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Human Pyrogeography: A New Synergy of Fire, Climate and People is Reshaping Ecosystems across the Globe

Christopher D. O'Connor*, Gregg M. Garfin, Donald A. Falk and Thomas W. Swetnam
School of Natural Resources and the Environment and Laboratory of Tree-Ring Research, University of Arizona

Abstract

Climate and fire have shaped global ecosystems for millennia. Today human influence on both of these components is causing changes to ecosystems at a scale and pace not previously seen. This article reviews trends in pyrogeography research, through the lens of interactions between fire, climate and society. We synthesize research on the occurrence and extent of wildland fire, the historic role of climate as a driver of fire regimes, the increasing role of humans in shaping ecosystems and accelerating fire ignitions, and projections of future interactions among these factors. We emphasize an ongoing evolution in the roles that humans play in mediating fire occurrence, behavior and feedbacks to the climate system. We outline the necessary elements for the development of a mechanistic model of human, fire and climate interactions, and discuss the role geographers can play in the development of sound theoretical underpinnings for a new paradigm of human pyrogeography. Disciplines such as geography that encourage science-society research can contribute significantly to policy discussions and the development of frameworks for adapting fire management for the preservation of societal and natural system priorities.

Introduction

Fire as an Earth system process is linked intimately to climate, people and places. For thousands of years, natural and human-caused fires have shaped landscapes across the globe, affecting structure and continuity of biomass, liberating and recycling stored nutrients, and converting natural landscapes for human uses (Bowman et al. 2009). Throughout early human history, the effects of human-caused fire were generally limited to local scales, moderated by population density and specific climate and site conditions that allowed human-ignited fire to spread (Whitlock et al. 2010). By determining temperature, available moisture and potential for fire, climate was the primary driver of net primary productivity for most terrestrial vegetation (Churkina and Running 1998; Stephenson 1990). Within climatic limitations, fire influenced the proportion of forest, shrub and grasslands on the landscape (Bond et al. 2005), as well as the relative proportions of fire-adapted species (Agee 1998; Covington 2003). Climate also influenced, to varying degrees, the success of human settlements and the ability of human populations to expand through agriculture. Although humans could modify their environments through fire and land clearing, the ability to spread fire was controlled by climate, which limited human modification of landscapes where either a lack of fuels or abundance of moisture limited fire (Figure 1) (Pyne 2001).

Over the past three centuries, human population density and distribution have increased exponentially (UN forthcoming), intensifying human influence and augmenting

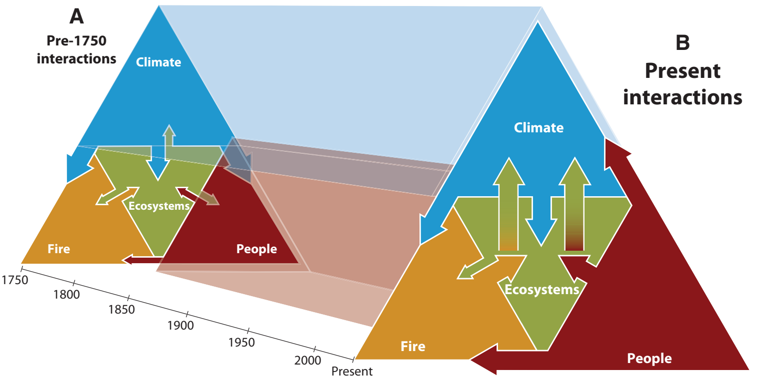

Fig. 1. The changing dynamic of global fire as it moved from a climate and ecosystem driven process to a strongly human-influenced process. (A) Fire as a climate-modulated system in which humans are able to promote or suppress fire at local scale but only under specific climate and landscape conditions. (B) A dynamic shift in the role of humans as drivers of global fire regimes begins after the industrial revolution. People now influence fire, ecosystems and climate directly. Human modification of landscapes and resulting influence on climate is portrayed by the red passthrough arrow. Fire's effects on ecosystems through natural and human-promoted ignitions are shown as direct arrows from fire to ecosystems and indirect feedbacks from fire to climate through ecosystems. Human-ignited fires can now overcome climate and ecosystem moderated limitations to fire ignition and spread. Arrows passing from people and fire through ecosystems to climate indicate the indirect connections between landscape modifications and biomass burning that feed into changing climate conditions. Figure design by Rebecca Macaulay, Graphic Designer, CLIMAS.

the impact of human-caused fire and fire emissions on the biosphere and troposphere (Figure 1). Conversion of forests and shrublands to agricultural or pastoral uses through burning, suppression of fire in fire-adapted landscapes, and continued expansion of the interface between urban populations and flammable forests are directly influencing fire on the landscape. Humans are augmenting natural fire in boreal (Schuur et al. 2008, 2009; Wickland et al. 2006), temperate (Alcamo et al. 2007; Field et al. 2007) and grassland systems, and introducing fire to desert (Fischlin et al. 2007) and tropical (Cochrane 2009; Cochrane and Laurance 2008; Cox et al. 2004; Page et al. 2009) biomes. Although climate and ecosystem properties continue to be important components of global fire regimes, in recent decades a shift from climate controlled fire regimes toward human-controlled fire regimes has taken place over much of the globe (Marlon et al. 2008; Pechony and Shindell 2010).

Warming temperatures, due to fossil and biomass combustion by humans, are also altering forest composition and accelerating rates of evapotranspiration, while increasing the atmospheric capacity for holding moisture (Houghton 2005). This dynamic is expected to increase natural fire ignitions through greater electrical storm activity (Krawchuk et al. 2009; Price and Rind 1994) where drier conditions with longer burnable periods are expected to prevail in many temperate and boreal forest types (Flannigan et al. 2009a,b). The fire response may not be geographically or temporally uniform because warming temperatures may lead to wetter conditions in some seasons and regions, which may reduce ignitions and spread of fires (Bergeron et al. 2004b; Flannigan et al. 1998; Krawchuk et al. 2006, 2009). Changes to surface albedo due to earlier snow melt, changing forests at high latitudes and an increase in high latitude fires (Allen et al. 2010; Bowman et al. 2009), are influencing surface temperatures and the potential for release of methane and CO_2 sequestered in permafrost (Tchebakova et al. 2009; Walker 2007; Wickland et al. 2006). In tropical forests of Southeast Asia, fire danger is exacerbated by the combination of decadal droughts and human-caused fires used to remove forest cover for agricultural use (Fearnside 2000; Hooijer et al. 2010; Lewis et al. 2011; Page et al. 2002, 2009). Under extremely dry conditions such as the 1997 El Niño event, even wet tropical forests and deep peat deposits can dry out sufficiently to burn, producing large outputs of greenhouse gasses (GHG) (Page et al. 2002, 2009).

Fossil fuel use and land-use changes led to an 80% increase in global annual emissions of CO_2 between 1970 and 2004 (IPCC 2007). These new sources are contributing to atmospheric concentrations of CO_2 that exceed the natural range of the gas over the last 650,000 years, resulting in conditions that are expected to raise global mean temperatures by 2–4 °C over the next century (IPCC 2007). Such changes in the climate system due to feedbacks from anthropogenic activity have the potential to influence fire and landscape change across the globe (Figure 1).

Human Effects on Fire and Landscapes Prior to 1750

Fire as a natural process has been part of the Earth system for the more than 420 Myr that plants have provided the fuels and oxygen necessary for flame (Pausas and Keeley 2009; Scott and Glasspool 2006). Fire frequency and severity vary with the amount, spatial distribution and condition of available fuels, as well as moisture, temperature and ignition sources. Fire severity is a qualitative measure of the effect of a fire on an ecosystem following an event (Keeley 2009) and is an important consideration for long-term land cover changes, especially in ecosystems not adapted to fire.

In comparison to temperate and boreal forests, natural fire has generally been a rare disturbance in moisture or fuel-limited ecosystems such as the tropical rainforests of Southeast Asia (Goldammer and Seibert 1989) and Central America (Power et al. 2010; Uhl and Kauffman 1990), where forest structure and climate-mediated moisture kept the abundant fuels too wet to ignite. Fires have historically also been rare in xeric desert and shrub ecosystems where low rainfall limits the amount and continuity of fuels (McLaughlin and Bowers 1982; Whitlock et al. 2010). Under fuel or moisture limited conditions, climate and ecosystem controls usually dominate over human influences on natural fire beyond local scales (Allen 2002; Parker 2002; Whitlock et al. 2010). By contrast, dry forests with continuous fuels and seasonal conditions such as the open ponderosa pine and dry mixed conifer forests of the American southwest, and tall grasslands such as the African savannah and North American prairies, frequently have favorable conditions for fire ignition, reducing the energy threshold necessary for humans to initiate fire (Andersen et al. 2003; Barrett et al. 2005; Whitlock et al. 2010). Where anthropogenic fire drove changes to cover types on the landscape, these effects were usually limited by proximity to population centers where forests were cleared for agriculture, and wood was collected for cooking fuel and building or cultural needs (Allen 2002; Clark and Royall 1996). It is important to note here, that direct and indirect human effects on fire regimes can be multiple and interacting, in some cases increasing and in other cases decreasing fire ignitions, extent, severity, etc., as well as altering the predominate seasons of fire occurrence.

The conversion of fire-limiting landscapes into burnable landscapes appears to be rare in human history, and prior to the 20th century, seems to have occurred only in isolated geographic areas such as islands (Whitlock et al. 2010). Such was the case of the Maori Polynesians who settled in New Zealand in the 13th century (McWethy et al. 2009). This group intensively burned the South Island over a period of a few decades, eventually converting over 40% of the land area from dense forest to open grasslands and agricultural fields as it remains today. The isolation of New Zealand and long natural fire return interval on the order of 1000–2000 years made this ecosystem uniquely susceptible to cover-type conversion through intentional persistent fire ignitions (McWethy et al. 2009). There are many other examples of human populations altering or controlling fire regimes in particular places and times; however at regional to global scales, and at least until the modern era, fire regimes have been more pervasively mediated by top-down climatic conditions than bottom-up human actions (Figure 1).

Climate was likely a primary driver of global biomass burning for most of the last two millennia; until 1750, global biomass burning tracked mean global temperature, indicating the dominance of climate regulation of fire regimes (Marlon et al. 2008). Only after the concurrent increase in human population, expansion of human settlements, and subsequent land cover conversion from forests to agriculture and other uses, did biomass burning begin to deviate from global mean temperature records (Figures 2 and 3).

Shift from Climate-Modulated to Human- and Climate-Modulated Fire

Human population growth and industrialization in the 18th and 19th centuries changed the human–fire connection in many newly colonized areas. Large-scale deforestation and expansion of agricultural and industrial land uses in the Americas, for example redefined the scale and capacity of humans to manage fire. Beyond catalyzing climate-mediated fire, humans began to control fire through systematic manipulation of fuels and landscape connectivity (Hobbs et al. 2002; Veblen et al. 2003). Livestock grazing, logging, and rapidly expanding agriculture led to an increase and eventual reduction of burning in densely populated areas where available fuels had been consumed. Guyette et al. (2002) reconstructed the phases of human-induced biomass burning from charcoal records from 1700 to 1990, using the Missouri Ozarks as a case study for the expansion and contraction of fire activity with changing human population dynamics (Figure 4).

Although the increase in atmospheric CO_2 concentrations since the industrial revolution is attributed primarily to the burning of fossil fuels, gas flaring, and cement production (Forster et al. 2007), deforestation and landscape modification activities, including fire, account for 37–39% of global anthropogenic CO_2 emissions since 1750 (Bowman et al. 2009). For the years 1997–2009, global fire emissions were dominated by anthropogenic burning in grasslands and savannas, accounting for 44% of fire carbon emissions. For comparison, wildfires accounted for approximately 15% of fire carbon emissions globally, though it should be noted that approximately 77% of total carbon fire emissions are expected to be sequestered by regrowth of biomass (Van der Werf et al. 2010).

The Last 20 Years: Global Effects of Humans and Fire

Across the globe, human activities are now overcoming climatic and ecosystem controls of fire (Figure 5). In some tropical and boreal regions, persistent use of fire to clear forests is resulting in the conversion of fire-resistant old-growth forest to fire-promoting grasslands or agricultural lands that may or may not have seasonal burning associated with them (Aide and Cavelier 1994; Goldammer et al. forthcoming; Lavorel et al. 2007; Shearman et al. 2009). Connectivity of fuel-limited landscapes is being promoted by the human-induced spread of invasive grasses in desert and shrub ecosystems (Stevens and Falk 2009; Zouhar et al. 2008). Conversely, in many semi-arid temperate forests that were once prone to frequent natural fire, human-imposed fire suppression has acted as an energy capacitor, storing potential energy in the form of landscape fuels until climatic conditions and ignition sources are capable of overwhelming human fire-controls (McKenzie et al. 2011).

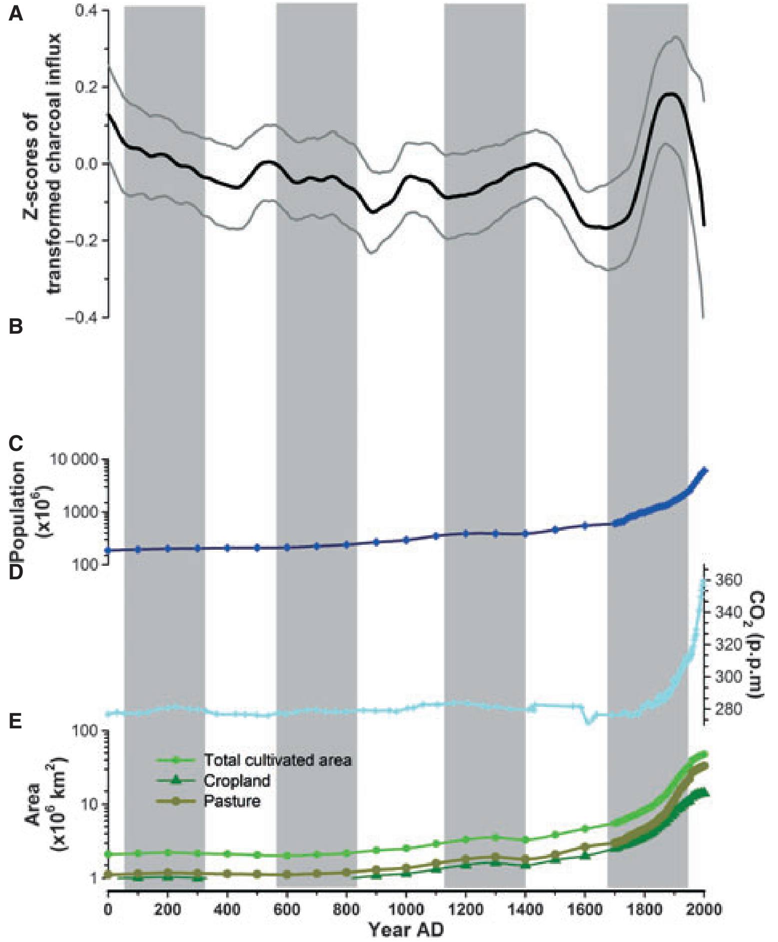

Fig. 2. Global biomass burning in relation to temperature, human population, atmospheric carbon dioxide, and land area under cultivation. *Y*-axis is scaled relative to the feature displayed, *X*-axis is time in years. Biomass burning (A) is variable over the 2000-year period but shows a gradual decline with mean global temperature (B) from the period 1 to 1750 AD and then a sharp increase until a peak at 1850 AD followed by a gradual decline to the year 2000. The other four factors displayed on the figure are relatively constant until about 1750 when human population (C) and carbon dioxide levels (D) increase exponentially to present. Land area in cultivation (E) peaks in the late 20th century as the global limit of arable land is approached (figure data provided by J. Marlon and adapted from Marlon et al. 2008).

In the last two decades, anthropogenic fire events have begun to affect land cover, ecosystem processes and atmospheric GHG concentrations at regional, continental and global scales. The following examples from boreal, temperate, subtropical and tropical biomes illustrate the influence of human activities on natural ecosystems that is changing the nature of fire in ecosystems.

Russian Fires of 2009–2010

Natural fire regimes are similar in old and new world boreal and temperate forests; however, the human contribution to area burned in Eurasian forests is very different from that in North America. In boreal Eurasia, 72–78% of the area burned in 2002–2003 was

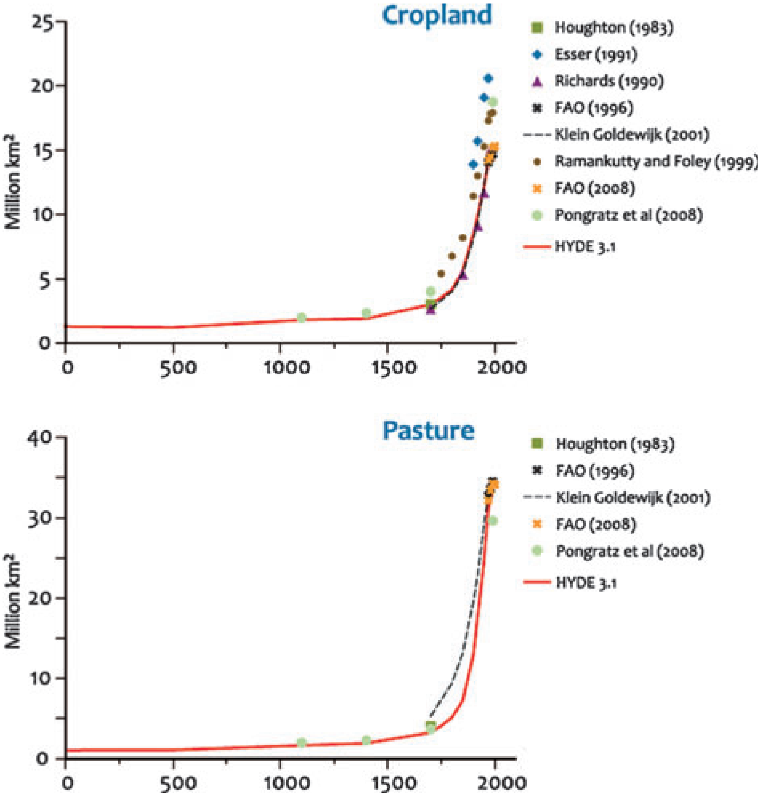

Fig. 3. Intensification of human land-use area for cropland and pasture over the past two millennia (courtesy of Klein Goldewijk et al. 2010a,b). Landscape conversion to cropland and pasture increase exponentially after ~1750 AD. Modification of landscapes for human use becomes a major driver of global fire after this period.

attributed to humans (Achard et al. 2008; Mollicone et al. 2006), whereas human-caused fire in boreal Canada and Alaska accounted for 6–36% of area burned from 1960 to 2000 (Kasischke and Turetsky 2006). In addition, the cessation of organized fire detection and eventual dissolution of a central Russian fire management agency in 2007 has resulted in a still larger proportion of human-caused fires burning in an uncontrolled manner (Figure 6) (Goldammer et al. forthcoming).

Paradoxically, the highest proportion of human-caused fires in Siberia is taking place in areas where human populations are decreasing as people relocate to economic centers farther West. Goldammer et al. (forthcoming) attribute this pattern in Siberia to intentional fire setting for economic gain. Fires in some areas of Siberia may be used to circumvent environmental regulations by allowing salvage logging of burned-over protected forests and easier access for mineral and gas extraction (Figure 7). This special case of an increase in fire frequency concurrent with decreasing human population runs counter to the traditional explanation of local human control of fire; it demonstrates an emerging economic motive for human-driven fire. Economic motives were similarly cited in a European investigation of the catastrophic fires in Greece in 2007. In the investigation, arson was identified as an effective method for opening public forests to private development and increasing temporary employment and economic aid to rural areas (IEEP 2008; Morehouse 2007).

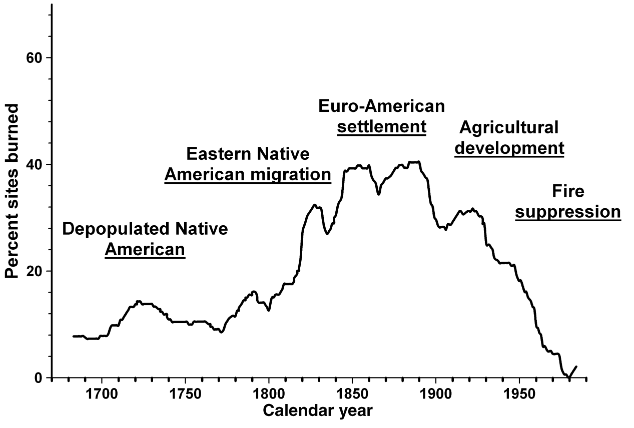

Fig. 4. An example of a recent human-controlled fire regime following a pattern similar to those seen in other instances where human population influx leads to periods of expanded fire use for land cover conversion followed by a reduction in fire with settlement, and an uncertain future as surrounding forests recover and accumulate fuels. Data are an 11-year moving average of the percent of sites burned annually in the Current River watershed, Ozark Mountains, Southeast Missouri. Figure adapted from Guyette et al. (2002). Text above the graph identifies the corresponding periods of human population expansion. The increase in burning follows increasing population density until the mid-19th century when animal grazing began to remove connectivity of fuels and fire began to decline. In the early 20th century, fire incidence was reduced dramatically through targeted fire suppression; though in recent decades, fire incidence is on the rise as the wildland–urban interface continues to grow.

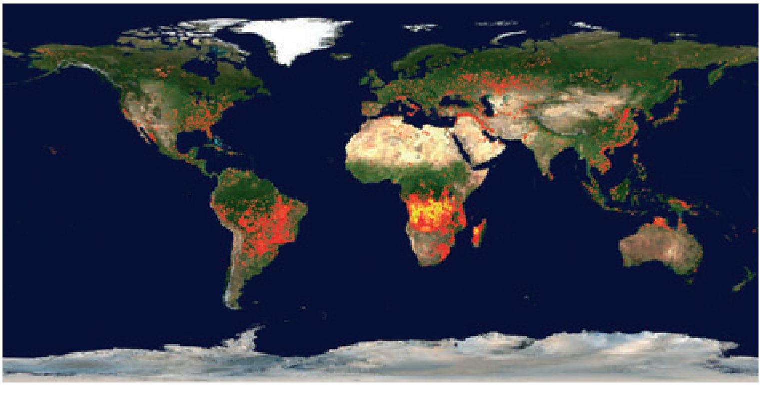

Fig. 5. Satellite image of global fire ignitions 30 June–14 July 2010. Fires are seen burning on all continents and are generally in close proximity to human population centers. Fires are especially dense in areas used for animal grazing in central South America and Africa. Forest fires are most notable in Eurasia and North America. Fires used for agriculture are centered on tropical regions of Southeast Asia, Central America, and Northern South America. Images provided by the MODIS Rapid Response System (http://rapidfire.sci.gsfc.nasa.gov/firemaps).

Fire in Western North America

In western North America, fire size and frequency have increased with warming temperatures, accelerating snow melt and extending fire-prone periods earlier into the spring and later into the fall (Flannigan et al. 2009a; Goetz et al. 2005; Tymstra et al. 2007; Westerling et al. 2006). In forest types that historically experienced frequent surface fires, livestock grazing, suppression of wildfire by humans, and variable effects of logging and road building have resulted in increases in forest densities and accumulated dead fuels

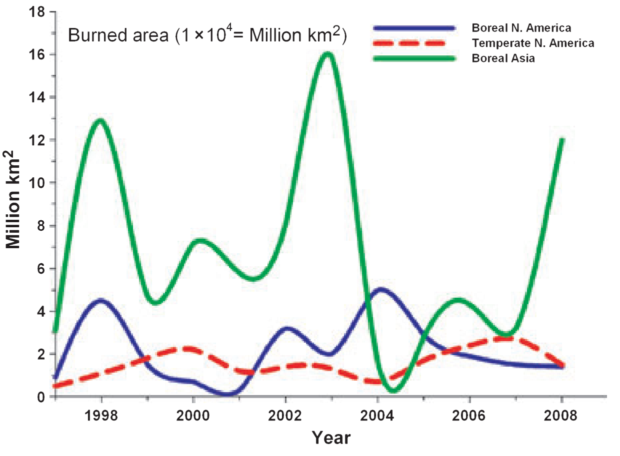

Fig. 6. Area burned in boreal and temperate North America and boreal Asia 1997–2008 (adapted from Giglio et al. 2010). North American burned area is highly influenced by targeted suppression, especially in temperate forests. Area burned in boreal Asia is influenced by human ignitions, fire weather and fire fighting capacity. The national fire fighting coordination center for Russia and former soviet republics was disbanded in 2007 leading to a continued increase in area burned.

(Allen et al. 2002; Covington et al. 1997; Kolb et al. 1994). These conditions can promote extensive, high-severity canopy fires, especially during hot, dry conditions (Figure 8) (Allen et al. 2002; Oberle 1969; Parsons and DeBenedetti 1979; Stephens and Ruth 2005).

It is important to note that these forest and fire regime changes described above most clearly have occurred in Southwestern ponderosa pine forests, and probably also many mixed conifer forests in this region (Brown and Cook 2006; Swetnam and Brown 2010). Forest and fuel changes are thought to be of less or no importance in many higher elevation forests of western North America (Sibold et al. 2006), and recent warming trends and droughts are pointed to here as more important factors driving the increasing trends of large fire occurrences and areas burned (Westerling et al. 2006).

Additionally the proximity of human settlements abutting flammable forests in the Western and Southeastern USA is increasing steadily (Falk et al. 2010; Hammer et al. 2009; Radeloff et al. 2005; Theobald and Romme 2007). In the USA, the wildland–urban interface (WUI) area has increased by 52% since 1970 (Theobald and Romme 2007) and the pace of WUI increase is expected to accelerate with the retirement of the post-WWII demographic cohort (Hammer et al. 2007, 2009). This increase in urban and exurban proximity to burnable areas contributes to the likelihood of human-caused fire ignitions, thus augmenting potential for landscape change and loss of human life and property. Proximity to the WUI also increases the social and political imperative for fire suppression, leading to increases in fuel accumulation and often local resistance to prescribed fire (Falk et al. 2010; McCaffrey 2006).

America Southwest Desert Fire and Invasive Grasses

With the help of humans, fire has become a powerful catalyst of vegetation type conversion in fuel-limited American deserts. Introduction of millions of grazing animals during the era of intensive cattle and sheep grazing in the early 20th century, and the subsequent importation of Eurasian and African forage grasses such as Buffelgrass (*Pennisetum ciliare*),

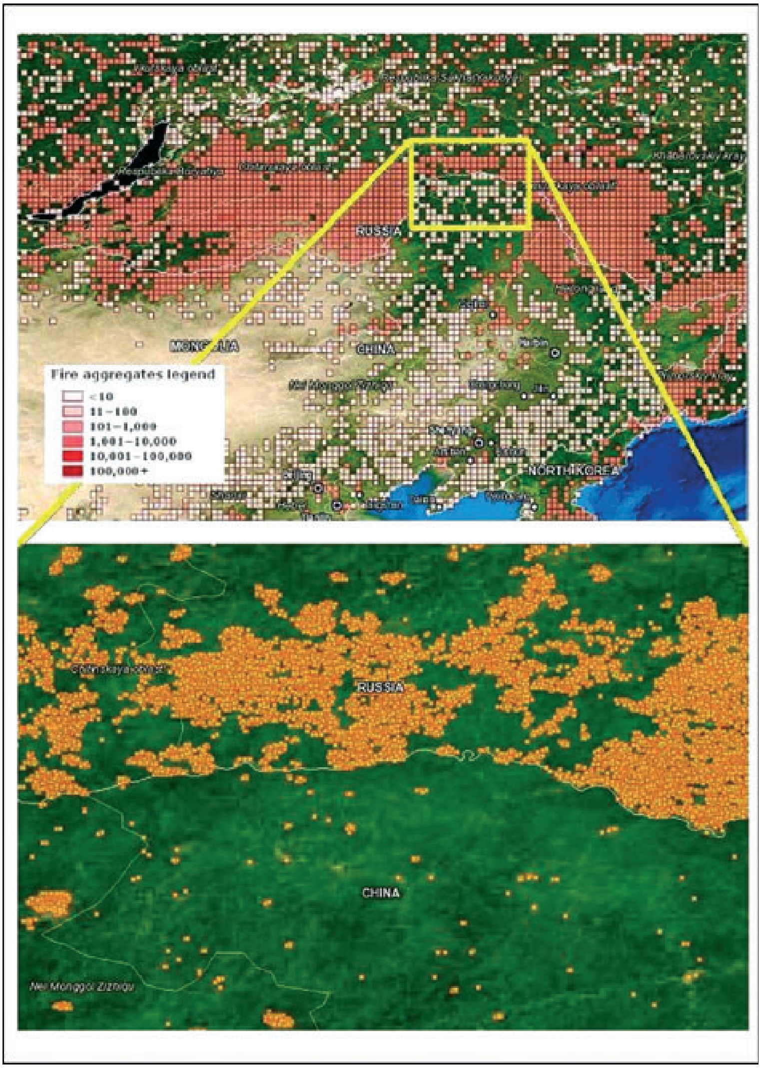

Fig. 7. Top: MODIS Terra fire detections from 2001 to 2010 in the Trans-Baikal region of Southern Siberia, northern Mongolia and China. Aggregate scale is for the number of fires within a tile over the 10-year period. Bottom: The Amur River region, showing a very striking land-use/policy effect on wildfire in Russia versus China. Point locations of fires are represented by orange squares. Bottom map is approximately 400 km across. Maps were generated from the University of Maryland FIRMS Web Fire Mapper, November 2010 (http://firefly.geog.umd.edu/firemap/).

Lehmann lovegrass (*Eragrostis lehmanniana*) and Red brome (*Bromus rubens*), have led to the subsequent spread of these grasses throughout the Sonoran Desert, creating a layer of continuous highly flammable fuels in a system that was naturally fuel-limited (Devoe et al. 2009; Stevens and Falk 2009). As these imported grasses continue to spread and connect once fuel-limited landscapes, new high-severity fire regimes threaten to convert cactus and succulent forb-dominated landscapes into continuous grasslands, further promoting fire and destroying native species assemblages (Figure 9) (McLaughlin and Bowers 1982).

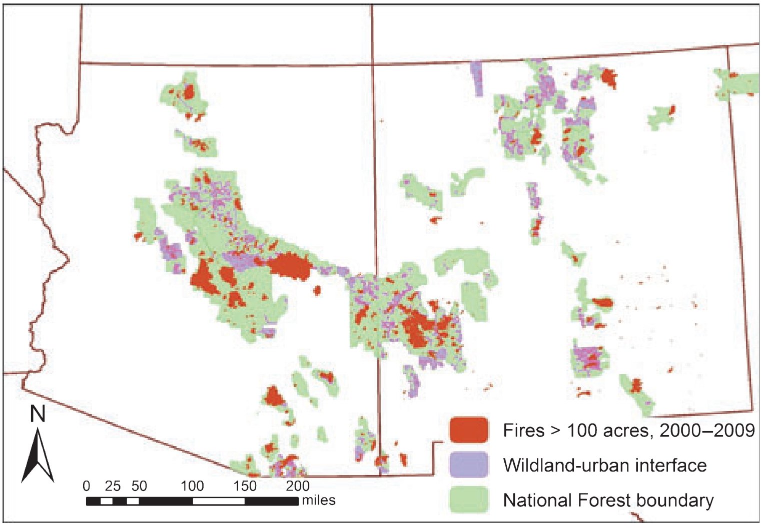

Fig. 8. Wildfires >100 acres recorded from 2000 to 2010 on US Forest Service land in Arizona and New Mexico, USA. Green polygons are federal forest boundaries, red polygons are fires, and lavender polygons are wildland–urban interface as determined by the NEPA process for consideration of fuels reduction. Map generated from US Forest Service GIS Region 3 datasets accessed November 2010 (http://www.fs.usda.gov/goto/r3/gis/datasets).

Buffelgrass is naturally cold-intolerant and was expected to spread only to lower-elevation areas where mild temperatures favored its growth. Over the past 20 years, milder winters in the southwest have allowed buffelgrass to spread to higher elevation foothills, threatening new species assemblages with fire and creating new a fuel layer that connects dry deserts to montane forest. Contributing further to the spread of buffelgrass, Hussey and Burson (2005) at Texas A&M University developed a more cold-resistant variety for use as forage in Texas and Sonora, Mexico in 1999. When this cold and disease-resistant strain of invasive grass reaches the 'sky island' mountain ranges of the Sonoran Desert, it will likely spread throughout the foothills potentially altering fire regimes over entire mountain ranges (Figure 10). The human-assisted spread of buffelgrass and its associated fire regime exemplifies how the actions of people are synergizing with climatic conditions to increase fire activity in previously fire-limited systems.

Tropical Fires in Southeast Asia

The warming and drying effects of El Niño events, particularly in Southeast Asia, have been noted for several decades now, as well as the connection with increased purposeful human-set fires for land clearing (Le Page et al. 2008; Page et al. 2002). For example, human ignition(s) of the largest known CO_2-emitting fire complex was aided by a severe El Niño event in Southeast Asia in 1997. This forest and peatland fire took place in regions of Indonesia that had been degraded by deforestation for several years, setting up fuel conditions conducive to a major fire (Field et al. 2009). These extraordinary fires burned over 1.4–6.8 million ha of forests and cropland and released an estimated 0.81–2.57 gT of carbon. These emissions were about 13–40% of total global CO_2 emissions for the year (Ballhorn et al. 2009; Page et al. 2002). Van der Werf et al. (2008) noted a 30-fold difference in CO_2 production between anthropogenic fires in Indonesia during moist conditions of the strong La Niña event in 2000 and subsequent dry conditions of

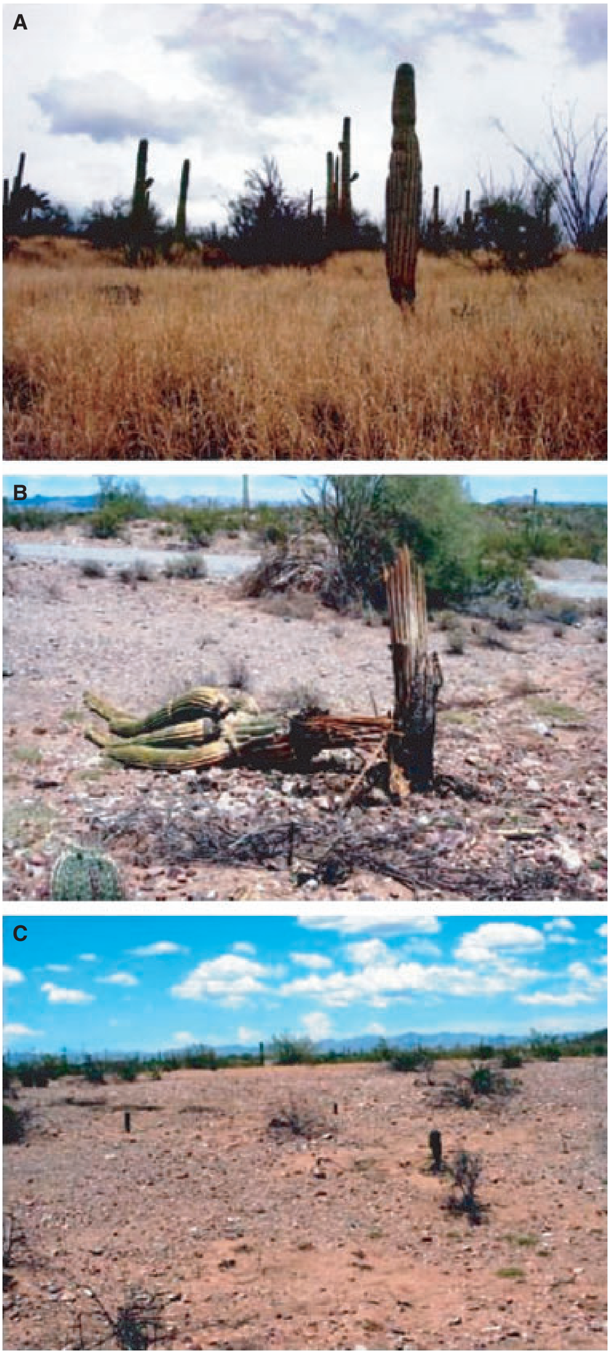

Fig. 9. The effect of introduced buffelgrass on plant communities and fire risk in the Sonoran Desert: (A) a stand of saguaro cactus (Carnegiea gigantea) where buffelgrass (Pennisetum ciliare) has invaded the understory, increasing the likelihood of a high intensity fire; (B) a fallen mature saguaro cactus succumbed to fire in southern Arizona; and (C) nearby saguaro cactus seedlings after the same fire. Saguaro cactus, a species endemic to southern Arizona and California, is extremely sensitive to fire, and often suffers mortality (Stevens and Falk 2009). Photos courtesy of the University of Arizona Desert Laboratory (A) and Jeffrey S. Fehmi (B, C).

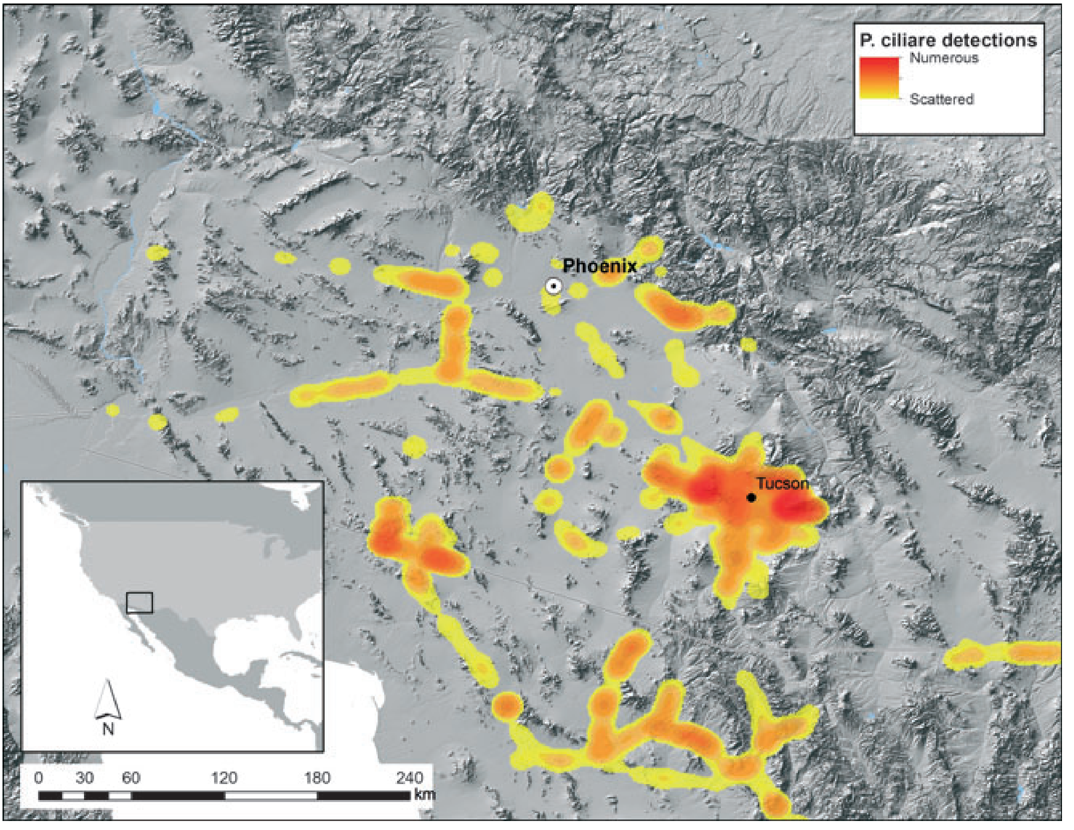

Fig. 10. Known buffelgrass distribution in Arizona in 2010, with the highest concentration of known populations occurring in the Tucson area. Image provided by Aaryn Olsson, Laboratory of Landscape Ecology and Conservation Biology, Northern Arizona University.

the El Niño event in 2006, suggesting that the synergy between human activities and climate is the driving factor for the occurrence of fires on this scale (Figure 11). Thus, the recent fires in Indonesia reveal the direct human contribution, through land clearing and modification of fuels, and indirect effects, through anthropogenic forcing of climate conditions conducive to major fires (Van der Werf et al. 2009).

Feedbacks on Fire

SPECIES SHIFTS IN ELEVATION AND LATITUDE

In the absence of fire, forests are expected to respond to warming temperatures through species turnover, slowly shifting species composition as the conditions required for germination of seeds from dominant species assemblages move up elevational and latitudinal gradients (Harsch et al. 2009; Kelly and Goulden 2008). Infilling of the understory by seedlings of more heat and drought-tolerant species assemblages is expected to cause a lagged turnover of species as an asynchrony between canopy and understory species assemblages develops, similar to the regeneration niche effect described by Grubb (1977). Climate-induced ecosystem changes may be catalyzed by fire, logging, insect outbreaks,

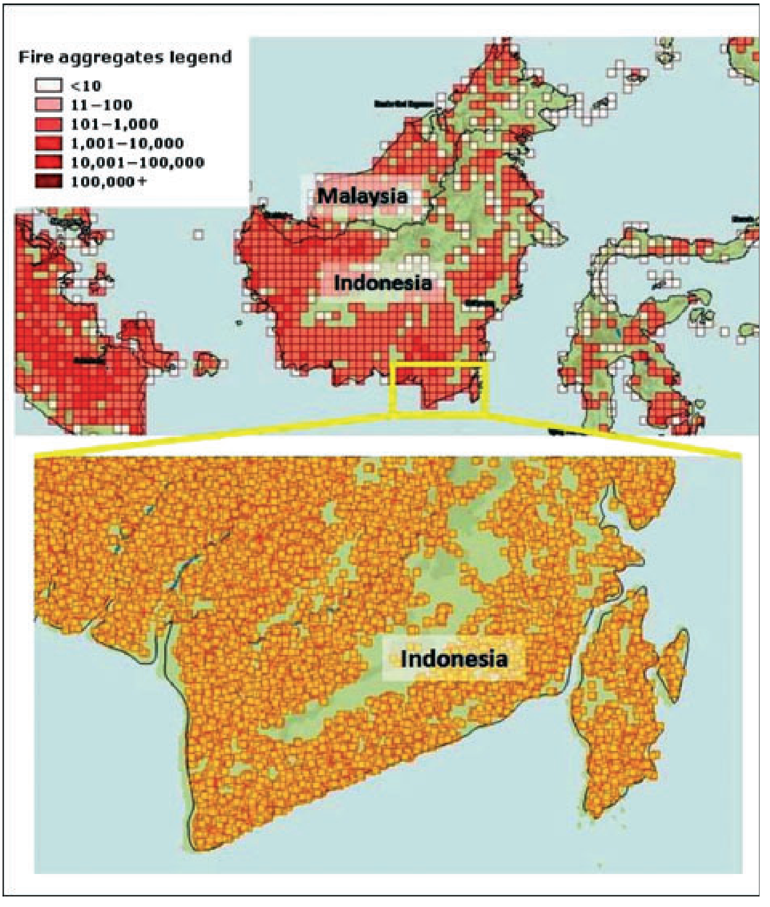

Fig. 11. Top: FIRMS Web Fire Mapper image of Indonesian fires on the island of Borneo, Indonesia 2000–2010. Aggregate scale is for the number of fires within a tile over the 11-year period. Bottom: Blow-up of fire locations in the peatlands of Southeastern Borneo, approximately 250 km across. Point locations of fires are represented by orange squares. The high density of fires does not include the 1997–1998 event that accounted for 13–40% of global CO_2 emissions for the year. Maps were created from University of Maryland FIRMS Web Fire Mapper, November 2010 (http://firefly.geog.umd.edu/firemap/).

or other events that disrupt mature species assemblages and promote germination of species adapted to warmer, drier conditions (Bergeron et al. 2004a; Running 2008; Turner 2010).

ALBEDO

A series of feedbacks on warming temperatures and fire are expected from changes in albedo at northern latitudes of Canada and Eurasia. Warming temperatures are expected to allow for the advancement of taiga forests northward into the Arctic Circle (Harsch et al. 2009). Dark canopies from expanded conifer forests reduce albedo, thus decreasing reflectance and increasing surface absorption of solar influx while at the same time creating an enhanced sink for atmospheric CO_2 (Goetz et al. 2007).

Biomass burning in tropical, temperate and boreal forests around the globe is expected to increase the production of black carbon aerosols, which can interact with fire directly by interfering with raincloud formation (Andreae et al. 2004). Black carbon can be widely distributed through atmospheric circulation and is known to reduce albedo of snow-covered surfaces at high elevations in the tropics and high latitudes where it settles (Bowman et al. 2009; Ramanathan and Carmichael 2008). However, over the long term, this stable form of carbon is also an important semi-permanent means of sequestering carbon in soils (DeLuca and Aplet 2008).

At mid-latitudes, the conversion of conifer forests to other forest types has mixed effects on albedo and likelihood of fire. Conversion of dark-canopied conifer forest to grassland, deciduous forest, or cropland has the effect of increasing albedo and locally reducing solar absorption. Following fire in high latitude conifer forests, conversion to grasslands promotes a cycle of frequent burning, whereas conversion to deciduous forests or croplands has the effect of reducing the potential for future fire (Goetz et al. 2007). Shortening the fire return interval in North American black spruce forests (*Picea mariana*) is likely to result in replacement by deciduous forest that sequester more CO_2 in the short term and have higher albedo than coniferous forests, potentially cooling high latitude regions of North America (Goetz et al. 2007). The amount of time necessary for forests to recover after fire is also expected to influence carbon flux and local warming at high latitudes. In the Canadian boreal zone, the minimum time necessary for stands to recover to pre-burn Normalized Difference Vegetation Index values was 5 years (Goetz et al. 2006), whereas a similar level of recovery in boreal Eurasia took 13 years (Cuevas-Gonzales et al. 2009). This difference is expected to increase carbon sequestration in North America in the short term while reducing winter albedo in the long term (Goetz et al. 2007).

PERMAFROST

Although the combustion of fossil fuels is currently the primary contributor of atmospheric CO_2, climate feedbacks affecting surface fire, conversion of land cover types, and the temperature-mediated release of polar carbon stores may rival fossil fuel combustion in their effect on atmospheric carbon. In Canada and Russia, the thawing of circumboreal permafrost and release of trapped methane (CH_4) has potential to release twice the CO_2 currently in the atmosphere (Schuur et al. 2008). Although less stable than CO_2, methane is a more effective GHG and, depending upon the rate of thawing, the loss of boreal permafrost is likely to result in an accelerated rate of temperature increase (Kuhry et al. 2010; Wickland et al. 2006). Recent increases in moss, litter and peat fires in Alaskan and Canadian black spruce forests (Kasischke et al. 2010; Turetsky et al. 2011) suggest that smoldering fire in these once incombustible frozen carbon pools will further raise the specter of accelerated warming and positive feedbacks to a warming global climate.

Models of Climate–Fire–People Interactions

Models of future fire conditions in the USA, Canada and Russia predict significant increases in fire severity and size over the next 100 years for much of the temperate and circumboreal region. The past 80 years of fire suppression in the USA, Canada and Russia have contributed to forest flammability, leaving once fire-adapted stands vulnerable and increasing the likelihood of large-scale stand replacing fire in many inland forests (Bachelet et al. 2003, 2005; Drever et al. 2009; Flannigan et al. 2009b; de Groot et al. 2003; Malevsky-Malevich et al. 2008; McCoy and Burn 2005; Nitschke and Innes 2008; Tymstra et al. 2007; Wotton et al. 2010, 2003).

However, local and regional climate continue to be important controls on fire. The unique climate circulation patterns in parts of Quebec and Alberta, Canada are expected to deviate from the circumboreal trend by producing an influx of moist air as temperatures rise (Bergeron et al. 2004b; Flannigan et al. 1998, 2009a; Krawchuk et al. 2006, 2009). Canada contains some of the few geographic regions where fire is expected to become less frequent even as human populations in these areas continue to grow. Thus, the outlook for wildfire in the circumboreal region is mixed, where drying trends dominate, a rise in ignitions, both human and lightning caused, point to a future of more severe fire until ecosystems have time to adapt to a new fire regime. Where moisture is expected to increase, fire activity is likely to decline.

A new generation of regional fire models is now incorporating human activity along with expected changes in temperature, moisture and global circulation patterns. Results from Flannigan et al. (2009b) and Kloster et al. (2010) show that including human population density and proximity to human settlements in regional climate and fire models improves their ability to simulate fire over the last century and will likely aid with fire forecasting. Models of fire spread and burn severity (Cary et al. 2006, 2009) suggest that fire spread is most influenced by climate conditions and ignition management, whereas fire severity and intensity appear to be more fuels driven. These results suggest that managing connectivity and abundance of ground fuels, and reducing human-caused ignitions have potential to reduce negative outcomes of future fire events.

Development of Theory on Fire, Climate and People

Continued study of the direct relationships between human activities and fire ignition and spread, as well as the more complicated indirect relationships that influence fire behavior through manipulation of landscapes and anthropogenic forcing of climate will be necessary before accurate quantification of this dynamic system can be made. We are at an exciting threshold of data acquisition where permanent monitoring systems from regional flux towers and real-time satellite imagery are providing more and better data than have ever been available. Developing models capable of using this new abundance of information will require adapting historical information to current conditions. Recent advances in paleoclimatology, paleoecology and anthropology are providing the information necessary to track the changing dynamics of people, climate and fire through space and time. These rich datasets provide the necessary components to assemble mechanistic models that link people, climate, fire and ecosystems through time. Development of these models would provide a major advancement in our ability to understand and predict future human and fire interactions, identify vulnerabilities in current management systems, and when combined with case studies for specific regions, identify appropriate actions for adaptation to future climate conditions (Joyce et al. 2009; Millar et al. 2007).

Our current limited understanding of the future of fire, climate and human interactions leaves policy makers to react to conditions after the fact. Developing sound theory of these interactions rooted in understanding of dynamics derived from historical reconstructions as well as recent and current conditions is needed. Theory and models will be necessary to make proactive decisions that mitigate negative effects of fire where it is a recent addition to human and natural systems, and promote positive effects of fire where it is crucial for ecosystem function. Development of models that fully integrate the burning of surface biomass, fossil fuels and the feedbacks from both systems will also be necessary for strong international agreements that address GHG emissions.

Contribution for Geographers

Geography and its sub-disciplines can do much to advance the study of these complex relationships. Geographers have the tools to develop the interdisciplinary scientific context for policies to change operational management actions and societal preparedness for and responses to interactions between climate, fire and society. Much work is needed to analyze the similarities and differences between these and many other case studies, intervening economic institutional and cultural factors, and associated management and policy contexts. Geographers are poised to bring together the physical, natural and human dimensions needed to suggest coherent recommendations for action. GIS, remote sensing and other visualization tools used by geographers can help policy makers better comprehend the scope of the issues, and to define policy responses through processes such as the United Nations Framework Convention on Climate Change, and documents such as the IPCC assessment reports. Geography's long-standing emphasis on nature, society and place could further elucidate cultural and place or region-specific factors and patterns, that would lead to locally relevant and acceptable frameworks for policy and action, especially in developing countries.

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Short Biographies

Christopher O'Connor is a research associate and doctoral student in the School of Natural Resources and the Environment and Laboratory of Tree-Ring Research at the University of Arizona in Tucson. His dissertation work examines how fire, insect outbreaks, human land uses and climate interact to shape western forest ecosystems. O'Connor served 2 years as a Peace Corps Volunteer in Niger, West Africa and has held technician positions with the US Forest Service and US Geological Survey. O'Connor was a Fulbright Fellow and recipient of the Lac Duparquet Research and Teaching Forest Fellowship during his master's work at the Université du Quebéc à Montréal (UQÀM) and is currently a Biosphere 2 Science and Society Fellow at the University of Arizona. He holds a BS in Agricultural Sciences and Entomology from Penn State University and an MS in Biology from UQAM in Quebéc, Canada.

Gregg Garfin is Assistant Professor and Assistant Specialist in Climate Science, Policy and Natural Resources in the University of Arizona's School of Natural Resources and the Environment, and Deputy Director for Science Translation in the Institute of the Environment. He has broad experience in applied climate and climate change research, and conducts extensive outreach at the interface between science and society. His ongoing research addresses drought monitoring and planning, adaptation to climate change, and the use and communication of climate science in decision making. His work has appeared in journals such as Science and Public Policy, the Annals of the Association of American Geographers, International Journal of Climatology and Journal of the American Water Resources Association. He is a founding partner in the National Seasonal Assessment Workshops (NSAW) to predict pre-season fire potential in North America. He is a co-investigator, and former Project Manager, of the Climate Assessment for the Southwest (CLIMAS), a NOAA-funded integrated assessment designed to identify and evaluate climate impacts on human and natural systems in the Southwest. Garfin received a PhD in Geosciences from the University of Arizona in 1998.

Donald A. Falk is an Associate Professor in the School of Natural Resources at the University of Arizona in Tucson. Falk's research focuses on fire history, fire ecology and restoration ecology. He holds joint appointments in the UA Laboratory of Tree-Ring Research and the Institute for Earth and Society. Falk's publications include numerous journal articles and four books covering genetics and conservation of rare plants, ecological foundations of restoration ecology, and landscape ecology of fire. Falk is an AAAS Fellow, and has received the Fulbright Short-Term Scholar award and the Deevey Award from the Ecological Society of America for outstanding graduate work in paleoecology. In 2008, he and collaborators (C. Miller, D. McKenzie and A. Black) were awarded the 'Outstanding Paper in Landscape Ecology' by the US Chapter of the International Association for Landscape Ecology. Falk serves on the Editorial Board for the Island Press-SER series, Science and Practice of Restoration Ecology, and is Science Lead for the FireScape project in southern Arizona, a collaborative program to develop landscape approaches to fire management. Falk received his BA in Interdisciplinary Studies from Oberlin College in 1972, MA in Environmental Policy from Tufts University in 1981, and PhD in Ecology & Evolutionary Biology at the University of Arizona in 2004. Falk was co-founder and Executive Director of the Center for Plant Conservation, originally at the Arnold Arboretum of Harvard University and now at the Missouri Botanical Garden, and subsequently served as the first Executive Director of the Society for Ecological Restoration International.

Thomas W. Swetnam is a Professor of Dendrochronology and Director of the Laboratory of Tree-Ring Research at the University of Arizona in Tucson. Swetnam studies changes in climate and forest disturbances using dendrochronology. He has worked extensively on wildfire history and ecology in pine and giant sequoia forests of the western USA and Mexico and South America, and he is currently studying fire, climate and carbon dynamics in central Siberia. Recent papers on these topics include: 'Multi-millennia fire history of the Giant Forest, Sequoia National Park, USA' (*Fire Ecology*, Swetnam et al. 5(3):117–147, 2009); 'Fire in the Earth System' (*Science*, Bowman et al. 324:481–484, 2009), and 'Forest Responses to Increasing Aridity and Warmth in the Southwestern United States' (*Proceedings of the National Academy of Sciences*, Williams et al. 107(50):21289–21294, 2010). He is Professor of Dendrochronology and serves as Director of the world's premier and largest laboratory dedicated to all aspects of tree-ring research and education, the Laboratory of Tree-Ring Research at the University of Arizona. He received a BS in Biology and Chemistry at the University of New Mexico and a MS and PhD in Watershed Management at the University of Arizona.

Note

* Correspondence address: Christopher D. O'Connor, School of Natural Resources and the Environment, University of Arizona, Biological Sciences East Building, Tucson, AZ 85721, USA. E-mail: oconnorc@email.arizona.edu.

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