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Key Points:

- This introduction summarizes papers published through the Fire in the Earth System Special Collection

Correspondence to:

A. East,
earthsurface@agu.org

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Author Contributions:

Conceptualization: Amy East, Amir AghaKouchak, Gabriel Filippelli, Fabio Florindo, Harihar Rajaram, Cristina Santin
Project Administration: Amy East
Supervision: Amir AghaKouchak, Graziella Caprarelli, Gabriel Filippelli, Fabio Florindo, Charles Luce, Harihar Rajaram, Lynn Russell, Cristina Santin, Isaac Santos
Writing – original draft: Amy East
Writing – review & editing: Amy East, Amir AghaKouchak, Graziella Caprarelli, Gabriel Filippelli, Fabio Florindo, Cristina Santin

Fire in the Earth System: Introduction to the Special Collection

Amy East[1], Amir AghaKouchak[2], Graziella Caprarelli[3], Gabriel Filippelli[4], Fabio Florindo[5], Charles Luce[6], Harihar Rajaram[7], Lynn Russell[8], Cristina Santin[9], and Isaac Santos[10]

[1]American Geophysical Union, Washington, DC, USA, [2]Department of Civil and Environmental Engineering, Department of Earth System Science, University of California, Irvine, CA, USA, [3]Centre for Astrophysics, Institute for Advanced Engineering and Space Sciences, University of Southern Queensland, Toowoomba, QLD, Australia, [4]Indiana University, Indianapolis, IN, USA, [5]Istituto Nazionale di Geofisica e Vulcanologia, Rome, Italy, [6]USDA Forest Service Rocky Mountain Research Station, Boise, ID, USA, [7]Department of Environmental Health and Engineering, Johns Hopkins University, Baltimore, MD, USA, [8]Scripps Institution of Oceanography, University of California, San Diego, CA, USA, [9]Research Institute of Biodiversity (CSIC-University of Oviedo-Principality of Asturias), Mieres, Spain, [10]University of Gothenburg, Gothenburg, Sweden

Abstract Fire has always been an important component of many ecosystems, but anthropogenic global climate change is now altering fire regimes over much of Earth's land surface, spurring a more urgent need to understand the physical, biological, and chemical processes associated with fire as well as its effects on human societies. In 2020, AGU launched a Special Collection that spanned 10 journals, soliciting papers under the theme “Fire in the Earth System” to encourage state-of-the-art publications in fire-related science. The completed Special Collection comprises more than 100 papers. Here, we summarize the articles published in this collection, considering them to be grouped into seven themes: paleofire and its ties to climate; evolution of fire patterns in the recent past and the future, including the effects of ongoing climate change; physical (atmospheric) and chemical processes associated with fire; ecosystem effects, including on biogeochemical cycles; physical landscape change after fire and its associated hazards; fire effects on water quality, air quality, and human health; and new methods and technologies applied to fire research.

Plain Language Summary In 2020, AGU launched a Special Collection that spanned 10 journals, soliciting papers under the theme “Fire in the Earth System” to encourage state-of-the-art publications in fire-related science. The completed Special Collection comprises more than 100 papers. This Introduction summarizes the articles published in the Special Collection.

1. Paleofire and Ties to Climate

Wildfires occur across a vast range of terrain and ecosystems, from the tropics to high latitudes. Several of the papers featured in this Special Collection presented new data on fire effects across space and time, exploring the connection between paleofire history and climate. Campbell et al. (2023) discussed the importance of understanding past fire activity for predicting future changes and improving data–model connections. Campbell et al. reviewed the emerging applications to paleofire in speleothem paleoenvironmental science, including an overview of fire regimes and paleofire proxies, laboratory and statistical analytical methods, and presented case studies from southwestern Australia. Ruan et al. (2020) studied a 22,000-year record of fire from a sediment core offshore of South Java, Indonesia. Using biomarkers and microcharcoal abundance, they developed a conceptual model of feedbacks among fire frequency and intensity, vegetation type, and regional climate. Ji et al. (2021) examined how climate and fire regimes are associated over millennial time scales in China. From a black-carbon record in a sediment core in northern China, they determined that wet climate increases biofuel abundance enough to promote greater wildfire activity, and that with strengthening of the Asian summer monsoon in a warmer climate, wildfires and associated carbon emissions could also increase. Huang et al. (2020) used palynological and charcoal analyses from the Toushe Basin, Taiwan, to infer middle to late Holocene changes in fire frequency that likely reflected weakening of the East Asian summer monsoon. Evidence of fire is even preserved in sediments of the Ross Sea, Antarctica, from which Ren et al. (2022) presented a pyrogenic carbon record that suggests frequent large fires in South America from late Pleistocene to mid-Holocene time. Li et al. (2022) presented a 100-year record of refractory black carbon (rBC) in an ice core from eastern Antarctica. This record showed long-term changes that likely reflected biomass burning and anthropogenic biofuel use in South America and Australia, including an increase in rBC abundance between the 1990s and 2015. From peatland cores in Borneo, Yamamoto et al. (2021) inferred at least 12 major fires in the last 6,000 years and tied them to intervals of high solar activity thought to have been associated with drier climate. Finally, Ying et al. (2022) identified connections between wildfire occurrence in Yunnan, southwest China, and dynamics of the Western Pacific and Indian Ocean warm pools mediated by the regional monsoon climate.

2. Recent Past and Future Evolution of Fire Patterns

The impact of climate change on the incidence and severity of fires is a rapidly expanding area of research and the focus of many papers featured in this Special Collection. A synthesis by Jones et al. (2022) discussed current understanding of regional and global trends and drivers of fire. They provided evidence that (a) the frequency and severity of fire weather has increased over 1979–2019 and will continue to grow in a warming climate; (b) fire weather is a major control on fire activity and the dominant variable in burned area of many mesic forest ecosystems, including the Mediterranean, the western U.S., and high-latitude forests; (c) climate models show that prevalence and severity of fire weather now exceeds preindustrial variability in some regions; (d) burned area has increased by 50% since 2001 in some extratropical forested regions but decreased in African savannahs, driving a net decrease of 27% in burned area globally in the past two decades; and (e) human activities and other factors commonly modulate the importance of weather in determining fire activity (Jones et al., 2022).

Two commentaries provided context on the role of human influence in fire, with particular attention to the context of climate change altering the potential for wildfires: Stoof and Kettridge (2022) discussed the need for integrated fire management and cross-sector understanding of social diversity in order to live with enhanced fire regimes in a warming climate. Their commentary noted that fostering community resilience in an era of extreme fires requires better connecting knowledge and people across geographic boundaries, working on different risks, and working in science and practice with more diverse groups of people. Pyne (2020) reflected on the immensity of changes to the Earth system resulting from anthropogenic fire, commenting that the Pleistocene was effectively replaced by the Pyrocene era as humans intentionally burned living vegetation biomass for purposes of hunting and agriculture, used fire in all stages of industry and urbanization, and then began burning fossil fuels.

Many of the Special Collection papers focused on intensification of the fire regime in specific regions due to climate warming, anthropogenic influences, or a combination thereof. Melia et al. (2022) combined climate modeling with daily observations of weather and fire conditions to simulate 21st-century fire-weather conditions for Aotearoa (New Zealand). They concluded that more severe, even extreme, wildfire weather will become possible in regions previously unaffected by this type of fire weather, even matching conditions recorded during the "very extreme" fire-season length and intensity in Australia over the 2019–2020 austral summer. Melia et al. (2022) also discussed the implications of the increasing fire risk for financial investments in tree plantations and governmental strategies for planting trees to reduce climate change. Kemter et al. (2021, also discussed below) emphasized that climate change is projected to increase the frequency of compounding events such as the extreme drought, fire, and intense rain that occurred in the cascade of hazards affecting Australia in 2019–2020. Park et al. (2021) examined how deforestation and vegetation degradation will affect future fire activity globally. Their modeling indicated that under Representative Concentration Pathways 2.6 and 6.0 burned area would decrease globally in the 2050s and 2090s due to socioeconomic factors such as economic and population growth reducing the use of anthropogenic fire for deforestation. However, Park et al. (2021) also predicted that South America, Indonesia, and Australia would continue to have a high risk of anthropogenic fires due to wood harvest and pastureland expansion. Rodrigues et al. (2021) examined climatic connections to fire frequency and magnitude in the western Mediterranean region between 1980 and 2015. Their study revealed that the North Atlantic Oscillation, Scandinavian pattern, and Western Mediterranean Oscillation had explicit spatial influences on the occurrence of fires. Wei et al. (2021) used Landsat data to measure the global burned area between 2015 and 2019, focusing especially on the effects of unusually large fires in the Amazon basin and Australia in 2019. Using Sentinel-2 imagery to examine in detail the numerous fires in the Amazon region in 2019, Xu et al. (2021) found that 90% were associated with human clearing of deforested fields on the forest margins (i.e., these fires were not tied to drought) and that more fires occurred deeper in the forest than in the preceding 3 years, likely indicating further proliferation of anthropogenic burning. Jain et al. (2021) used MODIS satellite observations to characterize forest-fire activity over central India from 2001 to 2020, finding a substantially greater fire activity since 2006. They found a significant increase in fire activity since 2006, attributed to rising temperatures and low precipitation, including extreme hot and dry conditions during winter and spring months that were previously not considered part of the fire season.

Eight papers discussed the changing fire regime in the western continental United States as climate warms and dries there. Goodwin et al. (2021) determined that greater tree mortality in western U.S. forests as a result of climate change (driven by drought and mountain pine-beetle infestations) is transitioning large amounts of biomass from living to dead, thereby supplying wildfires with more and drier fuels that increase fires' potential heat flux. Analyzing annual forest area burned in the western U.S., Juang et al. (2022) found an exponential relationship between increasing aridity and forest fires. Their study showed that two thirds of the increase in burned forest area over 1984–2019 was due to only the 10% largest fires of each year because individual fires with access to dry fuels grow at compounding rates. Abatzoglou, Juang et al. (2021) analyzed geographic synchronicity of fire danger (defined as a function of fire-weather index relative to forested area) across the western U.S. as a means to evaluate strain on fire-management resources; they identified a 25-day increase in synchronous fire danger over 1979–2020 and projected that such days would double over 2051–2080, straining fire-suppression capability. Brey et al. (2020) examined how future projected increases in vapor pressure deficit and other environmental conditions (precipitation, evaporation, relative humidity, root-zone soil moisture, and wind speed) could affect the U.S. summertime wildfire burn area. A study by Ren et al. (2022) projected burned area in a semiarid watershed of Idaho, USA. Their model results indicated an increase in burned area by the 2040s followed by a decrease in the 2070s owing to fire-limiting thresholds of fuel and flammability that vary with complex vegetation responses to increasing CO_2 and temperature in a warming climate. The Sierra Nevada region of California has experienced a major increase in wildfire activity since the 1980s, and modeling by Chen et al. (2021) determined that vapor-pressure deficit dominated spatial patterns of fire probability there, with fuel amount and human population density also being significant drivers in some subecoregions. Hernández Ayala et al. (2021) evaluated connections between antecedent rainfall, vegetation growth, and wildfire burned area in California, concluding that the largest wildfires in California's history were strongly correlated with above-average antecedent rainfall and anomalous vegetation growth. Dong et al. (2021) evaluated meteorological conditions associated with California wildfires and found that most (60%) occurred on hot, dry days, with moisture anomaly explaining most of the variability in wildfire size; burned area increased by ~3.6% per year (having doubled from 1984 to 2017), dominated by summer hot-dry days.

Four papers in the Special Collection documented increased fire activity in high-latitude regions where fire was formerly rarer. Sierra-Hernández et al. (2022) analyzed ice cores from the Wrangell-St. Elias Mountain Range in Alaska and found an increase in fire-generated ammonium and black carbon since the 1980s. By comparing these wildfire records with climate history, they discovered that temperature has become a more dominant factor affecting Alaska's fire regime in the last four decades. Grzesik et al. (2022) examined plant traits and fuel loads in black-spruce forests of boreal Alaska, identifying particular vulnerability of certain woodland types (that cover 27% of interior Alaska) to fire-induced vegetation shifts. Yanagiya and Furuya (2020) demonstrated the deformation of permafrost surfaces after a 2014 fire in Siberia, where more than 3 million m^3 of permafrost thawed, leading to irreversible subsidence. Yanagiya et al. (2023) built on those findings by studying additional geomorphic impacts of 2018 and 2019 fires in Siberia using field measurements and satellite Interferometric Synthetic Aperture Radar (InSAR), finding transient and spatially heterogenous ground deformation in the permafrost terrain that they attributed to fire effects on the active-layer depth. They concluded that the permafrost depth before the fire plays a crucial role in controlling postfire subsidence and thermokarst evolution.

3. How Does Fire Work? Physical and Chemical Processes

The Special Collection includes new research into physical atmospheric processes of fire behavior and fire–atmosphere interaction. Studying extreme pyroconvective behavior of the 2016 Pioneer megafire (Idaho, USA) using airborne radar and in situ aircraft sampling, Rodriguez et al. (2020) presented data that help explain how hot-moist updrafts trigger fire-generated thunderstorms (from pyrocumulonimbus clouds) that pose aviation hazards. Lareau et al. (2022) discussed the importance of long-range spotting in driving the rate of fire spread, inferred from new applications of weather radar data. Katurji et al. (2021) presented novel field measurements using turbulent thermal image velocimetry at the immediate fire–atmosphere interface, showing interactions between the flame zone and wind turbulence. Castellnou et al. (2022) developed a new four-part classification for pyroconvection based on atmospheric vertical profiles and extreme fire spread observed during the 2021 summer fire season on the Iberian Peninsula. They distinguished moist and dry convection effects on the atmospheric boundary layer and noted the correlation between vertical updraft velocity and the rate of fire spread. A study by Aubry-Wake et al. (2022) measured the effects of upwind wildfire activity on the Athabasca Glacier in the Canadian Rockies. Aubry-Wake et al. (2022) concluded that decreased albedo of the glacier surface resulting from the deposition of wildfire soot altered the radiation balance enough to increase ice melt by as much as 10%, even 2 years after fire.

Several papers presented results from the Western Wildfire Experiment for Cloud Chemistry, Aerosol Absorption, and Nitrogen (WE-CAN) project, comprising airborne measurements from western U.S. wildfire smoke plumes. Barry et al. (2021) sampled smoke plumes and smoke-affected clouds to study wildfire generation of ice-nucleating particles that reach the troposphere and showed that the majority of such particles are organic. Papers by Juncosa Calahorrano, Lindaas et al. (2021) and Lindaas et al. (2020), also using data obtained through WE-CAN, quantified the reactive nitrogen emissions in smoke plumes during summer 2018 western U.S. fires and measured rapid chemical changes after emission. Permar et al. (2021) used WE-CAN measurements of trace organic gases to show that 76% of the volatile organic compound emissions were explained by combustion efficiency and found little chemical variation among fires in coniferous ecosystems. Lindaas et al. (2021) studied ammonia emissions from wildfire smoke, quantifying changes in ammonium nitrate formation with smoke altitude and temperature, which have consequences for Earth's radiation budget and reactive nitrogen availability to downwind ecosystems. Juncosa Calahorrano, Payne et al. (2021) collected satellite data on emissions of acyl peroxynitrates (PANs, nitrogen oxide compounds that form rapidly in smoke plumes) synchronously with the WE-CAN project, finding that the fires contributed 19%–56% of tropospheric PANs during the 2018 western U.S. wildfire season.

High-resolution satellite and in situ airborne observations from the 2019 Fire Influence on Regional to Global Environments and Air Quality (FIREX-AQ) research campaign were used by Wiggins et al. (2020) to show that changes in fire radiative power directly translated into changes in tracers of smoke (CO_2, CO, and black carbon aerosol) in downwind smoke plumes from 13 fires. Subsequently, Wiggins et al. (2021) used FIREX-AQ data to reconcile top-down and bottom-up approaches for estimating wildfire aerosol emissions, identifying key uncertainties, and imperfect assumptions in each. Adachi et al. (2022) studied burned-biomass samples collected in flights for FIREX-AQ and earlier campaigns in Mexico and the northwestern US to determine that fine ash-bearing particles smaller than a few microns (small enough to be inhaled) represent 8.8–16.3 Tg yr^{-1} annually and can influence cloud condensation. Using airborne data from 12 wildfires and one prescribed fire through the Alpha Jet Atmospheric eXperiment, Iraci et al. (2022) presented calibrated measurements of methane, formaldehyde, ozone, CO_2, water vapor, and wind conditions near the top of smoke plumes.

Experimental and field observations in other papers generated additional new understanding of wildfire emissions. In chamber burn experiments, Pokhrel et al. (2021) evaluated the relationships between types of sub-Saharan African vegetation used as fuel and emissions of CO, NO, and $PM_{2.5}$; they concluded that fuel nitrogen content has a substantial role in NO emissions. An air-quality study by Selimovic et al. (2020) based in Missoula, Montana, presented detailed measurements of wildfire smoke content using 1,000 hr of particulate matter (PM), ozone, and NO_x measurements. C.-S. Zhu et al. (2022) and J. Zhu et al. (2002) estimated the wildfire component of $PM_{2.5}$ over the Yungui Plateau, China, and its meteorological contributors, concluding that fires (including long-range smoke transport from eastern Myanmar, northern Laos, and Vietnam) contributed approximately half of the vertical $PM_{2.5}$ at a height of 3–4 km. Loría-Salazar et al. (2021) analyzed smoke height boundary-layer effects using NASA MODIS and VIIRS aerosol products, using these to document the influence of mountainous terrain on vertical aerosol profiles during extreme smoke events. A study by Lee et al. (2022) investigated cloud water samples over eight summers at Whiteface Mountain, New York. These authors found that nearly half of the summertime cloud water samples were influenced by wildfire smoke, which contributed to the addition of sulfate, ammonium, potassium, and total organic carbon. During 2017 fires in British Columbia, Canada, Mao et al. (2021) used airborne lidar (laser backscatter profiles) to measure CO_2 emissions and improve estimates of associated carbon fluxes.

Modeling by Daniels et al. (2022) explored the relationship between fire-season intensity in maritime Southeast Asia and atmospheric carbon monoxide variability. These authors identified lead times for five climate mode indices at weekly time scales that increase the robustness of interpretations of carbon monoxide variability.

During the two and a half years that this Special Collection was open to manuscript submissions, some major wildfires and extreme fire seasons occurred that formed the basis for several papers. Abatzoglou, Rupp et al. (2021) studied conditions that led to large, high-impact fires burning 4,000 km^2 of forests in Oregon in September 2020, attributing the fires to compound extreme events: unusually warm temperatures with little precipitation drying fuels for 2 months prefire, combined with exceptionally strong downslope offshore winds driving rapid fire spread. Kemter et al. (2021) studied the cascading hazards contributing to severe ecosystem and human impacts of the 2019–2020 "Black Summer" wildfires in Australia. This fire season followed an unprecedented drought and was succeeded by heavy precipitation, leading to flooding and runoff that brought large quantities of ash and eroded soil from the burned areas into rivers, reducing water quality. Kemter et al. (2021) provided a comprehensive look at this three-part hazard of drought, fire, and flooding/erosion, highlighting the amplifying effects of individual impacts within hazard cascades and emphasizing the role of ongoing climate change in this series of disasters. Deb et al. (2020) studied the causes of the Black Summer 2019–2020 fire season in New South Wales, Australia, using empirically based statistical models. These authors found that drought, surface soil moisture, wind speed, relative humidity, heat waves, dead and live fuel moisture, and certain land-cover types combined to allow fire propagation, and they discussed applications for better fire-protection planning and management. Kumar et al. (2021) used remotely sensed vegetation optical depth data from the NASA Soil Moisture Active Passive mission to determine that the 2019–2020 Australian drought and bushfires significantly altered the partitioning of evaporative and runoff fluxes, leading to increased bare soil evaporation, decreased transpiration, and greater water runoff. Fasullo et al. (2021) modeled coupled climate responses to changes in emissions from the Australian wildfires of 2019 and the early part of the COVID-19 pandemic. Their simulations with the Community Earth System Model (CESM)-2 showed globally modest responses to reduced aerosol emissions associated with the pandemic, whereas the Australian fires were found to have cooled the globe by 0.95 ± 0.15 W m^{-2} in December 2019 and 0.06 ± 0.04 K by mid-2020, as well as having displaced tropical convection northward. Di Giuseppe (2022) used an unusual series of lightning-ignited major California wildfires in summer 2020 to test the efficacy of probabilistic and deterministic forecasting, concluding that a proposed probabilistic forecast approach could provide great value to users, particularly where economic costs of missed (false negative) lightning-strike forecasts are high.

A study by Wagman et al. (2020) modeled global climate forcing and response that could result from a regional nuclear-weapons exchange causing large urban fires. They concluded that fire plumes and their associated aerosol and black-carbon emissions resulting from 100 simultaneous fire storms after nuclear-weapon use would cause global cooling of shorter duration than previously assessed, likely lasting four years rather than 8–15 years. Wagman et al. (2020) inferred a broad range of climate impacts depending on fuel availability and consumption at the detonation sites.

4. Fire Effects on Biogeochemical Cycles and Ecosystems

Many papers in the Special Collection elucidated the importance of fire in biogeochemical cycles and ecological processes. Zubkova et al. (2022) presented a new conceptual framework for defining potential "fire regions" in Africa and Australia, which are regions with distinct fire potential based on environmental gradients and human activities. They found that a single biome can host several fire regions due to highly variable fire frequency, size, and intensity. Madani et al. (2021) used satellite vegetation observations and environmental data coupled with a modeling approach to investigate climate and wildfire effects on ecosystem gross primary productivity in Alaska; they concluded that warmer temperatures increase plant productivity and wildfire risk, and that although productivity recovers rapidly from less severe fires, thawing and increased fire activity in permafrost terrain will release long-stored carbon. Santin et al. (2020) conducted chamber burns of various North American vegetation types during the FIREX FireLab experiment to show that pyrogenic carbon not emitted into the atmosphere can constitute a significant carbon sink due to its long environmental recalcitrance, and that failing to account for this effect of incompletely consumed fuels may overestimate wildfire carbon emissions substantially. Desservettaz et al. (2022) used model simulations to constrain Australia's biomass burning inventory and carbon-monoxide emissions to better situate Australian fires in regional and global carbon budgets. Work by Corona-Núñez et al. (2020) using GOES and MODIS satellite data determined that tropical forest fires produce 19% of Mexico's CO_2 emissions, equivalent to 4 to 11 times more than national emissions from deforestation. Heindel et al. (2022) measured nitrogen deposition along a transect spanning a range of elevation and land use in the fire-prone Colorado Front Range. They found elevated nitrogen deposition from urban and agricultural

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sources at much higher levels than previously modeled, indicating the need for more intensive nitrogen monitoring in the wildland-urban interface because nitrogen and wildfire can combine to degrade water quality and fire-prone ecosystems substantially. Working at high-altitude sites on the Tibetan Plateau, C.-S. Zhu et al. (2022) and J. Zhu et al. (2002) found elevated abundance of biomass-burning tracers (levoglucosan, mannosan, and galactosan) that suggested long-range atmospheric effects of fires. Studying legacy effects of fires associated with deforestation in the Amazon region, de Oliveira et al. (2021) found that during a 3-year period after fire, burned areas experienced higher air and land-surface temperatures, but water and carbon-dioxide fluxes showed signs of recovery toward their original states. In contrast, Rhea et al. (2021) found that burned catchments in Colorado showed increased in-stream nitrogen concentrations and more biofilm productivity than unburned streams even 15 years after fire, with nitrate supply from burned hillslopes exceeding the demand by stream biota. McGuire, Rasmussen, et al. (2021) measured the spatial distribution of near-surface pyrogenic carbon on hillslopes after a 2018 fire in New Mexico, USA, and used hydrologic monitoring, terrain analysis, and a rainfall-runoff model to explain hydrogeomorphic, burn-severity, and canopy-cover controls on pyrogenic-carbon redistribution. Natali et al. (2021) evaluated carbon loss and mobility of metals resulting from burning of peat soils in Italy, inferring that 580 kg of CO_2 were released per cubic meter of burned soil, negatively affecting agricultural activities as well as contributing to greenhouse gas in the atmosphere.

The downstream fates of wildfire-generated carbon and other pyrogenic compounds were discussed by four Special Collection papers. Sampling paleolimnological records from subarctic lakes of northern Canada, Pelletier et al. (2020) demonstrated significant increases in trace metals, metalloids, and major ions after wildfires, although wildfire delivered lower fluxes of metal contaminants than did anthropogenic pollution. After the large Thomas Fire in southern California in winter 2017–2018, Kelly et al. (2021) measured black carbon and metals in aerosol, river, and seawater samples, finding that rapid aerosol delivery during the fire accounted for more metal transport to the coastal ocean than did postfire flooding of the nearby Ventura River. Kelly et al. (2021) also determined that seawater chemistry and phytoplankton biomass did not show significant responses. Also studying the Thomas Fire, Wagner et al. (2021) determined that large amounts of dissolved black carbon were present in coastal waters directly beneath the smoke plume, although these ash-derived concentrations were not high enough to shift the carbon isotope signature offshore in the Santa Barbara Channel. Häggi et al. (2021) compared levoglucosan abundance (as a proxy of low-temperature pyrogenic carbon) in the Amazon River to its abundance in marine sediments near the river mouth and found that it occurred only in negligible quantities. This result suggests that, in a large subtropical river system, river-derived levoglucosan and low-temperature pyrogenic carbon degrade almost completely before reaching the ocean.

Several papers quantified the effects of fire on forest and soil carbon stocks. Palviainen et al. (2020) synthesized the effects of fire on carbon stocks in boreal forests using 368 field plots and 16 long-term fire chronosequences; they found that fires caused an average initial decrease of 60% in carbon stocks, described recovery trajectories quantitatively, and discussed the climate-mediated role of potential evapotranspiration in the rate of carbon-stock recovery. Eckdahl et al. (2022) sampled organic and mineral soils at 50 burned sites in boreal forests of Sweden and found that 1 year postfire, a large fraction of the pyrogenic carbon had moved downward in the soil profile to be stored in the mineral soil rather than in the organic layers. Based on 18 years of vegetation data from North America's grassland biome, Donovan et al. (2020) concluded that large wildfires did not drive persistent vegetation declines, but that (with the exception of trees in one ecoregion) vegetation recovered relatively rapidly after fire. Wilson et al. (2021) determined that while summer precipitation is consistently an important factor driving postfire forest recovery in mountainous terrain of the U.S. Pacific Northwest, snow cover also exerts significant influence. Considering trends toward increasing fire activity, reduced snowpack, and earlier snowmelt, these authors expect that, in the future, Pacific Northwest forests will experience more frequent drought conditions that slow postfire revegetation. Cooperdock et al. (2020) sampled soils burned by wildfire in central Texas and, by comparing them to unburned soils, concluded that in a hot, dry climate, soil disturbances persist for years after fire, resulting in elevated temperatures (from excess solar-radiation absorption) and reduced microbial activity.

5. Postfire Landscape Processes and Physical Hazards

Fire can alter soil properties and processes of hillslope erosion greatly, so that even modest postfire rainfall can cause destructive flooding and debris flows in some settings. The characteristics of terrain, soil properties, fire history, and rainfall that generate postfire debris flows are subjects of rapidly growing research. Kean and

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Staley (2021) generated maps of postfire debris-flow probability and magnitude (volume) for southern California that can be used to prioritize watersheds for emergency preparedness and potential mitigation. They found that small debris flows can be expected almost every year and debris flows large enough to damage 40 or more structures have a recurrence interval between 10 and 13 years, comparable to a magnitude 6.7 earthquake in the same region; Kean and Staley (2021) noted that rainfall intensification in a warmer climate will increase the probability of major debris flows. Simulating changes in hydrologic and soil conditions that cause postfire debris flows, Thomas et al. (2021) defined threshold conditions for runoff- and infiltration-generated debris flows over 3 years postfire for the San Gabriel Mountains, southern California. Rengers et al. (2021), also working in the San Gabriel Mountains, used airborne and terrestrial lidar to determine that only 7% of postfire sediment erosion originated from channels, whereas 93% was derived from hillslopes; postfire erosion rates were of the same magnitude as millennial-scale bedrock erosion rates, suggesting that fires account for a majority of long-term erosion in that region. Flume experiments by Ng et al. (2022) investigated the effects of soil hydrophobicity (water repellency) on debris-flow entrainment and momentum growth. Their study demonstrated unique erosion patterns and showed that the erosion depth of a debris flow can be six times greater when occurring in a hydrophobic bed similar to one that would be present after a wildfire. Ouyang et al. (2023) investigated a series of postfire debris flows in a watershed in southern China in 2021 and conducted laboratory tests on soils from the burned catchment. Ouyang et al. then developed a numerical model based on rainfall interception (a function of leaf area index), infiltration, erosion, and runoff that could reproduce the characteristics of the debris flows observed in the field. Guilinger et al. (2020) used repeat change detection to characterize the evolution of sediment sources in debris flows after the 2018 Holy Fire in the Santa Ana Mountains (southern California) and found that storm rainfall evacuated dry ravel sediment from channels relatively early, increasing the importance of hillslope sources in later-season storms. Hoch et al. (2021) studied hydrogeomorphic recovery after three fires in the U.S. Southwest, using field and remotely sensed measurements of soil properties, vegetation cover, rainfall runoff, and debris-flow activity to constrain a hydrologic model of how rainfall intensity-duration thresholds for debris-flow initiation change with time. Hoch et al. (2021) found that whereas a 1-year recurrence-interval storm can cause debris flows in the first year postfire, a 10- to 25-year storm may be needed to cause debris flows after 2 years of soil and vegetation recovery. Studying a 2019 fire and postfire monsoon storms in central Arizona, McGuire, Youberg et al. (2021) showed that in desert terrain even low soil burn severity can increase debris-flow likelihood and volume.

In the aftermath of destructive, fatal, and costly postfire debris flows of January 2018 in Montecito, California, Alessio et al. (2021) investigated how rilling erosion had developed into debris-flow slurries; they identified contributing properties of lithology (particularly shale bedrock) and hillslope geometry that promoted debris-flow formation from rills. Barnhart et al. (2021) simulated the 2018 Montecito disaster with three debris-flow inundation models (RAMMS, FLO2D, and D-Claw) and found that model performance was more sensitive to flow volume and site morphology than to flow properties; estimated postfire debris-flow volumes were lower than rainfall-based predictions and observed inundation areas were larger than the volume-based model predicted.

Burned terrain experiences enhanced erosion even in the absence of debris flows, as two other studies reported. East et al. (2021) used Structure-from-Motion photogrammetry and sonar mapping of a lake bed to quantify sediment export from three watersheds burned by the 2018 Carr Fire, northern California, finding that basin-scale sediment yields were 5–64 times greater than before the fire despite a lack of debris flows. Perkins et al. (2022) evaluated hydraulic recovery in soils after the 2017 Nuns and Tubbs Fires, northern California. They determined that substantial recovery occurred in the predominantly grassland and chaparral study sites after just one rainy season following the fire, and that (unlike in well studied southern California watersheds) dry ravel erosion was minor, reducing the potential for within-channel postfire debris flows.

6. Impacts of Fire on Water Quality, Air Quality, and Public Health

Several papers in the Special Collection provided new insights into the effects of wildfires on water and air quality. A review by Paul et al. (2022) examined wildfire-induced impacts on waterborne pollutants, including increases in nutrients, ions, metals, certain organic compounds, and sediment, all of which are commonly elevated after fire, as are water temperature and streamflow. These authors also reviewed studies of fire effects on aquatic ecosystems and found that postfire water-quality changes last less than 5 years in most instances but in some cases persist more than 15 years. Using an 18-year record of water quality from an unburned watershed in

Alberta, Canada, Evans et al. (2021) detected elevated potassium in rainwater and river water that they traced to smoke plumes from distant wildfires, evidence that water quality can be impaired even long distances downwind of fires. A study by Xing et al. (2021) detected far-field effects of wildfire on air quality, concluding that biomass burning in peninsular southeast Asia significantly increased near-surface $PM_{2.5}$ concentrations, increased NH_3, and, through aerosol-radiation effects, decreased O_3 concentrations in southern China. Xie et al. (2020) used observations and modeling to evaluate $PM_{2.5}$ pollution caused by western U.S. fires over 20 years, finding that the 2017 and 2018 fire seasons there caused especially large $PM_{2.5}$ values that were greatly underestimated by the Global Fire Emissions Database. Lassman et al. (2023) retrospectively analyzed the effects of the extreme 2020 California wildfire season on regional air quality, comparing two approaches to modeling smoke emissions (one based on biomass-burning emissions and another based on remotely sensed fire-arrival timing) and discussing the performance of each method.

Many papers identified associations between wildfire smoke exposure and the occurrence of related human diseases and deaths. Nawaz and Henze (2020) found that biomass burning from deforestation in the Amazon region increased $PM_{2.5}$ exposure, with the result that during the 2019 fire season, approximately 5,000 premature deaths in Brazil were attributable to fire emissions, constituting 10% of all $PM_{2.5}$-related premature deaths in Brazil. The authors indicated a public-health-focused need for increased protection of Amazon forests. Magzamen et al. (2021) estimated cardiopulmonary morbidity and mortality related to wildfire smoke particulate matter ($PM_{2.5}$) in Colorado over 2010–2015. They found increased wildfire smoke $PM_{2.5}$ to be associated with increased hospitalizations for a suite of cardiopulmonary diseases, and with deaths from asthma and heart attacks. Magzamen et al. (2021) also identified apparent differences in health effects of local smoke plumes compared to long-range, downwind smoke exposure. Liu et al. (2021) determined that exposure to wildfire smoke PM2.5 in the summer of 2020 in Washington, USA (from local fires as well as long-distance smoke from fires in Oregon and California) led to higher mortality rates from all causes and especially from respiratory illnesses. Liu et al. (2021) concluded that reducing $PM_{2.5}$ exposure for people living below the poverty level would especially reduce smoke-associated deaths. O'Dell et al. (2021) determined that although most large U.S. fires occur in the western U.S., most deaths (74%) and asthma emergency-department visits and hospital admissions attributable to smoke occur in the eastern U.S. (75% between 2006 and 2018), implying that mitigation and awareness of smoke exposure are important well beyond the immediate fire-affected region. Studying nationwide U.S. records of intensive-care hospitalizations, Sorensen et al. (2021) identified significant associations between locally detected wildfire smoke $PM_{2.5}$ and intensive-care admissions 5 days later. They then modeled the effects on intensive care unit (ICU) resources of a simulated severe smoke event and predicted that ICU bed utilization could exceed 130%, indicating the need for hospitals to prepare additional critical-care resources when major wildfire smoke is forecast. However, estimating or projecting health impacts (e.g., respiratory-illness hospitalizations, premature deaths, and lost days of work) based on smoke $PM_{2.5}$ has substantial uncertainties, as Johnson and Garcia-Menendez (2022) showed for 2016 Southern Appalachian fires: uncertainty in impact estimates due to wildfire smoke spatial fields can be as high as 40%–50%, and greater for some morbidity outcomes (such as asthma hospitalizations). As part of the 2019 FIREX-AQ campaign, Dickinson et al. (2022) studied human health-risk implications from more than 100 volatile organic compounds in the smoke of three different wildfires in Idaho and Washington. They found that the associated benzene exposure could have increased human cancer incidence by as many as 19 cases per million people.

7. New Methods and Technologies in Fire Research

The value of new and emerging technologies in fire science is evident in the Special Collection papers, whether as the primary focus of the paper or as the means to answer specific research questions. For example, as summarized by Jones et al. (2022), remote-sensing technological advances over the past 30 years have been critically important to the proliferation of fire research across spatial scales and subdisciplines. Recent examples in this Special Collection include the work of Yanagiya and Furuya (2020), who used L-band ALOS2 data and C-band InSAR data from Sentinel-1 to map thermokarst from postfire permafrost thaw in Siberia, and Loría-Salazar et al. (2021), whose MODIS and VIIRS data were compared against ground-based observations, allowing them to summarize the scope, limitations, and opportunities for new applications of surface-level aerosol concentrations generated from wildfires. Lareau et al. (2022) showed the utility of Next Generation Weather Radar data for tracking wildfires, as fire perimeters estimated using radar were found to be consistent with satellite infrared measurements. Airborne radar measurements of a pyrocumulonimbus cloud by Rodriguez et al. (2020) were the first of their kind. Di Giuseppe et al. (2021) employed a new approach to estimate fuel consumed by fires at a global scale by using above-ground biomass inferred from L-band optical observations by the AERONET global satellite network. Improved accuracy from these methods removes the need for factoring-up assumptions that could cause large underestimations of wildfire emissions.

Machine-learning algorithms are being increasingly used to understand wildfire susceptibility. Wang et al. (2021) developed a machine-learning and game-theory model that identified physical relationships between wildfire burned area in the continental U.S. and vapor pressure deficit, relative humidity, and an energy release component (a function of fuel dryness), thus improving predictive capability for future fires. Tang et al. (2022) used machine learning to evaluate seasonal wildfire susceptibility and economic consequences of fire, focusing on the forested Daxinganling region of China. Horton et al. (2021) employed a fire-susceptibility model using machine learning to evaluate the primary driving factors of peatland fires in Kalimantan, Borneo, Indonesia. Although they obtained encouraging accuracy and precision from this approach, the model's predictive capability was found to be limited by the influence of human activity on fire ignitions. Kondylatos et al. (2022) applied machine-learning methods to predict next-day wildfire danger based on vegetation, meteorological, and soil-moisture data; when applied to two fire seasons in the Eastern Mediterranean region, this deep-learning approach evidently outperformed the more commonly used Fire Weather Index.

8. Concluding Remarks

The broad disciplinary scope reflected in the Fire in the Earth System Special Collection reflects the widespread importance of fire to ecosystems and human societies. Understanding the interactions of fire, humans, and climate is fundamental to prepare for the future ahead, but also extremely challenging as these interactions are many and intricate, particularly as climate change is altering fire regimes and as the human footprint on landscapes continues to grow. The Editors are grateful to all of the authors who have advanced the rapidly expanding field of wildfire science through the research they contributed to this Special Collection. We hope that these articles motivate more research and investments into fire science and technology in view of the growing exposure to wildfires and projected future climatic change.

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Data Availability Statement

Data were not used, nor created for this research.

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