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Will Landscape Fire Increase in the Future? A Systems Approach to Climate, Fire, Fuel, and Human Drivers

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Abstract

The extent of the Earth's surface burned annually by fires is affected by a number of drivers, including but not limited to climate. Other important drivers include the amount and type of vegetation (fuel) available and human impacts, including fire suppression, ignition, and conversion of burnable land to crops. Prior to the evolution of hominids, area burned was dictated by climate via direct influences on vegetation, aridity, and lightning. In the future, warming will be accompanied by changes in distribution, frequency, intensity, and timing of precipitation that may promote or suppress fire activity depending on location. Where area burned increases, fire may become self-regulating by reducing fuel availability. The effects of climate change on fire regimes will be strongly modulated by humans in many areas. Here, we use a systems approach to outline major drivers of changes in area burned. Due to the array of interacting drivers working in concert with climate's influence on burned area, and uncertainty in the direction and magnitude of changes in these drivers, there is very high uncertainty for much of the globe regarding how fire activity and accompanying smoke emissions will change in the coming decades.

Keywords Area burned · Climate change · Fire activity · Emissions · Systems approach

Introduction

Fire has long been a widespread form of disturbance within the global environment, with patterns of fire activity varying across space and time [1, 2]. Fire has reciprocal influences on biotic assemblages, including human communities, and changes in fire regimes due to environmental or human drivers—or both—can have significant socioecological impacts (e.g., [3–6]).

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Increasingly destructive wildfires[1] in some regions have directed much attention to the influence of warming temperatures on future fire potential. Fire seasons are lengthening globally, via an increase in severe fire weather potential on the six continents where fire occurs naturally [7]. Within this changing fire environment, wildfires may be becoming more resistant to control actions [8, 9]—a finding consistent with public perception of and concern over an increase in fire frequency and size in North America, Mediterranean Europe, and Australia (e.g., [10]). However, satellite observations of burned area (including all landscape fire, not just wildfire) show that over the past two decades, the global annual burned area has actually declined, driven primarily by land use and socioeconomic change in Africa [10–12]. Both may be true: while global area burned has recently declined, an increasingly warm environment is causing wildfires to burn under more extreme conditions at a time when the amount of homes and

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[1] Wildfire is one class of landscape fires, distinct from agricultural burning and other types of controlled burning or "prescribed" fire. Wildfires can be human-caused or naturally ignited, but because they are "unplanned" from a fire-management perspective, they often provoke a suppression response.

infrastructure located in the fire-vulnerable wildland-urban interface continues to grow [10, 13]. These inconsistencies demonstrate the complex interactions and forcings resulting from human manipulation of the environment including the use of fire, how climate establishes the conditions for wildfire potential, and the interplay between human activity, fire, and the changing climate [1, 14].

The complex interactions between humans and natural systems are being increasingly explored using systems-based approaches often termed social ecological systems (SES) or coupled human and natural systems (CHANS) [15, 16]. These systems approaches explore how humans influence and are in turn influenced by natural disturbance processes over space and time. A simplified example is the wildfire paradox: attempts by humans to remove wildfire from fire-dependent ecosystems have led to fuel buildup that makes future attempts to eliminate wildfire more difficult, leading to more frequent management effort, and increased losses when these efforts fail [9]. In recent years, there have been a number of efforts to map how additional social and ecological factors and feedbacks including climate change influence wildfire management and outcomes (see for example [17–20]).

In this manuscript, we take a systems approach to examining wildfire and climate change globally, acknowledging that humans and fuel are also important parts of the system and that reciprocal effects exist between many components of the system (Fig. 1). We review the contemporary literature pertaining to key drivers of landscape fire activity globally (including wildfire as well as agricultural burning and other types of controlled burning or "prescribed" fire) and accompanying atmospheric pollutants from smoke. We present a stylized systems framework that focusses on how climate, ecosystem condition (specifically burnable fuel), wildfire, and human actions interact. We use the term "drivers" to indicate these influences (e.g., climate, fuel, and human actions) which push the system toward increasing (positive forcing), decreasing (negative forcing), or relatively stable area burned. Over time, these influences are dynamic and may switch in direction or magnitude; for example, systems experiencing positive fire feedbacks (increasing area burned) eventually become fuel-limited, introducing a negative feedback that regulates subsequent fire activity. While our main objective is to examine the question of whether burned area will increase in the future, it is not possible to address this question without understanding how climate, fire, ecosystems, and humans have interacted in the past. Therefore, we begin by examining the system of interactions before the advent of hominids and move forward in time, examining how hominids have altered these interactions and what this might mean for the future. (Note that we use the term "hominid" to refer to humans and extinct relatives, i.e., genus *Homo*, but not to great apes.)

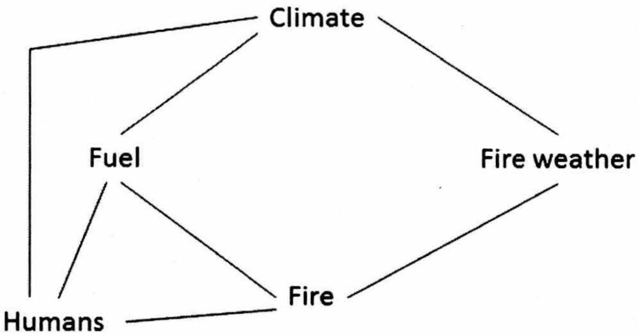

Fig. 1 The landscape fire-climate-fuel-human system. The directionality and strength of the influences are place- and time-specific

Fire Before Hominids

Earth is an intrinsically fire-prone planet, with the presence of an oxygenated atmosphere, fuel in the form of biomass (i.e., vegetation), and a tilted axis that drives seasonal dryness [21]. The first evidence of fire in the Earth system appeared in the fossil record approximately contemporaneously with terrestrial plant life, about 420 million years ago [22]. Continuous evidence of fossil trees and charcoal appeared since the late Devonian, approximately 390 million years ago [13]. As oxygen levels rose during the Late Permian due to the proliferation of vegetation, fires began to occur in an increasing number of ecosystems, as elevated oxygen rendered vegetation flammable at higher fuel moistures by facilitating ignition and continued combustion [22, 23].

In general, fire activity is promoted by elevated temperature, as long as vegetation is available to burn. For example, ice cores collected in Greenland and Antarctica demonstrate that periods of increased temperature coincided with elevated fire activity on millennial timescales in North and South America, between 110,000 and 10,000 years ago [24, 25]. (During this time period, inferences are necessarily at millennial to centennial scales and across broad spatial domains due to the nature of ice core records.)

Prior to the advent of hominids, the amount of fire on the landscape was a function of the abundance of fuel and the prevalence of weather conditions conducive to fire, both of which were driven by climate (Fig. 2). Climate acted as a top-down control on vegetation/fuel type and abundance. Climate also set constraints on the prevalence of conducive fire weather, with warming periods being linked to an increase in conducive weather episodes. Climate fluctuations can also influence the abundance of lightning strikes and affect whether lighting co-occurs with precipitation (which affects ignition probability). Apart from other natural ignition sources, including volcanic activity, lightning was the primary source of landscape fire before hominids.

Vegetation and fire also act in a series of forcings and feedbacks that can operate over annual to millennial timescales

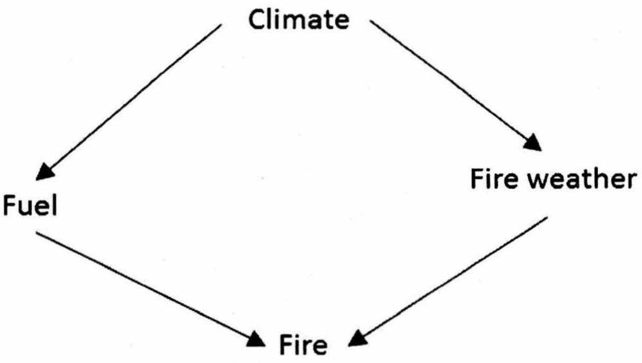

Fig. 2 The pre-hominid landscape fire system. Climate exerts a top-down control on fuel and fire weather, which in turn together influence the levels of landscape fire activity

(Fig. 3). At millennial timescales, the evolution and spread of vegetation may be facilitated or impeded by fire. For example, the spread of C_4 grasses[2] into more mesic environments during the Late Tertiary may have been promoted by increased fire activity, which created favorable environments for grasses by opening woodland canopies [26]. Many ecosystems have evolved in concert with wildland fire and are considered "fire-adapted," with plants showing various adaptations to fire including vigorous resprouting and serotinous cones that require fire to drop seed [21, 27]. At centennial timescales, shifts in vegetation due to changing climate may facilitate or retard fire spread (e.g., where tundra shifts to boreal forest) [24]. At annual timesteps, in ecosystems with high fire activity, recently burned areas act as a negative forcing on area burned, since it takes some time for vegetation to regrow to the point that it can carry fire [28, 29]. Thus, fire can restrict the availability of burnable fuel at the landscape level [30].

Fire may cause shifts in atmospheric composition drastic enough to cause climate forcing (Fig. 4). Widespread burning of peats and commensurate rise in atmospheric carbon dioxide (CO_2) has been proposed as one of the possible mechanisms that contributed to the rapid rise in temperature at the Paleocene-Eocene thermal maximum and may have facilitated global change at the end of the Permian [23, 31].

Fire in the Time of Hominids

Hominids evolved in eastern Africa approximately 2.5 mya. As populations grew and dispersed, they began to act as an additional driver within the system (Fig. 5).

During the Paleolithic and Mesolithic ages, hominids used fire extensively to clear ground for dwellings, to reduce underbrush in order to facilitate movement, to hunt, and to regenerate plant foods for themselves and grazing animals [21]. Impacts on vegetation included the opening of closed-canopy shrublands and woodlands and their replacement by annual species [21].

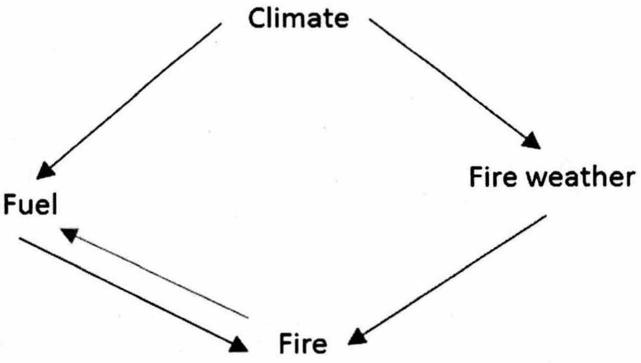

Fig. 3 The pre-hominid wildfire system, including climate forcing on fire weather and fuel growth, abundance, and structure. A feedback loop exists between fire and fuel, where fire influences not only the rate of fuel growth but also the vegetation type (e.g., forest versus grassland) and fuel affects the frequency of fire. (When an arrow is added for the first time, in this and in subsequent diagrams, it is shown in gray. The lighter color conveys only that the arrow is new, and nothing about its strength relative to other forcings)

Between the last glacial maximum (about 21,000 years ago) and the start of widespread agriculture (about 10,000 years ago), global biomass burning increased monotonically, according to charcoal evidence, with this trend being linked to both warming of the climate and expansion of vegetation as the ice sheets retreated [32].

As agriculture became prevalent during the Neolithic, *Homo sapiens* (i.e., humans) started to significantly alter the abundance and distribution of available fuel (Fig. 6). Humans required fire to transform some vegetation types to annual-dominated landscapes [21]. Increasing population in Europe corresponded to a widespread increase in burning between 4000 and 2000 years ago, based on charcoal records [32] and ice core records [33]. This increase may have corresponded with land clearing and conversion to pasture or agricultural land [32, 33].

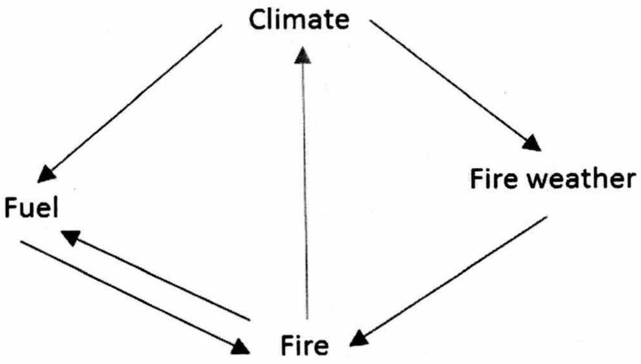

Fig. 4 The pre-hominid landscape fire system, including a fire-climate forcing

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[2] C_4 grasses utilize a different photosynthesis pathway than other grasses (known as C_3 grasses) which makes them better adapted to areas with warm or hot conditions during the rainy period of the year [26, 176]. Thus, C_4 grasses often dominate today's tropical and subtropical grasslands [26, 177].

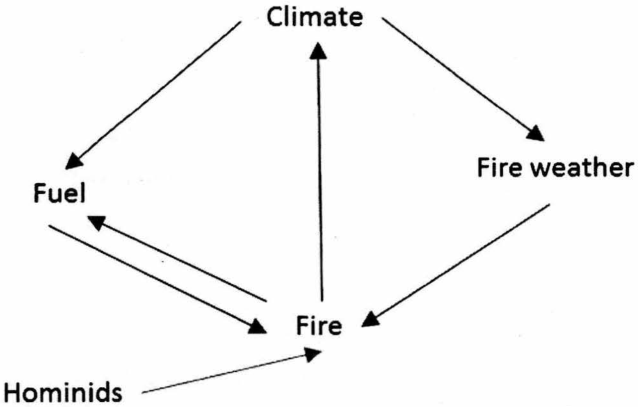

Fig. 5 The landscape fire system, including early-hominid use of fire to influence vegetation

As human-cultivated lands expanded (along with their impacts on fuel continuity and abundance), the upward trend in global fire activity ceased (approximately 10,000 years ago) [21]. Climate was likely also a factor in the global decline in biomass burning from 1 to 900 AD, when a period of global cooling corresponded with continued expansion of human populations and cultivated lands [34]. The influences of these various drivers (i.e., expansion of cultivated land and global cooling) are difficult to apportion.

During the Medieval Climate Anomaly (~ 900–1300 AD), increased fire activity corresponded with localized warming in boreal Alaska [35, 36], North America's Pacific Northwest [37], and the central Rocky Mountains [38]. Conversely, during the Little Ice Age (~ 1500–1800 AD), fire activity decreased in many regions globally [32, 35, 39]; however, the decrease in North America also coincided with the dramatic decline in Native American populations and their traditional burning practices [40].

Between 1750 and 1870, global burning increased sharply, with this rise being linked to more pervasive human influences including population growth and accompanying land use change [34]. After 1870, burning declined abruptly, likely due to the widespread expansion of intensive agriculture, grazing, and the eventual emergence of organized fire suppression [34].

From the systems perspective, hominids represent a new driver that uses fire to exert various controls over vegetation. As hominids migrated across the globe, they began to affect interactions among climate, fire, and ecosystems. Hominids used fire in a localized fashion to make room for dwellings and to encourage or inhibit the growth of certain plants. However, with the advent of agriculture, hominids (i.e., humans) began to use fire as a tool in the conversion of ecosystems to cultivated land—a more long-lasting, widespread, and substantial change. Thus, hominids act as both a positive forcing on fire activity (in using fire to change the landscape) and a negative forcing on fire activity (in converting burnable land to cropland or pasture, which may be burned less frequently or not at all).

Fire in the Era of Anthropogenic Climate Change

Currently, humans have a far larger influence on the landscape fire system than in the past, due to explosive population growth and technological advances. They influence the extent and composition of available fuel, apply (both intentionally and accidentally) and suppress fire, and impact global climate (Fig. 7). Climate and fuel still exert strong influences on fire activity, however.

During the past few decades, extensive datasets, including global satellite data and weather data assimilated from thousands of recording stations, have allowed for the detailed study of the interplay between fire and weather, as well as smoke dynamics, sometimes at temporal scales as fine as sub-daily and spatial scales smaller than 1 km.

Globally, in recent decades, on the order of 301–464 million hectares (about 2–3% of the planet's land surface) has burned annually [12, 41]. Despite recent increases in

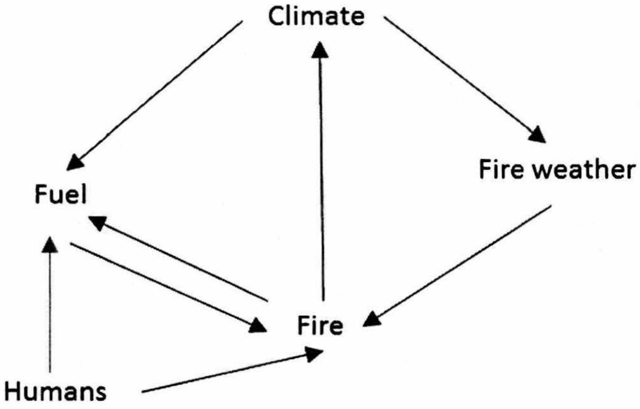

Fig. 6 The landscape fire system, including direct and indirect influences of humans on vegetation/fuel, e.g., for sustained agricultural uses

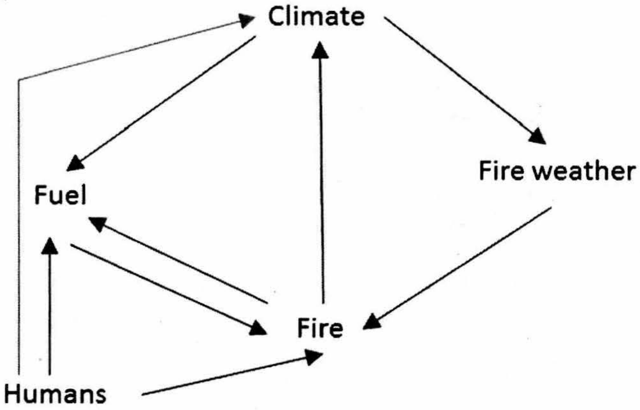

Fig. 7 The landscape fire system, including anthropogenic climate change

temperature and fuel aridity, global burned area declined significantly by 24.3% during 1998–2015 [11]. However, this trend varies spatially in direction and strength and is inconclusive for North America, South America, Eurasia, Australia, and Southeast Asia. The global reduction in burned area was driven by a decline of 1.27% per year in Africa [11]. Trends in Africa likely result from human-mediated landscape changes [11], suggesting that, in this region, global climate forcings that would increase fire activity are being overridden by human impacts.

Human population density and prosperity affect area burned [11]. Where density and prosperity are very low (which may represent marginally habitable land), area burned tends to be low. As density and prosperity increase, landscape fire activity also increases (signifying use of fire by rural populations) before dropping precipitously in heavily populated and relatively prosperous areas [11]. The burned area decline in the latter regions is likely a function of perceived threats to highly valued resources such as homes and infrastructure, prompting extensive fire suppression efforts, sometimes at enormous cost [10].

In addition to strong direct human influences, climate exerts substantial controls on fire activity. At the global scale, fire weather seasons have been growing longer, with the global mean fire-season length increasing by approximately 18% between 1979 and 2013 [7]. Fuel aridity has increased due to increases in temperature driven by anthropogenic climate change during the past few decades; fuel aridity and fire danger metrics correlate strongly with area burned [7, 42, 43]. Temperature promotes fuel aridity by increasing the evaporative demand of the atmosphere via the vapor pressure deficit [44]. This effect is implicit via the Clausius-Clapeyron relationship, where the moisture holding capacity of the atmosphere increases exponentially with temperature ($\sim 7\%\ C^{-1}$) [45]. Although temperature is positively correlated with burned area across the western United States (US) [46, 47], the strongest correlations between area burned and weather/climate variables are found when using metrics related to flammability rather than to temperature alone (e.g., potential evapotranspiration, precipitation anomaly, or fuel moisture) [14, 43, 46, 48, 49]. In fact, one of the strongest drivers of area burned may be the number of wetting rain days (precipitation $> = 2.54$ mm) [50].

Climate changes also cause shifts in snow dynamics. Warming reduces the fraction of precipitation falling as snow and speeds the rate of snowpack melt. These changes cause the timing of runoff and infiltration to shift earlier in the year and promote lengthening of the period with dry soils and fuel during the warm fire season [51–55].

Smoke and Emissions

The primary drivers of fire emissions are burned area, fuel loading (amount of material available for combustion in various biomass pools), combustion completeness (fraction of fuel load burned), and emission factors (mass of a pollutant emitted per unit mass of fuel burned) [56]. Fuel loading and combustion completeness vary significantly across ecosystems and biomass pools, respectively. Combustion completeness of grasses and fine litter pools typically approaches 100%. In contrast, the combustion completeness of live leaves and needles, larger diameter litter (large branches and logs), standing dead trees and shrubs, and organic soil is highly variable, depending on moisture content, ambient meteorology, and terrain. Emission factors vary by fuel component, fuel conditions, and the relative share of flaming or smoldering combustion. Organic soils, peat, and large-diameter dead woody debris favor smoldering combustion, which has much higher emission factors for $PM_{2.5}$ than flaming combustion that dominates grasses and fine litter [57, 58].

In recent decades, approximately 2.2 Pg/year of carbon has been emitted by wildland fire globally (including emissions from both natural and human-caused fires) [59]. Carbon from fossil fuel emissions is approximately five times greater at 10 Pg/year (10,000 million metric tonnes) [60]. Following fire, carbon is often reassimilated into vegetation onsite over a period of months or years and thus biomass burning cannot be considered a net carbon flux; however, where forests do not regrow after fire due to type conversions driven by climate changes or maintenance as croplands, net carbon emissions can be significant [61].

Biomass burning is the largest source of carbonaceous aerosols and a leading source of reactive trace gases [59, 62]. Fires in Africa are the leading source of global fire emissions (accounting for 52%), followed by Asia (22%) and South America (15%) [59]. Emissions depend on the area burned, the amount of fuel (biomass available for combustion), and combustion completeness (fraction of fuel consumed) [63].

Wildfire smoke is a substantial health hazard—both acute and long-term exposures are associated with increases in respiratory and cardiovascular morbidity and mortality [64–66]. The smoke constituent presenting the primary health hazard is fine aerosol, i.e., particulate matter with an aerodynamic diameter < 2.5 um ($PM_{2.5}$) [67]. Globally, it has been estimated that exposure to $PM_{2.5}$ from wildfire smoke results in over 300,000 premature deaths annually [68].

Fire and Climate in the Future

Under future climate, changes in temperature, precipitation, humidity, and cloudiness are expected to influence fuel moisture, thereby impacting burned area and combustion completeness, and thus smoke [69–71]. Changes in human habitation and land use patterns will also affect the distribution of fire [72, 73]. The boundaries of biomes may shift, causing changes in fuel structure and type and commensurate fire activity; shifting biome boundaries may affect climate via large changes in carbon storage as well as changes in surface energy fluxes that affect atmospheric circulation (Fig. 8) [61, 74–76].

Little is known about the relative strengths of the various drivers (e.g., humans, fuels, and climate) on area burned, or how these vary across different biomes and ecosystems [73, 77]. In addition, the magnitude of future climate change is not known due to internal variability in the climate system, uncertainty in modeling of climate response to external forcing, and uncertainty in the magnitude of external forcing due to humans [78, 79]. Thus, predictions of future fire activity are highly uncertain. In the following subsections, we examine predicted changes to key climatic influences on fire activity and underscore the level of uncertainty in these predictions. Then, we discuss likely changes in vegetation and fuels and their implications for fire and climate and end this section with a discussion of likely future fire emission scenarios and implications for air quality and climate.

Changes in Climate and Fire Weather: Predicted Effects on Fuel and Fire Activity

Robust Projections of Climate Change

Projections of future climate come from General Circulation Models (GCMs), which simulate the global climate system [80]. GCMs project the globe will warm as a result of rising greenhouse gas concentration in the atmosphere, with warming most rapid over continents and at high latitudes [79]. If all else were held constant, widespread increases in wildfire activity would be expected in many regions globally due to warming-induced increases in atmospheric moisture demand and fuel aridity (which is correlated with area burned) [69, 81, 82]. In historically snowy locations, warming-induced shifts to rain and early snowmelt may also reduce soil moisture availability in the subsequent warm months [52, 83].

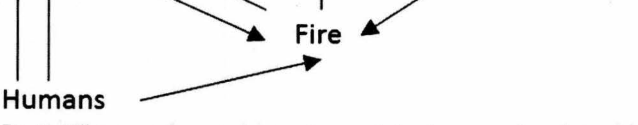

Fig. 8 Climate- or human-driven changes in land use may be substantial enough to provide a forcing on global climate

Whether and how these projected increases in temperature actually affect wildfire activity, however, will be heavily dictated by the availability of fuel [82, 84, 85], which will be strongly influenced by precipitation and other climate variables. For example, reductions in precipitation could promote fire activity in very wet regions such as tropical or temperate rainforests, or suppress it by causing reduced vegetation cover in semi-arid deserts. Conversely, increases in precipitation in fuel-limited systems (such as xeric shrublands and semi-arid deserts) could promote fire activity by enhancing surface fuel abundance or suppress it by increasing fuel moisture [77, 86]. CO_2 fertilization, increased precipitation, and longer growing seasons may enhance ecosystem productivity [87], increasing the foliage and litterfall available for burning in some areas. In addition, humans will continue to be strong influences on vegetation change globally, via expansion of croplands, deforestation, fire suppression, etc.

While there is broad agreement on an increase in temperature at both global and local scales, changes to patterns of precipitation are subject to uncertainties associated with seasonal (e.g., monsoonal), interannual (climate mode, e.g., El Niño Southern Oscillation (ENSO)), and decadal (climate oscillations such as Interdecadal Pacific Oscillation (IPO), Atlantic Multidecadal Oscillation (AMO)) climate patterns. Robustly projected changes in precipitation include decreases in annual totals in the subtropics, particularly on the poleward flanks as the overturning Hadley cells expand poleward [88], and increases in annual totals throughout much of the tropics and high latitudes [79]. The seasonality of these changes in precipitation will be important to forecasting changes in fire activity. For example, if decreases in precipitation in the subtropics occur during the winter but not during the summer fire season, fire activity might increase less than if the decreases in precipitation occur during the summer fire season.

Temperature increases will also affect the activity of insects. For example, under climate change, developmental stages of some spruce bark beetles are expected to accelerate, facilitating faster reproduction and increased intensity of outbreaks [89–91], while the reduced frequency of fatal winter temperatures has allowed for expansion of the range of Mountain pine beetle across North America [92, 93]. Tree mortality may increase due to infestation by these insects, with trees likely being more vulnerable due to increased drought stress [94–96]. The expansion of the range of fire-sensitive spruce and fir into surrounding forest types as a result of fire exclusion is also likely to contribute to larger-scale and higher-intensity outbreaks [97]. Increased size and/or frequency of beetle outbreaks could influence subsequent fire activity, though empirical evidence for this is as yet mixed [98, 99].

Models also project increases in precipitation variability and extreme events on both interannual and intra-seasonal bases, mainly because the near-surface specific humidity of the atmosphere increases exponentially as it warms [100, 101]. Climate change may increase tree mortality through more severe droughts [102], altering forest composition and increasing the amount of standing and down woody biomass available for combustion [103]. Over time, drought-driven tree mortality would reduce water demand, potentially creating a negative feedback on subsequent mortality.

Even in the absence of changes in total mean precipitation, changes in precipitation variability would influence landscape fire regimes. More extremes on the sub-seasonal scale may enhance runoff at the expense of soil infiltration, likely reducing live and dead fuel moisture. If precipitation tends to arrive in fewer but larger storms, the number of days with wetting rain will likely decrease, contributing to an increase in fire activity [50]. More variability on interannual scales may result in more fine fuel regrowth between years of extreme fire danger, potentially increasing fire frequency and severity. Importantly, vegetation structure and species composition will be affected by changes in climate and climate-driven changes in fire severity and frequency. For example, increased fire frequency may prevent individuals of some plant species from reaching reproductive age, favoring those more adapted to short fire-return intervals [104, 105].

Major Uncertainties in Climate Projections

While there are some robustly projected changes in large-scale temperature and precipitation (described above), projections are more uncertain for most individual regions and especially for non-temperature variables. For example, climate variability in many regions is sensitive to nuanced variations in tropical ocean and atmosphere circulation that GCMs still have trouble simulating reliably (e.g., [106]). Among the most notable sources of uncertainties are clouds. Uncertainties in the effect of anthropogenic forcing on clouds over tropical and subtropical oceans cause large uncertainties in both global temperature change and large-scale atmospheric and oceanic circulation that drive changes in regional hydroclimate [107–109] and have implications for future fire activity.

Of course, even considering variables and regions where models are in agreement as to how additional greenhouse gases affect climate, there is great uncertainty in future climate change due to uncertainty in future greenhouse gas emissions [110, 111]. Comparing various potential future emissions scenarios, the multi-model mean projected warming for 1900 to 2100 ranges from approximately 2 °C to 5 °C, depending largely on the trajectory of the twenty-first-century global greenhouse gas emissions [79].

Another uncertainty particularly relevant to extra-tropical precipitation, extreme weather, heatwaves, and fire is the degree to which rapid Arctic warming and ice melt (known as Arctic amplification) affect the jet streams and related features of extra-tropical atmospheric circulation [112–114]. It has been hypothesized that the reduced tropics-to-pole temperature gradient has caused a slowing of the jet stream and an increase in the latitudinal amplitude of its Rossby waves in the Northern Hemisphere, leading to more persistent and extreme weather events in the Northern Hemisphere extra-tropics [115]. This could lead to exacerbated drought conditions conducive to fire [116]. However, these findings have been shown to be highly sensitive to methodology [117, 118], and there have not yet been clear and consistent trends in jet stream latitude, upper tropospheric wind speeds, or Rossby wave amplitude in observations over the past several decades [113, 119], possibly because observational records are too short for an effect of anthropogenic forcing to have yet clearly emerged [120]. While models do robustly project a poleward migration of the Northern Hemisphere jet streams, this migration is small (1°) and does not correspond to increases in Rossby wave amplitude or frequency of blocking events [121, 122]. Overall, past and future trends in large-scale extra-tropical circulation were and will be driven by far more than Arctic amplification alone and will continue to be difficult to attribute to anthropogenic forcing due to a high degree of interannual variability, and complex dynamics with competing effects, some of which are still poorly understood and modeled [113, 123].

Influences on interannual and seasonal precipitation totals are also the subject of continued research. Projections of the El Niño Southern Oscillation (ENSO), a driver of fire activity in some regions via interannual fluctuations in precipitation [124, 125], are still highly uncertain [126, 127]. In addition, models disagree as to the seasonality of precipitation changes [128], with precipitation during fire season being a stronger driver than non-fire season precipitation in many ecosystems [43, 47].

Changes in Vegetation and Fuel: Predicted Effects on Climate and Fire

Changes in land cover will also critically affect climate and fire activity across many scales. In recent decades, increases in terrestrial net vegetation productivity have substantially reduced the rate of CO_2 accumulation in the atmosphere resulting from anthropogenic emissions [129]. Further, vegetation influences evapotranspiration amount and timing across all land areas. Evapotranspiration diminishes surface energy that would otherwise be partitioned toward sensible heating [130], and altered surface energy and moisture fluxes affect large-scale atmospheric circulation [131]. Future changes in vegetation cover will therefore have important impacts on soil moisture, runoff, surface temperature, and humidity at local scales, and on large-scale circulation [76, 83], with commensurate effects of fire activity.

Dynamical global vegetation models (DGVMs) used within the Coupled Model Intercomparison Project 5 (CMIP5) experiment have widely varying projections of changes in global terrestrial vegetation productivity and cover, largely due to uncertainties in effects of CO_2 fertilization, nutrient limitation, human land management, and the effects of climate variability on productivity, disturbances, mortality, and succession [132–140]. Continuing population expansion and conversion of burnable land to cropland or other irrigated space can affect landscape-level burn probabilities [72]. Conversion of rainforests to croplands may liberate large amounts of carbon to the atmosphere [141]. Management interventions such as prescribed burning and fuel treatments have the potential to reduce or limit increases in future burned area, if completed at a broad enough scale [142, 143].

Future Landscape Fire Emissions and Implications for Air Quality and Climate

Given the uncertainty in projections of area burned, recent studies estimate the late twenty-first-century global fire emissions will range between − 15 and + 62% of present-day emissions, varying with the combination of climate change scenarios and predicted human population changes [69, 144]. Under future climate, fire activity and emissions were predicted by two studies to increase in North America, Europe, and North Asia; decrease significantly in Africa (due to population changes); and remain roughly unchanged in South America [69, 144]. Increased emissions in the mid-latitudes and boreal regions were approximately offset by decreased tropical emissions. However, a third study estimated future global fire emissions would increase by 17% to 62%, with fires in South America accounting for over half the increase [70].

Factors influencing emissions vary across studies. Climate change may increase emissions through increased burned area in some or all regions [69, 70]. These increases may be roughly offset by reductions in the fuel loading available for combustion [69], but in some regions, increased precipitation and fuel availability may result in a combination of increased burned area and fuel load [144]. CO_2 fertilization may affect the burned area and is likely to decrease it via woody encroachment on grasslands, but some of this decrease may be offset by increased emissions due to increased fuel load [69]. Shifts in population, land use change, and timber harvest are likely to decrease emissions [70]. Though human ignitions may increase with population, the net impact of population changes is likely to decrease emissions via fire suppression [70]. The impact of land use change and harvest is expected to decrease global emissions by up to 5% to 35%, depending on the scenario considered [57].

Future emission fluxes and climate conditions are uncertain, resulting in zonal changes in black carbon concentrations (a reasonable proxy for $PM_{2.5}$) varying from − 50 to + 100% [144]. These zonal means understate the potential human health impacts considering the atmospheric lifetime of black carbon and the magnitude of the black carbon changes over the continents, especially in active fire regions. Under future climate, some regions (e.g., central South America, northeastern Siberia, and northwestern Canada) are likely to experience degraded air quality due to increased fire emissions; however, future wildfires will be of limited importance for air pollution in most regions [145]. In Southeast Asia, where smoke from fires used for land clearing and agriculture can be a significant health issue in the present day [146], studies project reduced emissions under future climate due to increases in population density and changes in land use [69, 70, 146].

Using the Systems Framework: an Example from the Western US

The systems framework can be leveraged to aid in examining changes in drivers of fire activity under climate change. Here, we use an example from the forests of the western US, a well-studied area. Area burned has increased during the past few decades [147], which is likely an outcome of several factors. Changes in climate (increasing temperatures and decreasing summer precipitation) have acted as a positive forcing on area burned by creating additional windows of weather conducive to fires [7, 42, 50, 52, 54, 147] (Fig. 9a). Changes in fire management now allow for fires to burn and expand in some locations where they are expected to deliver benefits to highly valued resources, also acting as a positive forcing on area burned (e.g., [148]). However, fire suppression is still largely the default reaction to ignitions, causing area burned to remain below the early-twentieth-century levels [149, 150]. Thus, fire suppression acts as a negative forcing on fire activity over the short term, but contributes to increases in fuel over the longer term, which acts as a positive forcing on fire activity by reducing fuel limitation [9]. Fuel loading and connectivity are above historical levels due to a century of fire suppression and timber harvest by humans [9, 151, 152]. Because forest area burned in the western US is below historical levels, it does not significantly contribute to global climate change [150]. However, humans continue on a trajectory of aggressive burning of fossil fuels, contributing to positive forcing on area burned in this region [42, 50].

Over the next century, continued increases in temperature and decreases in fire season precipitation are likely as a result of anthropogenic fossil fuel emissions, acting as a positive feedback on area burned by further increasing the occurrence of windows of weather conducive to fire and increasing fuel aridity [153, 154] (Fig. 9b). Because fire suppression is less (if at all) effective during extreme weather and in forests with high fuel loading due to past management practices, suppression capability is likely to be overwhelmed and humans may not affect fire activity during extreme conditions [8, 155]. Unless significant changes from the status quo occur, various obstacles will continue to preclude the implementation of prescribed burning at the scale necessary to reduce fuel (which would constitute a negative (regulating) feedback on fire; obstacles include air quality regulations, lack of funding, and

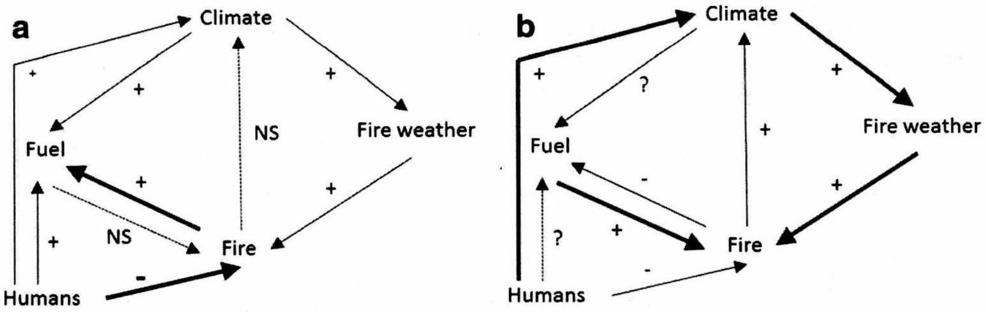

Fig. 9 The systems framework can be used to examine and understand feedbacks in fire activity under current (**a**) and future (**b**) predicted conditions. This example is for western US forests, broadly considered. Plus signs (+) indicate positive forcing, negative signs indicate negative forcing (−); effects that are not expected to be significant are denoted with "NS," and "?" indicates instance where the direction of the forcing cannot be predicted. Thicker arrows represent stronger drivers

strict prescriptions). If fire suppression is ineffectual as well, then humans might cease to have a significant effect on fuel in this region. However, in some regions, acceptance of managed fires has been increasing recently ("managed fires" refer to those on which land managers have a less-than-full-suppression objective), meaning that additional acreage may be burned by wildfires during less extreme weather conditions. At increased levels of fire activity, fire may become self-limiting in some areas [30]. Carbon emission levels would increase at higher levels of burning [156]; however, forests and woodlands may expand in areas where available moisture increases during the growing season, facilitated by the increase in water use efficiency from CO_2 fertilization or contract in areas where growing season moisture is expected to decrease and high vapor pressure deficits result in mortality of large woody vegetation [128, 157, 158]. Thus, the net effect on carbon and global climate is difficult to determine.

The net effect of future changes to the fire-climate system of the forested western US would likely be increased fire activity over the short term. Over the longer term, negative feedbacks resulting from increases in burned area and fuel limitation would constrain the system from experiencing further increases in forested burned area. However, the magnitude of these changes is uncertain, and the direction of these forcings would likely be different in other ecosystems.

Discussion: Major Challenges in Prediction of Future Fire Activity

Before human influences became globally significant, the climate-fire relationship was less complex. Currently, fire activity is driven by a system of controls and feedbacks affected not only by climate but also by human activity and its effects on vegetation and fuel, as well as human effects on climate itself (Fig. 8). The complexity of this system leads to a number of challenges in predicting future fire activity.

Many of these challenges are in the domain of forecasting future climate. Predictions from GCMs are in good agreement that temperatures will increase, though the magnitude of the change is uncertain. Increasing temperatures can be expected to increase atmospheric moisture demand and increase fuel aridity [46]. This will have the effect of intensifying droughts, which frequently exacerbate fire. In addition, the length of the fire season is likely to increase [7]. In the short term, this may produce more rapid curing of herbaceous vegetation and contribute to water stress of all live vegetation, increasing fire activity. Moisture content and curing rate of live fuel greatly affect the probability of ignition and rate of fire spread [159, 160].

However, GCMs vary in predictions of windspeed and precipitation for a given region (direction, magnitude, and seasonality), posing challenges in predicting future fire activity [79, 161]. Warming and increased precipitation, which is likely for much of the globe, may produce greater increases in fire activity than warming and drying (for example, by promoting continuous vegetation in areas that are now xeric shrublands and semi-arid deserts) [162]. However, these increases may be punctuated by periods of reduced fire activity when fire causes fuel to be limited [14].

In addition, it is the variability in climatic conditions over decadal, annual, and seasonal scales that determine the spatial continuity and arrangement of fuel types and their availability to burn. Periods of extreme weather conducive to fire spread (hot, dry, and windy) are a prerequisite for the growth of large fires once ignition has occurred [43, 163]. Precipitation amount, seasonality, duration, and timing are all important factors in vegetation abundance and continuity, timing of vegetation curing, and whether/when dead fuels reach fuel moistures at which they are available for burning (e.g., [43, 46, 50]). The fact that the strongest correlations between burned area and climate/weather metrics are found in studies that use variables that track vegetation flammability rather than just temperature poses challenges for forecasting area burned under climate change scenarios, as flammability depends on short-term fluctuations in precipitation, temperature, and winds. Future lightning activity is another wild card, with some studies predicting increases [164]. Even if future lightning levels are similar to today's, the location of storm tracks will greatly influence its spatial distribution. Thus, the relationship between fire and climate in the future depends greatly on weather conditions that are difficult to model. (GCMs do not simulate lightning directly and it must be inferred from other outputs [165].)

Another challenge in using climate conditions to predict future fire is that current fire-climate relationships cannot necessarily be used to understand the future. Extrapolations of current fire-climate relationships to no-analog conditions are likely to overpredict burned area, as recently burned areas are self-limiting, since fuel will not recover to the point where it can carry another fire for some time [14, 30, 166, 167]. The degree of self-limitation is a function of the vegetation type, time since fire, and biophysical setting related to climate [28, 29]. A second challenge is that different vegetation assemblages become flammable at different fuel moistures (e.g., [43]). As vegetation assemblages shift under future climate, extrapolating relationships between fuel moisture and burned area become dubious where novel species assemblages form, resulting in no-analog conditions (e.g., [61]).

Even if the trajectory of climate change was known, climate effects on vegetation are uncertain. At broad spatial and temporal scales, climate determines the biophysical setting for vegetation growth. While most of Earth's biomes have evolved in tandem with fire, they are adapted to specific fire regimes; changes in climate may result in departures from those regimes, with potentially disruptive effects ranging from introduction of invasive species to type conversion [21, 61]. Type conversions (e.g., a transition from forest to grassland due to widespread tree mortality) may occur due to the inability of a landscape to sustain the current vegetation due to increased water stress, for example, but more rapid and spatially extensive type conversions may occur due to disturbances such as fire (e.g., [61]). Type conversions may either increase burn probabilities, for example where closed forest is converted to shrub or grassland, or decrease burn probabilities where fuel on formerly burnable landscapes becomes too sparse. The combination of invasive grasses and fire can also be a significant factor in causing type conversions in a number of ecosystems by introducing or increasing the frequency of fire in systems poorly adapted to frequent fire [168, 169].

Challenges in modeling future fire activity are not limited to the climate and vegetation domains, but are rife in predictions of future human activities as well. Direct human influences on vegetation globally may be as powerful as those from climate, with these impacts producing both positive and negative feedbacks on global fire activity [21]. Human actions may drive increased fire levels in some cases (e.g., with fire-induced deforestation and agricultural burning) and decreased fire in others (e.g., through aggressive fire-suppression activities) (e.g., [11, 40]). At the global level, continued expansion of cropland and pasture may dampen climate-driven increases in landscape fire. Since the onset of the Medieval Climate Anomaly, humans have been able to disrupt and in some cases uncouple the once robust relationship between biomass burning and temperature [32, 40]. Uncertainty in emissions scenarios is substantial, but predictions for the twenty-first century indicate temperature increases of double to quintuple those estimated during the Medieval Climate Anomaly and Little Ice Age. This raises a question: is there a threshold in the magnitude of climate change after which humans will no longer be able to affect this relationship? With instances of extreme weather occurring more frequently, and fire suppression being less effective under extreme weather, perhaps this threshold has already been surpassed in some areas.

An important human factor will be the trajectory of population growth. Since population density and wealth are negatively correlated with burned area [11], if society continues on a trend toward increasing population density, decreases in burned area might be expected. However, recent demographic shifts in some areas show rural populations moving to urban centers; thus, population density may be decreasing in many rural areas. When rural populations shift to urban areas, human ignitions and burned area may decrease, but when fires occur, they may grow larger due to increases in fuel connectivity [170, 171]. The strength and direction of these human effects in relationship to those in other parts of the system will ultimately determine whether fire activity increases or decreases regionally.

Projections of landscape fire and climate must necessarily rely on modeled projections of the major drivers of climate, vegetation, and human management, though these models can, to some extent, rely on empirically observed relationships and physical models [14]. Given uncertainties in climate, vegetation, and human drivers, uncertainty in predictions of future fire activity is substantial [14, 172, 173]. Currently, global fire models do not agree on whether climate change will increase or decrease the frequency of fires in individual locations, let alone on the magnitude of changes [174]. A challenge in comparing results across a suite of existing global fire models is that the set of drivers they incorporate (fuel moisture, fuel load, ignitions from lightning and anthropogenic sources, fire suppression, rate of spread, and burned area), the spatial scale at which they operate, and the level of complexity within each model vary considerably [174]. In addition, the short duration of global fire records makes validating the outputs of these predictive models difficult [14, 69]. Global fire models currently do not simulate fire with the level of complexity common in models used to render fire progression during wildfire incidents or those used for national-scale risk products (e.g., [163, 175]). However, global models incorporate broad-scale drivers and feedbacks such as the effects of CO_2 fertilization and projected changes to human demographics, factors that incident-level models do not currently handle (e.g., [73, 128]). The potential exists to couple more sophisticated fire models with existing vegetation models, but integrating these models will be complex and computationally intensive.

At this point, it is not possible to assign probabilities to changes in any of the human, climate, or vegetation drivers of fire activity, meaning predictions can at best rely on scenario planning as a tool [172]. Simulations might be made in a factorial design, where the contributions of different scenarios can be assessed [14].

In summary, robust predictions of area burned under future climate require an understanding of the coupled dynamics of the major drivers of the landscape fire system (climate, fire, fuels, and humans), and how to feasibly simulate these dynamics quantitatively. The dynamics and strengths of these drivers vary not only regionally but also over time (Fig. 9), and there are likely severe limits on our abilities to project changing dynamics into the future. For example, culture and technology are major drivers of how humans interact with fire (e.g., the number of ignitions in the USA currently peaks on July 4 due to a cultural tradition and the technology that produced fireworks) but changes in culture and technology represent systems with enormous internal variability that cannot be modeled. The depth of study and the ability to simulate the landscape fire system vary regionally, with greater understanding in some well-studied regions such as the western US and Australia. Understanding is also, of course, the highest for the recent past and near-term future. For example, in the western US, the high correlation between fuel aridity and forested burned area in recent decades strongly suggests that as warming continues, burned area will continue to increase in tandem with fuel aridity into the near-term future (next few decades) (e.g., [42, 46]). However, the sensitivity of fire activity to climate in any time period is modulated by land-cover and human variables that vary across a range of time and spatial scales. The largest source of uncertainty inhibiting fire models is likely humans: how will they affect the landscape and fire? Uncertainty also arises due to a lack of understanding about how changes in climate, CO_2 levels, and fire will affect future vegetation communities (e.g., [128]). Uncertainty increases with time into the future [172]. In making predictions, forecasters must rely on a set of empirical and physical models, which are improving as research advances and the short timeframe of reliable observational records of fire and climate grows [14]. However, the landscape fire system is an integration of many highly coupled and complex physical, biological, and cultural systems, with hard limits likely to permanently inhibit accurate long-range projections of wildfire activity.

Conclusions

Global fire activity in the future will be influenced by a system of climate, vegetation, and human drivers. The strength and sometimes even the direction of these drivers are challenging to predict, and system-wide feedbacks further complicate the picture.

We present here a systems framework to help make sense of this complexity. Climate, in tandem with vegetation, has been a strong driver of fire activity throughout the Earth's history and will remain so. However, human influences on ecosystem condition/flammability and fire activity have increased over the past century due to the explosive population growth and technological advances. Humans now also exert an impact on the climate, via fossil fuel emissions, which in turn influences fire activity. The sign and magnitude of feedbacks among climate, vegetation, and fire may shift over time, depending on interactions among the various factors. For example, there are indications that changes in climate are lessening human ability to suppress fires in some regions (e.g., western Europe and the western US) but not in other regions (e.g., Africa). Looking to the future, the relative influences of the primary drivers may be deduced in some systems, at least over limited time horizons (such as a few decades). However, for other systems and over longer time horizons, how these drivers interact in this increasingly complex system is unclear.

Uncertainty associated with feedbacks, changes in precipitation, lightning, and winds translates into limited capabilities for quantitative assessment of what the future holds. Warming is likely to increase fire activity in some areas, but not everywhere. For example, warming in already arid environments may reduce fuel availability to the point where fire cannot spread, but warming in fuel-loaded areas such as western US forests may lead to increased fire at least in the short term.

In sum, landscape fire will continue to be a presence on the Earth's surface into the future, but it is difficult to say whether climate or humans will be a stronger influence on its prevalence.

Compliance with Ethical Standards

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

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

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