Pyrogeography and the Global Quest for Sustainable Fire Management

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Abstract

Fire is an ancient influence on the Earth system, affecting biogeochemical cycles and ecosystems. Humans have had a profound influence on global fire activity through setting and controlling fires, modifying the flammability of landscapes, and, more recently, changing the climate through the combustion of fossil fuels. We review this web of complex direct and indirect effects of fire on Earth using the framework provided by the emerging discipline of pyrogeography that unites biological, atmospheric, and social perspectives on fire. We describe the transition from fire activity before humans evolved, through the hunter-gatherer and agricultural phases, to the current period in Earth history dominated by industrialization (Anthropocene). We illustrate how pyrogeography provides the necessary framework to understand fire in the Anthropocene, including the management of pyrogenic emissions, protection of human life, conservation of biodiversity, and provision of ecosystem services.

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INTRODUCTION

Fire is central to any consideration of sustainable environmental management given the pervasive influence on ecological and biogeochemical processes of the combustion of biomass (the bulk of which is made up of plants, or phytomass) and fossil fuels. Yet, the numerous influences of fire, the complexity of interactions, and the spatial (local to global) and temporal scales (near instantaneous to geological) involved make understanding and managing fire remarkably difficult. The blurring of the boundaries between "natural" and "anthropogenic" further complicates discussion of landscape fires. For instance, the primary causes of anthropogenic greenhouse effects are the combustion of fossil biomass and the clearing and burning of forests. Yet, fire is a key process in many ecosystems, such as savannas, and forests dominated by *Pinus* and *Eucalyptus*, where the suppression of fires by humans can have deleterious effects by increasing the occurrence of severe wildfires that threaten biodiversity, diminish ecosystem services, and cause economic and social disruptions. Disturbingly, there is strong evidence that severe fire incidents have been increasing globally in recent years (1). The quest for the sustainable management of fire, therefore, demands synthetic thinking that unites knowledge from a broad spectrum of disciplines and practices drawn from around the world (2–4). This is the primary objective of this review.

An emerging discipline that provides the intellectual framework to understand the complexity of fire on Earth is "pyrogeography" (**Figure 1**). Like biogeography, this approach spans geographic scales from the local to the global, has an evolutionary frame, and thus has a geological dimension. And, like other geographic disciplines, pyrogeography has a clear commitment to understanding the interrelationships between cultures and their environment. Despite fire's pervasive influence in many disciplines, there is currently no established academic discipline specifically concerned with the role of fire on Earth (4). Moreover, global change policy and ecosystem management approaches have not satisfactorily considered the multitude of biogeochemical effects caused by fire. Pyrogeography, therefore, provides new perspectives on landscape fire management in a changing world, including the importance of landscape fire in biological conservation and the global carbon cycle, and the nexus between landscape fire and human health and livelihoods. The field of pyrogeography also provides an intellectual arena for consideration of fire in a global context by enabling currently isolated scholars studying varied aspects of fire to add value to each other's work. Such a synergy of perspectives is crucial given the increasing evidence that current fire management paradigms are unable to cope with the manifold challenges associated with (*a*) an increasing vulnerability of human settlements caused by two-directional migration trends—by an urban fringe expanding into fire-prone vegetation (the so-called wildland-urban interface, WUI) and the rural exodus leaving behind abandoned and increasingly flammable land-use systems, (*b*) increasingly severe fire weather associated with global climate change, (*c*) more stringent air quality guidelines to regulate wildfire smoke, (*d*) concern about the impact of fire on the global carbon balance,

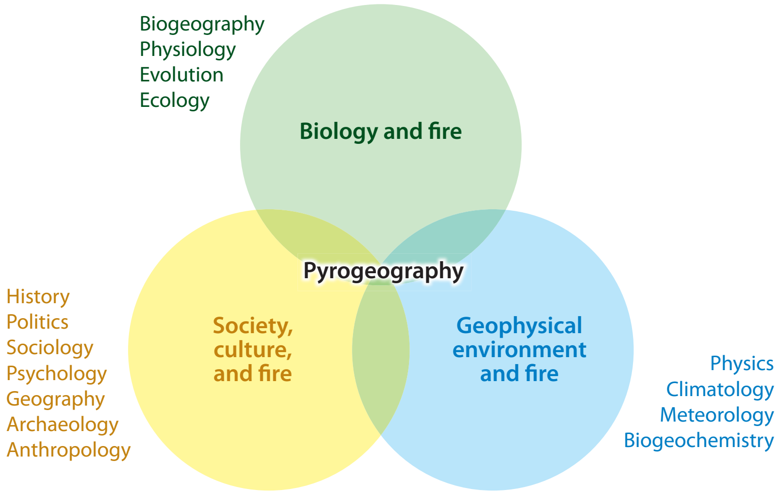

Figure 1

Pyrogeography is the study of fire on Earth combining and synthesizing academic disciplines from the biological sciences (e.g., evolution, ecology, biogeography), physical sciences (e.g., physics, biogeochemistry, meteorology), and social sciences (e.g., anthropology, archaeology, history, sociology, human geography).

and (*e*) increasing tension between biodiversity conservation and fire management objectives.

To make our task tractable, we use the "pyric phases" model as an organizing principle to consider fire, its environmental effects, and its management challenges (**Figure 2**) (5). This model considers how fire activity has changed through geological time, with particular emphasis on the influence of humans, and builds on the "pyric transition" concept first outlined by Pyne (6–8) that emphasized the inherent and changing interrelationships between humans and fire. Pyne's pyric transition concept alludes to the well-known demographic transition that describes changes to human population structures as a consequence of industrialization (9). In brief, the pyric phases framework employs the classic fire triangle that represents fire as a physiochemical process between oxygen, heat, and fuel (**Figure 2**). The fire triangle is then applied to consider the primary drivers of fire activity on Earth before fire-wielding hominins evolved as well as how hunter-gatherer, subsistence agricultural, and industrial societies subsequently changed natural landscape fire activity. These transitions have taken place at different times in different parts of the world, and all of these stages continue to exist on Earth today. This model, therefore, provides a context to consider the effects of fossil-fuel combustion on the Earth system and how climate change will influence landscape fire activity and ecosystem services in the future. It is important to note at the outset that the pyric phase model does not claim to be to a monolith theory of the diversity of fire activity in space and time, nor does it argue that human fire usage follows clear and inevitable stages. Instead, it is a convenient framework to grapple with the complexities inherent with understanding fire on Earth. To provide geographic context for the pyric phase model, we first provide a sketch of current fire activity on Earth.

CURRENT FIRE ACTIVITY ON EARTH

The advent of satellite technology has enabled global analyses of landscape fire (10, 11). Striking features of the current global patterns of fire are the high frequency and extent of burning in tropical savannas as well as less frequent but extensive burning in midlatitude forests in both hemispheres and in the boreal forest zone.

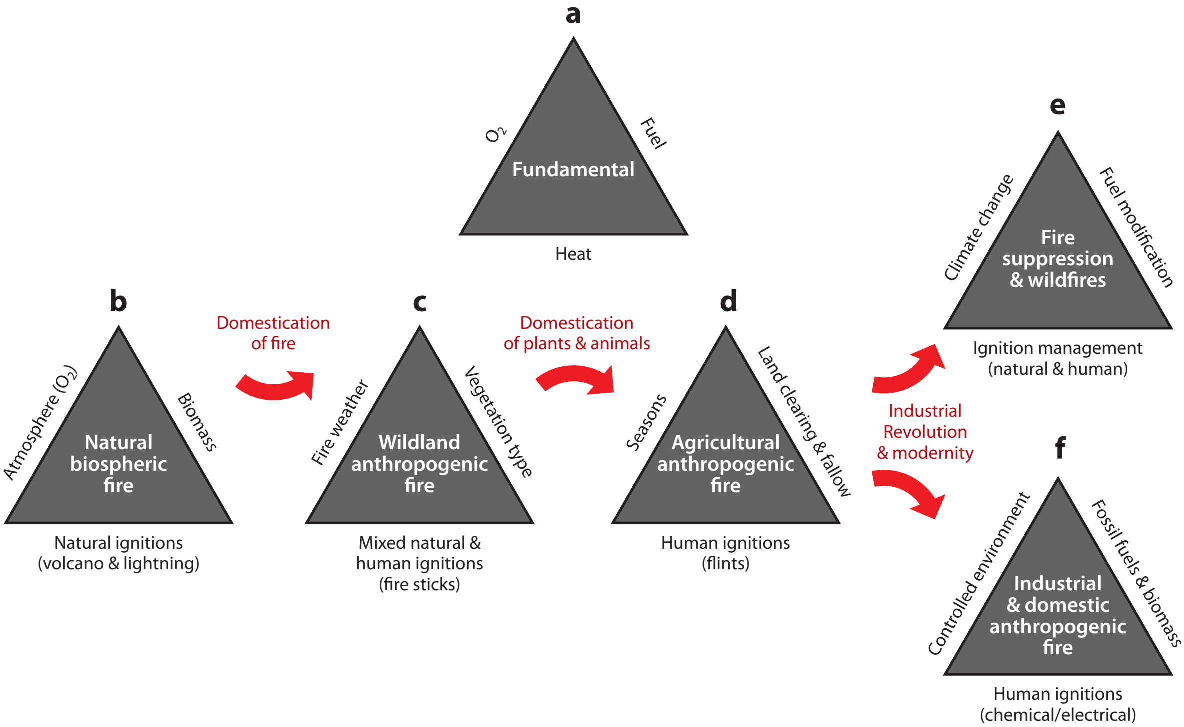

Figure 2

Global pyric phases model. (*a*) The model is based on the classical fire triangle concept, which represents fire as a physiochemical process made up of three vital ingredients: oxygen, heat, and fuel. (*b*) The evolution of terrestrial vegetation, sufficient oxygen in the atmosphere, lightning, and volcanic ignitions allowed fire to become a biospheric phenomenon. (*c*) Use of fire by hominins and humans led to modification of vegetation for a variety of motives, including game and habitat management. Prehistoric traditions remain important in many contemporary wildlands, albeit in modified forms. (*d*) Fire is an important tool for clearing land to establish fields and is incorporated into many agricultural systems to burn dead biomass in specific seasons to prepare fields for cultivation, remove postharvest residues, and stimulate pasture growth. (*e*) Industrialization has influenced landscape fire activity by changing ignition patterns, enabling the development of suppression technologies, and causing climate change via greenhouse gas pollution. (*f*) Fossil fuels increasingly replaced biomass as an energy source following industrialization. All these phases remain on Earth. Modified with permission from Bowman et al. (5).

Landscape fires occur very rarely in tropical forests, but agricultural frontiers in Asia and Amazonia have sharply increased the frequency of burning (**Figure 3**). Landscape burning oscillates seasonally between the Northern and Southern Hemispheres and responds strongly to interannual climate modes, such as El Niño (12, 13). Fire activity varies among agriculture regions: It is rarest in regions with intensive agriculture, high fertilizer inputs, and high levels of mechanization, such as Europe and the US Midwest; and it is highest in the Russian Federation where about one-third of the world's total agricultural fires currently occur (14). Agricultural fire activity displays strong seasonal variation; for example, across the circumboreal, there is a distinct spring peak associated with cropland burning in Eastern Europe and European Russia, and an autumn peak is associated with cropland burning across central Asia and Asiatic Russia (14).

It is well recognized that contemporary patterns of fire activity are the emergent property of climate, biology, and human influences; the complexity of interactions between these factors makes global generalizations difficult.

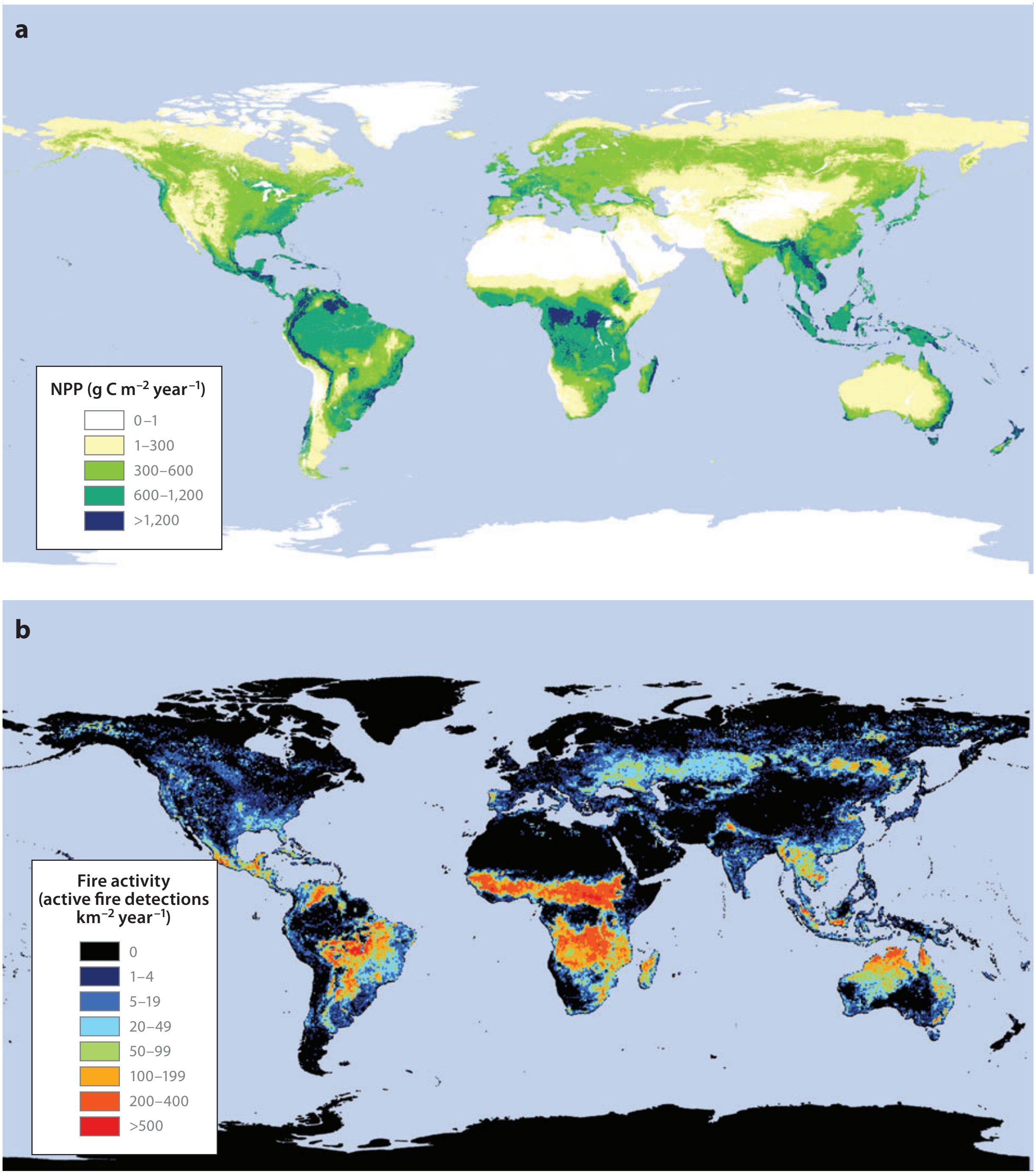

Figure 3

Relationship between (*a*) net primary productivity (NPP, g C m^{-2} year^{-1}) and (*b*) fire activity on Earth (annual average number in 1° grid cells) observed by satellite between 2001 to 2006. Reprinted with permission from Bowman et al. (76).

Broadly, however, across the globe, fire is constrained by fuel and climate conditions, resulting in a bell-shaped relationship of fire activity to a gradient in precipitation, and thus also to a gradient in net primary productivity (15–17). Despite hot dry conditions, fire is restricted in arid environments because of low biomass production, except following periods of above average rainfall. Conversely, high rainfall associated with high biomass environments limits fire to periods of drought (15). The greatest fire activity occurs in environments with medium-high levels of net primary productivity that have pronounced annual dry seasons (13).

PYRIC PHASES OF EARTH

Prehuman Fire

Charcoal in Silurian sediments signals that the necessary conditions for landscape fire were realized shortly after plants colonized land around 420 Mya: ample fuel (i.e., flammable vegetation), abundant ignition sources (e.g., lightning and volcanism), and conducive climatic conditions for combustion (e.g., hot, dry, windy conditions) (18, 19). It is important to note that, in addition to global climatic variation, a powerful determinant of fire activity through geological time is the relative concentration of atmospheric oxygen (20). For example, in the late Permian (270 Mya) when atmospheric oxygen levels were at 30% (significantly higher than the current 21%), even damp vegetation could burn, thereby sharply increasing the extent of global fire activity (20). Conversely, vegetative combustion does not occur when atmospheric oxygen levels fall below 13%, and this is thought to have restricted fire activity early in the Late Devonian, 380 Mya. Because of the influence of fluctuating atmospheric composition and climatic conditions, great care is required in drawing parallels between current geographic patterns of fire activity and those in previous geological times. An additional factor that further confounds such extrapolation is the evolution of traits that render plants tolerant of fire and promote or suppress landscape fire activity.

Bond & Scott (21) have proposed that the radiation and spread of angiosperms (flowering plants) in the Cretaceous (135–65 Mya) were stimulated by feedbacks between climate conditions that were conducive to widespread landscape fire activity (high atmospheric oxygen, warm temperatures, seasonally dry climate, and dry lightning) and the evolution of particular plant traits. They assert that higher rates of productivity and reproduction of angiosperms relative to gymnosperms (e.g., conifers) allowed flowering plants to recover quickly after fire and accumulate biomass more rapidly, thereby promoting more frequent fire. Furthermore, Bond & Midgley (22) propose that certain flowering plants subsequently changed patterns of fire on Earth with their capacity to form uniquely fire-resistant broadleaf forests that reduced fire because the closed canopies and deeply shaded, moist understory preclude the accumulation of flammable surface fuels.

Underscoring the ancient (~60 Mya) relationship between fire and plant evolution are molecular phylogenies, calibrated with fossils, which chronicle the evolution of plant traits that enable plants to survive and even promote fire. These traits include the capacity to resprout from stems (e.g., epicormic strands) (23), serotiny (i.e., aerial seed banks), retention of dead foliage to favor crown fires (24), and shedding of branches to limit the egress of fire into tree crowns (25). These findings and other ecological and functional biological studies have led to the inescapable conclusion that evolution has created an enormous diversity of traits that enable plants to coexist with fire disturbance. Animals living in flammable landscapes have also developed behaviors that enable them to survive recurrent fires. These include fleeing fire fronts; seeking shelter in logs, tree cavities, and burrows; or taking refuge in unburned areas (26–28). Some predatory birds are attracted to fire fronts to catch fleeing animals. Herbivores congregate on areas recovering from fire to consume lush regenerating vegetation (29). The time since the last fire affects the structure and composition of vegetation, creating habitats that suit different animal species. A key point, however, is that there is not a simple division between those organisms that are adapted to fire versus those that are not, rather organisms show variation to different types of fire disturbance. Different patterns of fire activity, therefore, have contrasting biological effects, and over time, this results in a filtering of species to create biological communities with similar fire tolerances, which, in turn, influence subsequent fire activity. In a nutshell, there is interdependence of fire with the biota resulting in biotic communities with both characteristic plant and animal responses to fire and particular patterns of landscape fire activity, collectively known as the "fire regime." Key elements of the fire regime include spatial (extent and patchiness of burning), temporal (season, frequency), and behavioral (intensity, flame height, speed) patterns, as well as type (crown, surface, belowground) of fires (30).

The combination of monsoonal climate and flammable grasses with the C4 photosynthetic pathway has resulted in savannas being the most fire-prone ecosystems on Earth (31). The expansion of savanna biomes across Asia, Africa, and the Americas 7–8 Mya has been explained as a consequence of a positive feedback loop between monsoonal climate, fire, the diversification of C4 grasses, large grazing animals, and hominins (32, 33). C4 grasses evolved in the late Miocene (~15 Mya) in response to declining levels of atmospheric CO_2, providing competitive advantages over plants with the C3 photosynthetic pathway. Monsoonal climates are characterized by year-round high temperatures and by a wet season, which favors high rates of primary productivity, alternating with a dry season, which desiccates the grass layer, producing large amounts of fine aerated combustible plant matter. The transition between dry and wet seasons is characterized by a high frequency of lightning storms. Modeling has shown that the current global distribution of savanna is much greater than would be predicted on the basis of plant physiology alone, and if fire were to be hypothetically removed from the Earth system, large areas of savanna would be replaced by forest (34). The balance between savannas and closed forest has been explained as interaction between tree growth rates and fire frequency. Forest encroachment and subsequent canopy closure are promoted by factors that increase tree growth rates (e.g., elevated availability of water, nutrients, CO_2), decrease fire frequency, or both (35, 36).

The ancient struggle between pyrophobic forests and pyrophytic vegetation, such as savannas, remains unresolved, resulting in large areas of Earth that can switch between these alternative stable states (37), maintained by feedbacks between the vegetation, fire, and environment. For instance, in Australia, pyrophobic (fire-sensitive) rainforest is found juxtaposed to highly pyrophytic (fire-adapted) *Eucalyptus* forests (38, 39). The states can remain highly resistant to change as they are reinforced by complex feedbacks between fire, vegetation, and other environmental factors (40). However, a dramatic shift in fire regime and subsequent disintegration of the fire-vegetation interaction can lead to a rapid state change. One such potential forcing of state change is increased landscape burning by humans.

Fire and Hominins

Along with language and art, the use of fire is a defining feature of humans as there are no other extant animal species that can make fire, and with the possible exception of some raptors, none use fire. Furthermore, there are no known prehistoric cultures that did not routinely use fire, although there is an enormous diversity of human fire uses that operate at sharply contrasting spatial scales. These include very localized fires (the footprint of fuel harvesting is, however, much larger) for cooking, illumination, warmth, religious and cultural practices, manufacturing products, and long-distance communication. At the landscape scale, fires can be used to manipulate habitats, facilitate travel, possibly trigger localized rainfall events (41), increase the abundant concentration of game, eliminate pests, and attack enemies. Because humans evolved in frequently burned savannas, it is not possible to pinpoint the precise time of the domestication of fire. The first reliable record of fire use by hominins has been dated at 1 Mya (42), and by 400 kya, fire appears to be routinely used by possibly all hominin populations (43, 44). It has been suggested that hominin evolution, and particularly brain size, has been influenced by cooking by making available more digestible and nutritious foods (45).

As human fire use stretches back into the Quaternary, the ecological effects are confounded with global and regional climate changes. For example, investigators (46) analyzed paleoecological data from around the world since the last glacial maximum and showed that over the past 21,000 years fire activity has varied across the globe, corresponding to long-term changes in global climate and shorter-term regional changes in climate, vegetation, and human land use. During the end of the last glacial period (21–16 kya), there was less fire activity on Earth than there is today, largely explained by a cooler, drier global climate and lower levels of CO_2, which suppressed plant growth, meaning that there was less phytomass to burn (46), although higher biomass forest, such as equatorial rainforest, may have been more vulnerable to burning (47). Power et al. (46) detected an increasing trend in vegetation fires since the start of the current interglacial period (the Holocene, ~12 kya); however, this increase has been paralleled by increased spatial heterogeneity of fire activity, with some regions burning more than present and others burning less.

The dominance of climate variation in the late Quaternary fire record can lead to the unsubstantiated conclusion that human fire use in the past was insignificant. Even so, islands that have been colonized by people in the last millennia provide clear evidence of the capacity of preindustrial anthropogenic burning to transform ecosystems independent of climate change. For example, pollen and charcoal records show that, in just two centuries following the arrival of Māori people to the South Island of New Zealand in the thirteenth century AD, about 40% of the forest had been destroyed by fires (48). This analysis shows low levels of fire activity prior to Māori colonization, and correspondingly, the tree flora was not highly fire adapted, which rendered this environment particularly vulnerable to human-set fires. There is no evidence of climate change at the time of Māori colonization that would have caused the spike in burning. Mathematical modeling suggests that small populations of colonizing humans may have intentionally set fires in areas of flammable nonforest vegetation that set off a feedback that created larger areas of flammable vegetation (49).

Humans have always coexisted with flammable biomes (e.g., Africa) or have done so since the late Pleistocene (e.g., Australia), making it much more difficult to disaggregate the relative influence of climate from anthropogenic impacts on fire regimes using available paleoecological historical proxies (5). For example, beyond recording fire activity, microscopic charcoal particles in sediments provide little information about many facets of fire regimes that are influenced by humans, such as the manipulation of vegetation, fuel loads, and ignition at regional and local scales (50). Likewise, different historical data sources lead to conflicting conclusions about the impact of Aboriginal burning on the Australian biota. The Australian case, briefly outlined below, highlights the complexities of understanding prehistoric impacts on the environments globally. One researcher's analysis (51) of historical records from the time of European colonization led him to claim that, at that time, Aboriginal people used fire so skillfully across the entire Australian continent that they had created "the biggest estate on Earth," as illustrated by the title of his book. By contrast, a meta-analysis of late-Quaternary charcoal in sediments throughout Australasia led investigators (52) to claim that climate variation has been a far more influential driver of fire activity than burning by indigenous peoples. Yet, analysis of the charcoal and dung fungus *Sporormiella* in one core that spans the period of Aboriginal colonization suggests that the anthropogenically led extinction of the Australian megafauna resulted in higher fuel loads that then increased fire activity, leading to the dominance of fire-adapted vegetation (53).

Regardless of these debates, contemporary Aboriginal burning practices have been shown to have created a fine-scale mosaic of seral stages across landscapes, which are critical habitat for small animals [such as reptiles and small- and medium-sized mammals (54)], provide feed for kangaroos (55), and preserve small patches of fire-sensitive vegetation in tropical savannas (56). Indeed, analysis of indigenous burning practices from around the world reveals a common pattern of numerous small fires set before the onset of the fire season, thereby creating a mosaic of burned and unburned areas (57, 58). Such patchworks of burned and unburned areas limited the spread of any naturally ignited fires. Contemporary fire managers employ a similar strategy by burning under controlled conditions to reduce fuel loads and thus limit the severity of subsequent wildfires.

Fire and Agriculture

Agricultural fires represent part of a major, and ongoing, transformation of Earth that began during the Holocene and is associated with the development of sedentary agriculture-based societies. Fire plays a pivotal role in the clearing of forests to create permanent fields. Currently, the focus of land clearance and burning is in tropical forests, contributing significant amounts of greenhouse gas pollution (~12% in 2008) (59). The spread of agriculture through Europe and Asia in the Neolithic was associated with clearing of forests by burning. There is an ongoing controversy as to whether or not this also resulted in a significant release of greenhouse gas that may have changed Earth's climate. Ice cores record a mid-Holocene (~6 kya) reversal of the downward trend of carbon dioxide (CO_2) and methane (CH_4) greenhouse gas concentrations that had begun in the early Holocene. Although most scientists believe this is a natural process, one researcher (60) has argued that this turnaround is the result of anthropogenic burning of forests for agriculture. By the beginning of the twenty-first century, land-use expansion into wildlands and intensification of land use resulted in the majority of Earth's ice-free land surface being occupied by human-dominated biomes (with 40% directly used for agricultural and settled areas), leaving less than 22% of the land surface qualifying as wildlands, the majority of which is in cold or dry environments (61). In agricultural landscapes, fire is used to remove crop residues, especially in agrosystems with limited mechanization or fertilizer inputs. Indeed, an ancient agricultural system is the swidden with a cycle of burning to clear vegetation and fallow periods to allow biomass and nutrient capital to build up before repeating. In tropical developing nations, swidden or "slash-and-burn" agriculture remains an important source of subsistence for millions of people (62, 63). Agricultural fires contribute 8–11% of the current global fire activity each year (14) and approximately one-third of the 3.5–3.9 billion metric tons of dry matter per year (Pg/year) burned in anthropogenic fires (64).

It has been suggested that the amount of fire activity peaks on agricultural frontiers and then sharply declines once the phase of extensive land clearance ends (6). This pattern is apparent in a composite of global charcoal records from the past 2,000 years (65). These data show an abrupt increase in global fire activity between AD 1750 and 1870 despite a global cooling trend that previously caused a decline in burning from AD 1 to ~1750. Marlon et al. (65) attribute this increase to prolific burning plus more intensive land use in Europe and forest clearance in the Americas and Australia, following European colonization. After 1870, and despite a warming climate and population growth, charcoal records indicate a decrease in global vegetation burning, which they attribute to more intensive agriculture, less forest clearance, and fire suppression in flammable forests. Such declines were also facilitated by the increasing reliance on fossil fuels and a corresponding decrease in biomass burning for energy. This fuel substitution marks the critical step in Pyne's (6) pyric transition model that also defines the beginning of the Industrial Revolution and of the Anthropocene in the late-eighteenth century (66). Here, we use the term Anthropocene as it captures the totality of anthropogenic impacts on the Earth system following the Industrial Revolution. However, there is debate as to whether this term should be formally recognized as a geological epoch because it is not associated with a clear division from the Holocene effects of humans on the environment (67).

Industrialization and Fire

During the Anthropocene, humans have dramatically altered fire regimes around the globe, both directly and indirectly. These direct and indirect effects add a new layer on the natural, hunter-gatherer, and agricultural burning regimes that also continue to exist on Earth. Direct effects include the suppression of fire using a range of technologies, increasing the number of ignitions caused by population growth and its associated infrastructure (e.g., train lines, power lines), greater accessibility to remote areas, and urban sprawl into flammable landscapes. Indirect effects include the deliberate and accidental spread of flammable plants and overgrazing by livestock. Fire seasons are changing in response to climate change driven by the release of greenhouse gases from the combustion of fossil fuels and by the clearing and burning of forests for agriculture and forestry. Fire activity in the Anthropocene must, therefore, be understood as being shaped by atmospheric, biological, and socioeconomic dimensions. Below we explore these issues in more detail.

ANTHROPOCENE PYROGEOGRAPHY

Atmospheric Effects

In addition to heat, fire transfers to the atmosphere large quantities of water vapor, inorganic carbon particles, carbon monoxide (CO), CO_2, CH_4, nitrogen oxide (NO_x), and sulfur oxide (SO_x) gases as well as much smaller quantities of a wide diversity of organic and inorganic compounds in liquid, solid, and gaseous forms, some of which are highly toxic. Currently, landscape fires release ~2.0–3.2 Pg C to the atmosphere annually (68), although there is substantial interannual variability. For instance, during the extended El Niño-Southern Oscillation–related drought of 1997, fires that were set to clear forests in Borneo escaped control and burned peat lands, resulting in the release of the equivalent of 13–40% of the annual global carbon emissions from fossil fuels (69). Were it not for anthropogenic deforestation fires, CO_2 emissions from landscape burning would be almost perfectly offset by the uptake of carbon by regenerating vegetation. Unfortunately, CO_2 emissions from deforestation fires have become a substantial driver of global climate change. Between 1850 and 2000 global land use and management released 156 Pg C to the atmosphere, with ~60% of this from the tropics (70).

Landscape fires also release black carbon into the atmosphere, the second strongest contribution to global warming after CO_2 (71). Black carbon aerosols warm the lower atmosphere (troposphere), as do burned land surfaces with low albedo, a measure of Earth's surface reflectivity. Troposphere warming inhibits convection of moisture and regionally reduces annual precipitation (72). Deposition of black carbon over snow and ice also reduces albedo, contributing to Arctic sea-ice retreat (73) and Arctic warming (74). Yet, replacement of forests by treeless vegetation after fire may increase albedo, resulting in regional cooling, and this effect may be pronounced in the boreal zone because of increased snow cover and the much higher winter albedo of treeless areas (75). Likewise, some aerosols, such as sulfates, in smoke may also result in tropospheric cooling. The examples above show that some effects of landscape fire on climate may be self-cancelling. Considering all climate-forcing components, Bowman et al. (76) concluded that, since the Industrial Revolution, deforestation fires have contributed ~20% of the total increased radiative forcing to the atmosphere. Critically, they assumed emissions from wildfires are offset by regenerating forests, yet they highlighted the risk that global warming could increase the recurrence of severe fires and thereby reduce the capacity of vegetation, and particularly forests, to absorb CO_2. This could potentially drive a positive feedback between climate change and landscape burning (2, 73, 76, 77).

It remains equivocal if global warming is already responsible for changed global landscape fire activity. An analysis of fires in the western United States showed that since the mid-1980s large wildfire events have become more frequent, and wildfire seasons have lengthened (78). The increase in fire activity was correlated with higher spring and summer temperatures and earlier spring snowmelt and could not be convincingly related to land-use changes that would increase fire risk (78). Likewise, weather data from southeastern Australia show that an index of forest fire danger increased by 10–40% from 2001–2007 relative to 1980–2000 (79). A number of studies have used the projections of global change models to investigate plausible future fire activity. Again, there is no clear consensus. For example, the modeling by Williams et al. (79) indicated a significant rise (up to a 65% increase) in days with extreme fire danger conditions by 2020 in southern Australia. Krawchuk et al. (80) refute assertions that a warmer climate will necessarily lead to more fire in the Earth system. Their modeling suggests that climate change may increase fire activity in some regions and decrease it in others, resulting in no net increase in the amount of fire on the globe. Patterns of change in fire activity are highly uncertain. Moritz et al. (81) disclosed significant disagreement among global climate models on the direction of change of fire activity (increasing or decreasing) for more than half of the world's land area in the coming decades; however, they found more convergence between models of longer-range predictions. Overall, these authors suggest that regions in the mid-to-high latitudes will experience higher probabilities of fire occurrence, whereas in the tropics, there may be a decrease in the probability of fire activity.

It is important to note the numerous limitations and assumptions of model projections of future fire activity. These analyses focus on the spatial distribution of fire and are typically mute regarding other key aspects of fire regimes, such as fire intensity, severity, and seasonality (82). Furthermore, one of the biggest constraints to forecasting fire activity under a warming global climate is that models currently do not incorporate fire-climate-vegetation feedbacks that could have a further warming effect on global climate, and as such, contemporary projections may significantly underestimate changes to fire activity (73, 76). For example, elevated CO_2 may promote plant growth and, therefore, increase fuel loads, yet, conversely, extended drought may decrease plant productivity in the long run, thereby decreasing fuel loads. Smoke from vegetation burning in the tropics may inhibit cloud formation and lead to regional decreases in precipitation, amplifying drought stress and increasing fire risk (83). Humans take advantage of drought to clear vegetation and may continue to do so in the future, leading to further carbon emissions and hence amplifying climate change (69).

In addition to affecting climate, smoke plumes can detrimentally impact human health at the local, regional, and global scales given that smoke pollution can be spread far from the fire front via global climatic teleconnections (84, 85). Smoke contains some gases as well as small particles [<2.5 μm in diameter ($PM_{2.5}$)] that are poisonous and carcinogenic and that can cause respiratory and cardiovascular diseases (86). The global mortality attributable to smoke pollution from landscape fires has been recently estimated as an annual average of 339,000 individuals (87), although there is substantial interannual variation in mortality reflecting differences in fire activity under the influence of various climate modes, such as El Niño (88). Smoke from single severe fire events can impact millions of people. For example, in western Russia, extremely hot and dry weather conditions during the summer of 2010, combined with inappropriate land management practices and weakened fire management capacity of the decentralized forest management system, led to more than 80,000 hectares of forest, agricultural land, and peat land being burned (89, 90). These fires generated extensive smoke pollution, which enveloped Moscow, impacting ∼15 million people for several weeks in August, as well as affecting populations in China, Japan, and North America (91). Similarly, deforestation fires in Indonesia during an extended El Niño dry season in 1997 created dense smoke pollution, which affected hundreds of millions of people across Indonesia, Malaysia, Singapore, the Philippines, and Thailand (92). In Indonesia alone, an estimated 20 million people suffered respiratory illness as a result of the smoke pollution (84). Localized smoke pollution from fires set for forestry, wildlife, agricultural, or fuel management purposes can also cause ill health in affected communities and can exceed air quality standards for human health. Indeed, concerns of air quality are an increasingly important constraint on the use of fire by land managers (93).

Landscape fires are potentially an important source of other dangerous pollutants that could affect human populations worldwide. For example, vegetation fires account for 8% of the annual global mercury emissions, often in the toxic form of methyl mercury (94). Presently, mercury primarily originates from fires in equatorial Asia, boreal Asia, and the Southern Hemisphere, i.e., South America, yet the largest terrestrial pool of mercury lies in the soils of the boreal zone. There is a risk that global warming will increase temperatures in boreal regions, leading to larger, more frequent fires, which will mobilize vast amounts of carbon into the atmosphere (95) and also sharply increase mercury emissions. This would have hazardous impacts on human health and may lead to mercury toxicities in food chains in the Northern Hemisphere (96, 97). There is also a risk that landscape fire smoke can transport radionuclides contained in vegetation and soils contaminated by radioactive pollution (98, 99). For example, the 1986 Chernobyl nuclear disaster radioactively contaminated 6 million hectares of forests and abandoned agricultural lands in the Ukraine, Belarus, and Russia, including combustible peat lands (100).

Biological Effects

Human activities directly and indirectly influence fire behavior and fire regimes with substantial effects on biological systems that in turn provide a feedback on fire activity (**Table 1**). An obvious example is the active suppression of fires. For most of the twentieth century, large areas of public land in Canada, the United States, and Australia were subjected to policies of complete fire suppression, supported by a wide array of sophisticated firefighting technology, such as water-bombing aircraft (5, 101). This policy has been driven by the need to protect infrastructure, forest resources, plantations, and agricultural enterprises from wildfire. Absence of fire from flammable ecosystems over long time periods has been shown to lead to several perverse outcomes, including the accumulation of high fuel loads and thus increased risk of intense wildfire and, in some cases, declines in biodiversity. For example, fire suppression in ponderosa pine (*Pinus ponderosa*) forests in the western United States has led to a shift in fire regime in these forests from frequent low-intensity surface fires to high-intensity crown fires because of the encroachment of a dense combustible understory. Fires following long periods of suppression can be of very high severity and can kill entire stands of trees (102, 103). The high densities of trees are thought to have increased the vulnerability of trees to disease and insect outbreaks, especially if stressed by climate change (104, 105).

Fire suppression activities have a number of unintended impacts on ecosystems (106). These include creating invasion corridors for weeds and pests along firebreaks and tracks, which can trigger slope erosion and cause fouling of waterways. The dropping of fire retardants can pollute terrestrial and aquatic ecosystems with nitrogen and phosphorus-rich compounds, and

Table 1 How humans influence fire regime parameters by modifying key variables that affect fire activity[a]

Human influences	Fire variable	Fire regime parameters
Land cover change	Wind speed	Fire spread
Artificial barriers (roads, fuel breaks) Habitat fragmentation (fields) Exotic grasses Land management (patch burning, fuel treatments) Fire suppression	Fuel continuity	
Grazing Timber harvests Exotic species establishment Fire suppression Fuel treatments Land use and land cover (deforestation, agriculture, plantations)	Fuel loads	Fire intensity and severity
Land management (logging, grazing, patch burning) Vegetation type and structure (species composition, cover, stem density)	Fuel moisture	
Human population size Land management Power line failures Road networks Arson Time of day Season Weather conditions	Ignitions	Number of and spatial and temporal patterns of fires

[a]Modified and reprinted with permission from Bowman et al. (5).

a wide diversity of synthetic compounds that have poorly known toxicities for humans and other organisms (107). Finally, back-burning operations can completely destroy unburned refugia critical for the survival of animals, a problem particularly acute in landscapes already fragmented by land clearance (106).

An alternative management approach to fire suppression has been the use of planned burns (also called "prescribed burns") to reduce fuel loads and, hence, fire intensities, thereby broadening the windows of opportunity for firefighting (108). This practice is controversial among ecologists because planned burns can sharply increase the frequency of fire, disadvantaging plants that need longer fire-free intervals to reproduce (109). Furthermore, this practice can disadvantage some animals if the burning season coincides with reproduction, such as ground-nesting birds (110). A key unresolved issue concerns the spatial pattern and size of prescribed burns (111). Potentially prescribed burning can create habitat mosaics that are optimal for biodiversity conservation. In reality, however, conservation objectives are severely constrained by the imperative to protect life and infrastructure, often in heavily fragmented landscapes such as those found on the interface between urban areas and wildlands (the WUI). In some cases, fires that do not pose threat to communities or other assets are left to burn freely, thereby reducing the extremely high costs associated with suppression. Such lightning-set fires are often considered as natural and thereby beneficial to biodiversity, although this may not be case if they are of very high severity owing to massive fuel accumulations.

Human colonization has resulted in deliberately and unintentionally spread plants that have become weeds. These plants can change fuel types and markedly increase fire severities, resulting in ecosystem changes. For example, the alien ornamental *Lantana camara* has invaded Australian rainforests, fueling fires of sufficient intensity to kill trees (112). The most notorious examples are invasive grasses that can trigger a "grass-fire cycle" (113). The grass-fire cycle is a feedback loop whereby exotic grasses invade and promote frequent fire because of their abundance of dry and aerated fine fuels. This grass invasion and accompanying increase in fire frequency set into motion a cycle that is able to transform a fire-sensitive native woodland or savanna into flammable, frequently burned exotic-dominated grassland (113). The exotic grasses recover quickly after a fire (their reproductive tissue is protected below ground) and rapidly produce prolific biomass, thereby promoting recurrent fire that kills any juvenile native trees that have regenerated. Woody species become trapped and killed by successive fires unless as juveniles they are able to grow sufficiently quickly to escape the fires that burn repeatedly through the grass layer. The frequent fires promoted by the grasses can also alter nutrient cycles, which further favor the invading grasses over native woody species (114). Grass-fire cycles are described for alien grasses in many parts of the world including *Bromus tectorum* (cheat grass in western North America (115), *Schizachyrium condensatum* (tufted beard grass) in Hawai'i (116), and *Andropogon gayanus* (gamba grass) in northern Australia (117).

High levels of grazing in savannas can reduce fire frequency, enabling woody plants to increase in dominance (118, 119). For example, extensive woody plant encroachment in grasslands across north Queensland, Australia, has been attributed to cattle grazing and changed fire regimes (120). This trend can be reversed by reduced herbivory coupled with sustained burning, an approach used by pastoralists to eliminate so-called woody weeds from overgrazed savannas. In southern African savannas, Archibald et al. (121) suggest that there is a complex interplay between fire frequency and extent of herbivory. Savannas heavily grazed by white rhino, wildebeest, impala, warthog, and zebra can develop "lawns" dominated by Chloridoideae short-grass species that do not burn. With less intense grazing, these lawns can switch to highly flammable grasslands that only support herbivores, such as African buffalo, adapted to gazing Andropogoneae bunch grass species. Archibald et al. (121) suggested that frequent large fires could eliminate lawns from a landscape with corresponding declines in mammal diversity.

Social Effects

Highly urbanized societies have developed unrealistic attitudes and policies about landscape fire management. This disconnection between the reality of fire and modern lifestyles is powerfully expressed on the WUI (**Figure 4**). In the developed world, living in flammable landscapes is attractive to many urbanites because of the high amenity value of natural settings, the cheap land, or both (122). The blending of suburbs with vegetation types that are prone to high-intensity fires has resulted in an increasing number of disasters that destroy thousands of dwellings and kill hundreds of people (123–125). Protecting communities in flammable landscapes becomes a political imperative that drives increasing government expenditures on firefighting programs (126). Consequently, firefighting budgets are ballooning globally, with the United States currently spending over a billion dollars annually (73). Yet, once fires exceed critical intensities (~2,500 kilowatts per meter), fire suppression becomes impossible (127). For this reason, there is a need for more academic and political debate about the role of government on the WUI with a focus on urban planning, which includes the delineation of zones that are unsuitable for development and the need for mandatory building codes for fireproof structures (128). Likewise, among disaster management planners, there are tensions between advocates for compulsory evacuation of communities and those who argue that

Figure 4

The wildland-urban interface (WUI) on the slopes of Mount Nelson, Hobart. Because of the geographic setting of the city of Hobart, there is an extensive WUI, rendering it extremely vulnerable to bushfire disasters. The 1967 fire killed 62 people and destroyed 1,400 houses. Photograph by David Bowman.

people should be able to stay and defend their own properties. These debates tap into deeper political philosophies about the rights and responsibilities of the individual and the state, resulting in sharply contrasting approaches among democracies, such as in the United States and Australia (123). The broader role of surveillance and policing is also of increasing importance given that criminals sometimes use fire to facilitate the development of wildland (129) and the threat posed by sociopathic individuals and terrorists in triggering fire disasters (130, 131).

Managing fuels on the WUI is also extremely complicated and vexatious. Exurbanites are offended by strategies that they perceive to reduce natural amenity values, such as controlled burning and mechanical thinning of flammable vegetation. Fire management is made more difficult by mosaics of public, private, uncleared, and developed properties. Concerns about biodiversity values add another layer of complexity, as does smoke from prescribed fires, which can pollute urban airsheds, causing air quality to exceed local standards. There remains an enormous need to further utilize appropriate communications strategies to explain the role and risks of fires on the WUI. By highlighting the disastrous nature of wildfires, the media routinely fails to provide any ecological or historical context to this issue. This has engendered a widespread perception that all landscape fires are ecologically destructive, which builds on cultural prejudices shaped by past campaigns to suppress all fires, such as Smokey (the) Bear (132, 133). Such negative attitudes hamper efforts to reinstate fire to achieve ecological outcomes and to manage fuels. With increasing scientific recognition of the role of fire in forest ecosystems, the fire prevention messages have become less strident (133).

Land-use change is also a driver of increased fire activity on the WUI interface. Urban drift in Mediterranean Europe has resulted in heavy fuel loads owing to cessation of traditional landscape burning and to reduced livestock grazing pressure on abandoned agricultural lands; some of this land has been converted to highly flammable plantations (134), and other lands have become fallow and subjected to natural succession. Subsequently, in recent decades, there has been a rise in the number of large, intense fires across Spain, France, Italy, and Greece (135). This has not been observed in the southern Mediterranean basin, where there has been less dramatic socioeconomic change and traditional land-use practices are still employed (136). In some regions, such as Eastern Europe and Eurasia, unexploded land mines, artillery, ammunition, and bombs (unexploded ordnance) complicate fire management and pose an extreme risk to firefighters (98).

Recognition that landscape burning is an important contributor to greenhouse gas pollution is also shaping policy about fire management worldwide. For example, given the importance of deforestation on greenhouse gas pollution, biodiversity loss, and regional air pollution, there is an urgent need to halt tropical forest destruction. This is the prime motivation of schemes such as Reduced Emissions from Deforestation and Forest Degradation (REDD) in tropical forests (137). Yet, there is a risk that such schemes could result in perverse outcomes, e.g., forbidding traditional swidden agriculture in tropical forests or converting natural grasslands and savannas (138) to forests with the attendant losses in biodiversity and the associated need for fire suppression in surrounding areas. There remains vigorous debate as to whether fire and fuel management can be designed to increase forest carbon storage in flammable forests (139). In north Australian tropical savannas, a voluntary carbon offset program aims to reduce non-CO_2 green emissions (e.g., CH_4, NO_x) on Aboriginal lands. This is achieved by setting low-intensity fires early in the dry season when mild fire weather conditions prevail. Although it is claimed that this mimics traditional Aboriginal fire management, this is debatable given substantial differences in the spatial scale of these programs and the reliance on helicopters to spread fires in remote, and now uninhabited, areas. In the western United States, it has been suggested that prescribed burning and mechanical thinning can potentially reduce carbon emissions by returning crown fire regimes to surface fire regimes (140). Campbell et al. (141) dispute this, asserting that emissions from prescribed burning exceed the emissions avoided by reducing wildfire extent and intensity. Bowman et al. (142) argue that the role for such intensive fuel management may be in averting the switch of forest systems to treeless systems, which would store much less carbon. In addition to controlling carbon stocks, fire management is important in protecting water supplies. Severe fires can cause large quantities of sediment (soil, nutrients, and ash) to run off into rivers and lakes (143). For instance, a water treatment plant had to be built to purify the severely polluted water after a bushfire that burned almost all of the catchment of the main reservoir for the city of Canberra, Australia.

Currently, accurate and reliable data on the present economic burden of fire are scarce, blunting international comparisons. For example, the 1997 fire disaster in Southeast Asia is estimated to have caused approximately US$9 billion in economic costs, and only about US$1 billion were from the health impacts from smoke pollution (144). There is a disparity between the fire management budgets of the developed and developing countries. For instance, Indonesia had a firefighting budget of only US$25 million to manage the disastrous 1997/1998 episode when 9.8 million hectares were burned of which 4.8 million hectares were tropical forest (145), and a large portion of this came from foreign aid (146). By contrast, during the severe 2000 fire season in the United States, nearly 3.4 million hectares were burned, and the cost of fire suppression was approximately US$1.4 billion.

In traditional societies, fire management has been organized at the local community level, and in the developed world, this role has been increasingly regulated and centralized by governments. To achieve sustainable fire management, a mix of all these levels of governance is required. This is because local knowledge and legitimacy with local communities are essential for effective fire management. Building, and sustaining, robust social institutions that have sufficient resources to manage fire is challenging for the developed and developing world alike.

Yet, the increasing scale of fires and the costs and complexity of suppression technologies require support from national and provincial governments. Furthermore, given that fire effects are increasingly transnational, such as greenhouse gas and smoke pollution, there is a need for international agreements. There are existing bilateral agreements for international cooperation in fire management and wildfire disaster response, and some international protocols and agreements indirectly address landscape fire, such as the United Nations Framework Convention on Climate Change, the United Nations Convention to Combat Desertification, and the United Nations Convention on Biodiversity, as well as the programmatic work of UN agencies and other international organizations. There is a growing need to streamline these arrangements to create a global compact to address the challenges of managing landscape fire in a rapidly changing global environment (147).

The challenge of fire management in the Anthropocene cannot be underestimated. There will be necessary trade-offs between competing social and environmental values. It is likely that this will lead to the increasing diversity of and development of novel fire regimes. Optimal fire management solutions demand much better data, particularly basic information on the costs and benefits of different approaches. Solutions to future fire management may necessitate experimentation with new and unorthodox management strategies, such as using large animals to consume fuel (148).

CONCLUSION

The management of fire is a prerequisite for Earth system management given the pervasive influence of fire and the enormous economic costs of fire disasters. We argue that the holistic, emerging discipline pyrogeography has a key role in adaptive responses to the challenge of fire management in the Anthropocene because this approach provides the ability to simultaneously consider the atmospheric, biological, and socioeconomic dimensions of fire. Pyrogeography provides a global and evolutionary perspective of fire activity based on the recognition that landscape fires are an ancient, fundamental component of terrestrial ecosystems. A core principle of pyrogeography is the enormous diversity of fire activity and its environmental effects. Most fundamentally, pyrogeography avoids the intellectual traps of conceptualizing fires as natural or necessarily environmentally harmful. Humans have an ancient covenant with fire, founded once our hominin ancestors domesticated landscape fire over one million years ago. This has led to great diversity in human relationships with fire among individuals, institutions, and cultures. Thus, pyrogeography provides a conceptual framework for comparative analyses of contrasting approaches to fire management and for considering how society can accommodate changed fire activity, driven by land-use changes and anthropogenic climatic change. Given the high levels of uncertainty, the quest for the sustainable use of, and coexistence with, fire will hinge on social and political engagement with the complexity of fire management and adaptive management responses from local to global scales. This entails risk and demands substantial investment in monitoring and evaluating environmental and socioeconomic costs and benefits, a commitment to building social capital, and the political will to work through the necessary ecological and social trade-offs.

SUMMARY POINTS

1. Fire has been pivotal in the evolution of life and influences the functioning of the Earth system.
2. Humans and fire are coupled, blurring the distinction between natural and anthropogenic burning.
3. Human relationships with fire are diverse among individuals, institutions, and cultures.
4. Current approaches to fire management are unable to avoid major economic and social disruptions caused by fire disasters.
5. Global warming will likely increase fire activity and the incidence of fire disasters, further exacerbating greenhouse gas pollution.
6. Sustainable fire management demands understanding the interplay of atmospheric, biological, and socioeconomic dimensions of fire on Earth.
7. Pyrogeography provides an intellectual framework for holistic thinking about sustainable management of fire.

FUTURE ISSUES

1. Understanding the spatial and historical variability of the core components of fire regimes (area, intensity, severity, season, frequency of burning) remains rudimentary for most biomes on Earth.
2. Detailed descriptions of fire regimes and their biogeochemical effects demand coordinated cross-disciplinary research collaboration.
3. The development of a way of better quantifying the direct and indirect economic costs of fire disasters will improve the cost-benefit analyses of contrasting fire-management approaches at regional and international scales.
4. Knowledge sharing among fire managers is embryonic and demands international leadership.
5. Incorporation of fire effects into Earth system models is a pressing research challenge given the risk of underestimated powerful positive feedback on climate change.
6. Broader appreciation of the pervasive and complex beneficial and deleterious influences of fire on the environment must be established among policy makers and the global community.

DISCLOSURE STATEMENT

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Errata

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