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EXTREME EVENTS (A SOBEL AND SJ CAMARGO, SECTION EDITORS)

Recent Advances and Remaining Uncertainties in Resolving Past and Future Climate Effects on Global Fire Activity

A. Park Williams[1] · **John T. Abatzoglou**[2]

Abstract Fire is an integral component of the Earth system that will critically affect how terrestrial carbon budgets and living systems respond to climate change. Paleo and observational records document robust positive relationships between fire activity and aridity in many parts of the world on interannual to millennial timescales. Observed increases in fire activity and aridity in many areas over the past several decades motivate curiosity as to the degree to which anthropogenic climate change will alter global fire regimes and subsequently Earth's terrestrial biosphere. Importantly, fire responses to warming are not ubiquitous and effects by humans, fuels, and non-temperature climate variables are also apparent in both paleo and observational datasets. The complicated and interactive relationships among these variables necessitate quantitative modeling to better understand future fire responses to global change. Macro-scale fire models exhibit a wide spectrum of complexity. Correlation-based models are inherently superior at representing the current global mean distribution of fire activity but future projections developed from these models cannot account for important processes such as CO_2 fertilization and vegetation response after extreme events. Process-based models address some of these limitations by explicitly modeling vegetation dynamics, but this requires false assumptions about processes that are not yet well understood. Continued empirical evaluation of interactions between fire, vegetation, climate, and humans, and resultant improvements to both correlation- and process-based macro-fire models, are mandatory to better understand the past and future of the Earth system.

Keywords Fire · Climate change · Warming · Paleofire · Fire statistical analysis · Fire modeling

Introduction

Fire is fundamentally interwoven within the Earth system as a forcing on, and responder to, vegetation, atmospheric composition, climate, and human activities [1–4]. Charcoal deposits preserved in ancient sediments indicate that fire emerged in tandem with terrestrial plant life approximately 420 million years ago [5] and that fire activity varies as a result of changes in climate and vegetation across a wide range of temporal and spatial scales [6•, 7]. Climate and fire may alter vegetation characteristics in tandem or independently and altered vegetation in turn feeds back to alter climate and fire [1, 6•]. Further, fire, climate, and vegetation can all affect biotic agents such as pests (e.g., bark beetles), seed distributors (e.g., birds), or humans in ways that feed back to affect fire regimes [3]. Humans also manipulate fire directly by introducing ignitions and either suppressing or promoting fire spread [8, 9]. Approximately 2.0 Pg year^{-1} of carbon have been emitted by global wildland fire (natural- and human-caused fires) in recent decades [10], significant relative to the nearly 10 Pg year^{-1} currently emitted by the burning of fossil fuels [11]. While much of this carbon is re-assimilated into post-fire regrowth, approximately 23 % of fire emissions are attributed to tropical deforestation that is not likely to be balanced by full regrowth [10] and thus constitutes a source of atmospheric carbon [e.g., 12, 13].

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✉ A. Park Williams
williams@ldeo.columbia.edu

[1] Lamont-Doherty Earth Observatory, Columbia University, 61 Rt 9W, Palisades, NY 10964, USA

[2] Department of Geography, University of Idaho, Moscow 875 Perimeter Dr., Moscow, ID 83844, USA

Projections of the response of global fire activity (e.g., fire frequency, area, and severity) to anthropogenic climate change generally indicate increases due to warming, but with much spatial variability [14]. Thus far, warming-related increases in fire activity since 1900 have been observed in the western USA in the last half-century [15], but this followed suppression-driven decreases in the first half of the twentieth century [16]. Globally, fire activity potentially decreased throughout the twentieth century due to human activities, but with compensating increases in tropical areas since the 1960s associated with deforestation [17].

Recently, fire's potential interactions with climate change have gained global attention due in part to extreme "mega-fire" events that have corresponded with extreme droughts [18], including those across Southeast Asia during the 1997/1998 and 2015/2016 El Niño events [19–21], Australia in 2009 [22], Russia in 2010 [23, 24], Amazonia in 2010 [25], and the southwestern USA in 2011 [26]. Although these examples were synchronous with drought conditions, which may be intensified by anthropogenic climate change [e.g., 27], other human effects have also been important. Many of the fires in Southeast Asia, Australia, and the USA were ignited by humans or by man-made infrastructure (e.g., downed power lines). Land management also affected many of these fires. For example, some of the longest-lasting Russian fires in 2010 were promoted by draining and drying of peatlands [28, 29], and a century of fire suppression has led to fuel build-up in the western USA forests [1].

The complex interconnections among fire, climate, vegetation, and humans [e.g., 30] make it challenging to distinguish cause and effect and understand how future changes in climate and human activities will affect fire activity on regional to global scales. Reliable fire projections could guide policy decisions regarding sustainable resource management and provide insight regarding future changes in the terrestrial carbon balance and resultant climate change [31•, 32–34]. Major strides have been made in the understanding of fire regimes and climate–fire relationships in the past decade, thanks in large part to a global satellite-based record of fire activity [35] that allows for robust characterization of fire responses to a wide variety of climate- and land-cover types [e.g., 8, 31•, 32, 36–38]. Here, we attempt to distill recent advances in scientific knowledge made in the last 2 to 3 years on fire–climate–vegetation–human interactions to better understand how regional-to-global fire regimes may change throughout this century and where dominant uncertainties remain.

Empirical Lessons

There are many ways to empirically evaluate the relationships between climate and fire. We first survey recent advances in the evaluation of these relationships on relatively long timescales from paleo-reconstructions of fire, climate, fuels, and human activities. We then survey advances made from more recent observational records.

Paleo Studies

Ice Cores

Ice cores store information about past fire activity because gases and deposited particulate matter are preserved within snow as it is buried and packed into ice. Although ice-core collections are limited geographically, their strength as proxies is that they can extend back tens or hundreds of thousands of years and the information they store is an integration of processes occurring on continental to global scales. Ice cores from Greenland show that millennial periods of increased temperature during the last glacial cycle coincided with rapid increases in North American fire activity due to the warming influence on fuels via changes in physiology and/or distribution (e.g., transition from tundra to forest) [39]. During the past two millennia, the Greenland ice core reconstruction indicates close centennial-scale correspondence between boreal forest fire activity, temperature, and drought [40], though human burning activities (land clearance) in temperate Europe may also be evident in these cores [41]. In the Southern Hemisphere, an Antarctic ice core indicates reduced fire activity in the past several centuries, likely due to reduced burning of savannas in South America, southern Africa, and Australia as a result of human-induced landscape fragmentation [42].

Charcoal Sediments

Charcoal-based reconstructions can be collected from many locations globally and combined to represent a range of spatial scales over hundreds to several thousands of years. Marlon et al. [6•] used 703 charcoal records from across the globe to examine the variability in regional-to-continental fire activity during the Holocene. Consistent with ice-core results, Marlon et al. [6•] find that fire activity increased in Europe and North America throughout the early Holocene due to widespread reorganizations of ecosystems following the last glacial period. This early Holocene effect of climate on fire via ecosystem changes may have been most dominant at relatively high latitudes where boreal conifer-dominated forests established after ice sheets receded [43, 44]. Some recent charcoal studies have highlighted further complexity to the relationship between high-latitude fire and warming, however, as warming in southern boreal zones appears to promote less flammable broadleaf forests [45, 46].

During the late Holocene, charcoal records highlight the continued dominance of climate over fire activity at regional to continental scales. Warming during the Medieval Climate Anomaly (~900–1300 AD), for example, corresponded with increased charcoal-derived fire activity in boreal Alaska [44, 47], the Pacific Northwest of North America [48], and the central Rocky Mountains [49], though in that case fire activity decreased while temperatures were still high, likely indicating a fuel limitation. Subsequent decreases in the global fire activity at the onset of the Little Ice Age (~1500–1850 AD) are again consistent with the generally positive correlation between temperature and fire activity [6•, 44, 50], but this decrease in North American fire activity also coincided with the massive decline of Native American populations, who undoubtedly affected fire regimes prior to European arrival [e.g., 51].

While humans are known to have affected historical fire regimes, these effects are difficult to detect on the broad spatial scales often evaluated in charcoal-based studies because human effects have been highly variable in time and space [e.g., 52]. For example, Marlon et al. [6•] indicate that increasing population in Europe over the past several thousand years corresponded to a widespread *increase* in European burning during ~4 to 2 kya (also supported by ice core evidence [41]) and then to *declines* in burning over the past 2 kya [6•]. The increases and subsequent decreases in European burning over the past ~4 ky may have corresponded to anthropogenic clearing of forest and subsequent fuel limitation [e.g., 53–55], exemplifying the opposing influences that humans can have on fire regimes and why it may be difficult to infer direct human effects from a comparison of population data to fire reconstructions [e.g., 6•]. Human impacts on the environment have become increasingly unmistakable during the past century, with increases in fire activity in some regions (e.g., Pacific Islands, central Europe, and Australia) due to human ignitions and/or land clearing and decreases in fire activity in other regions (e.g., western USA and sub-Saharan Africa) due to land-use change and/or fire suppression. Collectively, such changes can fundamentally alter fire–climate relationships through time and can confound the attribution of changes in fire activity.

Tree Rings

Fire scars on trees are often preserved visibly within tree-ring sequences [56], fueling the recent archival of many tree-ring-based fire reconstructions within an international paleofire database. In the western USA, tree-ring reconstructions indicate a strong pre-European correspondence between wildfire and drought [e.g., 57–66]. The high temporal precision of tree-ring-based reconstructions is not possible with charcoal or ice core records and can elucidate more nuanced climate effects such as the tendency in relatively dry areas for high fire activity to be preceded by anomalously wet years, which promote fuel growth [e.g., 67] and fire spread [65]. Tree-ring-based fire reconstructions also indicate a substantial reduction in fire activity during the first half of the twentieth century throughout the western USA [e.g., 63, 68]. The dramatic early twentieth century reductions in fire activity in the western USA and elsewhere [e.g., 69] is concerning because fire suppression has caused many areas to accumulate a “fire deficit,” where increased fuel loads due to lack of fire have increased the likelihood of unusually high fire activity in the future [1, 70, 71]. The fire deficit across the western USA is heterogeneous, with the largest deficits in lower-elevation dry forests where suppression priorities are highest. There is less evidence of a fire deficit in mesic, higher elevation, or remote forests [72]. Tree-ring fire reconstructions and plot data indicate that suppression-induced fire deficit in the western USA has led to increased fire severity [73] and changes in species composition, which in turn affect fire regimes [74]. Notably, one fire-free century may not represent a departure from expected undisturbed conditions for some forest types in the western USA [e.g., 75–77], but such a hiatus in fire activity is very uncommon for other forest types [e.g., 59].

Warming promotes fire via the exponential effect of temperature on the atmosphere’s vapor-pressure deficit [e.g., 78], which enhances the atmosphere’s evapotranspiration potential (PET) and depletes fuel moisture. This link to temperature appears particularly strong in boreal coniferous forests [e.g., 79, 80], though tree-ring burn scars from boreal Canada also indicate that warming-induced increases in fire activity have already become self-regulating in some areas by creating large swaths of younger, lower biomass forest that effectively act as fuel breaks [81]. The legacy effects of past fire on fuel characteristics impact subsequent fire potential and are important to consider in the development of projections of future fire activity. Paleo data provide critical insight into the functioning of relatively low-frequency (decadal to centennial) processes that are not possible to observe.

Observational Studies

Studies that collect and/or utilize observational data aim to better understand the drivers of relatively short-term variations and trends in fire activity with a higher precision than is possible through paleo approaches. Global analyses of macro-fire activity are limited to the use of recent satellite observations of burned area and are therefore too short to put observed trends or anomalies into a historical context. Regional or country-wide observational records can extend further back (several decades to a century) but often involve combining numerous datasets and correcting for biases associated with inhomogeneities [e.g., 16, 82]. Among observational studies, burned area and fire frequency are the most extensively examined, as fire impacts and severity (e.g., tree mortality and carbon emissions) remain challenging to accurately quantify [83].

An observational fire dataset that combines unique temporal depth, consistency, and spatial extent is the satellite-derived Monitoring Trends in Burn Severity (MTBS) product, which extends back to 1984 for the USA [84]. MTBS only represents large fires and excludes the vast majority of reported fires. However, MTBS fires larger than 404 ha accounted for over 92 % of forest area burned in the western USA based on the comprehensive wildfire database developed by Short [85]. Thus, the MTBS dataset is of limited use for evaluations of fire frequency or spatial distribution but it is well suited for studies of area burned (see more description of MTBS strengths and limitations in a review by Short [86]). Dennison et al. [87] used MTBS data to document significant increases in the frequency and area of large fires in the western USA during 1984–2011. These trends were spatially heterogeneous, with the greatest increases occurring in Rocky Mountain and Southwestern USA forests (documented with greater detail in [88]). Figure 1a combines the MTBS dataset with a more up-to-date but shorter satellite-derived burned area product [89] to show that western USA burned forest area increased significantly ($P < 0.01$), and potentially exponentially, during 1984–2015. While the annual western USA forest-fire areas of the past ~15 years have been high compared to those of the latter half of the twentieth century, they may still be lower than pre-twentieth century levels in many areas due to fire suppression [e.g., 76, 90].

Attribution of recent trends in area burned is challenging due to co-occurrences of trends in climate, fuels, and human activities. An advantage, however, is that climate is more temporally variable than other co-occurring processes such as land and fire management. Several studies have noted a strong positive correlation between temperature and fire activity (e.g., burned area and fire frequency) across large parts of the USA [88, 91–98]. However, observational studies generally find stronger correlations between fire activity and climate variables that more comprehensively represent potential flammability such as PET or fuel moisture than temperature alone [88, 91, 93, 99]. Precipitation has a more complex relationship with fire activity [e.g., 88], as it can enhance fire potential in fuel-limited fire regimes by promoting fuel growth and also suppress fire potential by reducing flammability.

In Fig. 1b, we demonstrate a preliminary attribution effort, showing that the significant increase in western continental USA forest-fire area during 1984–2015 has corresponded to a significant warming-driven increase in annual PET. The record of burned forest area in Fig. 1a and the PET record in Fig. 1b correlate well ($r = 0.88$), and this correlation remains strong ($r = 0.82$) after both linear trends are removed (Fig. 1c), lending support to a mechanistic relationship. Assuming the interannual relationship shown in Fig. 1c is consistent at the decadal scale, the positive trend in PET accounts for ~78 % of the positive trend in burned area since 1984. Importantly, burned area is affected by other climate processes and also by non-climate factors, and work still needs to be done to parse apart the roles of anthropogenic warming and natural temperature variability during this period [e.g., 27]. Nonetheless, the strength of the observed interannual relationship between PET and forest-fire area and the co-occurring positive trends suggest that (1) continued warming will promote continued increases in western USA forest-fire area while fuels are not limiting, consistent with previous empirical evaluations [e.g., 15, 92], and (2) other processes besides increased PET have also contributed to the increase in the western US forest fire area and will continue to do so.

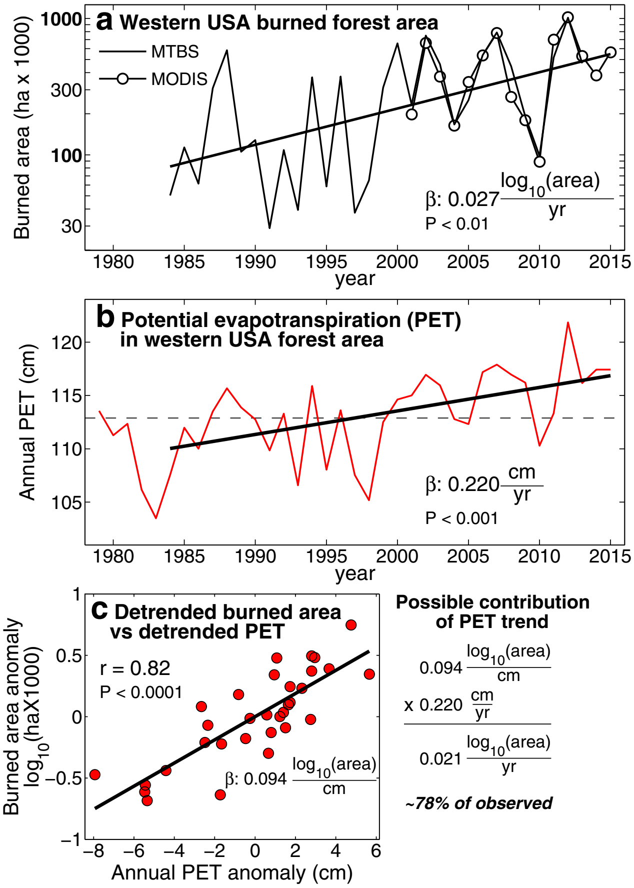

Fig. 1 Annual burned area and atmospheric moisture demand in western continental USA forests. **a** Annual burned area derived from satellite records from 1984 to 2015. The MTBS record is extended through 2014 and 2015 with MODIS. **b** Annual potential evapotranspiration (PET) calculated from the Penman-Monteith equation [e.g., 27] from 1979 to 2015. **c** Scatter plot of the time series in (**a** and **b**) after linear trends during 1984–2015 are removed. Math to the right calculates the possible contribution of the PET trend to the burned-area trend if the interannual covariability of these variables also applies to trends. Western USA forest in this analysis is any continental USA area west of 100°W that is defined as forest or woodland by the Environmental Site Potential land-cover dataset from the LANDFIRE database (http://www.landfire.gov/)

Weather conditions are also critical drivers of fire activity, and it is generally the co-occurrence of optimal fire weather (hot, low humidity, and windy) with already dry fuels due to anomalously dry climate that promotes fire spread [96, 100–105]. Jolly et al. [102•] show that the global mean annual duration of the fire-weather season increased by approximately 18 % during 1979–2013 and the global area experiencing long fire-weather seasons more than doubled during this time. This global evaluation of observed fire-weather trends and previous evaluations at regional scales [e.g., 106] does not explicitly separate the effects of anthropogenic climate change from those associated with natural variability and that is a next step toward more accurately anticipating future changes in fire weather.

Should continued warming lead to continued increases in fire potential in the western USA and elsewhere? This question is difficult to answer based on fire–climate relationships such as that shown in Fig. 1 that are derived from temporal covariation with a single independent variable during the short observational time period. Using a uniquely long burned-area record for 1902–2008 from the northern Rocky Mountains, Higuera et al. [107•] showed empirical fire–climate relationships to be non-stationary in time. These non-stationarities were posited to arise as a result of aggressive and successful suppression efforts during the mid-twentieth century when climatic conditions favored suppression, thus contributing to increased fuel density. The subsequent reemergence of more fire-favorable climate over the last three decades coincided with the legacy of suppression over previous decades and resulted in the strongest fire–climate relationship of the record. Therefore, statistical models developed using recent fire–climate relationships significantly over predict the area burned in the northern Rocky Mountains during the early-to-mid twentieth century. A similar result was found for the Mediterranean, where increases in fire activity and the strength of fire–climate relationships beginning in the 1970s were associated with fuel build-up due to rural depopulation [108]. Importantly, empirically derived instabilities in fire–climate relationships do not imply instabilities in the actual processes that govern fire. They instead highlight the importance of fuel characteristics and human activities as modulators of fire response to climate variability as well as the importance of sampling from a broad range of climates and biophysical conditions when empirically evaluating fire–climate relationships.

Although observational records are often too short to reliably quantify the interacting effects of the many drivers of temporal variations of fire activity in a given area, the laws that govern the fire frequency and size appear to be ubiquitous globally [109]. This suggests that if we can learn the laws that govern *spatial* variability in the mean state of fire across the globe we should be able to apply those lessons to estimate how fire should change in response to *temporal* changes in the governing factors [e.g., 8, 31•, 32, 110, 111•, 112]. This approach allows for space-for-time inferences, where the interactive effects of climate/weather, land management, and fuel characteristics may be detectable spatially even though the impacts of these processes often play out too slowly to be accurately depicted in observational studies.

Recent advancements in this realm of pyrogeographic statistics have largely been motivated by the potential for improving the representation of fire in Earth system models [111•]. Pausas and Ribiero [113] built upon the foundational global pyrogeographic studies described above to detect a statistically significant hump-like relationship between vegetation productivity and fire activity that had been previously hypothesized. An improved understanding of the relationship between fire activity and vegetation productivity (also noted previously [e.g., 8, 32, 114]) marks an important advance beyond studies that treat mean climatology as a single direct driver of fire regimes. Importantly, many studies do not distinguish among types of fire regimes (e.g., crown fire versus surface fire), which are dependent on vegetation *type* instead of productivity only. Archibald et al. [115] have begun to address this issue using climate predictors to estimate the probability that a given fire regime, defined by fire size, frequency, intensity, season, and extent, exists in a given location.

Human activities can also cause state-changes to fuel and fire regimes. Pyrogeographic studies have made substantial recent advances in the quantification of how human demographic factors such as population density and socioeconomics affect fire activity [e.g., 116–122]. An emerging consensus is that human population density and wealth both have net negative impacts on burned area due to fire suppression and fuel fragmentation. These negative forcings appear to generally outweigh the positive effects of anthropogenic ignitions and fire use except for among very low population densities.

Fire Modeling and Future Projections

Fire modeling is done at a range of scales, from physics-based models with high spatial and temporal resolution [e.g., 123–125] to more highly parameterized macro-scale models operated at the larger scales of interest for this review. These macro-scale models apply a range of approaches, from empirically-derived statistical modeling to more process-based approaches that combine mechanistic modeling with empirical formulations.

Empirically-derived statistical modeling incorporates observed relationships between fire activity and potential causal factors to infer how fire activity would respond to hypothetical changes in the causal factors [e.g., 38, 110, 111•, 126]. Projections of fire activity made solely by applying empirically derived climate–fire relationships (such as that in Fig. 1) to projections of climate change generally suggest enhanced fire activity for most regions globally as a result of increased fire-season aridity [e.g., 31•, 127–135], despite the fact that these increases will clearly be tempered in some regions as fuels become limiting [e.g., 136]. In other regions where fire–climate relationships have historically been difficult to detect, warming and other climatic or land-management changes may lead to the emergence of these relationships.

The complex interactions between the effects of climate, fuels, and humans on fire activity give rise to the need for complex modeling approaches that can account for these interactions as many factors simultaneously change and interact in the future. Given the need for many degrees of freedom when building an empirical model that accounts for a variety of interacting factors, the space-for-time approach described in the last section is a tempting method to generate future projections of fire activity [111•]. Indeed, there have now been multiple efforts to force empirical spatially-derived models with future climate data and the projections account for far more complexity than would be the case if temporal fire–climate relationships had been simply extrapolated into the future [31•, 32]. In California, extrapolations of temporal relationships with climate [97, 137] imply more acute increases in fire activity than those that holistically consider changes to climate, vegetation, human land use, and fire suppression based on a pyrogeographic modeling framework [138, 139]. Considering Mediterranean biomes globally, Batllori et al. [140] used a pyrogeographic model to demonstrate divergent changes in fire activity resulting from climate change. They found that warming and wetting should cause increases in fire activity while warming and drying should cause decreases in fire activity due to decreases in fuel availability implied by the drying.

While observations from a global domain allow for a robust characterization of the current combined effects of climate, fuel, and human population on fire activity in space, and it follows that these relationships should also apply in time, projections based on current empirical pyrogeographic models generally represent changes in the future *mean* state because they are developed on temporally averaged data. Thus, these models do not incorporate the effects of climatic *sequencing* on fuels and fire activity. Given the short period of observations in many parts of the globe, it is difficult or impossible to fully validate the temporal projections made by these spatially derived models. As spatially extensive observational records of fire activity grow longer, it will become increasingly possible to use spatial and temporal variability together to develop empirical pyrogeographic models that can represent higher-frequency variations in time that can be more readily validated [e.g., 141, 142•].

Further, projections of fire activity based only on long-term changes in the mean state of forcing variables may be problematic because they do not explicitly account for the effects of extreme events. This is particularly true for fire regimes with long fire return intervals where landscape flammability can only occur under highly anomalous climatic conditions [143]. Extreme climate events may cause state-shifts in land cover that force fire regimes to diverge, at least temporarily (e.g., years to millennia), from those consistent with the mean climate [e.g., 144]. Indeed, Parisien et al. [142•] found that an empirical model of Canadian fire based on both climatological means and interannual climate variability was able to better account or the self-regulating property of fire [e.g., 81, 145] than a model based only on climatological means. Conversely, fire can lead to vegetation-type conversions that may lead to *increased* potential for future fire. In the western USA, forest and woodland may be replaced by non-native annual grasses such as cheatgrass (*Bromus Tectorum l*), which is fire adapted and promotes increased fire frequency and spread [146]. Similarly, Brando et al. [25] observed that enhanced fire due to recent severe droughts in southeastern Amazonia drove type conversions from forest to flammable grass species near forest edges, promoting further fire spread and type conversion. Empirical modeling efforts are now underway to better represent fire-regime shifts in response to climate changes [147, 148].

The above examples of fire–fuel interactions occur at spatial, temporal, or species-specific scales that may be too fine for the large-scale empirical modeling approaches described above. Further, empirical models can only be validated for conditions with empirical precedents. In the future, non-analog changes in climate, atmospheric CO_2, and human population demographics (and technology used to suppress or promote fire) are likely to create conditions not fully represented by empirical models. Non-analog future conditions incentivize the use of process-based models that simultaneously simulate climate, vegetation, and human factors, their interactions, and their effects on fire activity using first principals [149]. Importantly, the “first principles” modeling approach is not free of the empirical modeling approaches described above, as dynamic global vegetation models (DGVMs) and macro-scale fire models are parameterized to optimize agreement with observations. Yang et al. [150, 151•] used observations of climate, human demographics, and atmospheric CO_2 to drive a DGVM and an embedded fire module to simulate global fire activity during 1901–2010. In the Yang et al. studies, global burned area declines steadily over the past century primarily due to declines in the tropics and mid latitudes associated with land-use change, deforestation, and fire suppression. This is in agreement with charcoal records [152] but difficult to verify with observations.

Considering the future, Knorr et al. [153•] connected a DGVM with an empirically calibrated fire module to simulate the impacts of changes in climate, atmospheric CO_2, and human demographics on regional-to-global fire emissions throughout the twenty-first century. They projected net positive (though highly heterogeneous) trends in global fire emissions due to warming (drying of fuel) and increasing CO_2 (increased fuel growth), but a compensating net negative effect due to increasing human population. It is important to note that this projection of a net negative human impact is nearly entirely driven by sub-Saharan Africa and the projected human impact is neutral in most regions globally, exemplifying the likely dominance of future trends in African fire on global pyrogenic emissions. Combining the net effects of climate change, increased atmospheric CO_2, and local human effects, Knorr et al. [153•] project global fire emissions to remain approximately constant or slightly increase for the rest of this century, and to be unlikely to return to pre-1900s levels by 2100. Importantly, Knorr et al. [153•] use a single fire model and it has been shown that fire-activity projections are widely variable among models [154], so these results should be viewed as preliminary and as motivation for future efforts of this kind where the spatially explicit, partial contributions of various forcings are examined.

Linking the past to the future using a highly process-based modeling approach, Kelly et al. [155•] combined charcoal-based fire reconstructions and other paleoenvironmental data with vegetation-fire modeling to reconstruct carbon dynamics in Alaskan boreal forests since 850 AD. They forced a DGVM-fire model with paleoenvironmental reconstructions and show that wildfire has likely been the dominant source of variability in carbon storage within Alaskan boreal forests over the past 1200 years. The simulations also suggest that increased fire frequency since 1950 has led to large carbon losses relative to the historic range of variability. This has critical implications for the future carbon balance of the northern hemisphere boreal zone, where continued increases in fire activity are expected due to rapid warming and limited capacity for suppression by humans [156].

Obsticles Inhibiting Reliable Fire Projections

Several uncertainties inhibit reliable projection of future regional and global fire activity. Efforts to parameterize and validate regional-to-global fire models are currently constrained by the relatively short duration of high-quality observational records of fire activity. Because the observational record of global fire activity has far more variability in the spatial domain than in the temporal dimension, macro-scale fire models (both empirical and "process-based") are generally parameterized to optimize agreement with a map of *mean* fire conditions during the period of record. Projections made from such modeling approaches are based on projections of mean predictor conditions with no temporal variability along the way [31•]. In reality, fires occur as discrete events and alter the landscape (e.g., ecological succession, fuel abundance, and connectivity) such that by, say 2050, a landscape may have a much different fuel structure than that which would be predicted based on the mean climate of 2050 [149]. Errors caused by ignoring legacy effects of specific events are likely to be increasingly averaged out as larger regions are considered, however, because integrative effects of wildfire events are implicit to some degree in correlation-based models. This does not appear to be the case everywhere, however, as mean climate can be very similar for both tropical forest and savanna vegetation cover types [157]. Additionally, the relatively short satellite-based fire record and resultant modeling of long-term mean conditions limits rigorous validation of simulated temporal changes in fire activity. Another source of uncertainty comes from the fact that satellite-based records inherently miss small fires, which may have important contributions to actual burned areas and emissions beyond those calculated from satellite records, particularly in tropical regions [158].

Importantly, empirically-based fire modeling requires the assumption that interactions among predictor variables are fully characterized within the ranges of variability of the observations. This assumption is not entirely valid for vegetation. Increased atmospheric CO_2 is projected to lead to changes in vegetation–climate relations by enhancing plant water-use efficiency [159]. Enhanced water use efficiency is projected to allow vegetation biomass to increase in many regions globally, but this process and its interactions with other growth-limiting resources is not fully understood [e.g., 160–164]. Satellite observations of global vegetation greenness do suggest that a positive CO_2 effect on vegetation productivity is already underway [165, 166] (as well as greening and an extension of the early growing season due to warming [167]) but it is not well understood how added biomass and change in growth timing is affecting vegetation structure [168], which is important for fire intensity and spread. More broadly, it is not well understood how global vegetation systems will respond to climate change even in the absence of physiological CO_2 effects, as these responses will be species-, site-, and season-specific and highly dependent on difficult-to-model processes such as plant mortality, insect and pathogen outbreaks, and recovery or succession following disturbances [169–171].

Likewise, it is probably not accurate to assume a constant relationship between humans and fire. In global models, human impact is often approximated as a function of population density, socioeconomics, and perhaps distance from an urban area or road. These impacts are based on an empirical snapshot of the current (or recent) spatial relationships between population density and satellite-derived fire occurrence and size [e.g., 9, 119–122, 138, 172]. In the future, changes in technology and cultural values may have regional-to-global effects on ignitions, suppression practices, and land use that cause deviations from established statistical responses to standard population demographic metrics.

Finally, much uncertainty in the response of fire to climate change is due to uncertainty in climate change itself. Of that uncertainty, much is due to uncertainty about future global socioeconomic development, international environmental regulation, and the resultant trajectory of global anthropogenic greenhouse gas emissions [173–175]. Currently, the difference between climate-model projections of warming by 2100 AD for the two most commonly considered greenhouse-gas emission pathways is approximately as large as the uncertainty among climate models for a single emissions pathway [176]. Uncertainties in climate modeling are also important because fuel growth and dry-down, ignition, and fire spread are influenced by difficult-to-model meteorological features such as precipitation amount and variability [177], lightning [178–182], and extremes in boundary-layer wind and vapor-pressure deficit [26, 183]. Additionally, natural decadal climate variability can cause trends that deviate from projections, adding near-term uncertainty to fire projections even if all other aspects of the Earth system are modeled perfectly.

Projections of future fire activity inherently integrate the uncertainties in projections of several complex and interacting variables. Uncertainties can be partially quantified at a range of scales following the framework of Knorr et al. [153•] where projections are made in a factorial manner to determine the partial contributions of various assumptions to projected changes. As observational records of fire activity and its predictors grow longer, it is critical that models are increasingly validated against the historical temporal variability in observed records, and even in paleo records when possible. More temporal-based modeling may be relatively feasible in the USA, where a Landsat-based record of large fires extends back to 1984 and government records may be used to extend even further. Regardless of datasets used, researchers should maximize degrees of freedom for statistical relationships by designing data-flexible studies that can accommodate updated observational data when they become available.

Conclusions

The future of wildfire regionally and globally will be affected by changes in climate, atmospheric CO_2, fuels, humans, and their complex interactions. Among recent macro-scale fire projections, there is much spatial heterogeneity and the most consistent projection is toward warming-driven increases in high-latitude fire activity. These projections are generally consistent with observational and paleo records of fire and climate, though the coincidence between high-latitude fire and warmth is strongly modulated by vegetation dynamics and is by no means ubiquitous in time or space. Outside of the high-latitudes, compensating forcings from relatively poorly constrained projections of climate changes (particularly precipitation), vegetation changes, and population effects cause much spatial heterogeneity in fire projections. In particular, large uncertainties across fire-prone sub-Saharan Africa due to poorly known fuel responses to climate, CO_2, and humans will be important to resolve given the large carbon fluxes from wildfire in that region.

Among macro-scale fire modeling approaches, there is a wide spectrum of complexity that can be incorporated when making projections of the future. There are tradeoffs between relatively simple assumptions of temporally constant vegetation cover, monotonic climate change, and human demographic effects versus more complex incorporation of dynamic vegetation cover, interannual climate variability, human socioeconomic factors, and nuanced fire variables such as fire perimeters and rates of spread. A middle-ground between correlation-based and mechanistically-based models may provide the best current approach for understanding future changes in fire activity. Future efforts should migrate toward enhanced complexity at a prudent rate as observational datasets, physical understanding, and computational capabilities improve [e.g., 149]. To this end, continued work is essential to better understand the first-principals and statistical representations of the complex interactions among climate, meteorology, vegetation, humans, and fire, and this enhanced understanding necessitates enhanced collaboration between empirical and dynamical modelers.

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Compliance with Ethical Standards

Conflict of Interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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