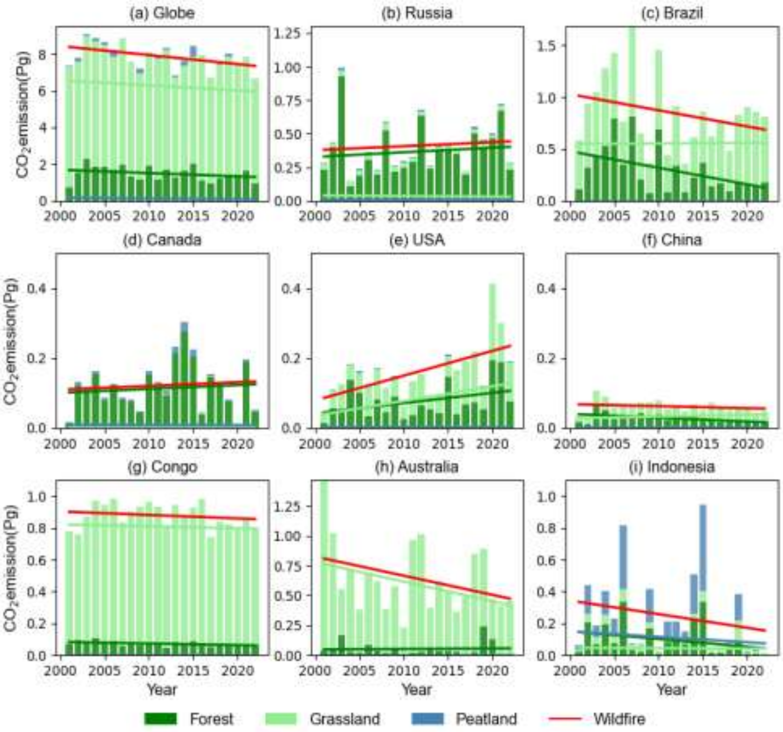

Figure 4. Annual means of WCEs from different biome types for the globe and some selected countries (sorted by forest areas) based on four biomass burning emission datasets. Lines of different colors represent the linear trend of WCEs from different biomes. (a) Globe; (b) Russia; (c) Brazil; (d) Canada; (e) USA; (f) China; (g) Congo; (h) Australia; (i) Indonesia.

2.3 Uncertainties in WCEs estimates

Satellite-derived fire carbon emission products play a critical role in contemporary fire monitoring, yet large discrepancies remain across datasets due to differences in estimation methodologies and input data (Liu and Yang, 2023). Burned area products differ widely in detection capabilities, particularly for small agricultural fires, crop residual burning, and fire events obscured by cloud and smoke (Randerson et al., 2012). For example, MODIS Collection 6 improved small-fire detection, whereas FireCCI emphasized finer spatial resolution (Chen et al., 2023; Lizundia-Loiola et al., 2020). Additional uncertainties arise from assumptions related to fuel combustion (Van Wees et al., 2022; Potter et al., 2023), emission factors (Jayarathne et al., 2018; Wiggins et al., 2021), conversion factors (Kaiser et al., 2012), and fire emission inventories (Liu et al., 2020). Combustion completeness depends strongly on burning depth, which varies from a few centimeters in grasslands to >80 m in tropical peatlands (Che Azmi et al., 2021; Van Der Werf et al., 2017). Furthermore, emission factors and FRP-to-emission conversion coefficients vary with vegetation type, combustion conditions, and sensor characteristics, thereby introducing systematic errors across products (Fan et al., 2023; Kaiser et al., 2012). Persistent discrepancies between top-down (FRP-based) and bottom-up (area-based) approaches lead to large regional and interannual divergences in CO_2 estimates (Nguyen and Wooster, 2020). Reducing these inconsistencies will require multi-sensor fusion, atmospheric inversion, and expanded ground validation networks (Chevallier et al., 2019).

Reconstructing and projecting WCEs are complicated by uncertainties in fire–climate–ecosystem feedback and deficiencies in representing processes within ESMs. Although fire-enabled DGVMs capture substantial spatiotemporal variability, only ~30% of CMIP6 ESMs explicitly represent fire–climate feedback, resulting in systematic underestimation of emissions in boreal and tropical regions (Bowman et al., 2020; Pan et al., 2020). Many models fail to reproduce the observed decline in global burned area since 2000, largely due to insufficient representation of anthropogenic suppression, land-use change, and vegetation feedback (Andela et al., 2017; Li et al., 2024). These limitations were evident during extreme wildfire events including Australia's 2019–2020 fires and Canada's 2023 wildfires, where models struggled to capture vegetation mortality, peat combustion, and prolonged fire weather conditions (Abram et al., 2021; Walker et al., 2020). Projections under high-emission scenarios suggest that up to 53% of global vegetated areas may transition from carbon sinks to carbon sources by 2100, emphasizing the importance of refining combustion processes, more effectively incorporating land-use policies, and better accounting for socioeconomic drivers of fire (Bowman et al., 2020; Knorr et al., 2016).

In summary, estimates of WCEs exhibit consistently large uncertainties across observational, historical reconstruction, and future modeling domains. Comparative analyses of datasets reveal variations of up to 40%: 2.90–3.79 Pg CO_2 yr^{-1} for historical periods, 0.71–3.97 Pg CO_2 yr^{-1} for contemporary observations, and 0.43–3.37 Pg CO_2 yr^{-1} for future projections. The primary factors driving such wide ranges are disparities in satellite detection, fuel combustion modeling, emission factors, and the treatment of fire–climate–human interactions within models. Collectively, these findings highlight that uncertainties in WCE estimates are not a single-product problem but a cross-scale challenge arising from observation, parameterization, and model-structure limitations. Reducing these uncertainties will require tighter integration of multi-source observations, advancing fire parameterizations, and explicit incorporation socioeconomic processes and extreme fire events into fire-enabled ESMs.

3 Dominant Drivers Regulating WCEs

The drivers regulating WCEs are closely related to the factors that drive wildfire occurrence(Jones et al., 2024). WCEs are directly determined by the amount of biomass combusted, which depends on the area burned, fuel loadings, combustion completeness, and emission factor of dry biomass (Chen et al., 2024). These metrics, in turn, are controlled by a combination of natural and anthropogenic divers, which can be broadly categorized as climate and fire weather, vegetation and fuel characteristics, ignition sources, wildfire regimes, fuel treatment, and fire suppression activity (Jones et al., 2024; Moritz et al., 2005; Parisien and Moritz, 2009) (Fig. 5). However, the relative importance of these drivers varies substantially across temporal and spatial scales. For instance, at the shorter temporal scales (days, weeks, or months), weather conditions and atmospheric circulation patterns strongly determine the availability and flammability of fuels, thereby influencing wildfire extent, severity, and associated CO_2 emissions (Moritz et al., 2005). At the longer temporal scales (decadal), climate determines the spatial distribution of vegetation and fuel quantities and shapes wildfire behavior, which in turn determines WCEs (Walker et al., 2020). At the micro- and meso-scales (1 km^2 ~ 10^3 km^2), WCEs are more controlled by fire weather/climate, fuel/vegetation characteristics, topography, and ignition sources (Moritz et al., 2005; Parisien and Moritz, 2009). Nevertheless, at global scale, human activities may alter vegetation and climate which influence fire activities in terms of their frequency and extent (Table 2). Although relative importance of driving factors varies temporally and geographically, influenced by biophysical conditions and human activities, climate change is the primary driver of the interannual variability of WCEs (Abatzoglou et al., 2021).

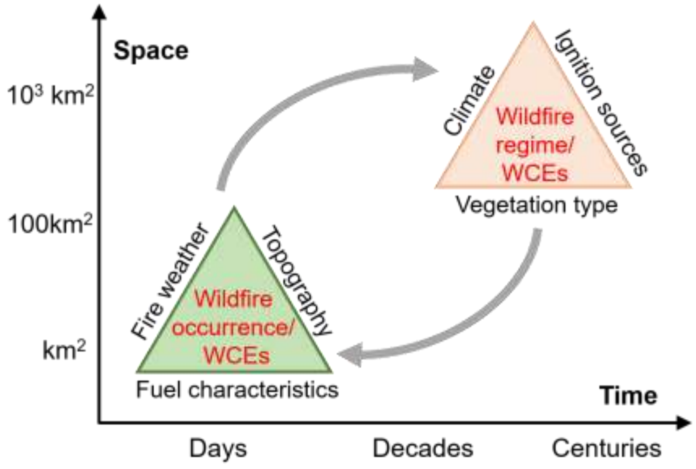

Figure 5. Wildfire occurrence and CO_2 emissions are governed by multiple controls operating across broad scales 300 of space and time. The framework illustrates both the factors controlling wildfire occurrence and WCEs (triangles) as well as the interactions between processes operating across different scales (arrows). Adapted from Moritz et al. (2005).

Table 2. Attribution of dominant drivers of wildfire occurrence and WCEs across globe and each continent.

Globe/ Continent	**Drivers of wildfire occurrence and WCEs**			**References**
	Climate/Weather	Vegetation/Fuel	Human activity	
Globe	Fire weather (++)	Total biomass stocks (-) Tree biomass stocks (-) Non-tree biomass stocks (+)	Population density (+)	Jones et al. (2022)
	Precipitation (--) Temperature (+)		Average distance from the nearest city (---) Population density (+) Ratio of rural to total population (-)	Wu et al. (2021)
	Precipitation (--) Temperature (+) Solar downward radiation (+)			Tang et al. (2021)
Asia	Fire weather (++)	Total biomass stocks (-) Tree biomass stocks (-) Non-tree biomass stocks (+)	Population density (+)	Jones et al. (2022)
	Precipitation (--) Temperature (+)			Tang et al. (2021)

Europe	Fire weather (++)	Total biomass stocks (-) Tree biomass stocks (-) Non-tree biomass stocks (+)	Population density (+)	Jones et al. (2022)
	High temperature (+) Prolonged drought periods (+) Strong winds (+)	Fuel moisture content (-)	Distance to infrastructures or wildland-urban interface areas (-) Unemployment rates (+) Housing density (+)	Ganteaume et al. (2013)
Africa	Fire weather (++)	Total biomass stocks (-) Tree biomass stocks (-) Non-tree biomass stocks (-)	Population density (-)	Jones et al. (2022)
	Rainfall (++) Dry season (+)	Tree cover (+++)	Grazing (-) Population density (-) Road density (-) Percentage of communal land (+)	Archibald et al. (2009)
North America	Fire weather (++)	Total biomass stocks (-) Tree biomass stocks (-) Non-tree biomass stocks (+)	Population density (-)	Jones et al. (2022)
	Fire season length (-) Spring temperature (+) Spring precipitation (+) Annual precipitation (+) March insolation (+) Summer insolation (--)	Abundance of fire-prone species (+)		Ali et al. (2012)
South America	Fire weather (++)	Total biomass stocks (-) Tree biomass stocks (-) Non-tree biomass stocks (+)	Population density (+)	Jones et al. (2022)
	ENSO class (++) Precipitation (-)		Landscape fragmentation and deforestation (+)	Alencar et al. (2015)
Oceania	Fire weather (++)	Total biomass stocks (+) Tree biomass stocks (-) Non-tree biomass stocks (-)	Population density (-)	Jones et al. (2022)
	Surface soil moisture (-) Wind speed (+) Relative humidity (+) Heat waves (+)	Dead and live fuel moisture (-) Certain land cover types (+)	Grazing (+)	Deb et al. (2020)

Note: ‘‘+’’ means positive impact and “-” means negative impact. Drivers with more symbols (e.g., +++/---) represent more important compared in one study.

3.1 Climate and fire weather

Climate exerts a significant influence on both wildfire occurrence and WCEs over short- and long-term timescales. At a short-term timescale (spanning days to weeks), climatic anomalies such as droughts and heatwaves directly affect fire weather (e.g., temperature, humidity, and winds) (Abram et al., 2021). These sudden shifts in climate can significantly enhance wildfire occurrence risk, creating conditions where vegetation becomes drier, more flammable, and more susceptible to ignition, thereby increasing the likelihood of wildfires and their associated WCEs (Liu and Wimberly, 2015). In contrast, long-term (decadal to centennial) climatic trends in temperature and precipitation affect broader vegetation productivity, fuel accumulation, and landscape heterogeneity (Jones et al., 2022). These long-term climatic trends shape wildfire regimes by determining the types and distribution of fuels across large areas, which in turn influences both the frequency and intensity of wildfires and thus CO_2 emissions (Liu et al., 2012; Schoennagel et al., 2017).

With global warming, the frequency of such extreme climatic conditions is expected to increase, which is likely to result in larger, more intense, and more frequent wildfires (Schoennagel et al., 2017; Senande-Rivera et al., 2022; Gutierrez et al., 2021). The trend is already evident in many fire-prone regions, with models projecting significant increases in wildfire activity under future climate scenarios. Specifically, projections suggest a 29% global increase in area burned due to climate change, with particularly sharp rises in boreal forests (+111%) and temperate forests (+25%), alongside longer fire seasons (Senande-Rivera et al., 2022). In boreal forests of North America, wildfires are projected to release a cumulative 12 Pg CO_2 by 2050, accounting for approximately 3% of the global WCEs under the Paris Agreement's 1.5°C warming target (Phillips et al., 2022). Such projections underscore the critical importance of addressing both short- and long-term climate drivers of wildfire activity, as they collectively shape the future trajectory of wildfire-induced CO_2 emissions and their impact on global climate targets.

3.2 Vegetation and fuel characteristics

The magnitude and intensity of WCEs are strongly regulated by fuel combustion processes, which are determined by vegetation and fuel characteristics (Loehman, 2020; Bowman et al., 2020). Critical fuel factors controlling wildfire regime include fuel types, fuel structure, and fuel loadings (Bowman et al., 2020; He et al., 2004; Walker et al., 2020), which impact the spreading speeds, sizes, and intensity

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of wildfires (Keane, 2012; Ganteaume et al., 2013). High-moisture contents in coarse fuels and live biomass reduce fire intensity and WCEs, whereas lower moisture content in fine fuels accelerates wildfire spread and increases emissions (Fischer et al., 2015).

Different fuel types exhibit distinct combustion characteristics because of variations in physical structure and chemical properties, which further affect wildfire activities (Liang and Hurteau, 2023; Parisien et al., 2023). In general, coniferous species with dense lateral branches, flammable foliage and bark burn more rapidly and emit more CO_2 compared to broadleaf trees (Fonda, 2001; Oliveira et al., 2023).

Fuel loadings are another factor prominently affecting wildfire regimes and WCEs. The WCE is conventionally estimated using the equation: $WCE = A \times B \times CC \times EF$, where A is burned area, B is fuel loading, CC is combustion completeness, and EF is the emission factor of dry biomass (Chen et al., 2024). Previous studies showed a significant decline in global burned area (Andela et al., 2017) but a nonsignificant decrease of WCEs, suggesting the fuel combustion and emission intensity per unit of burned area are increasing (Zheng et al., 2021). This pattern likely reflects the high sensitivity of WCEs to fuel loadings, particularly under relatively modest fire weather (Walker et al., 2020) and forest biomass and fuel loadings have increased partially due to CO_2 fertilization and forest growth, which lead to increases in burned area and WCEs from 1850 to 2005 (Lasslop and Kloster, 2015).

Comparatively, fuel loadings are also affected by human activities, such as fuel management. Effective fuel management strategies, such as prescribed burns, can mitigate WCEs, enhance ecosystem resilience, preserve biodiversity, and improve overall ecosystem health (Bowman et al., 2020; Schoennagel et al., 2009). For instance, fuel reduction in fire-prone forests reduces 7% CO_2 emissions and 50% non-CO_2 greenhouse gas emissions compared to unmanaged forests (Volkova et al., 2014). The intensified wildfire suppression efforts in Alaska could lower CO_2 emissions by 0.89-3.87 Pg of CO_2 between 2021 and 2050 (Phillips et al., 2022).

3.3 Ignition patterns

As a primary catalyst for wildfire occurrence, ignition patterns determine where, when, and how frequently wildfires start, thereby profoundly shaping the ultimate scale of WCEs. Ignition sources can be broadly categorized as natural or human-caused (Balch et al., 2017; Jones et al., 2022). Natural ignitions encompass lightning strike, volcano eruption, rolling rock, spark, friction, and spontaneous combustion (Hantson et al., 2022; Perez-Invernon et al., 2023). Lightning strike is the predominant cause of natural wildfire under dry conditions, particularly in boreal forests (Perez-Invernon et al., 2023; Veraverbeke et al., 2017). Future lightning strikes across the conterminous United States are projected to increase 12 ± 5% for every degree of warming and about 50% over this century, which is expected to further escalate WCEs (Romps et al., 2014). However, alternative study employing upward cloud ice flux as a predictor suggests that lightning flash rates could decrease by approximately 15% in 2100, owing to alterations in atmospheric dynamics under high-warming scenarios (Finney et al., 2018). The key igniter for lightning wildfires is proposed to be Long-Continuing-Current (LCC) lightning flashes and the rate of LCC is projected to increase by 41% by the 2090s under RCP6.0 scenario (Perez-Invernon et al., 2023). These differing projections highlight the uncertainty in predicting future lightning activity and its impact on WCEs, underscoring the need for further research to refine our understanding of how climate change will influence lightning strikes and the frequency of lightning-induced WCEs.

Human-caused ignitions, either intentional or unintentional, are major contributors to global WCEs (Kountouris, 2020). The intentional human-caused ignitions may include the use of fires in deforestation, land clearing, and charcoal-making, while the unintentional human-caused fires are mainly accidental ignitions from smoking, heating, and cooking (Liu et al., 2012; Tian et al., 2013). The spatial distribution of human-caused WCEs varies widely. In North America, high frequency of human-caused WCEs occurred in the area with dense population and intensive land use change, but are negligible in the area with less human activities (Hantson et al., 2022). Similarly, in the boreal forest regions of Northeast China, the spatial distributions and emissions of wildfires are closely related to the local population density (Liu et al., 2012). In the contiguous United States, fire-occurrence database from the Fire Program Analysis (FPA FOD) and GFED revealed that human-caused fires accounted for twice as much CO_2 emission (36.67 Tg CO_2 yr^{-1}) as lightning-caused fires (19.96 Tg CO_2 yr^{-1}) (Liu and Yang, 2020).

3.4 Topography

Topography is the most stable factor influencing wildfire occurrence, spread, and WCEs, primarily exerting localized effects through its modulation of hydrothermal conditions that govern wildfire weather, fuel moisture content, fuel loading patterns, and ignition (Ganteaume et al., 2013; Littell et al., 2016). Steep slopes facilitate accelerated wildfire propagation through gravitational displacement of burning materials, significantly increasing the difficulty of containment and suppression compared to flat terrain where wildfire is relatively easier to control (Quintiere, 2016). Topography also plays a critical role in modulating wind behavior, which in turn significantly affects wildfire spread, severity, and thus WCEs (Quintiere, 2016). For instance, mountain ranges, valleys, and canyons can modify wind speed and direction, facilitating the expansion of wildfire fronts (Harris and Taylor, 2017). Wind can carry embers and firebrands across longer distances to unburned areas, accelerating wildfire spread (Fernandez-Pello, 2017). Furthermore, variations in topographic conditions lead to differences in vegetation type and fuel availability, with certain terrain features (e.g., south-facing slopes) being more prone to accumulating desiccated flammable fuel, thereby increasing wildfire risk and WCEs (Moritz et al., 2005). High-elevation areas are generally more susceptible to lightning-induced ignitions compared to lowland areas, particularly during drought periods on the southern slope of the Alps (Conedera et al., 2006).

4 Extreme Wildfire Seasons and Associated CO_2 Emissions

Climate extremes (such as heatwaves and droughts) and human activity have greatly increased the frequency of extreme wildfire seasons (EWS) (Bowman et al., 2017). Although no universally accepted definition of EWS currently exists, we define an EWS here as the year in which WCEs exceed one standard deviation over the mean of WCEs during 2001-2022. This operational definition identifies wildfire seasons characterized by exceptionally large, fast-spreading, and intense wildfires that deviate markedly from the historical range of variability in burned area, fire severity, and associated carbon emissions. Satellite observations and atmospheric inversion products reveal that, since 2000, several EWS have markedly amplified the interannual variability of global WCEs, with some EWS even exerting a single-event impact capable of altering the global annual WCE budget (Zheng et al., 2023). Such events can substantially amplify annual WCEs, alter regional carbon balance, and generate profound ecological and societal consequences (Bowman et al., 2017; Tedim et al., 2018).

4.1 Trends and spatial patterns of EWS emissions

Mounting evidence indicates that the frequency of the largest and most destructive EWS have escalated worldwide (Zheng et al., 2023; Cunningham et al., 2024; Bowman et al., 2017), further destabilizing the terrestrial carbon balance and amplifying the risk of carbon-cycle feedbacks to the climate system (Jones et al., 2022; Senande-Rivera et al., 2022; Walker et al., 2019). Recent studies show that global CO_2 emissions from EWS increased from 0.22 Pg CO_2 in 2015 to 1.06 Pg CO_2 in 2021 (Zheng et al., 2023). These escalated GHG emissions by EWS accelerate global warming, which further leads to more droughts and high temperature, contributing to occurrence and spread of extreme wildfires (Zheng et al., 2023). We found that approximately 43% of the vegetated land shows an increasing frequency of EWS globally (Fig. 6), coinciding with a 54% rise in extreme fire weather days (FWI 95th percentile) (Jones et al., 2022). Further analysis reveals that EWS are rapidly expanding into high-latitude boreal forests due to longer, warmer, and drier fire seasons (red pixel in Fig. 6).

Using density-based spatial clustering algorithm (DBSCAN), we identified a dramatic increase in EWS across most regions worldwide, with the exception of four negative hotspots (blue boxes) that represent areas of decreasing EWS. A comparison with the hotspot analysis of WCEs (Fig. 2), which revealed six negative hotspots, shows an intriguing discrepancy in the Amazon Rainforest and sub-Saharan Africa, with an increase in EWS frequency occurring despite a decline in WCEs. This divergence likely reflects the predominance of low-impact fires associated with declining human ignitions and the historically limited documentation of extreme wildfire trends (Bowman et al., 2011; Byrne et al., 2024). These findings suggest that the traditional focus on average fire intensities may obscure opposing patterns in extreme wildfire seasons, which cause the greatest damage and release the largest amounts of CO_2 emissions (Cunningham et al., 2024).

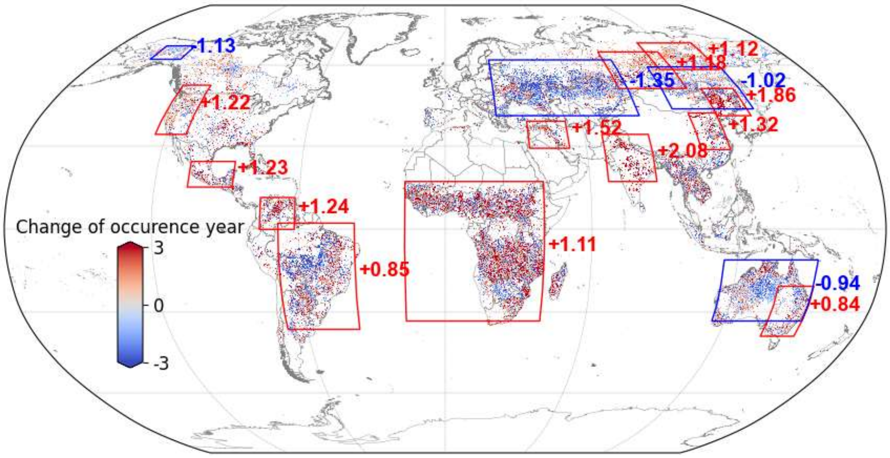

Figure 6. Spatial distribution of changes in frequency of EWS between 2001-2011 and 2012-2022, gridded at 0.1° resolution. (a) Spatial pattern; (b) Latitudinal distribution. The EWS is defined as the year that exceeds one standard deviation over the mean of WCEs during 2001-2022. The change is obtained by subtracting the number of EWS between 2001-2011 and 2012-2022. Hotspots of increasing and decreasing frequency of EWS are indicated by red and blue boxes, respectively.

4.2 Recent EWS and their implications for WCE variability

Recent EWS revealed the intertwined climatic and human forces that shape global fire dynamics. Although all occurred under hot and dry conditions, their dominant drivers differ, with climate anomalies in Canada and Russia, combined climatic and human influences in Australia, and direct human ignition associated with deforestation in the Amazon. Together these cases demonstrate the diverse mechanisms underlying large-scale fire activity and provide essential context for understanding recent variations in WCEs.

2023 Canadian Wildfires: In 2023, Canada experienced the most severe wildfire season ever recorded. By October, approximately 15 million hectares had burned, accounting for about four percent of the national forest area and more than six times the historical average from 1980 to 2020 (Byrne et al., 2024). The fires were driven by persistent high temperatures and widespread drought that began in late April and continued through the fire season (Jain et al., 2024). Total emissions were estimated at around 2.37 Pg CO_2 (Byrne et al., 2024), far exceeding typical annual Canadian emissions. With extensive burned area, emission intensity per unit area is higher compared with other boreal regions due to variations in fuel type and combustion efficiency (Luo et al., 2017). Aerosol monitoring indicated at least six major $PM_{2.5}$ pollution events with long-range transport across the Northern Hemisphere (Wang et al., 2023). The 2023 Canadian wildfires illustrate how prolonged heat and drought can convert boreal forests from relatively stable carbon reservoirs into episodic but globally significant sources of atmospheric CO_2, challenging emission models that are calibrated mainly on historical wildfire variability.

2021 Russian Wildfires: The 2021 wildfire season in Russia was unprecedented, with extensive burning across Siberia and the Russian Far East. Record-breaking heat and prolonged drought created extreme fire conditions (Voronova et al., 2022). According to Greenpeace Russia, approximately 17 million hectares of forests were affected, making it one of the largest fire seasons since the beginning of satellite monitoring in 2001 (Chebykina et al., 2022; Greenpeace Internaional, 2021). Estimated emissions reached about 1.70 Pg CO_2 (Lapenis and Yurganov, 2023), accounting for nearly half of the Northern Hemisphere's total wildfire emissions in that year. Fire behavior explains much of this pattern: surface fires dominate in Russian boreal forests, resulting in lower fuel consumption per hectare compared with the crown-fire dominated systems of Canada (Luo et al., 2017). $PM_{2.5}$ emissions were about 78 percent higher than the 2004–2021 average, as reported by the Copernicus Atmosphere

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Monitoring Service (Romanov et al., 2022). The Russian case highlights a distinct high-latitude emission pathway, in which extensive surface fires across remote boreal landscapes can generate large cumulative CO_2 emissions despite lower fuel consumption per unit area than crown-fire-dominated systems.

2019-2020 Australian "Black Summer" Wildfire: The 2019–2020 Australian "Black Summer" wildfire season represented one of the most catastrophic natural disasters in the country's history. Prolonged drought, low soil moisture, and early-season ignition in Queensland and northern New South Wales created conditions for widespread burning (Godfree et al., 2021; Van Oldenborgh et al., 2021). The fires burned an estimated 24 to 33 million hectares and emitted about 0.72 Pg CO_2 (Binskin et al., 2020; Van Der Velde et al., 2021), accounting for approximately one quarter of global WCEs in 2019. The event also produced vast quantities of stratospheric smoke, estimated at 2.1×10^{-3} Pg, which caused a cooling effect of more than 1.0 ± 0.6 W m^{-2} over cloud-free oceanic regions in the Southern Hemisphere (Hirsch and Koren, 2021). This radiative perturbation likely contributed to the extended La Niña conditions that persisted for nearly three years (Fasullo et al., 2023). The Black Summer fires therefore demonstrate that EWS can affect the Earth system not only through direct CO_2 emissions, but also through aerosol–radiation interactions that propagate beyond the burned region.

2019 Amazon Wildfires: In 2019, the Amazon region experienced a sharp increase in wildfire activity, primarily driven by human ignitions related to deforestation and agricultural expansion (Artes et al., 2020). Satellite data from Brazil's National Space Institute recorded 75,336 fires between January and August, representing an 83 percent increase compared with 2018 (De Oliveira Andrade, 2019; Gibbens, 2019). The fires affected Brazil, Bolivia, Paraguay, and Peru, with a total burned area estimated at 33.6 million hectares. Brazilian fires alone released around 0.50 Pg CO_2, equivalent to approximately 32 percent of global WCEs in 2019. These tropical fires emitted less carbon per unit area than boreal wildfires because higher fragmentation and limited fuel continuity reduced combustion completeness (Bowring et al., 2024; Luo et al., 2017). However, widespread deforestation continues to heighten the region's vulnerability to recurrent burning and long-term carbon loss (Butt et al., 2021). The Amazon case illustrates how human ignitions and forest fragmentation can generate large regional WCEs even when combustion completeness is lower than in boreal systems, while repeated burning and deforestation may erode long-term forest carbon storage.

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5 Future perspectives

As climate warming accelerates and fire regimes intensify, characterizing and mitigating WCEs and their cascading impacts has become an urgent scientific and societal priority. Building on the evidence synthesized in this review, three priorities merit particular attention: (i) improving predictive skill for fire activity and associated CO_2 emissions; (ii) advancing mechanistic understanding of climate–wildfire biophysical and biogeochemical interactions and feedbacks; and (iii) strengthening constraints on post-fire vegetation recovery and carbon dynamics. A cross-cutting challenge that permeates all three priorities is the increasing prevalence of EWS, which can dominate annual emissions and disproportionately shape regional carbon balances (Section 4). Consequently, improving future projections will require the explicit representation of EWS-related CO_2 emissions rather than reliance on climatological means or long-term averages. Collectively, these priorities aim to reduce uncertainties in future projections, mitigate wildfire impacts, and enhance ecosystem resilience under a changing climate.

5.1 Improving predictability of WCEs under compound extremes

Current Earth System Models often underrepresent non-linear interactions among climate, vegetation, ignition sources, and human activity, contributing to substantial uncertainty in simulated fire activity and emissions (Bowman et al., 2020; Gao et al., 2021; Hanan et al., 2022). This limitation is particularly pronounced for EWS, during which compound extremes such as concurrent heat, drought, and wind and threshold behaviors can amplify burned area, combustion completeness, and CO_2 emissions beyond the capacity of models calibrated on average conditions. Future progress will benefit from scenario-based frameworks spanning divergent socioeconomic and emission pathways (Riahi et al., 2017), together with interdisciplinary approaches that bridge ecology, atmospheric science, and computational methods. EWS focused evaluation and prediction should become a standard component of model development, including routine benchmarking against satellite derived extreme season emission estimates and explicit diagnosis of model structural errors that emerge under compound extremes.

Recent advances in artificial intelligence and machine learning provide opportunities to assimilate heterogeneous datasets, identify latent spatiotemporal structure, and improve predictive skill and uncertainty quantification when coupled with process-based fire models (Jain et al., 2020). Realizing this potential will require careful integration with physical and ecological constraints, explicit treatment of

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extremes, and community standards for benchmarking, intercomparison, and transparent reporting of uncertainty sources.

5.2 Advancing climate-wildfire interactions in Earth system models

Wildfires function both as a consequence and a driver of climate change through direct greenhouse gas emissions, changes in surface albedo, and aerosol cloud interactions (Huang et al., 2021; Liu et al., 2019; Tošić et al., 2020). High latitude ecosystems warrant particular attention because rapid warming and intensifying fire regimes may trigger carbon-climate feedbacks at the global scale (Flannigan et al., 2009; Zheng et al., 2023). Moreover, shifting fire regimes can catalyze long term ecological transitions toward more fire adapted communities, fundamentally altering terrestrial carbon storage (Coop et al., 2020; Liang and Hurteau, 2023). A deeper mechanistic understanding of these coupled processes, especially their nonlinearities during EWS, is essential for credible projections of wildfire trajectories and their Earth system implications. Model development should prioritize process complete representations of coupled feedbacks among fire, climate and carbon and their sensitivity to warming driven changes in fuels, moisture constraints, and ignition regimes.

5.3 Constraining post fire recovery and long-term carbon consequences

While post fire vegetation recovery can partially compensate for wildfire carbon emissions, recovery trajectories are highly variable and depend on fire severity, fire return intervals, soil properties, and climate extremes (Smith et al., 2022; Steel et al., 2021). When fires are severe or recur too frequently, ecosystems may cross resilience thresholds, precipitating persistent state shifts such as transitions from forest to grassland with profound consequences for long term carbon sequestration (Rogers et al., 2020; Lasslop et al., 2016). Capturing these dynamics requires integrating aboveground and belowground processes, including plant physiology, soil microbial activity, and nutrient cycling, into recovery assessments. Leveraging advances in remote sensing, experimental manipulations, and dynamic vegetation modeling will be critical for constraining recovery rates, diagnosing mechanisms, and quantifying the net carbon balance following repeated disturbances (Wang et al., 2015). Because post fire recovery interacts with feedbacks among fire, climate and carbon to determine long term carbon outcomes, coordinated evaluation frameworks that jointly assess emissions, feedbacks, and recovery under the lens of EWS are urgently needed.

Data availability

The data used for this study is available in the Science Data Bank open access archive under: https://www.scidb.cn/preview?dataSetId=0bf00588e5a34e9e9a4e2ad4c4c15ed0&version=V1 (Liang et al, 2026. Spatial patterns and temporal dynamics of world carbon emissions from 1700-2100 [DS/OL]. V1. Science Data Bank). All data are available on request from the corresponding author.

Author contributions

YL: Conceptualization, Methodology, Visualization, Funding Acquisition, Writing – Original Draft, Writing – Review & Editing, TM: Data Curation, Formal Analysis, Funding Acquisition, Writing – Review & Editing, BL: Funding Acquisition, Writing – Review & Editing, ZL: Formal Analysis, Supervision, Writing – Review & Editing, HH: Supervision, Writing – Review & Editing, JY: Writing – Review & Editing, YP: Writing – Review & Editing, CY: Writing – Review & Editing, XW: Writing – Review & Editing, MW: Writing – Review & Editing, WX: Writing – Review & Editing, JZ: Writing – Review & Editing.

Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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