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Blazing a Trail: A Review of the Physical, Ecological and Social Drivers of Landscape Fire in an Era of Unprecedented Global Change

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Summary

The complexity of the interaction between humans, ecosystems, climate and fire makes finding suitable management practices and policy for human societies to sustainably coexist with fire an immense challenge. This process is hampered by failure to understand landscape fire as the function of interrelated ecological, biophysical and cultural components which operate, with feedbacks, across temporal and spatial scales. A recent series of disastrous fire events around the world indicate that landscape fires are threatening societies as never before; impacts include smoke-related health problems, loss of human life and property, loss of biodiversity, the diminished provision of ecosystem services and accelerated flux of atmospheric greenhouse gas. Landscape fire, however, is a critical and essential component that underpins ecosystem function in many terrestrial ecosystems.

Across the globe, anthropogenic global change is destabilizing fire regimes with harmful and unexpected consequences for ecosystems and for people. Failure to regard landscape fire in its totality; its drivers, its constraints, and its interaction with humans and the environment will lead to a greater incidence of the types of disastrous fire events witnessed across all inhabited continents in recent years. This paper aims to review recent literature on landscape fire by examining the complex interactions between the physical, ecological and social realms of fire. This is timely given that unprecedented global change is likely to make sustainable human existence with fire more problematic.

Introduction

The Earth is an inherently flammable planet. Currently there are two dominant forms of combustion: terrestrial biomass burnt by landscape fires and fossil and harvested biomass burnt by humans for many purposes (Pyne 2004). Landscape-scale fires are critically important for both human societies and to the majority of terrestrial ecosystems worldwide (Bowman et al. 2009). Tensions exist, however, between the potential for uncontrolled fires to cause deleterious social, economic and environmental impacts and the inherent need of some ecosystems for recurrent fire disturbances. More problematically, anthropogenic climatic change driven by fossil fuel combustion and land use changes are leading to novel patterns of fire on Earth (Flannigan et al. 2009). These unprecedented changes have the capacity to alter the structure and function of ecosystems and to impact atmospheric and biogeochemical cycles. Collectively, these changes will further transform the way in which humanity coexists with fire via direct and indirect feedbacks (Lavorel et al. 2007).

Humans have an ancient and unique relationship to fire and have utilized and spread fire around the earth since the early stages of hominine evolution. The antiquity and complexity of the human-fire-vegetation nexus blurs the distinction between natural and anthropogenic landscape fire. Throughout history people have manipulated fire activity by modifying ecosystems, altering vegetation and controlling ignition (Marlon et al. 2008; Carmenta et al. 2011). The relationship between humankind, fire and landscapes is thus so entangled that disaggregation is an implausible objective (Pyne 1994). Nonetheless, debate continues about the relative influences of humans versus climate on current and historical fire activity (Marlon et al. 2008; Pausas and Keeley 2009); as the extent to which anthropogenically mediated fire activity deviates from background 'natural' levels of fire has important ramifications for our capacity to manage and persist in fire-prone landscapes. For example, it remains unclear whether recent large disastrous fire events (Flannigan et al. 2009) represent a natural disturbance or they indicate clear failures of human management. Disturbingly, there is strong evidence that severe fire incidents have been increasing in recent years in many parts of the world

(Goldammer and Stocks 2011) and the need to understand the drivers of these fire events is therefore urgent. In order to outline the complexity of fire activity on earth, we will artificially disaggregate the biological, climatic and human components of landscape fire and examine each individually, while underscoring the complex relationship and feedbacks that exist between the drivers of fire activity on Earth.

Contemporary societies remain fundamentally dependent on fire, but this dependency has many different guises, from swidden agriculture to industrial combustion of fossil fuels (Bowman et al. 2011). More than ever before humans are altering patterns of fire on Earth by land clearance, by mixing agricultural and invasive exotic species with native biota, by changing patterns of ignition and by actively suppressing fires. A relatively recent permutation of human-fire interaction, fossil fuel combustion, is causing profound global change. Besides altering vegetation and ignition, humans now directly impact the ultimate control on fire activity, climate, via the release of greenhouse gases from combustion (Flannigan et al. 2009). Alarmingly, the amplification of fire activity linked to global warming may overwhelm our capacity to manage landscape fire and further, may represent a positive feedback loop to climate change as changing global patterns of fire have the potential to accelerate the flux of greenhouse gas to the atmosphere, enhancing global warming and potentially leading to further increases in fire activity (Crutzen and Goldammer 1993; Stocks et al. 1998; Bowman et al. 2009).

Globally, landscape fires are responsible for enormous, albeit difficult to quantify, social and economic costs (Gonzalez-Cabán 2013). The negative impacts of uncontrolled fires include loss of human life, loss of livelihood and property (e.g. animals and agricultural assets), indirect costs of settlement evacuations and impacts on regional economies stemming from resource loss and the enormous expense of fire suppression activity. Beyond the immediate damage to lives and property, landscape fires are causing wide-ranging negative health impacts which stem from the release of smoke and other pollutants that are transported long-distances from the initial fire via global teleconnections (Heil and Goldammer 2001; Goldammer et al. 2009). Global pre-mature deaths attributed to smoke pollution from landscape fires have been recently estimated at an annual average of 339,000 (Johnston et al. 2012). It is therefore critical that we comprehend the culturally mediated drivers of fire and the relative deviation from background levels of 'natural' fire activity, in order to minimise the impacts of landscape fire on human health, property, and ecosystems. Clearly the path to a sustainable relationship with fire demands an integrated perspective of fire in the earth system, considering the interlinked physical, biological and social dimensions of landscape combustion (Pyne 2007).

Rationale for Review

There are scholars who have argued the need for a more synergistic understanding of the interconnected social, ecological and biophysical drivers of fire (Crutzen and Goldammer 1993; Pyne 1994) but regrettably, their call to broaden fire scholarship to include human and ecological elements, interactions and feedbacks, has been muffled among prevailing traditions of scientific reductionism whereby landscape fire has long been regarded as an abstract physiochemical reaction and the study of its drivers and impacts arbitrarily divided amongst various disciplines with little cross-referencing between them (Pyne 2007). Indeed, there is a gap between the visionary work of those few scholars and the majority of the scientific literature centerd on the physical aspects of fire and fire behaviour. This disproportionate focus on the physical realm has hindered the appreciation of landscape fire as a biological and cultural phenomenon of immense evolutionary, ecological and social importance (Pyne 2007). The primary motivation of this review is to provide a timely synthesis of the tripartite ecological, physical and cultural dimensions of fire, reviewing significant recent literature. To do this I will outline fire's ancient evolutionary role in the earth system, consider human's unique relationship with fire and examine how anthropogenic global change is leading to new patterns of fire on Earth with the potential for adverse impacts from local to global scale. Finally, I will discuss how a more integrated discourse on landscape fire is prerequisite to developing management options to coexist with the potential for fire events of unprecedented scale and impact under global change conditions.

Fire in the Earth System

Fire's ancient presence in the earth system, predating humans by hundreds of millions of years, indicates that natural landscape fire was characterised by a complex interaction between biotic and abiotic factors. Charcoal data show that fires began to burn on Earth shortly after plants colonized land (420 million years ago), thus creating the necessary preconditions for burning: flammable fuel and sufficient atmospheric oxygen to sustain combustion (Scott 2000; Glasspool et al. 2004). Landscape fire additionally requires an ignition source, climatic conditions that allow for the growth of ample vegetation for fire to spread, subsequent climatic conditions that lead to desiccation of the vegetation (typically, a seasonal dry period) and atmospheric and weather conditions conducive to combustion (Krawchuk and Moritz 2011).

Pre-human fire was therefore dependent on the interplay between ecological variables: controls on vegetation, and physical variables: climate, weather, topography and ignition sources such as lightning and volcanoes. There are an array of different sources and proxies that provide data about landscape fire over very different temporal and spatial resolutions. Satellite remote sensing records daily fire events, tree-ring data and chemical isotopes span decades, centuries or even millennia; and written documentation and long-term sediment go back several thousands of years and finally, charcoal and geologic records offer evidence of fires that burnt millions of years ago as shown in Figure 1.

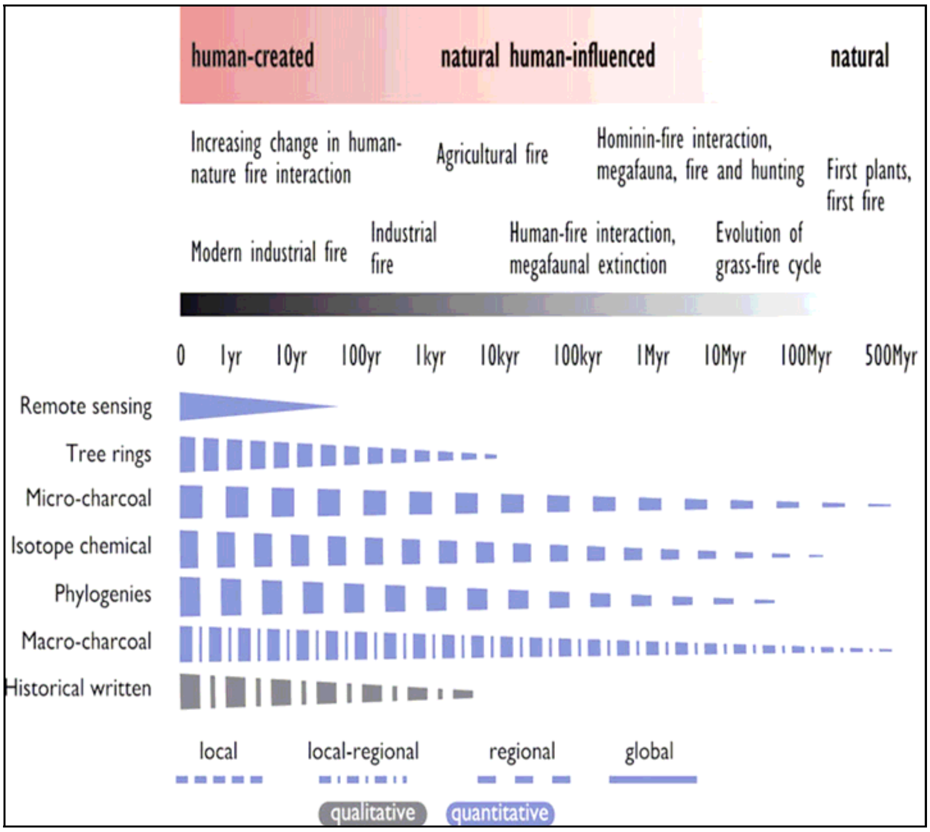


Figure 1. Sources of information about landscape fire at varying spatial and temporal resolutions, spanning the period from the advent of fire on Earth 400 million years ago to the present day Anthropocene, where landscape fires form only a partial picture of combustion on earth, augmented by the prolific burning of fossil fuels. The various sources and palaeoecological proxies for fire cover different spatial and temporal scales. Source: Whitlock et al. (2010).

Palaeoecology of Fire

Charcoal preserved in sediment layers is an important source of information about fire activity in the Earth system over millions of years of geological history (Scott 2000). Other proxies for burning, such as tree-rings and chemical isotopes, allow us to trace historical fire activity over narrower temporal resolutions; decades, centuries and millennia. Together these data sets provide insight into the palaeoecology of both pre-human and anthropogenically influenced fire; however, there are limitations and biases. Vegetation and charcoal tend to fossilize more readily in areas of humid climate, around lakes and rivers, while fossil evidence of fire is scarce in precisely the areas of the world which are most likely to burn, semi-arid systems, because sedimentary layers are less likely to accumulate in these drier environments (Midgley and Bond 2011). Nonetheless, advances in palaeoecology have uncovered evidence of landscape fires which have ignited naturally across the entire range of terrestrial biomes, throughout deep time (Scott 2008).

Palaeoecological records reveal correlations between fluctuating fire activity and levels of atmospheric oxygen. In the late Permian (ca. 270 million years ago) with atmospheric oxygen levels at 30% (significantly higher than the current 21%), fires began to occur in a wider range of ecosystems across the globe (Scott and Glasspool 2006). Scott and Glasspool (2006) showed that the higher the relative proportion of oxygen in the atmosphere, the greater the probability that the vegetation will burn. Conversely, decreases in atmospheric oxygen are paralleled by declines in charcoal, indicating a significant reduction in biomass burning, with seldom evidence of fires in periods when atmospheric oxygen levels have fallen below 13%.

While there have been attempts to identify trends in climatic variation and fire activity throughout geological history (Marlon et al. 2008; Pausas and Keeley 2009), correlations between fire and climate are not as clearly discerned as trends between atmospheric oxygen and fire at a global scale. The signals are less clear because of the complexity and feedback loops that characterise interaction between climate, fire and vegetation. We will return to discuss fire and climate interactions in detail at a later stage.

Evolutionary Significance of Fire

Evidence of wide-spread landscape fire dates from ca. 350 million years ago (Scott 2000) and charcoal records indicate that fire has interacted with plants and animals for several tens of millions of years (Scott 2000; Pausas and Keeley 2009). However, the ecological and evolutionary significance of fire in shaping landscape patterns and vegetation distribution, forging diversity and regulating energy and biochemical cycles, has historically been under-appreciated and rather poorly understood (Bond and Keeley 2005; Goldammer 2006). Darwin himself failed to recognize fire as a key selection pressure (Bowman 2003a). For example, it was traditionally thought that the global distribution of biomes was a function of climate and, to a lesser extent, geology. In a seminal study Bond, Woodward et al. (2005) refute this long-held view, using process models to show that there are many places on Earth where fire decouples vegetation from climate. Satellite imagery has shown that approximately 40% of Earth's land surface is covered by flammable ecosystems that experience frequent fire, such as tropical savannas, grasslands, Mediterranean shrublands and pyrophytic forests (Chuvieco et al. 2008) and in these ecosystems fire is the primary driver of vegetation form and assembly. Bond et al. (2005) proposed that if fire were to be hypothetically removed from the earth system, global forest area would consequently double, notably replacing C4 grasslands and savannas which are the most frequently burnt ecosystems on Earth (Bond and Keeley 2005; Chuvieco et al. 2008). In other words, many parts of the world experience climatic conditions that could theoretically support forest yet flammable, non-forest vegetation dominates the landscape due to recurrent fire disturbance (Bond et al. 2005).

Advances in palaeoecology have highlighted fire's pronounced evolutionary impact and shown that long before humans prevailed on Earth, many ecological assemblages had evolved to require intermittent disturbance by fire. Bond and Scott (2010) proposed that the radiation and spread of angiosperms in the Cretaceous (135 Ma – 65 Ma), a momentous evolutionary event, was underpinned by novel fire activity which resulted from physical conditions conducive to fire; high atmospheric oxygen, warm temperatures, seasonally dry climate and dry lightning. Bond and Scott (2010) argue that angiosperms displayed higher rates of productivity and reproduction than their predecessors, which allowed them to recover quickly after fire and meant that they could accumulate flammable biomass more rapidly, and thereby promote more frequent fire. This represented a positive feedback loop which was advantageous to angiosperms, allowing them to withstand successive fires, to spread and to diversify (Bond and Scott 2010). A recent review by Bond and Midgley (2012) expands on this paper and analyses the profound impact that angiosperms had on global fire ecology, identifying two divergent mechanisms. Bond and Midgley (2012) propose that flowering plants not only narrowed fire return intervals via rapid rates of productivity but they also formed uniquely fire-resistant assemblages. Certain tall, broadleaf forests they argue are exceptional in their ability to resist fire because their closed canopies and deeply shaded understorey preclude the accumulation of flammable surface fuels and therefore exclude fire as the understorey is too sparse and/or too moist to burn (Bond and Midgley 2012).

Novel molecular-dating techniques have also reframed our understanding of fire's antiquity and evolutionary role. Crisp, Burrows et al. (2011) analyzed phylogenetic relationships to show that 'fire-dependent' communities in Australia date back as far as 60 Ma, 50 million years earlier than previously thought. By tracing the evolutionary history of epicormic resprouting (a trait which allows trees to recover after fire) in the Myrtaceae family, Crisp, Burrows et al. (2011) showed that it emerged concomitant with the rise of fire-prone sclerophyllous biomes in Australia. Similarly, He, Lamont et al. (2011) used dated molecular phylogenetic methods to demonstrate that serotiny (i.e., the presence of seed in the canopy which is dependent on crown fire for regeneration) arose in the Australian Banksia genus 60 million years ago. Midgley and Bond (2011) suggest that the remarkable temporal overlap between the results of the two studies is evidence of ancient fire regimes on the Australian continent which selected for communities of fire dependent species millions of years prior to human arrival. The advent of phylogenetic and palaeo-methodologies illuminate the importance of fire in shaping ecosystems through deep time, and its continued ecological significance in ecosystems of the contemporary world.

Fire is linked to the evolution of tropical savanna biomes and the expansion of C4 grasses in the late Miocene, a time when atmospheric CO_2 was much lower than today (Beerling and Osborne 2006). C4 grasses evolved a photosynthetic pathway to more effectively utilize scarce CO_2, although it was complex interaction between climate, fire and low atmospheric CO_2 which led to the expansion of savanna biomes across Asia, Africa, and the Americas 7-8 Ma (Keeley and Rundel 2005). Fire, facilitated by wet-dry monsoonal cycles, allowed C4 grasses to invade and replace woodlands. During wet periods, high photosynthetic efficiency allowed C4 grasses to produce large amounts of fine, aerated biomass which then cured to highly flammable fuels during the subsequent dry season. Further, monsoonal climate provided abundant ignitions sources in the way of lightning. In a positive feedback loop, fire allowed C4 grasses to expand into forest whereby their high productivity increased fire frequency and severity, conferring them advantage over tree species that could not grow quickly enough to escape being killed by successive fires. Today, C4 savannas burn more frequently than any other ecosystem globally, with fires routinely returning every 2-3 years (Hoffmann et al. 2002) and sometimes twice annually (Cochrane, Alencar et al. 1999). The same fire cycle mechanism that drove the global expansion of C4 grasses underpins the current dominance of C4 grasslands in areas that could climatically support forest (Bond and Midgley 2012).

Fire is a predominant control on vegetation distribution across various spatial scales. Under common climatic and geological conditions, fire has been shown to maintain two or more coexisting alternative stable vegetation states. The alternative states are maintained by feedbacks between the vegetation, fire and the environment. In Australia, pyrophobic (fire-sensitive) rainforest is found adjacent to, or even completely engulfed by, highly pyrophytic (fire-adapted) Eucalyptus forests (Bowman 2000). The two alternative states have highly contrasting fire regimes and display traits which promote their own dominance and therefore, resist a switch to the alternative state. In the flammable eucalypt forests, interactions between biotic and abiotic factors promote the frequent return of fire, which in turn, promotes the presence of flammable, fire-tolerant vegetation which regenerate quickly after fire. In contrast, the rainforest is highly resistant to fire and rarely burns, and its fire-sensitive vegetation has properties which deter fire such as perennially high moisture content under a fully closed canopy, and thus prevent the encroachment of fire-promoting species such as eucalypts (Warman and Moles 2009; Wood and Bowman 2012). The states can remain highly resistant to change as they are reinforced by complex feedbacks between fire, vegetation and other environmental factors (Jackson 1968). However, a dramatic shift in fire regime and subsequent disintegration of the fire-vegetation interaction can lead to a rapid state change (Scheffer et al. 2001). Murphy and Bowman (2012) developed a conceptual model to describe the fire-driven mechanisms that maintain savannas and closed forest as alternative stable states. They argue that forest development is limited by the interaction between tree growth rates and fire frequency and that forest encroachment and subsequent canopy closure will be promoted by factors that increase tree growth rates (e.g. elevated availability of water, nutrients, CO_2) or decrease fire frequency.

Globally, plant species across an enormously wide range of genera possess traits which allow them to persist and reproduce in environments prone to recurrent landscape fires. However, species and biotic communities are not adapted to fire per se, but rather to the particular spatial and temporal pattern of a series of recurring fires, known as the 'fire regime' (see text box) (Bond and van Wilgen 1996). The relationship between landscape fire and vegetation is interdependent; fire influences ecosystem form, structure and composition, while the quantity and the moisture content of the vegetation directly influence probability of ignition, the intensity and spread of fire. Given, that climate is a predominant control on vegetation form, species composition and on weather patterns conducive to fire, climate is therefore a significant component of fire regimes. Nonetheless, fire regimes cannot be easily predicted by either climate or vegetation alone because of the interactions between these and other variables. Vegetation, for instance, is also controlled by soil fertility, topography and human land use, and vegetation can in turn modify local climate. These interactions and feedbacks complicate simple predictive relationships between climate, fire and vegetation.

The idea of landscape fire as an endogenous and necessary ecological disturbance factor which is controlled by a complex web of interaction between physical, biological and human aspects of the landscape is still an emergent concept in the study of fire (Attiwill 1994; Whitlock et al. 2010). Furthermore, the biological response in an ecosystem to a single fire can take many forms, depending on the fire's physical parameters and on the ecological response of the assembled species to successive fires.

Fire Regimes

A single fire may disturb less than 1 ha or burn over a million hectares at one time. Similarly, the interval between successive fires in an ecosystem may be as brief as intra-annual, or several hundred years long (Bond and van Wilgen 1996). The pattern of fire in a particular ecosystem is characterized by the scale (area burnt), frequency, intensity, heterogeneity, severity, seasonality and type (crown or surface fire) of successive fires; together these characteristics are known as the "fire regime".

Over evolutionary time scales, fire regimes select for a suite of fire response traits in the organisms that they impact. Species that display adaptive traits to fire can be broadly split between "sprouters"; those which survive and recover from a fire, and "seeders"; those which are killed by fire but reproduce quickly afterwards from seed (Gill 1981). Plant species can display either one (obligate), or both of these traits (facultative) (Vivian et al. 2010). Fire adaptive traits are strongly influenced by the fire regime of an ecosystem and parallel suites of traits have convergently evolved in discrete vegetation assemblages that share similar fire regimes across the globe. For example, in surface fire regimes, plants commonly survive fire and regenerate; analogous mechanisms are found in highly diverse plant taxa. For example, thick bark protects the cambial meristem of conifer trees of the Pinus genus worldwide and allows for resprouting post-fire (He et al. 2012), while many angiosperm species, such as Cork Oak (*Quercus suber*) produce epicormic branches after fire (Pausas 1997), and the monocot Xanthorrhoeaceae grass tree family of Australia retains thick leaf bases which protect the growing tissue from the intense heat of fire and allow them to withstand successive fires and regrow (Brennan et al. 2011).

Serotiny is another convergently evolved fire adaptive trait, which appears to have evolved in separate lineages across the globe in response to crown fire regimes. Serotiny is the presence of seed held in woody capsules in the canopy which is released in response to fire. In the Northern hemisphere, serotiny is unique to conifer species, while in the South, serotiny is a characteristic feature of shrublands in Mediterranean climate regions including the South African Fynbos and Western Australian heathlands, all of these ecosystems are characterized by a crown fire regime (Bond and van Wilgen 1996).

Fire and Biogeochemistry

Beyond direct impacts to vegetation, landscape fires can affect many other processes and components of ecosystems, including soils and nutrient cycles, hydrology, the atmosphere and trophic webs with knock-on impacts for fauna. Accordingly, fires can significantly alter the capacity of an ecosystem to provide services that humans rely upon including inter alia, the provision of clean air and water, soil stability and fertility and carbon sequestration. Certini (2005) reviewed the impacts on forest soils from fires of different intensities (characterized by temperature and duration of the burn). Fires can have biological, chemical and physical effects on soils and the impact of fire on soils depends on the fire's intensity and the temperature the soil is exposed to during fire. In general, only the top few centimeters of soil are affected as they are subjected to the highest temperatures. In high intensity fires, rocks can split and break down due to the extreme temperatures. Fire influences the chemical composition of soil by abruptly changing the cycling of nutrients between plants and soils. Nutrient losses following fire are influenced by soil type, soil biota, vegetation type, fire intensity and the nutrient content in the above ground biomass. Fires of low to moderate severity such as slow-burning surface fires cause a quick pulse of nutrients released from burnt biomass and organic matter which are quickly taken up again by the standing and regenerating vegetation (Certini 2005). Such fires, however, can render soils hydrophobic, meaning that water is less able to penetrate them and runs off laterally, leading to erosion.

Severe fires, such as intense crown fires, can have more profound and long lasting impacts on soil chemistry, soil organisms and soil structure (Certini 2005). Additionally, severe fires can significantly impact water catchments in two ways; firstly because regenerating vegetation display higher rates of evapotranspiration than unburned mature vegetation, water yields in burnt catchments can sharply decrease for several decades following fire (Attiwill 1994). Secondly, fires can alter infiltration characteristics and erodibility of the soil and increased erosion following severe fires can cause large quantities of sediment (soil, nutrients and ash) to runoff into rivers and lakes (Parise and Cannon 2012). These heavy loads of suspended sediment can alter water chemistry, reduce light penetration through the water column and thus change rates of aquatic primary productivity which subsequently causes flow-on effects in aquatic trophic webs. Erosion following fires can have dramatic impacts on watersheds, polluting drinking water supplies for humans and increasing the probability of landslides (Parise and Cannon 2012).

However, just as plants possess traits to survive recurrent fires, the nutrient and water cycling of a given ecosystem can display high levels of resilience to the impacts of a stable fire regime. Plants are very effective at capturing nutrients released into the soil by fire, and in many ecosystems, early successional species colonize rapidly following fire and display mechanisms, such as symbioses with N-fixing mycorrhizal fungi, which allow them to rapidly re-accumulate nutrients released by fire (Romme et al. 2011).

Effect of Fire on Wildlife Populations

Like plants, many faunal assemblages have evolved to survive fire events and some even demonstrate specialized relationships with fire. Animals survive the fire by fleeing (e.g. birds) or by taking refuge underground (e.g. some mammals, reptiles) or in unburned patches of vegetation that are protected from fire (e.g. in wet gullies). Fire also plays an important role in maintaining populations of certain animal species. Fire affects the age, structure and composition of vegetation thus creating habitats that suit different animal species. In the Kapalga Fire Experiment in Northern Australia, results showed that no single fire regime benefits all animals in that ecosystem (Andersen et al. 2005). Depending on frequency, intensity or timing of a fire some animal species benefit and others are disadvantaged. The results also showed that small mammals were most sensitive to fire frequency in general. Frequent fires decreased the population size of small mammals in tropical savannas, although no two species showed the same response. In particular, arboreal species such as possums were most impacted by high intensity fires late in the dry season (Andersen et al. 2005).

Although many species of animals do suffer reductions in populations during or immediately after a fire, most populations will recover. After a fire many animals are vulnerable due to shortages of food and/or predation by other species. The 1998 enormous wildfires burnt through Yellowstone National Park in the USA, consuming more than 1.4 million ha and taking three months to extinguish (Pausas and Keeley 2009). These fires drew vast public and scientific attention due to the unprecedented nature of their extent. At the time, science knew little about the impacts such a large disturbance would have on the ecosystems and Yellowstone became a hub of scientific inquiry into the effects of the fire. Scientists made predictions about the short and long term impacts of the fires on vegetation, biogeochemistry, primary productivity, wildlife and aquatic ecosystems (Romme et al. 2011) and long term monitoring has allowed the quantification of such impacts. Focusing on the ungulate species in the park, the actual fires caused surprisingly low levels of mortality but it was predicted that the indirect impacts of changes to vegetation would influence wildlife populations both short and long term (Singer et al. 1989). The loss of food sources due to the fires, coupled with harsh winters saw a drop in elk population in the park in the immediate years following the fires. However, 2-5 years after the fire, forage quantity and quality has recovered in burned area and by 1995, 7 years post fire, the Elk population had returned to pre-fire levels (Singer and Harter 1996).

Anthropogenic Landscape Fire

Fire has a deep history in the Earth system clearly pre-dating humans by hundreds of millions of years, however, when early humans gained the ability to carry and utilise fire they irreversibly altered patterns of fire on Earth. Earliest evidence of hominine use of controlled fire dates back to 1.0 Ma in South Africa (Berna et al. 2012), however, more robust evidence for human use of controlled fire is prevalent from 400,000 years ago (Bar-Yosef 2002; Roebroeks and Villa 2011). Humans evolved in fire-prone savannas and undoubtedly early hominins coexisted with fire (Bowman et al. 2009). This habitation of flammable ecosystems complicates precise estimates of the time of domestication of fire by people, however, it is generally attributed to the late Pleistocene, ca. 50,000 years ago, at which point humans began to alter the distribution, frequency and scale of landscape fire, carrying and spreading fire as they colonised new lands (Pausas and Keeley 2009). Fire became an indispensable universal tool for human societies and its use became integral to myriad subsistence and cultural practices, including hunting, clearing land for settlement, seeing by night, cooking, facilitating travel, controlling dangerous animals, promotion of plant food sources and even as a weapon (Pausas and Keeley 2009; Bowman et al. 2011). In certain places on earth, use of fire by humans has altered background patterns of fire so much that they drastically modified the landscape, altered distribution of vegetation and began to forge new anthropogenic fire regimes (Bowman et al. 2011).

In Australia, the magnitude of impact that controlled use of fire by Aboriginal people, sometimes referred to as “fire-stick farming” (Jones 1969), had on the Australian biota is a contentious issue. Some authors have claimed that Aboriginal used fire skillfully to manage “the greatest estate on Earth” across the entire Australian continent (Gammage 2011), while others such as (Mooney et al. 2011) claim that climate has been a far more influential driver of fire activity than indigenous burning. Indeed in Australia, where the biota has evolved with fire over millions of years, separating the impacts of climate from many millennia of human impacts on past fire regimes is extremely complicated. Nonetheless, it is widely accepted that Aboriginal strategic use of fire to facilitate resource availability, for instance to promote suitable habitats for herbivores or to increase the local abundance of food plants, has had profound impacts not only on fire regimes but also on the landscape vegetation and biodiversity (Bowman 1998). Indigenous burning practices have been shown to have created a fine-scale mosaic of seral stages across landscapes which became critical habitat for small animals such as reptiles and small-to-medium sized mammals (Bird et al. 2008), which in turn were important food species in Indigenous economies. Bowman (1998) demonstrated that Aboriginal fire management practices were important for maintaining infrequently burnt patches of fire-sensitive vegetation, such as rainforest or Callitris woodlands, in otherwise flammable landscapes, as these fire-sensitive refuges contained species of value to Aboriginal societies.

Internationally the ecological impact of pre-historic human use of fire is a hotly debated topic. While there is general agreement that humans used fire purposefully over long periods of time, contention arises over the spatial extent of anthropogenic burning and the degree to which humans were able to deviate from natural fire regimes. In spite of the difficulties in differentiating between ‘natural’ fire regimes and the influence of pre-industrial human societies on fire activity, there is evidence that humans have had significant impacts on fire activity for tens of thousands of years both directly by modifying the number and timing of ignitions and indirectly, by altering fuel structure and abundance (Bowman 1998; Pausas and Keeley 2009) and these impacts would have significantly influenced ecosystem structure, composition and function. Controlled fire has been a critical component of agricultural systems since the Neolithic revolution, ca. 12,000 years ago, when many societies transitioned from hunter-gatherer economies to more sedentary agricultural-based societies (Pausas and Keeley 2009). We will return to discuss the interrelationship between agriculture and fire further.

There are few unequivocal examples of the effects of fire use by humans in transforming vegetation and ecosystems because of the difficulty in disentangling climate influences from anthropogenic impacts on fire regimes. The best examples come from islands that have been colonised by people in recent centuries, during a period of relative climatic stability. Pollen and charcoal records show that the arrival of Māori people to the south island of New Zealand in the 13th century AD was accompanied by wide-scale burning and resultant destruction of temperate rainforests (McWethy et al. 2009). By the time Europeans colonised in the mid nineteenth century ca. 40% of the forest had been destroyed by fires. This is a remarkable example because it shows that anthropogenic fires lit by small, transient and non-agricultural societies had immense, irreversible impacts on these forests (McWethy et al. 2010). What’s more, this prodigious burning by Māori people took place in a very brief time frame, within two centuries, and the massive increase in fire activity in this time is appears to be independent of climate. The use of fire to clear forests had subsequent harmful impacts on local ecosystem, notably increased erosion and changes to soil chemistry which also impacted aquatic systems.

In New Zealand, the effects of anthropogenic fire on vegetation and biochemistry were particularly profound because these ecosystems were historically characterized by an absence of (or extremely rare) fire activity and accordingly the species comprising these temperate rainforests possessed few adaptive strategies to withstand fire. McWethy et al. (2010) note that the example of anthropogenic fire activity and subsequent switch from forest to non-forested vegetation on the South Island of New Zealand underscores the susceptibility of closed-canopy forests to novel fire regimes and they suggest that similar vegetation types will be particularly vulnerable to changes in fire regimes that may be induced by climate change or changes in human patterns of burning in the future.

Climate and Fire Activity

Disaggregating the relative influence of climate from anthropogenic impacts on fire regimes throughout history is most difficult in parts of the world where humans and their ancestors have coexisted with flammable vegetation over many millennia, such as Africa and Australia (Bowman et al. 2011). Many important studies have identified climate as the primary driver of fire regimes across the globe, however this does not discount the profound impact humans have had, and continue to have, on fire activity via manipulation of vegetation, fuel loads and ignition at regional and local scales (Aldersley et al. 2011; Coughlan and Petty 2012). Power et al. (2008) analysed palaeoecological data from around the world since the last glacial maximum and showed over the last 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 ka) there was less fire activity on Earth than there is today largely explained by cooler, drier global climate and lower levels of CO_2 which suppressed plant growth, meaning that there was less biomass to burn (Power et al. 2008). Power et al. (2008) detected an increasing trend in biomass burning since the start of the current interglacial period (ca. 12 Ka), however, this increase has been paralleled by increased spatial heterogeneity of fire activity, with some regions burning more than present and others burning less.

Focusing on the last 2000 years, Marlon et al. (2008) conducted a similar global analysis of charcoal data and found that although climate is the primary control on fire activity globally, patterns of landscape fire have increasingly been influenced by human land use over the last two millennia. They found that global biomass burning decreased from AD 1 to ca. 1750, affiliated with a global cooling trend. Between 1750 and 1870 they detected an abrupt increase in global fire activity which they ascribe to prolific burning and land use change in Europe associated with the industrial revolution and forest clearance in the Americas and Australia following European colonisation. Since 1870, biomass burning at a global scale fell sharply despite a warming climate and population growth, which they believe is explained by land-use changes and practices that have reduced fire prevalence and include forest clearance, intensive grazing and agriculture, fire suppression policies and the substitution of fossil fuel combustion for biomass burning (Marlon et al. 2008). These palaeo studies underscore the importance of climate on patterns of fire globally, but fail to adequately capture regional variance and explain demographic and localised climate influences on fire at smaller spatial scales.

At a regional scale, historical and current patterns of fire activity also show strong climate signals, particularly in association with large scale ocean-atmosphere circulation patterns such as the El Niño-Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO) and Atlantic Multi-decadal Oscillation (AMO), which operate over multi-annual to decadal scales, and are also referred to as 'teleconnections' (Kitzberger et al. 2001; Goldammer and Stocks 2011). In the Amazon and across South East Asia extended drought events during El Niño phases cause the normally moist fuels in tropical rainforests to dry out and render them susceptible to fires. Accordingly, there is a strong correlation between high fire activity and El Niño periods in these regions (Cochrane et al. 1999; Goldammer 2007). Likewise, fires of extreme intensity and scale in Southern Australia tend to occur under drought conditions during El Niño events, especially when preceded by a wet La Niña period which has led to high accumulation of biomass (Verdon et al. 2004). Similarly, drying conditions caused by the La Niña phase of the ENSO in other regions of the word have been shown to increase fire activity in places such as Patagonia and Southern USA (Swetnam and Betancourt 1990; Kitzberger 2002; van der Werf et al. 2004).

In summary, at a global scale fire activity is strongly sensitive to climate, while at regional and local levels, human land use, vegetation and local climate factors also strongly influence how and when fire occurs. Given that humans, via the release of greenhouse gasses, are now impacting climate, which we know to be the ultimate control on fire activity in the Earth system, it is likely that the effects of global warming will lead to shifts in fire activity across the globe (Flannigan et al. 2009). However, forecasting what these changes may look like and how they will impact human societies is complicated by the myriad ways that humans influence fire activity through land use and impacts on vegetation.

Global Pyrogeography

Fire, unlike any other terrestrial disturbance, can be thought of as having its own ecology. The drivers and constraints of landscape fire across time and space may be conceptualized in terms of traditional ecological concepts such as resource availability (a function of vegetation and climate) and dispersal ability (a function of natural or human ignition source and suitable weather conditions) (Krawchuk et al. 2009; Parisien and Moritz 2009). The advent of satellite technology to detect landscape fire has precipitated a deeper appreciation of the truly global-nature of landscape fire (Justice et al. 2003; Csiszar et al. 2005) and has strongly contributed to the development of the discipline of 'pyrogeography' (Murphy et al. 2011). Pyrogeography seeks to understand landscape fire as a product of interaction between vegetation, climate and humans, and to explain the distribution of fire in time and space, on the explicit premise that the drivers and impacts of ecosystem fire occur at multiple spatial and temporal scales (Whitlock et al. 2010). Satellite data show that landscape fire exhibits distinct patterns on earth and have revealed geographical hotspots of fire which shift seasonally over the course of the year (see Figure 2). Recent studies have attempted to explain these patterns over gradients of rainfall, temperature, primary productivity, human population density and socio-economic metrics and to evaluate the relative influences of climate, ignitions and land use on fire activity across the globe (Meyn et al. 2007; Parisien and Moritz 2009; Krawchuk and Moritz 2011).

Le Page et al. (2010) used MODIS (Moderate Resolution Imaging Spectroradiometer) images such as those pictured in Figure 2 above to broadly describe windows of burning, or 'fire seasons', over the course of the year around the globe. In temperate and Mediterranean-climate regions of the Southern Hemisphere (Southern Australia, Sub-Saharan Africa and South America) most landscape fires occur during the southern summer months between October and March. Similarly, in the Northern Hemisphere, fires in the temperate and boreal regions burn predominantly during the dry summer months of May to September. In tropical regions the movement of the Inter-Tropical Convergence Zone(ITCZ) brings a distinct dry period to each hemisphere which allows the vegetation to desiccate and fires to ignite. Accordingly in the tropics North of the equator most fires occur during the seasonal dry period of November and March, while fires in the southern hemisphere tropical savannas and forests generally take place during the dry period of June to October (Le Page et al. 2010).

A conceptual model for the pyrogeography of Australia (although it may also be applied in other parts of the world) identifies four key drivers of fire regimes: 1) rates of fuel accumulation, 2) rates of fuel desiccation, 3) suitable weather for fire spread and 4) ignition (Bradstock 2010; Murphy et al. 2011). These four factors can be thought of as "switches" and all four must be activated in order for fire to occur. However, the switches operate over different time scales as illustrated below in Figure 3. The first switch is biomass growth, or fuel quantity. In arid environments fuel quantity is strongly controlled by preceding wet years (or 'antecedent rainfall'), while in wetter places the amount of time since the last fire strongly influences fuel quantity ('post-fire accumulation'). The second switch is the availability of the biomass to burn, which essentially is a function of fuel moisture and is influenced by climate. In wetter places, anomalously dry years or droughts, are often required to sufficiently dry out fuels enough to burn. Seasonality of fire is also an important control on fuel moisture, in the monsoonal tropics, fuels continue to desiccate during the dry season and are more combustible late in the dry season compared to early in the dry season. The third switch is the capacity of the fire to spread, which is controlled by immediate weather conditions such as strong wind speeds, low humidity and high temperatures. Finally, the fourth switch is the presence of ignitions from either lightning or humans. Variance in the relative influence of the four switches and the rates of 'switching' between ecosystems results in high diversity of fire regimes, or 'pyrodiversity' (Bradstock 2010).

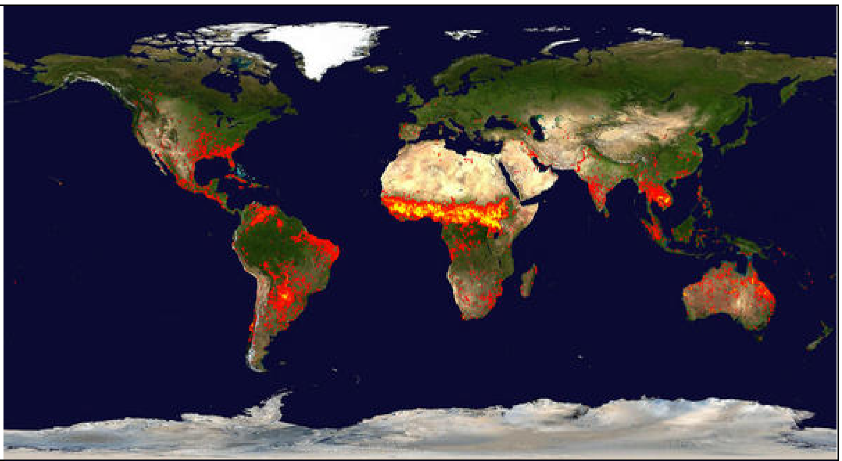
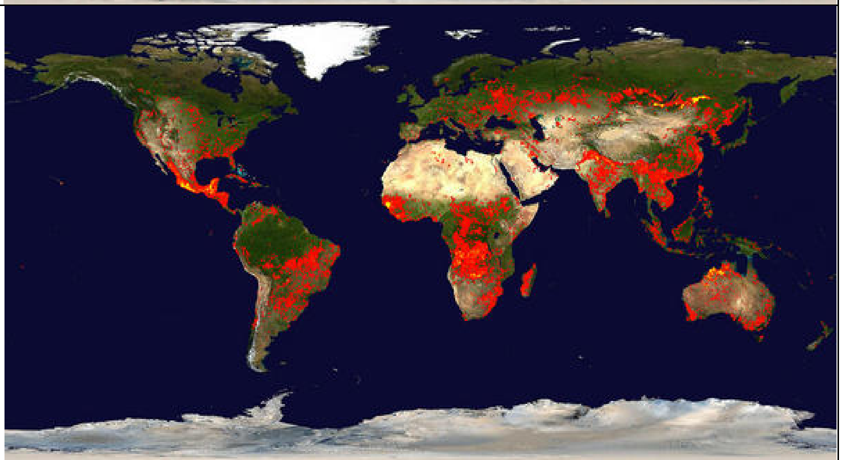
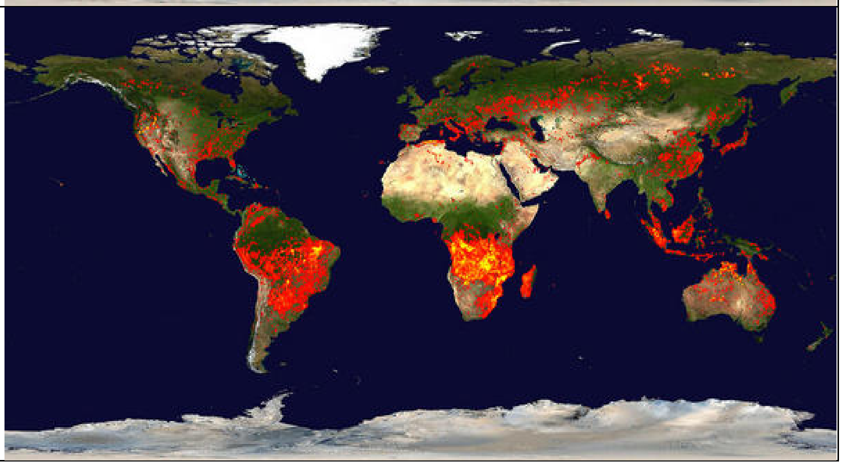
January (01/01/2012 - 01/10/2012)	
April/May: (04/30/2012 - 05/09/2012)	
August: (08/08/2012 - 08/17/2012)	

Figure 2. Satellite imagery shows fire activity across the globe for 10 day periods for different months throughout 2011 and 2012. Clear patterns are discerned, with concentrated areas of burning shifting seasonally. Moderate Resolution Imaging Spectroradiometer (MODIS) Sensors on board NASA's Terra and Aqua satellites record the locations of fires burning across the globe over 10-day periods. Each colored dot indicates a location where MODIS detected at least one fire during the compositing period. Color ranges from red where the fire count is low to yellow where number of fires is large. Source: NASA rapid response Global Fire Maps (http://rapidfire.sci.gsfc.nasa.gov/firemaps/).

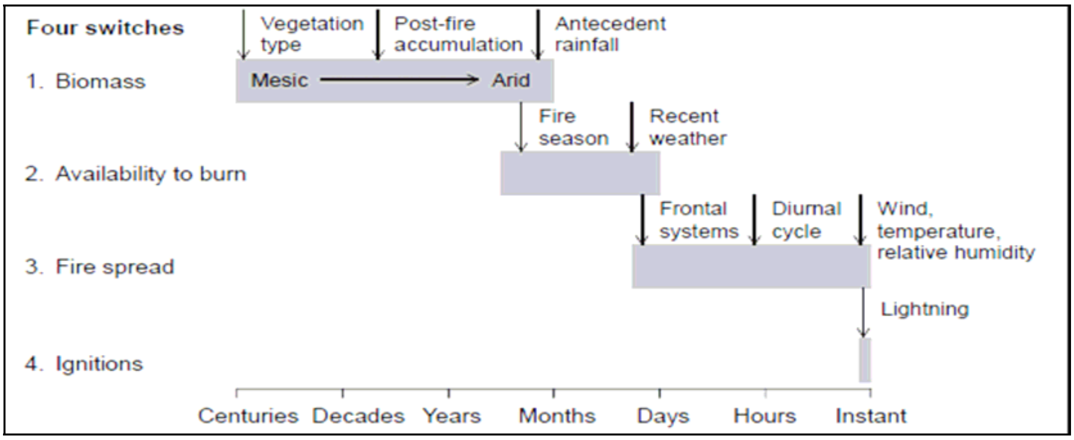


Figure 3. The four switches concept of Bradstock (2010) is a pyrogeographical framework for explaining variation in fire regimes based on variance in the rates of switching. All four switches: biomass growth, biomass desiccation, fire weather and ignition, must be in alignment for landscape fire to occur. However, these limits to fire activity, or the rates of switching, occur at different time scales as shown by the x-axis. In different ecosystems, different processes or 'switches' limit landscape fire activity. Source: Murphy et al. (2011).

Fire activity has been shown to be constrained along gradients of precipitation and primary productivity, with variation across such gradients in the relative importance of fuel quantity and fuel moisture as limits to fire activity (Meyn et al. 2007; Bradstock 2010; Krawchuk and Moritz 2011). In xeric places, aridity limits the growth of sufficient, continuous vegetation to burn while conversely in mesic places where there is abundant vegetation, high rainfall precludes fire as the vegetation does not dry out sufficiently to burn (Krawchuk and Moritz 2011). This concept is known as the 'varying constraints' hypothesis and has been shown to be a strong predictor of the distribution of large, infrequent fires (Meyn et al. 2007) and an explanatory framework for patterns of landscape fire activity more generally across the globe (Krawchuk and Moritz 2011). In biomass rich, rarely dry ecosystems, such as tropical rainforests, fire activity is limited more by fuel moisture content than by amount of fuels. In the humid tropics, fire activity is strongly linked to long-term climatic oscillations, such as El Niño which cause long-term drought and allow the normally moist vegetation to dry out sufficiently in order to burn (Goldammer 1993). In biomass-poor ecosystems which have seasonal dry periods, such as African savannas or temperate grasslands, the main limiting factor on fire is the quantity and connectivity of flammable vegetation which is controlled by antecedent rainfall to promote ample biomass growth. At a broad scale, climate is the predominant control over both fuel amount and arrangement and also over weather conditions that lead to fuel desiccation (Meyn et al. 2007). Additionally, studies using satellite data have found that landscape fire tends to occupy an environmental middle ground; in tropical and subtropical regions, areas that experience frequent fire activity correlate well with areas of medium levels of net primary productivity and intermediate levels of precipitation and temperature (van der Werf et al. 2008). Krawchuk et al. (2009) found that net primary production was the most significant explanatory variable in fire frequency around the globe.

Pyrogeographical studies have also greatly expanded our understanding of anthropogenic impacts on global fire activity, although the difficulty in disaggregating human influence from climatic controls on fire regimes remains a clear obstacle. Nonetheless, there is strong evidence of humans as drivers of fire activity across the globe (Krawchuk et al. 2009; Lauk and Erb 2009). In some places, humans are significantly augmenting background rates of fire while in others, anthropogenic land-use and activity have significantly decreased fire activity to levels below pre-industrial levels (Pyne 2007). For example, in wet tropical regions such as South America and South-East Asia humans are significantly increasing fire activity in closed forests that would have burnt only very rarely in the past as historically climate has precluded fire via the high moisture content of the vegetation (Cochrane 2003; Krawchuk et al. 2009). In these regions humans currently promote fire through intentional ignition during drier seasons, via accidental escape of deliberately lit burns, by fragmentation of the closed forest and subsequent change in the 'fire-resistant' structure of the vegetation due to logging for example, and often in correlation with periods of drought (Goldammer 1990; Cochrane and Laurance 2002). Accordingly, humans are effectively circumventing climatic limits to fire in these regions.

In order to quantify human drivers of fire activity around the world Chuvieco et al. (2008) attempted to detect relationships between human population density, economic conditions and proxies for land use intensity with satellite data of global fire activity for the period from 2001-2006. Clear anthropogenic signals in inter-annual variation were detected in fire activity across the two regions on Earth that experience most frequent fire, the Southern Boreal zone across Asia and the sub-equatorial belt across Africa, America and South-East Asia, strongly associated with agricultural burning practices. Chuvieco et al. (2008) note that increases in human factors such as population density and economic status tend to make fire activity more uniform in time. That is, where humans and resources are concentrated, the extent of landscape burning seems to be more stable inter-annually, whereas in regions where anthropogenic influence is lower, inter-annual variability in fire activity is higher due to the superordinate influence of climatic cycling. However, the limited time series of the data constrained the study and they were not able to detect activity in areas where fire return intervals are longer than the five-year period and as such failed to capture anthropogenic influences on fire in parts of the world where fire plays an important role but at longer multi-annual or decadal scales.

Agricultural Fire

Deliberate controlled burning is widely employed in agricultural systems around the world for a range of purposes including field-preparation, soil fertilization and disposal of crop residues, consequently agricultural fires remain a significant component of landscape fire activity globally. Using satellite data Korontzi et al. (2006) found that agricultural fires contribute 8-11% of global fire activity each year. In some regions the proportion of total landscape fire comprised of agricultural burning can be significantly higher, demonstrating that in certain parts of the globe human management has a significant effect on the timing and distribution of landscape fire. For example, more than a third of the world's total agricultural fires occur in the Russian Federation (Korontzi et al. 2006). Worldwide, agricultural fire activity displays two distinct peaks over the course of a year; from April to May dominated by cropland burning in Eastern Europe and European Russia, and cropland burning across central Asia and Asiatic Russia in August.

Le Page et al. (2010) further investigated the seasonality of fire across the globe as revealed by MODIS satellite imagery (Figure 2) and detected clear anthropogenic influences. They found that while climate determines the window of potential fire activity, humans exert significant control on the timing of fires within those climatic windows. Le Page et al. (2010) describe three main categories of anthropogenic burning which significantly impact the timing of fire within the climatically delineated windows for burning; firstly, fires associated with crop production (the major focus of the paper of Korontzi et al. [2006]). Secondly, tropical deforestation fires deliberately lit for land clearance and agricultural expansion purposes in ecosystems that would otherwise rarely burn. In these tropical forests, the vegetation is generally cut late in the wet season and burnt at the end of the dry season in order to maximise biomass consumption. Finally, the third category comprises anthropogenic fire practices in the tropical savannas of Africa and Australia, these are the most frequently burnt parts of the globe and here human activities strongly bias the seasonality of fire activity. These three categories highlight the diversity of anthropogenic landscape burning practices and show that humans deliberately light fires at preferential times in order to achieve specific agricultural or land practice aims.

Modelling the quantity of biomass burnt in anthropogenic vegetation fires across the globe Lauk and Erb (2009) calculated a range between 3.5 and 3.9 billion tons dry matter per year (Pg dm/yr), which equates to more than a quarter of the annual total biomass harvested by humans. They found that patterns of landscape fire across socio-political boundaries could be delineated. Shifting cultivation practices in least developed countries contribute one third of the total biomass consumed in anthropogenic fires each year (Lauk and Erb 2009). In the less economically-developed regions across the sub-equatorial belt, anthropogenic fires remain highly prevalent and economically important (Goldammer 1990). Global hotspots of anthropogenic landscape fire include Sub-Saharan Africa, Latin America, South-East Asia and Central Asia. By contrast, anthropogenic vegetation fires are not as common in industrialized regions. Pyne (2013, in press) has referred to this dichotomy as the "two grand combustion realms": One that relies on the combustion of fossil fuels, the other dominated by open biomass burning, as illustrated in Figure 4. Pyne (2004) notes that the two spheres of burning tend to overlap only temporarily during periods of 'pyric' transition.

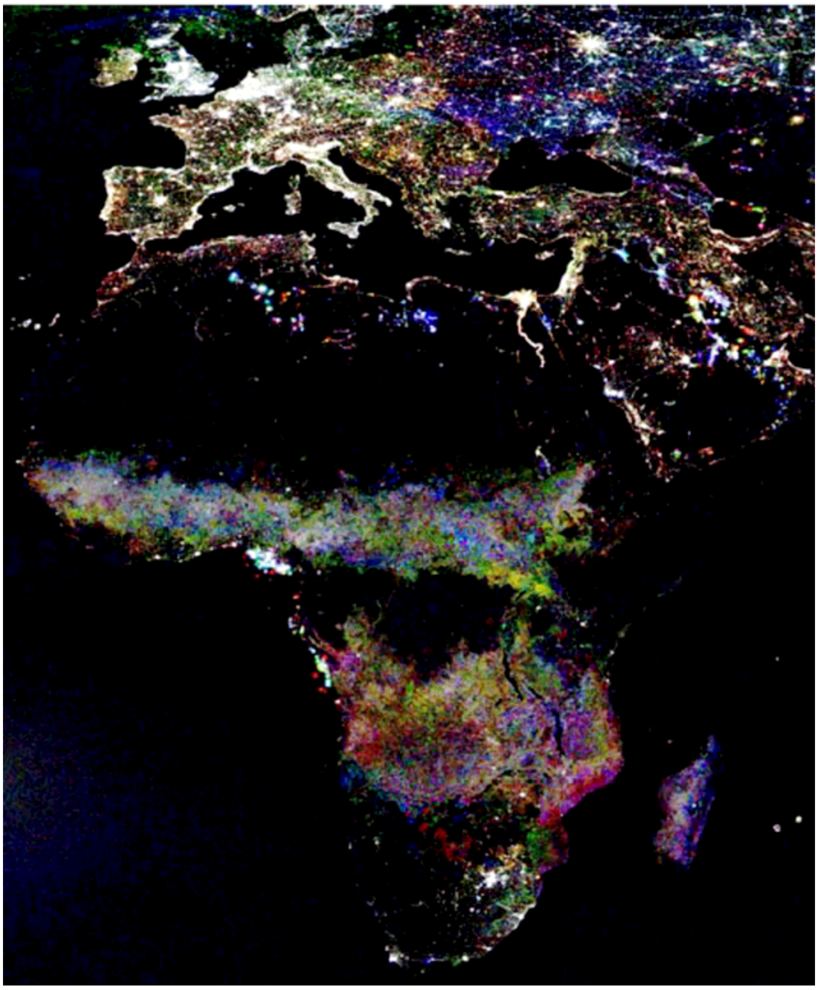


Figure 4. The two realms of Earthly combustion as described by Pyne (2013, in press). One lit by the industrial burning of fossil biomass and the other by the burning of surface biomass; a three-year composite (blue: 1992, green: 2000, red: 2008). Source: DMSP nightlights process by the NOAA National Geophysical Data Centre; from Pyne (2013, in press).

Pyric Transitions

Bowman et al. (2011) expand the concept first outlined by Pyne (2001, 2004, 2009) to describe transitions in human-fire interactions, which they refer to as 'pyric phases'. As Bowman et al. (2011) point out, these transitions have taken place at different times in different parts of the world and all these stages continue to exist on earth today. Accordingly there is enormous scope for examining the ways in which complex ecological, economic, political, technological, and social factors shape human-fire relationships. Changes in human societies and modes of production, for example, from hunter-gatherers to shifting cultivation to sedentary agriculture to industrial and finally, to post-industrial societies, translate into changes in fire regimes (Pausas and Keeley 2009).

Depicted in Figure 5 below, the 'pyric phases' framework appropriates the classic fire triangle (A), which represents fire as a physiochemical process between oxygen, heat and fuel. Modifying this triangle, they show that with the arrival of plants on land, fire became an important biochemical process on the pre-human Earth (B) – plants provided the atmospheric oxygen and flammable fuels and abiotic environmental components such as lightning and volcanoes supplied the necessary source of ignition. The next triangle includes an initial human presence (C) and shows that when prehistoric humans began to domesticate fire they did so by influencing vegetation and the timing of ignitions in order to promote resources, such as food and land clearings. In very remote areas with very low human population densities, variations of these wildland-anthropogenic burning practices still occur today. The next triangle emphasises the importance of fire in agricultural land management (D) and fire's routine use for land clearance and conversion for agricultural purposes. Agricultural burning practices are employed to unlock nutrients held in biomass pre- and post- harvest as this flush of nutrients promotes crop and pasture growth. In tropical developing nations, swidden or 'slash-and-burn' agriculture remains an important source of subsistence for millions of people (Reyes-García et al. 2008; Mertz et al. 2009). Industrialized societies meanwhile have fundamentally altered patterns of landscape fire in recent centuries (E), in places such as Europe, North America and Australia. Humans alter the timing and quantity of ignitions, modify vegetation and landscape, and therefore disrupt fuel quantity and connectivity. Further, in many parts of the world, fire management practices of the last century have allowed humans to suppress wildfire, which has altered the frequency and intensity of fire regimes. Triangles (E) and (F) correspond to the realm of fossil fuel combustion as described by Pyne (2001, 2009).

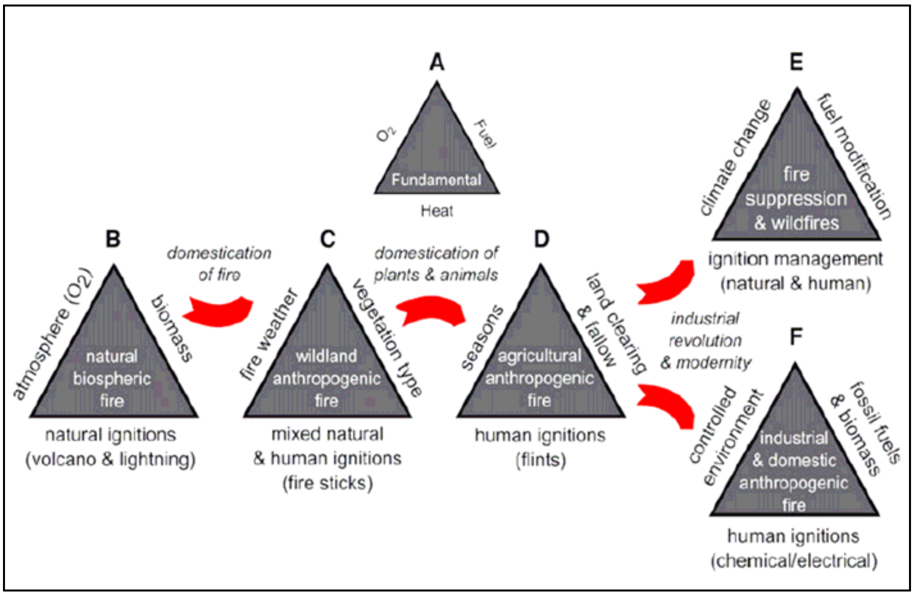


Figure 5. The pyric phases concept of Bowman et al. (2011) depicts the complexity of human relationships to fire, mediated by cultural, economic, environmental and physical landscapes. These triangles do not represent a linear progression, but rather, highlight the diversity of anthropogenic impacts of fire regimes across the globe. All of the stages are still currently found on Earth.

The industrial revolution refers to the radical changes in agriculture, manufacturing, transport and technology that were precipitated by the invention of the internal combustion engine and which led to profound shifts in social, economic and cultural conditions across Western Europe in the mid eighteenth century, later spreading to North America and other parts of the world. The study of global charcoal records by Marlon et al. (2008) demonstrates that the pyric transition sensu Pyne (2001) that accompanied the industrial revolution was characterized by prolific, unconstrained landscape burning between 1750 and 1870, as vast areas of forest were burnt and cleared during European colonization of the Americas and many parts of the Southern Hemisphere. This period of extensive burning was followed by an abrupt global decline in landscape fire from 1870 largely explained by vast agricultural expansion and population growth that fragmented landscapes in many parts of the world and generally rendered them less flammable, in addition to policies of deliberate fire suppression in Northern America and other European colonies (Marlon et al. 2008). More profoundly, however, the advent of fossil fuel combustion represents the beginning of an era characterized by unparalleled human manipulation of the Earth system. Atmospheric chemist Paul Crutzen recognized that the unprecedented extent to which newly industrialized societies had begun to transform ecosystems, landscapes, the atmosphere and finally, global climate via industrial combustion and land use intensification was so profound that it represented the beginning of a distinct geological period, the 'Anthropocene' (Crutzen 2002). In many parts of the industrialized world, human activity has profoundly changed fire regimes and in many places, significantly reduced landscape fire to below pre-industrial levels (Bowman et al. 2011).

Fire in the Anthropocene

Since the industrial revolution, fossil fuel combustion has replaced biomass combustion in many parts of the world (for energy and countless other purposes) and has resulted in the release of enormous quantities of greenhouse gases to the atmosphere. Greenhouse gas from fossil fuel combustion and deforestation have a well-described global warming effect (IPCC 2007) and it is predicted that changing global climate will in turn lead to new patterns of fire on earth given climate's dominant control on landscape fire. Further, humans have simultaneously altered landscapes as never before, between 1700 and 2000 a critical shift occurred as human impacts transformed the terrestrial biosphere from predominantly natural environments to predominantly anthropogenic landscapes (Ellis et al. 2010). By the beginning of the 21st century land-use expansion into wildlands and intensification of land use in semi-natural settings had resulted in the majority of the earth's land surface being occupied by agricultural and settled 'anthromes' (human dominated biomes), with less than 20% remaining in a semi-natural state and only a quarter evading human appropriation entirely (Ellis et al. 2010). This means that currently and in the future, ecosystem and fire management will take place in primarily anthropogenic landscapes. There are countless ways in which humans modify the landscape around them that impact fire activity, which will in turn affect human coexistence with fire into the future. These include, but are not limited to, the spread of exotic species, the pollution of soils and the atmosphere, logging, fire suppression policies, grazing and agricultural land abandonment. We will discuss each of these further in detail.

Fire and Climate Change

There is much uncertainty over how anthropogenically induced climate change will influence fire regimes in the future. As discussed earlier, climate is a dominant driver of fire; influencing both fire fuels (vegetation) and the conditions for fire (Krawchuk et al. 2009). In the long-term climate determines distribution and quantity of flammable fuels and in the short term influences weather conditions conducive to fire spread and fuel moisture. Krawchuk et al. (2009) used multivariate statistical generalized additive models (GAMs) to examine how global patterns of wildfire may change under future climate change conditions. Their modeling refutes simplistic predictions that a warmer climate will necessary lead to more fire in the earth system and found that under climate change conditions some regions are likely to experience more frequent fires, while others may see a decrease in fire activity. The predicted spatial variation among regions in future fire activity reflects the underlying interaction between temperature and precipitation variables which influence the constraints on fire, or the 'switches' (Bradstock 2010). Although Krawchuk et al. (2009) predicted no net increase in the amount of fire on the globe, they note that the ecological or social impacts of altered fire regimes are likely to be significant, with many parts of the world experiencing 'invasion or retreat' of fire activity (Krawchuk et al. 2009).

A meta-analysis by Flannigan et al. (2009) of fire and climate change studies from around the world (although the vast majority of studies are based on North America) found that research to date indicates an increasing trend in global area burned and fire occurrence under global warming scenarios. However they also predict great spatial variability in future landscape fire trends, with some areas likely to experience no change or even decreases in area burned and fire occurrence.

Moritz et al. (2012) found that there is significant disagreement between global climate models on the direction of change of fire activity (increasing or decreasing) for more than half the world's land area in coming decades, but found some general agreement between models further into the future. Their work indicates that regions in the mid- to high-latitudes will experience higher probabilities of fire occurrence, while in the tropics there may be a decrease in the probability of fire activity. There are several significant limitations to modeling techniques for forecasting future fire activity under global change conditions, making long-range predictions of patterns of landscape fire complicated. Aspects of the fire regime beyond area burned, such as fire intensity and severity are more difficult to predict and need further research (Flannigan et al. 2005). For example, the seasonality of potential fire activity is likely to shift in parts of the globe, particularly temperate and boreal regions of the world, where there is evidence that fire seasons are already increasing and will likely continue to lengthen in the future (Stocks et al. 1998). Westerling et al. (2006) examined fire data from the Western United States for the last quarter of the twentieth century. They found a sudden, significant rise in wildfire activity in the mid-1980s, with more frequent large-wildfire events, longer wildfire durations, and longer wildfire seasons. The underlying driver to these increases were higher spring and summer temperatures and an earlier spring snowmelt associated with warming climate, particularly in areas where human land-use has relatively little effect on fire risks (Westerling et al. 2006).

Extreme weather events predicted under climate change are also likely to alter patterns of landscape fire, yet despite the significance they may have for future fire activity, incorporating extreme weather anomalies into models is particularly difficult (Bradstock 2010). Weather data from south-Eastern Australia, an area that has witnessed a string of disastrous fire events in recent decades, show that fire danger, predominantly a function of weather conditions, increased by 10-40% from 2001-2007 relative to 1980-2000 (Williams et al. 2009). Additionally, modelling indicates a significant rise (up to 65% increase) in days with extreme fire danger conditions by 2020 (Williams et al. 2009) which are likely to have serious consequences for human ability to manage fire during these extreme weather events.

One of the biggest constraints to forecasting fire activity under a warming global climate is that statistical 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 (Bowman 2009; Flannigan et al. 2009). For example, elevated CO_2 may promote plant growth and therefore increase fuel loads, while conversely, extended drought may decrease plant productivity in the long term (decreasing fuel loads) and desiccate fuels (increasing propensity to burn). The interactions between high CO_2, vegetation, fire, climate and people are tightly interrelated and changes to these interactions are extremely difficult to predict (Bond and Midgley 2012). For example, Hoffmann et al. (2002) identified a positive feedback loop whereby anthropogenic clearing and land-use change in tropical savannas results in warmer and drier climate, accelerated fire frequencies, and further tree cover loss. Humans play a central role in this fire-vegetation-climate feedback because the majority of fires in tropical savannas are lit by people. Fire remains an economic land management tool for millions of subsistence farmers who live in these savannas. As population pressure increases in these regions, humans are likely to overcome climatic limitations on fire frequency and accelerate this fire cycle, resulting in vast ecosystem degradation (Hoffmann et al. 2002). Due to the complexity of feedbacks and links between climate, vegetation, people and fire, forecasting future fire regimes involves very high degrees of uncertainty.

Alarmingly, increased fire activity may represent a positive feed-back to climate change as greater fire activity could potentially generate a massive flux of carbon and other greenhouse gases to the atmosphere, which may in turn lead to accelerated rates of global warming and potentially more fire (Bond-Lamberty et al. 2007; Bowman et al. 2009). There remains great uncertainty over how human behaviours may interact with changing climate and vegetation to influence fire activity in coming decades. The interactions between people, vegetation, climate and fire follow non-linear patterns and are likely to include unpredictable positive and negative feedbacks (Flannigan et al. 2009). The case of the Boreal forests highlights the complexity of interactions and possible feedbacks between fire and climate change.

Climate Change, Fire and the Boreal Forests

The circumboreal zone covers ca. 12 million km^2, stretching across North America and Eurasia (Goldammer and Stocks 2011) and represents a very significant global carbon pool as it is home to 20% of global vegetation cover (Mouillot and Field 2005) and a third of total terrestrial stored carbon (Apps et al. 1993). Organic-rich soils of the boreal contain double the amount of carbon than the atmosphere (Tarnocai et al. 2009). In the boreal forests, fire is the dominant disturbance, driving forest structure and function and carbon cycling. It is estimated than an average of 5-15 million hectares burn annually in boreal forests, mainly in Canada, Alaska and Siberia, with significant inter-annual variation influenced by climate (Flannigan et al. 2005). Over the last 40 years, area burnt has been increasing in the Canadian boreal forests, a trend which has been attributed to anthropogenic climate change (Gillett et al. 2004).

Global warming is expected to significantly increase fire activity in the Boreal forests (Flannigan et al. 2009). The season of potential fire activity is anticipated to lengthen under warming conditions. Studies show that climate change will increase both the frequency and severity of forest fires. This will result in larger areas burnt, shorter fire-return intervals, change in forest structure and potentially species distribution (Stocks et al. 1998; Kasischke 2000). Further, altered fire regimes in the Boreal will have significant implications for global carbon cycle and may lead to a positive feedback to global warming. Increased fire activity could accelerate the release of the vast quantities of carbon and other greenhouse gases, such as methane, currently stored in the vegetation and in soils under permafrost to the atmosphere which would lead to greater warming and potentially more fire (Bond-Lamberty et al. 2007) see Figure 6. However, the magnitude and direction of influence that increased fire activity in the Boreal may have on climate remains unclear due to the cooling effects of increased albedo by fire. Fire, could potentially slow warming because loss of dark forest after fire exposes more snow and increases albedo (solar energy reflectance) in winter, which has a cooling effect on the land surface (Randerson et al. 2006). The net influence of increased fire activity on climate in the boreal remains unclear and needs further investigation given the complex interactions and feedbacks between these elements (Hinzman et al. 2003).

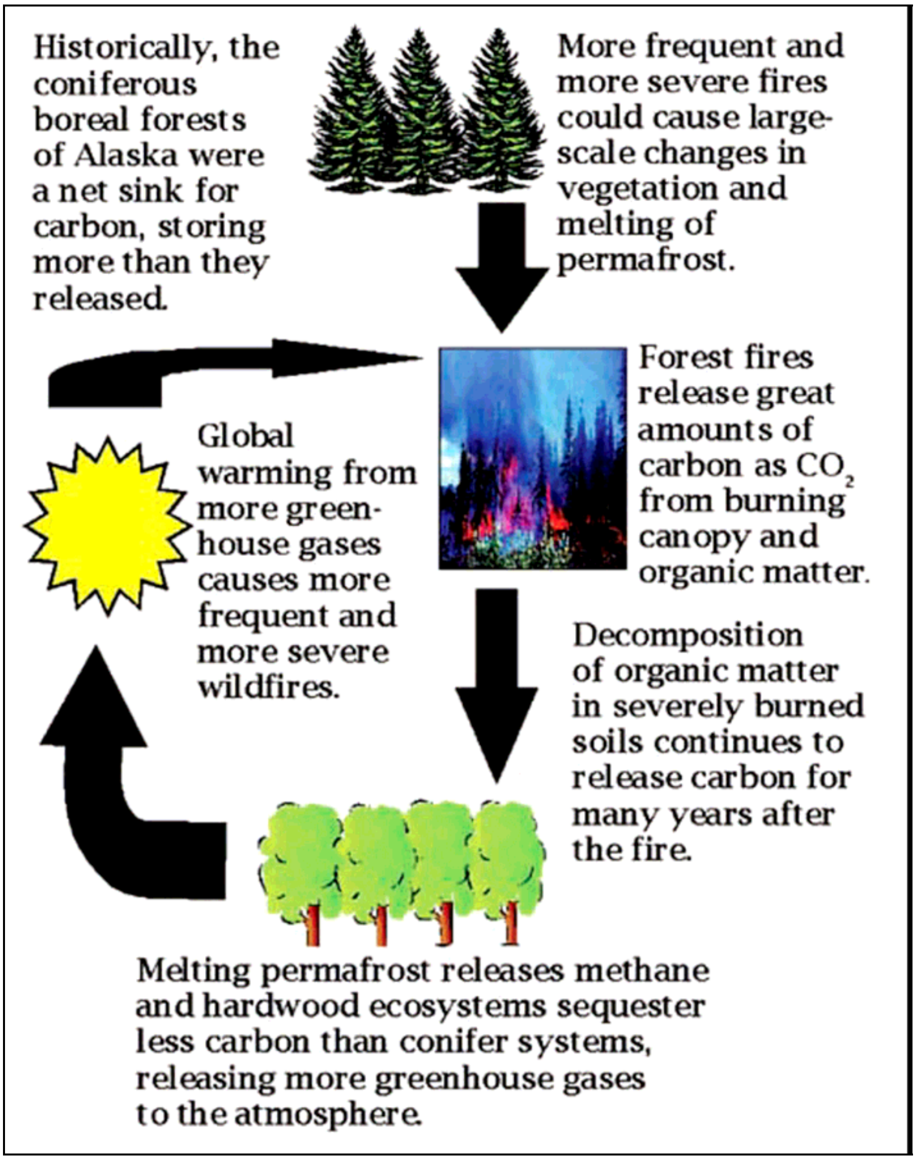


Figure 6. The interaction between changing climate and fire activity in the Boreal forest has several complicated interactions and feedbacks. Increased fire activity in the Boreal under a warming climate may have important global climatic and biogeochemical consequences, including a potential positive feedback cycle leading to accelerated release of CO_2 and methane from permafrost. Source: Hinzman et al. (2003).

Landscape fire and biomass combustion impact climate in two primary ways; via the release of gases (water vapor, CO_2, CH_4, NO_X, SO_X, etc.) and other aerosols which alter the radiative energy balance of the atmosphere and by changing the albedo (or light-reflective properties) of the land surface (Bowman et al. 2009). Landscape fire is a critical component of the global carbon cycle, and annually landscape fires release ca. 2-4 Pg of carbon to the atmosphere, more than half of which derives from savanna regions and with strong inter-annual variability from forests worldwide (van der Werf et al. 2006). Biomass combustion (including landscape fire) releases approximately one third as much CO_2

as fossil fuel burning and industrial processes (Raupach et al. 2007). In terms of carbon dioxide, landscape fire emissions are thought to be in equilibrium in the long-term as the CO_2 released by fire is taken up by regenerating vegetation post-fire, however, this balance is currently being disrupted by anthropogenic deforestation fires and burning of peatlands in the tropics. Biomass burning is shifting to a net flux of carbon to the atmosphere because unsustainable land clearance practices are inhibiting the ability of terrestrial systems to re-absorb this CO_2 from the atmosphere. DeFries et al. (2002) estimated that between 1980-2000 tropical deforestation released a net average of 0.6-0.9 Pg C per year. Further, it is estimated that deforestation globally has contributed ca. 20% of the CO_2 accumulated in the atmosphere since the industrial revolution (Houghton 2003).

Biomass burning contributes equivalent amounts of other potent greenhouse gases and atmospheric pollutants as fossil fuel combustion (Crutzen and Andreae 1990). For example, landscape fire is a predominant source of emissions for methane and nitrous oxide. The gases have different radiative forcing properties, for example methane is approximately 25 times more potent as greenhouse gas than CO_2 and vegetation fires release more methane than fossil fuel combustion, similarly for nitrous oxide, making biomass burning a globally important source of greenhouse gases (Andreae and Merlet 2001). Currently, most biomass burning emissions originate from savanna and forest conversion fires in the tropics, however, there is evidence that under global warming conditions emissions from boreal and temperate forest fires may increase significantly (Stocks et al. 1998).

The net impacts of emissions from landscape fire on global climate are highly complicated and as yet unclear, owing to the diverse radiative properties of aerosol components and effects of albedo. Biomass burning produces □40% of total global emissions of black carbon, the second strongest contribution to current global warming after CO_2 (Bond et al. 2004). Furthermore, deposition of black carbon over snow and ice significantly alters surface albedo and increases solar absorption and melting, which may be strongly increasing rates of Arctic sea ice retreat (Flannigan et al. 2009). Shindell and Faluvegi (2009) demonstrated that increasing concentrations of black carbon over the last 30 years had significantly accelerated Arctic warming. Additionally, smoke from biomass burning contains particles which scatter sunlight and result in a cooling effect on terrestrial land surfaces. Smoke particles can also reduce the evaporation of water from oceans and land. Biomass smoke can further influence regional water budgets as aerosols from fires can impact clouds formation (leading to a greater number, but smaller size of cloud droplets) and therefore decrease local precipitation or lead to more intense storm events (Andreae and Rosenfeld 2008). While biomass burning is a significant source of atmospheric aerosols and greenhouse gases, there is much uncertainty over interannual variability and the underlying drivers of biomass burning emissions from regional to global scales (van der Werf et al. 2010). Randerson et al. (2006) argue that the net impact of landscape fire and biomass burning may not result in a positive feedback to climate change when considering the impacts of greenhouse gases, aerosols, black carbon deposition, and changes in albedo over the long term. Further investigation is needed in order to better understand the balance of positive and negative radiative-forcing properties of emissions from landscape fires (Bowman et al. 2009).

Smoke from Landscape Fire and Health

Landscape fires and biomass burning are a major source of atmospheric pollutants, impacting air quality locally and across international borders and as such represent a serious public health issue (Andreae and Merlet 2001; Goldammer et al. 2009). Globally, the majority of smoke emissions are derived from anthropogenic burning in tropical rainforests and savannas, where they have been recurrent episodes of severe pollution that affect some of the poorest regions of the world (van der Werf et al. 2010). Smoke from biomass burning contains a large and diverse number of chemicals, many of which have been associated with adverse health impacts (Naeher et al. 2007). In terms of impact on human health, particulate matter smaller than 10 micrometers (PM_{10}) and less than 2.5 micrometers in diameter ($PM_{2.5}$) in biomass smoke are particularly important and concentration of these particles increase dramatically during air pollution episodes caused by vegetation fires. Additionally, carbon monoxide and volatile organic compounds in smoke from vegetation fires can significantly impact the health of people who are close to the areas of burning (Schwela 2004). These particles can cause spikes of respiratory and cardiovascular illness in populations exposed to smoke from landscape fire and given that smoke plumes can be transported in the atmosphere long-distances via global teleconnections, can also impact people in areas far removed from the origin of the burning (Schwela 2004). For example, extremely hot and dry weather conditions combined with significant changes in land management practices led to an extreme episode of fire activity in Western Russia in the summer of 2010, with more than 80,000 hectares of forests, agricultural land

and peatlands burned between July and September (Goldammer 2010). These fires generated extensive smoke and air pollution, which enveloped Moscow and impacted ca. 15 million people for several weeks. Compounded by high temperature and minimal precipitation, this smoke pollution event had serious health consequences for the people of Moscow. Goldammer (2010) reports an increase in mortality in Russia of 18% compared to background levels for this period, attributed to the extreme heat and respiratory and cardiovascular disease associated with the smoke pollution. Indeed, according to official Russian government sources the heat wave and smoke pollution was directly responsible for ca. 56,000 deaths more than the corresponding months in previous years (O'Brien and Goldammer 2011). Furthermore, smoke from the Russian fires had trans-boundary consequences, impacting China, Japan and reaching as fire as North America.

Most of the fires that led to the 2010 Russian smoke pollution event were deliberately or accidentally lit by humans yet occurred in concert with extreme weather conditions. Similarly, extensive and recurrent trans-boundary smoke events from landscape fires across South East Asia arise predominantly from anthropogenic burning practices but are most severe during dry weather conditions associated with El Niño drought events (Cochrane 2003). In the study of Johnston et al. (2012) the highest number of annual deaths attributable to exposure to biomass smoke occurred during a strong El Niño year. During an extended El Niño dry season in 1997, fires in Indonesia, particularly forest and peat fires deliberately lit for land clearance purposes, created dense smoke pollution that spread and settled over much of the region, impacting numerous countries including Indonesia, Malaysia, Singapore, Philippines and Thailand and tens of millions of people in the region (Schwela 2000). An estimated 20 million people suffered respiratory illness as a result of the smoke pollution in Indonesia alone (Heil and Goldammer 2001). While similar smoke pollution events are documented in South-East Asia, the 1997 episode was considered unprecedented in extent and intensity (Heil and Goldammer 2001). In response to the health crisis created by the smoke pollution, the World Health Organization in tandem with the United Nations Environment Program, the Global Fire Monitoring Centre, the World Meteorological Organization (WMO) and Japanese and Singaporean governments developed guidelines to cope with transboundary vegetation fire events (WHO/UNEP/WMO 1999).

In South East Asia fire is a prevalent land management tool utilised on a small scale by local farmers and also on a much larger scale by business enterprises and governments that seek to clear and convert forests to establish agricultural crops (Page et al. 2002). During the extended ENSO-related drought of 1997 the exceedingly dry conditions meant than many deliberately lit fires spread out of control and entered into the carbon-rich peatlands. In addition to the thick haze of smoke pollution that settled over Southeast Asia and the associated severe deterioration in air quality and health problems, it is estimated that the 1997 fire episode in Indonesia released between 0.81 and 2.57 Gt of carbon to the atmosphere (Page et al. 2002). This is of enormous global significance as it is the equivalent of 13-40% of annual global carbon emissions from fossil fuels. Furthermore, it is thought that smoke emissions from biomass burning in the tropics may inhibit cloud formation and lead to regional decreases in precipitation during smoke pollution events. This is a potentially alarming feedback as anthropogenic burning may lead to intensification of drought stress during El Niño and increase the susceptibility of tropical forests to fire (Tosca et al. 2010).

The severity of impacts of smoke from biomass burning on human health has only begun to attract widespread international political and scientific attention in recent years (Johnston et al. 2012). Given the trans-boundary nature of the problem, there is an urgent need for international cooperation to reduce the impacts of vegetation fire smoke pollution. These include formulation of international and national policies to address the underlying causes of smoke pollution, such as decreasing excessive, unsustainable burning practices (particularly in Tropical regions), the establishment of sound fire and smoke management practices and protocols, and international cooperation on fire management issues. In this regard, international collaborative efforts, such as those facilitated by the Global Fire Monitoring Centre have been pioneering (Schwela 2004; Goldammer and Zibtsev 2010).

Fire and Other Hazardous Emissions

Landscape fires are also an important source of other dangerous pollutants, such as mercury and radioactive compounds. Biomass burning accounts for 8% of global annual mercury emissions (Friedli et al. 2009) and interestingly, distribution of mercury emissions are decoupled from global carbon emissions from biomass burning. While most carbon released through biomass burning is emitted from fires in African savannas, the majority of mercury emissions from biomass burning originate from fires in equatorial Asia, boreal Asia, and southern hemisphere South America. Mercury emissions can form harmful compounds, such as methyl mercury, which is toxic to humans and other animals (Friedli et al. 2009). The largest terrestrial pool of mercury lies in the soils of the boreal zone, and similarly to carbon, there is a risk that under global warming, increasing temperature in boreal regions may lead to larger, more frequent fires and therefore accelerate mercury emissions which could have hazardous impacts on human health and lead to mercury toxicities in food chains in the northern hemisphere (Sigler et al. 2003; Turetsky et al. 2006).

In some parts of the world, there is an alarming risk that landscape fire will release to the atmosphere and spread radionuclides and other hazardous chemical if wildfires burn across land contaminated by hazardous chemical and radioactive pollution. For example, the nuclear disaster that occurred in Chernobyl in 1986 has left 6 million hectares of radioactively contaminated terrain in Ukraine, Belarus and Russia (Statheropoulos et al. 2013). In the Chernobyl exclusion zone, radioactive material has largely accumulated in the peat layers of the soils. International collaboration efforts between scientists from the Ukraine, USA, and Germany have been initiated to assess the situations and find strategies to minimise the risk of catastrophic wildfire burning across the contaminated forests and abandoned agricultural lands, as the subsequent release of radioactive material which would have a disastrous impact on human populations (Goldammer and Zibtsev 2010).

Furthermore, there are other hazardous materials, such as unexploded ordnance (UXO) - the terrible legacy of military conflict, which complicate fire management in certain parts of the world, such as Eastern Europe and Eurasia. Unexploded ordnance (UXO) (landmines, artillery ammunition, bombs) contaminant hundreds of thousands of hectares of forest and other lands across Western, Eastern and Southeastern Europe (Goldammer and Zibtsev 2010). Fires burning through territory which contains UXO pose an extreme risk to civilian populations, and particularly to fire-fighters, as the heat and force of the fires can trigger the explosion of undetonated material. A pioneering project is underway on abandoned military land in the German state of Brandenburg (formerly part of the German Democratic Republic) which is heavily contaminated by unexploded artillery grenades and bombs (GFMC 2010; Goldammer et al. 2012). The project is trialing application of low intensity prescribed fire to contaminated terrain, ignited from the protection of armored military tanks, with the aim of reducing the risk of uncontrolled, intense wildfires that are likely to detonate the UXO and threaten the safety of fire-fighters and others.

Fire Disasters – Economic and Social Costs

In addition to the health impacts of smoke pollution and the potential mobilisation of hazardous materials, landscape fires threaten and impact people and property on all inhabited continents. In recent decades, there has been an increasing incidence of large, uncontrolled fire events that have severely impacted ecosystems, people's lives and livelihoods and public and private infrastructure around the world (FAO 2006; Bowman et al. 2009). Disastrous fire episodes in which many people have been killed or impacted in other ways, such as the 2007 fires in Greece, the 2009 Black Saturday Fires in Australia, 2010 fires in Western Russia, fires in Israel in 2010, fires around Slave Lake in Canada in 2011, and a severe wildfire season across many states of the USA in 2011 are drawing both public and political attention to the dangers posed by uncontrolled fires (Goldammer and Stocks 2011). A new term "megafires" has been coined – albeit disputed and often unreflectedly used – to describe these large-scale fire events with corresponding severe impacts on people, property and ecosystems (Flannigan et al. 2009).

The social and economic costs associated large disastrous fires are known to be extremely high, however, they are very difficult to quantify. Along with the direct economic costs of burnt infrastructure and loss of livelihoods (e.g., agricultural crops, livestock) annual investment in fire management, in terms of responding to fire outbreaks, fire suppression and fire management to reduce risk (e.g., prescribed burning) are in the order of several billions of dollars each year around the world (Flannigan et al. 2009). For example, the 1997 fire episode in South East Asia is estimate to have caused ca. $US 9 billion of economic costs, of which only approximately $US 1 billion were from health impacts from smoke pollution (Schweithelm et al. 1999). During the same period, fires in South America also associated with extreme El Niño weather events are estimated to have burnt an area greater than 20 million hectares and caused between $US 10-15 million of damages (Cochrane 2003). Indeed, the economic impact of fires in tropical developing nations is disproportionate to the funding these countries have available to spend on fire management. Cochrane (2003) outlines the contrasts in fire management budgets between developed and developing states, reporting that in

2000 the USA faced one of its worst fire seasons in recent history and nearly 3.4 million hectares were burnt. The cost of fire suppression in the USA that year was in the order of $US 1.4 billion dollars. Contrastingly, Indonesia had a firefighting budget of only $US 25 million dollars to manage the disastrous 1997 episode, a large proportion of which came from foreign aid (Cochrane 2003).

Social and Economic Drivers of Fire Activity

According to the United Nations Food and Agriculture Organization, people are the main cause of fires which negatively impact society and the environment (FAO 2007). Deliberate or accidental fires lit by humans, and those that accidentally escape control, are contributing to the rise in extreme fire events that, as outlined above, are having severe impacts on ecosystems, people and property. The growing awareness of the impacts of uncontrolled fires has drawn attention to ways in which humans have altered patterns of fire around the world in recent decades. In addition to climate change there is a suite of social and economic factors that have contributed to the rise of extreme fire events that challenge the limits of human ability to manage fire and minimize fire's deleterious impacts. Such changes result from shifting demographics, migration of people, growing populations, diverse socioeconomic factors and land management practices (Pausas and Keeley 2009). Globally, changes in fire regimes and underlying causes of change are extremely diverse and vary significantly between regions. Some of the factors include, but are not limited to: the introduction of exotic species that are dramatically altering fire regimes by increasing fine fuels and shortening fire return intervals, land clearance and deforestation in tropical forests that historically experienced fire only very rarely, increasing fuel loads caused by land abandonment and migration (e.g., in Mediterranean Europe) and policies of fire suppression in temperate states such as Canada, the USA and Australia where fire activity declines in the short term but may ultimately lead to extremely large and intense fires in the long term as fuels accumulate (Pausas and Keeley 2009; Goldammer and Stocks 2011).

In recent decades there have been changes to fire incidence across Mediterranean Europe, largely as a result of socioeconomic changes and shifts in population demographics (FAO 2006). Industrialization and economic development have caused major changes in land use including mass migration away from the countryside to urban areas, resulting in abandonment of agricultural lands and an associated decrease in livestock grazing pressure (Pausas 1999). In combination with large areas converted to timber plantations this has led to an accumulation of available fuels. Further, the migration of people to industrial centers has caused a loss of local knowledge and skills about how to manage fire and also a decrease in interest in managing fire due to lower values placed on these lands (Pausas and Keeley 2009). Subsequently there has been a rise in the number of number of large, intense fires across Spain, France, Italy and Greece in recent decades, indicating a shift from frequent small fires to large, difficult to control wildfires that cause the loss of lives and property. The idea that this new fire problem has arisen out of social causes is underscored by the fact that anthropogenic burning dominates fire activity in this region and that similar trends in increasing numbers of large, dangerous fires have not been observed in the Southern Mediterranean basin where there has been less dramatic socio-economic change and traditional land use practices are still employed (Dimitrakopoulos and Mitsopoulos 2006).

The Grass Fire Cycle

Humans have deliberately and unintentionally spread alien grasses into diverse ecosystems around the world. These flammable invasive grasses are able to drastically alter fire regimes, impacting biodiversity, ecosystem function and in some cases leading to local extirpation of native woody species. This process is known as the 'grass-fire cycle' and was first described by D'Antonio and Vitousek (1992) with the example of invasive C4 perennial grasses altering fire regimes and transforming woodlands in Hawai'i. The grass-fire cycle is a feedback loop whereby exotic grasses invade and promote frequent fire due to their abundance of dry and aerated fine fuels. This grass invasion and accompanying increase in fire frequency sets into motion a cycle that is able to transform a fire-sensitive, native woodland or savanna into flammable, frequently burnt exotic-dominated grassland (D'Antonio and Vitousek 1992). The exotic grasses recover quickly after fire (their reproductive tissue is protected below ground) and rapidly produce prolific biomass, thereby promoting recurrent fire which kills any juvenile native trees that have regenerated. Woody species become 'trapped' and killed by successive fire 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 favors the invading grasses over native woody species (Mack and D'Antonio 2003).

In Northern Australia high-biomass exotic grasses, such as Gamba grass (*Andropogon gayanus*) and Buffel Grass (*Cenchrus ciliaris*) have been introduced to large areas as cattle pasture (Setterfield et al. 2010). These grasses overcome the primary limit to fire activity in native savannas: sufficient biomass. In these semi-arid systems fires occur only when enough vegetation grows during periods of above average rainfall. The invasive grasses however produce abundant biomass even in dry years and are leading to frequent intense fires that cause high mortality of native woody species and in the worst cases, a biome switch from native savanna to exotic grassland. Similar grass-fire cycles are described for alien grasses in many parts of the world. Some of the most aggressive cases include *Bromus tectorum* (Cheat Grass) in Western North America, *Hyparrhenia rufa* (Thatch Grass) in tropical Central America, *Melinis minutiflora* (Molasses) in Hawai'i and tropical Northern Australia and *Schizachyrium condensatum* (Tufted Beard Grass) in Hawai'i (Keeley 2006).

The Wildland-Urban Interface

Conversely, there has been a growing trend of migration from urban centres to the periphery of highly flammable ecosystems in places such as North America, Australia and elsewhere in Europe, and a corresponding increase in housing and population in areas adjacent to vegetation types that are prone to high-intensity crown fires (Mell et al. 2010; Bradstock et al. 2012). This expansion of settlement at the 'Wildland-Urban Interface' (WUI) is contributing to increasingly disastrous impacts of wildfire, given the dangerous mixture of communities and infrastructure, increased anthropogenic ignitions and highly flammable ecosystems (Stephens et al. 2009). Fires at the WUI represent a severe threat to people and property as tragically demonstrated by recent catastrophic fire in Southern Australian, the USA, Canada, Greece and Israel. In addition to highly vulnerable populations and property, settlement on the WUI makes management of fire to reduce risk and to maintain fire's critical biological role in these ecosystems extremely complicated.

For most of the twentieth century governments in temperate states, such as Canada, the USA and Australia adopted policies of complete fire suppression in an attempt to minimise risk to people and structures at the WUI, however, suppression has been shown to have led to several perverse outcomes including the accumulation of high fuel loads and thus increased risk of intense wildfire, a shift in fire regime in some vegetation types and increased stress on biodiversity, despite ever-increasing budgets allocated to fire management activities and more sophisticated fire suppression technology such as water-bombing aircraft (Gill and Stephens 2009; Bowman et al. 2011). There are other management practices that are employed in order to make fire suppression more effective, which also include many trade-offs and a significant amount of controversy, these include clearance of vegetation to form buffers, or 'fire breaks', between high fuel loads and human assets and prescribed burning under controlled conditions to reduce fuel loads. Continued catastrophic fire events call in to question the efficacy of suppression methods. Under extreme conditions these approaches fail to prevent fires which start in forests and shrublands from encroaching into settled areas as fuel loads do not limit the spread of fire (Bowman et al. 2011).

(Beyond) Fire Suppression in the Ponderosa Pine Forests of the USA

Throughout the 20th century in the Western USA a policy of fire exclusion was widely pursued in an attempt to protect people, property and timber assets from fire damage. Policies of fire exclusion, however, ignore the biological role of fire in ecosystems and subsequently led to changes in forest structure. Changes such as forest thickening are thought to have rendered large areas of forest more susceptible to high-intensity crown fires and to outbreaks of pests and disease (Veblen et al. 2000). The forests of Ponderosa Pine (*Pinus ponderosa*) were traditionally characterized by a regime of frequent surface fires but fire exclusion practices have led to significant increases in stand density and high fuel accumulations. Accordingly there has been a shift in fire regime in these forests from frequent low-intensity surface fires that caused limited tree mortality to severe, high-intensity crown fires (Allen et al. 2002). A denser understorey forms a 'fuel ladder' by which flames can enter the tree canopy and kill entire stands of surface-fire-resistant trees (Syphard et al. 2009). Further, Berry and Hesseln (2004) argue that overstocked stands of trees due to fire exclusion are stressed by high competition for resources and are therefore more vulnerable to disease and insect outbreaks.

Concomitant with fire suppression policies that instead of protecting resources and communities have made them more susceptible to large intense fires, has been massive expansion of the WUI and subsequent increase in population at risk from large fires. Alternatives to fire exclusion, including reintroduction of fire via prescribed low intensity burning of the surface layer and mechanical thinning are now being employed for the dual aims of improving forest health and reducing fuel loads (Covington et al. 1997). However, fragmentation of the landscape, public opposition and high population densities make implementing these management prescriptions difficult. There is also uncertainty about the amount of forest management required to significantly reduce risk of catastrophic wildfire, which is also significantly influenced by climatic variability (Veblen et al. 2000). Veblen, Kitzberger et al. (2000) hypothesized that while thinning and prescribed burning may reduce the probability of small fires spreading and becoming uncontrollable during average years, extreme weather conditions and droughts may still lead to high-intensity crown fires that pose high risks to people and infrastructure.

Management Options

Continued large catastrophic fire events have shown that complete fire exclusion is both an impractical and ineffective way to minimize fire risk in the landscape in the long-term and that not only has it failed in its aims of protection of people and property, it has had detrimental impacts on ecosystems and biodiversity in many places where it has been attempted (Dombeck et al. 2004). In recent years, there has been an increasing trend to allow fires that are started by lightning to burn (so far as they do not pose immediate risk to people or infrastructure) in order to reinstate the biological role of fire in natural ecosystems and to reduce the extremely high costs associated with suppression. This approach of course, is feasible only when the fires do not pose threat to communities or other assets and requires large areas of predominantly natural ecosystems and low human population density. As exemplified by the shift in fire regime in the Ponderosa Pine forests of the Western USA, allowing the return of naturally-lit fires to burn in forests that have had fire excluded from them for several decades can result in large, destructive crown fires that are difficult to control due to the high fuel loads that have accumulated in the absence of fire (Allen et al. 2002). As such, the proximity of such forests to the WUI mandates intervention to reduce fuel loads, such as mechanical thinning and prescribed fire, to reduce the probability of destructive crown fires.

The use of prescribed fire is increasingly being seen as a means not to eliminate wildfire altogether, but rather, to decrease fuel loads in order to minimize high-intensity fires that overwhelm fire-fighting capabilities and cause destruction (Jensen 2006). Fuel quantity is the only component of the fundamental fire triangle (ignition – fuel – weather) that we can actively control. With climate change is likely to make conditions hotter and drier in many parts of the world, the need to reduce fire risk becomes more urgent (Adams and Attiwill 2011). Further as outlined above, the sprawl of suburban communities into flammable environments restricts management options while increasing vulnerability of people and property (Dellasala et al. 2004). Management options cannot significantly alter the trajectory of a hotter, drier future of more extreme fire weather, but they may be able to influence the timing and intensity of wildfires. Decreasing fire intensities, by lowering fuels loads through prescribed burning and mechanical thinning in ecosystems that historically had a fire regime of frequent, low-medium intensity fires, can improve ecosystem function and the maintenance of soils, water supplies and biodiversity, in addition to reducing risk to human communities (Dellasala et al. 2004).

In fragmented landscapes, with communities and infrastructure surrounded by areas of flammable vegetation and various forms of land tenure (public and private), landscape scale fire management is challenging. Further, resources available for fire management are finite and it is often argued that priorities for fuel management should be those places where communities and flammable ecosystems meet: the WUI (Dombeck et al. 2004). The focus on fire management treatments at the perimeters of human settlements has obvious tradeoffs between reduction of risk and biodiversity. The complex challenge for managers is to be able to understand and predict the effects of fire management treatments on biodiversity (Gill and Stephens 2009). Here, the concept of fire regime is important, particularly for understanding plant response to fire. Commonly, ecosystems to be treated with prescribed fire will contain a number of threatened species that may become the focus of management objectives. Managers are then faced with the conflicted task of trying to balance fire regimes that suit certain threatened species against the requirements of other species while maximizing risk reduction (Dellasala et al. 2004). Any particular combination of fire severity and fire frequency will naturally favor some species and disadvantage other. However, rather than trying to manage on the basis of single species, it has been argued that there is far too much uncertainty in fire regimes for entire ecosystems, with the responses of microfauna and macrofauna being much more poorly understood than the fire response of plants, and that a more robust approach would be to aim for diversity of fire regimes in a given area, with high heterogeneity of time since fire across the landscape (Adams and Attiwill 2011). Additionally, it is important to keep in mind the trade-offs for biodiversity if prescribed burning is not implemented. In this regards, the consequences of large-scale high-intensity fires on biodiversity must be kept in perspective. An extreme intense and uncontrolled wildfire that burns over an extensive area can be far more detrimental to biodiversity than a series of low-intensity burns aimed at minimizing catastrophic fire (Williams et al. 2009).

Management Trade-Offs

The concept of reinstating a ‘natural’ fire regime is hindered by the challenges we face in terms of ecosystem fragmentation, weeds and invasive species and other anthropogenic pressure placed on native ecosystems and native species by proximity to human settlements. There are no simple solutions for managing the coexistence of people and property amid flammable ecosystems and management necessarily involves a series of trade-offs, largely informed by social values and the economic restrictions of management budgets. The debate over how to best manage fire, for instance the role of hazard reduction burning, is inherently cyclical because it is continuously influenced and informed by scientific research and real-world experience (Bowman 2003a). Fire management can only realistically aim to achieve a finite set of objectives. Because of the difficulty of balancing conflicting values, such as biodiversity protection with hazard reduction, managers in the past have often failed to state clear objectives or to formulate achievable operational guidelines for landscape fire management (Bowman 2003a). Of the Australian context, (Bowman 2003b) writes:

“There can be no doubt that some styles of management are more sympathetic to biodiversity and ecosystem services than others. I believe the currently ascendant 'bushfire disaster' mode of management is ultimately more destructive of biodiversity than a program of recurrent fires to reduce fuel loads.”

Sustainable fire management mandates that clear and specific objectives are stated and should acknowledge the complicated trade-offs inherent in management. The coexistence of humans in flammable landscapes represents an on-going challenge, without quick or simple solutions. The nature of a particular fire risk, and therefore potential management solutions, are context specific and will likely change as they are impacted by increasing changes in social and biophysical systems associated with population growth, cultural change, vegetation change and climatic shifts (Gill and Stephens 2009). Management objectives should be focused on long-term goals, rather than short-term fixes and should be strongly informed by ecological principles (Dombeck et al. 2004). Accordingly, fire management and planning in flammable ecosystems should be based on understanding of ecosystem dynamics and processes such as biogeochemical cycles, fire history, potential fire behavior, past management actions, land-use changes, threatened species and relative risk to human communities (Adams and Attiwill 2011). This is best addressed by a framework of adaptive management that allows management options to be informed by up-to-date information about these factors. Adaptive management is the process of monitoring, evaluating and making informed changes to management based on monitoring results (Dombeck et al. 2004).

Besides management options that manipulate vegetation and fuel loads, an obvious and much-neglected option for minimizing risk to people and property from landscape fires is land-use planning to minimize the juxtaposition of residential estates and people to inherently flammable ecosystems (Bowman et al. 2011). Planning, however, has received very poor political support in the past as it is perceived to conflict with people’s right to live in proximity to beautiful, albeit dangerous, environments. Additionally, community engagement with issues surrounding fire management and active intervention by residents to prepare their homes against wildfires are important factors that impact the loss of lives and property (Bihari and Ryan 2012). In this regard, community engagement can be a powerful fire management tool. Given that fire danger at the WUI results from a ‘complex mix of physical, ecological, economic and social developments’ (Carroll et al. 2007), community support for fire planning and management is critical to the long-term success of landscape planning and management practices in minimizing fire risk at the WUI and maintaining the critical ecological role of fire in many ecosystems (Bihari and Ryan 2012).

Community Based Fire Management

Community Based Fire Management ('CBFiM') is increasingly being seen as a potentially powerful tool in the prevention of damaging wildfires and the application of fire for specific, useful purposes particularly in places where landscape fires are primarily anthropogenic in origin and the ecosystems naturally experience low levels of fire activity. CBFiM is similar to community based forest management, which has been promoted largely throughout tropical developing countries with mixed success in recent decades, in that local people play a central role in planning and carrying out management activities. CBFiM generally centres on activities associated with fire prevention and knowledge transfer to the community.

Social Institutions

While community participation and engagement in fire management is increasingly recognised as important, government institutions remain the central body of fire management and planning in most parts of the world (Pyne 2007). During the 20th century in states such as the USA, Canada and Australia fire management and research was conducted almost entirely by state institutions (Pyne 2007). Lavorel et al. (2007) believe that many of the problems that we face in fire management globally stem from a misfit between ecosystems with shifting fire regimes and the political, economic and environmental institutions that societies use to deal with fire. They claim that the catastrophic fire events in Indonesia in 1997 and large-scale disastrous fires in Southern Australia over the last decade may be 'interpreted as a temporary misfit between institutions regulating fire use and management and ecosystem conditions under the climate anomalies associated with El Niño' (Lavorel et al. 2007). Further, they argue that land-use change associated with economic and social shifts globally are also increasingly exposing the inadequacies of traditional fire-related institutions to deal with changing ecosystems and fire regimes. The influence of social institutions and cultural factors on fire activity is illustrated in Figure 7 below, with clear differences across political boundaries in some areas and no discernible pattern in others.

Similarly, political transitions can also have a significant impact on fire activity as old institutions break down. For example, under the administration of the former Union of Soviet Socialist Republics (USSR), Russia boasted a large and effective forest fire suppression capability, however, after the collapse of the Soviet Union in 1991, budgets for fire control (prevention, detection, monitoring, and suppression) were greatly reduced (Goldammer 2006; Goldammer and Stocks 2011). As a consequence of these political and economic changes and the subsequent reduction in investment in fire management, Russia has been experiencing very extensive, uncontrolled fires which burn over large areas. Goldammer and Stocks (2011) claim that these institutional issues, as much as the extreme heat wave and drought, contributed greatly to Russia's inability to manage the catastrophic fires of 2010.

The international nature of landscape fire problems, such as trans-boundary pollutions events, means that management should include international perspectives and international cooperation. Multinational institutions such as the Global Fire Monitoring Center (GFMC), supported by the United Nations, are encouraging countries to collaborate and build mutual institutions that recognise the shared benefits to be gained from improving fire management capacity across borders. This involves building regional networks that work together to solve regional fire problems and enhancing capacity to multilaterally share scientific and technical expertise and resources to manage landscape fire (Goldammer 2013).

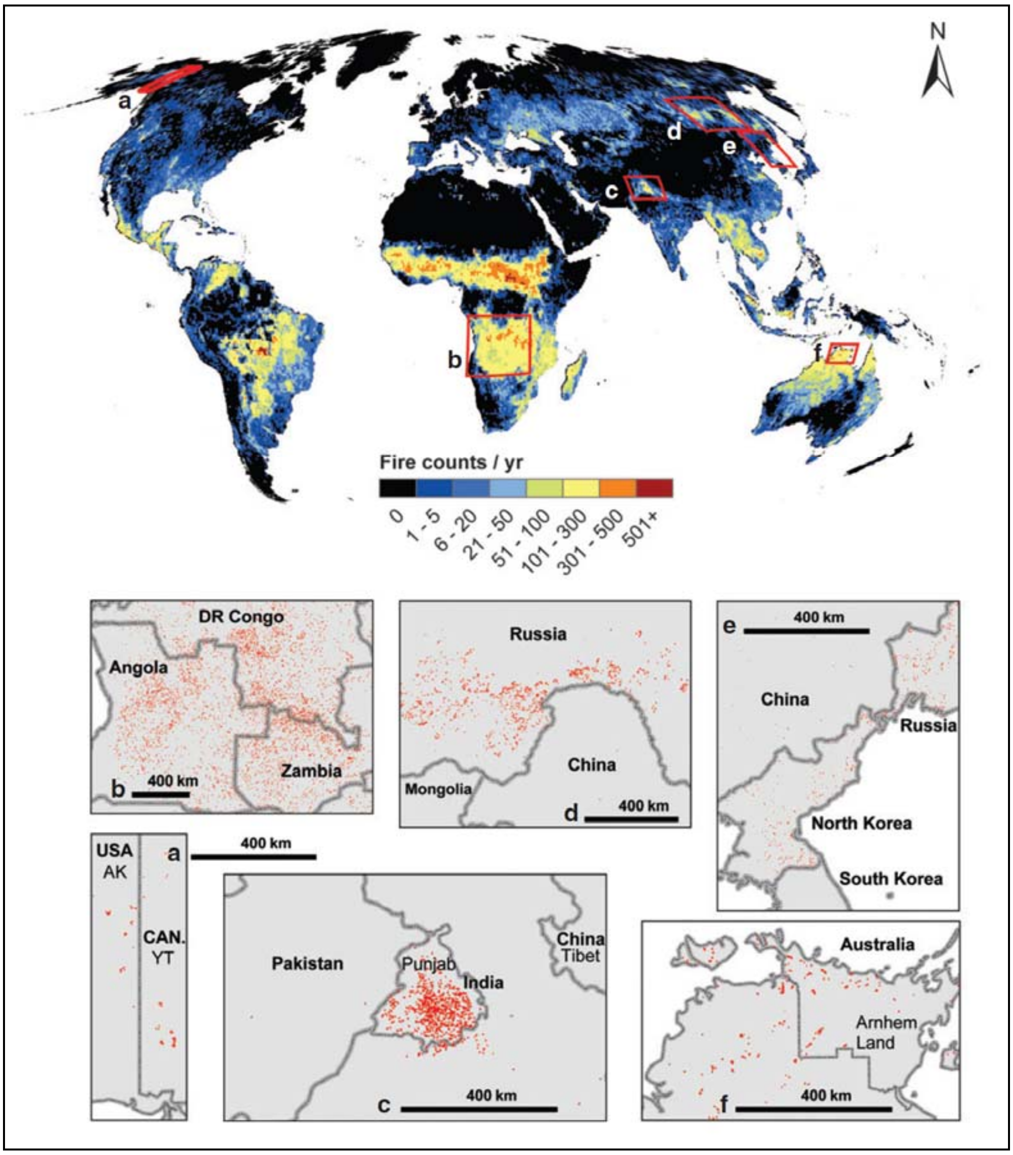


Figure 7. Active fire counts demonstrate global distribution of fires, both anthropogenic and natural, for the period 2001–2007 (above). Fire counts per year data recorded with the MODIS sensor on board the NASA TERRA satellite. Source: Giglio et al. (2006). Variation in fire activity stemming from differences in fire management policy and cultural practices are seen across political boundaries in c, d and e. In other regions, such as a, b and f cultural and social differences across political boundaries do not appear to influence fire. Source: Bowman et al. (2011).

According to Pyne (2007) fire problems are socially constructed, arising from human values and perception of risk. He believes that fire problems are problems only because humans define them as such and that the vast majority of the diversity fire management problems that we face across the globe can be resolved by social means. Pyne (2007) does not suggest that we can eliminate risk altogether or suppress fire entirely, but rather argues that humans have the ability to manipulate fire activity, within climatic restrictions, to determine the type and quantity of fire that we will accept. More concretely, Pyne (2007) claims that through land management, careful land-use planning and regulating activities we can come closer to finding solutions to our most urgent fire management problems. In order to do this though we must broaden the scholarship of fire to examine, understand and offer alternatives to the institutions, social values, and cultural choices that mediate human-fire interaction. A more multidisciplinary scholarship of fire that places humans and social values at its centre is critical to inform decision-making that impacts our landscapes and the role of fire in those settings. Furthermore, sustainable fire management demands that we rethink the role and structure of the institutions we charge with managing fire in the landscape, at local, national and international levels. In order to find ways to sustainably coexist with fire we must fundamentally re-evaluate the aims and objectives of fire management while recognising that the diversity of factors that are leading to fire regime shift will require equally diverse strategies to manage them and will necessarily involve trade-offs.

Conclusions

Landscape fires are critically important for both human societies and to the majority of terrestrial ecosystems worldwide. Palaeoecological sources have revealed that fire has an ancient presence in the Earth system and was a key factor that influenced the evolution of many terrestrial ecosystems. Pre-historic humans developed a species monopoly over fire with the ability to start and manipulate fires and for many millennia people have carried and spread fire with them as they traversed the Earth. Today, fire remains a central component of human societies and cultures and is used for myriad purposes, indeed human relationships to fire are extremely diverse and many forms are currently found around the world.

We live in an era of unprecedented global change as humans have fundamentally altered landscapes as never before. Furthermore, humans have been able to increase or decrease fire activity through land use activities such as clearance and deforestation, or by agriculture and grazing, urban settlement, accidental and deliberate introduction of alien species, by altering ignition patterns and actively suppressing fires. Some places are now experiencing much more burning than historical background rates, while others are witnessing a decrease in burning or a change in the frequency and intensity of fire activity. In some environments which rarely burned in the past due to climatic constraints, such as the tropical rainforests, humans are increasing fire activity as a means to clear vegetation to intensify land use. Burning of tropical rainforests is causing widespread ecosystem damage, impacting biodiversity and releasing large quantities of greenhouse gases. Additionally, humans have begun to influence the ultimate control of fire activity across the globe. Global warming driven by anthropogenic combustion of fossil fuels and deforestation is leading to novel fire regimes on Earth. These shifts in global fire activity have serious ramifications for biodiversity and ecosystems that rely on recurrent fire disturbance to underpin nutrient cycling and regeneration, and for human societies that coexist in flammable landscapes. Changes to fire regimes have the capacity to alter the structure and function of ecosystems and to impact atmospheric and biogeochemical cycles. Collectively, these changes will further transform the way in which humanity coexists with fire via direct and indirect feedbacks.

In many places tensions exist between fire's biological role in ecosystems, fire's cultural role as a land management tool and the potential for fire to cause deleterious social, economic and environmental impacts. Human coexistence with fire has inherent risk involved as uncontrolled fires can have catastrophic impacts on people and property. Globally, landscape fires are responsible for enormous, albeit difficult to quantify, social and economic costs. These include loss of human life, loss of livelihood and property (e.g. animals and agricultural assets), indirect costs of settlement evacuations and impacts on regional economies stemming from resource loss and the enormous expense of fire suppression activity. Furthermore, smoke and other atmospheric pollutants released by landscape fire can significantly impact air quality and human health both locally and across international borders.

Alarmingly, there is strong evidence that severe fire incidents have been increasing in recent years in many parts of the world. A recent suite of catastrophic fire events on all inhabited continents have drawn political and public attention to the destructive effects that landscape fire can have on communities, ecosystems and economies. Under global warming conditions, fire activity is predicted to further change throughout the world, with some places likely to experience more frequent and intense fires, while others may see a decline in fire activity. It has been suggested that amplified fire activity in regions such as the Boreal forests may represent a positive feedback loop to climate change whereby larger, more frequent fires accelerate the release of Carbon and other greenhouse gases to the atmosphere, leading to more warming and more fire. The need to understand the drivers of these fire events is therefore urgent.

This review has argued the need for a more holistic study of the drivers of fire activity across the globe, focussing on the interconnected biological, physical and social components of landscape fire. In the past, the relationship of people to fire and the culturally mediated ways in which people influence landscape fire have been peripheral to the core study of fire science and management that has traditionally centred on the physical components of landscape fire. Finding ways to sustainably coexist with fire must start by recognising fire's critical biological role in terrestrial ecosystems and by the acknowledgement that fire problems are socially constructed. It is therefore imperative that we try to comprehend the way human behavior and choices about landscape drive patterns of landscape fire.

In order to frame sustainable management options that minimise the deleterious impacts of landscape fire on human health, property, and ecosystems, we need to conceive landscape fire as a critical Earth system process which links and impacts biological systems, human activities and regional and global biogeochemical cycles. We can address our most urgent fire problems through social means but this requires a revaluation of the institutions we employ to manage fire and a clear statement of values and priorities for landscape and fire management. Humans cannot eliminate risk altogether or suppress fire entirely but societies, through their choices about land use and management, can inform the type and quantity of fire that they will accept. Clearly, finding a balance between reduction of risk to communities and infrastructure from fire and the ecological role of fire will be challenging. Our choices must necessarily be context specific and must acknowledge that the diversity of factors that are leading to fire regime shifts will require equally diverse strategies to manage them and will necessarily involve trade-offs. In some places, fire management may require reinstating fire into ecosystems, while in others it may need to restrict burning in ecosystems where prolific fire can be harmful. Given the social, economic and environmental challenges we face in an era of anthropogenic climate change and unprecedented land use intensity, sustainable fire-management demands a multidisciplinary, holistic approach.

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