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Pathways for climate change effects on fire: Models, data, and uncertainties

Amy E. Hessl
West Virginia University, USA

Abstract
Fire is a global process affecting both the biosphere and the atmosphere. As a result, measuring rates of change in wildland fire and understanding the mechanisms responsible for such changes are important research goals. A large body of modeling studies projects increases in wildfire activity in future decades, but few empirical studies have documented change in modern fire regimes. Identifying generalizable pathways through which climate change may alter fire regimes is a critical next step for understanding, measuring, and modeling fire under a changing climate. In this progress report, I review recent model-, empirical-, and fire history-based studies of fire and climate change and propose three pathways along which fire regimes might respond to climate change: changes in fuel condition, fuel volume, and ignitions. Model- and empirical-based studies have largely focused on changes in fuel condition with some models projecting up to 50% increases in area burned under a 2 x CO_2 climate. Fire history data derived from tree-rings, sediment charcoal, and soil charcoal have helped identify past trajectories of change in fire regimes and can point to possible future conditions. However, most fire history research has focused on changes in area burned and fire frequency. Changes in fire severity may be equally important for the earth system and require further attention. Critical research needs include next generation dynamic vegetation models (DGVMs) that consider changes in vegetation alongside changes in human activities and long fire history records from a variety of vegetation types suitable for validating these DGVMs.

Keywords
climate change, fire, fire history, sedimentary charcoal, tree-rings

I Introduction

Increased fire activity resulting from anthropogenic climate change will be one of the major drivers of vegetation change under a warming climate (Dale et al., 2001; Overpeck and Rind, 1990; Williams et al., 2010). Carbon emissions from wildfires currently produce approximately 1410–3139 Tg C year^{-1}, equivalent to about 26–31% of the emissions stemming from fossil fuel combustion and industrial activities (Schultz et al., 2008; van der Werf et al., 2006). Biomass burning also produces approximately 40% of global black carbon emissions (Bond et al., 2004), the second largest contributor to global warming after carbon dioxide (Jacobson, 2001; Ramanathan and Carmichael, 2008). Given these feedbacks to the biosphere and the atmosphere, measuring rates and directions of change in wildland fire activity and understanding the

Corresponding author:
West Virginia University, Box 6300, Morgantown, WV 26506, USA.
Email: amy.hessl@mail.wvu.edu

mechanisms responsible for such changes are key research goals.

The Intergovernmental Panel on Climate Change (IPCC) Working Group II projects increased fire frequency and intensity in many areas of the globe, particularly where climate models project more persistent drought (IPCC, 2007). Projected increases in wildfire activity are supported by a large body of modeling studies (reviewed in Flannigan et al., 2009). For example, climate change may alter the likelihood of increased wildfire sizes and frequencies (Brown et al., 2004; Le Page et al., 2010; Piñol et al., 1998; Stocks et al., 1998) potentially leading to increased emissions and loss of forest cover in some regions (Scholze et al., 2006). Despite the dire predictions, few empirical studies have documented recent change in fire regimes (Gillett et al., 2004; Hu et al., 2010; Kasischke and Turetsky, 2006; Westerling et al., 2006) and fewer still have documented such changes outside of North America (Mouillot and Field, 2005; Pausas, 2004). North America has a unique history of land use, including fire suppression, which could cloud interpretations of fire-climate interactions. Additional empirical studies with long-term data sets covering a diversity of ecosystems are required to evaluate the extent to which climate change has already altered fire regimes at a global scale.

One way to explore the mechanisms responsible for changing fire regimes is to study how climate changes in the past affected fire activity (Daniau, 2010; Marlon et al., 2008; Power et al., 2008). Paleoenvironmental reconstructions of past fire regimes can also help place recent extremes and variability in perspective and provide a baseline for ecological management (Gavin et al., 2007; Marlon et al., 2008, 2009; Swetnam et al., 1999). Data sets can be developed from historical records such as fire atlases (when available) and paleoenvironmental proxies such as fire-scarred trees, sedimentary charcoal, and soil charcoal. Paleoenvironmental data have already been developed in many regions of the world where fire monitoring is absent and can thus provide long records to compare to modern variability (Falk et al., 2010). However, there are significant challenges with applying these records, particularly when evaluating change over time. If these challenges can be overcome, projections of future changes in fire regimes will improve by combining fire history data with empirical and model-based studies.

Although many empirical models and some field-based studies support the association between climate change and elevated fire activity, the mechanisms responsible for such changes are less clear. In the western United States, increased fire activity in the late 20th century is associated with warmer temperatures, earlier snowmelt, and a longer fire season (Westerling et al., 2006). This modification of fuel condition is only one of many potential pathways toward increased fire activity under climate change. Increased frequency, duration, and severity of droughts (Barnett et al., 2008; Overpeck and Udall, 2010; Seager et al., 2009) could also lead to alterations of both fuel load and fuel condition (Brown et al., 2004). Alternatively, increased precipitation at decadal timescales could increase wildfire severity and extent by increasing the density of vegetation and connectivity of fuels at a landscape scale (Miller and Urban, 2000; Turner and Romme, 1994). Different pathways and mechanisms will be relevant in different regions and vegetation types. Identifying and defining generalizable pathways through which climate change may alter fire regimes in different settings is a critical next step for understanding and modeling future ecosystem processes, natural hazards, and biogeochemical cycles under a changing climate. Therefore, the purpose of this progress report is to: (1) review recent model-, empirical-, and fire history-based studies of fire and climate change; (2) propose three pathways along which fire regimes might respond to a changing climate; and (3) identify critical research needs in an effort to refine future projections of fire activity.

II Models of climate change and fire

Since as early as the 1990s, general circulation model projections of climate change have been used to develop empirical models of future fire hazard and fire weather. These models develop empirical relationships between past climate and fire activity on a monthly or seasonal basis and then apply these relationships to projected climate conditions from either global circulation models (GCMs) or downscaled regional climate models (RCMs). GCMs and RCMs typically use a fixed state of atmospheric CO_2 (for example, twice current CO_2 concentration (2 x CO_2)) to develop future climate projections. Models projecting changes in fire regimes have used the outputs from these models, therefore they also typically follow this 2 x CO_2 scenario. Results from modeling studies have consistently shown that a 2 x CO_2 climate could increase fire intensity, rate of spread, and lengthen the fire season in the Western United States (Brown et al., 2004), California (Fried et al., 2004; Lenihan et al., 2008), the Mediterranean (Mouillot et al., 2002), and in the boreal forests of Canada (Bergeron and Flannigan, 1995; Flannigan and Van Wagner, 1991; Stocks et al., 1998; Wotton et al., 2003) and Russia (Stocks et al., 1998). Area burned estimates derived from 2 x CO_2 models vary widely for similar regions, although models consistently project dramatic increases in fire activity. For example, 2 x CO_2 climate projections for California may lead to a 15–50% increase in area burned in the coming century (Fried et al., 2004; Lenihan et al., 2003) depending on the model. Average annual area burned in Canada is projected to increase by 74 to 118% by the end of this century based on a 3 x CO_2 scenario, but considerable variability exists across eco-zones (Flannigan et al., 2005). Earlier work for Canada using a 2 x CO_2 climate scenario suggested a 46% increase in seasonal severity rating with a similar increase in area burned (Flannigan and Van Wagner, 1991). Models for North America as a whole suggest that 2 x CO_2 climate projections correspond to a 10–50% increase in fire season severity (Flannigan et al., 2000).

Other models project 'burn likelihood' or 'fire proneness' based on meteorological forecasts. Changes in meteorological conditions in Spain indicate an increasing likelihood of fire during the second half of the 20th century (Piñol et al., 1998). Similar increases in fire proneness based on meteorological observations were projected for southern Switzerland where trends in climatic variables point to conditions favorable for drought and forest fire (Reinhard et al., 2005). Interestingly, some models suggest decreases in fire activity based on projections of a more mesic future climate. The average fire weather index over much of eastern Canada decreased under a 2 x CO_2 simulation (Wotton et al., 2003), an outcome which is in agreement with some fire history data (Bergeron and Flannigan, 1995).

This empirical-based modeling approach makes several assumptions, particularly that the relationship between fire and climate (e.g. area burned and Palmer Drought Severity Index), will not change over time. However, relationships between fire and climate are vegetation and fuel specific (Littell et al., 2009). Since we expect vegetation to shift with climate change (altered disturbance regimes will themselves alter vegetation), we may then expect that the relationship between fire and climate on a monthly or seasonal basis will change as well. Essentially, these empirically based models of future fire include changes in fuel condition as a result of climate change, but do not include changes in fuel volume, fuel structure, or continuity. Neither do they account for changes in human activities (ignition or suppression) that may occur coincident with climate change.

For many regions, it is unlikely that area burned or burn likelihood predictions under a 2 x CO_2 (or a 3 x CO_2) scenario would be sustained for more than a few decades without a change in vegetation and fuel type. Models representing future fire-climate or fire-weather alone cannot address transitions in vegetation or fire regimes that result from changes in ignitions, fuel volume, or fuel connectivity. Next-generation models will need to incorporate potential changes in vegetation and fuel structure as a result of climate change, disturbance, and even land-use change. This will require models to move away from climate projections derived from a fixed state of CO_2 and toward transient models of both climate and vegetation change. There have been several attempts to model the interaction between climate change, wildfire, and vegetation along a time series of changing conditions (Bachelet et al., 2001; Neilson and Drapek, 1998); however, these studies have produced variable results and are not focused on fire as a major driver.

Although dynamic global vegetation models (DGVMs) like the Lund-Pottsdam-Jena Dynamic Global Vegetation Model (LPJ) include fire as a process (Sitch et al., 2003; Thonicke et al., 2001), they do not include parameters for ignition rates, fuel volume, or fire weather. As the importance of fire in the global carbon cycle has become more apparent, fire has been more explicitly modeled as a process in DGVMs (Lenihan et al., 2003, 2008; Thonicke et al., 2010). For example, LPJ-SPread and InTensity of FIRE (SPITFIRE) uses modeled vegetation data as input for fuel loads and includes modules for estimating ignitions, fire spread, and vegetation mortality. Disturbance from fire is then fed back into the vegetation model. SPITFIRE includes critical variables for understanding interactions between climate, vegetation change, and human activities including: topography, human versus lightning ignitions, fire weather, fuel condition and volume, and human impacts on fuel volume (Lehsten et al., 2009; Thonicke et al., 2010). A critical test for models like SPITFIRE will be to determine whether they can be validated against not only high-resolution satellite products such as MODIS but also against long-term fire history records that capture decadal to millennial length variations in fire activity caused by climate change, vegetation change, and human action.

III Empirical evidence of changing fire regimes

Extensive research supports linkages between historical climate variability and fire (Beckage et al., 2003; Flannigan et al., 2000; Gedalof et al., 2005; Knapp, 1995; Lafon et al., 2005; Littell et al., 2009; Mote et al., 1999; Skinner et al., 1999); however, a limited number of studies have documented increases (or decreases) in fire activity associated with climate change, in part because of the large, long-term data sets required. Accordingly, most empirical evidence supporting climate change impacts on fire regimes comes from the United States and Canada where long observational records of fire regimes exist. Area burned in Canada clearly increased over the 20th century (Amiro et al., 2001; Gillett et al., 2004), consistent with model results (see above). Also of great concern, however, are the recent changes in fire regimes in the tundra of Canada and Alaska. Recent fires in the tundra, unprecedented in the paleoecological record of the last five millennia, appear to be associated with longer and more extreme dry seasons (Hu et al., 2010). Similar observations have been made in boreal forests where longer fire seasons have led to greater depth of burning and higher emissions (Kasischke and Turetsky, 2006; Turetsky et al., 2011). In the Intermountain West of the United States, the frequency and extent of large wildfires increased since 1970 (Westerling et al., 2006) and this trend appears to be tied to increases in the length of the fire season rather than elevated fuel loading as a result of fire suppression. Changes in fire activity in Europe are not as clear. In the Mediterranean, there were clear increases in the annual number of fires and area burned during the 20th century, but changes were coincident with an increase in vegetative cover associated with agricultural abandonment (Pausas, 2004).

Empirical studies require long-term, consistent records of fire occurrence and area burned in order to detect change and these records are limited in most regions and rarely present in the developing world. Regional and global data sets from satellites (e.g. MODIS thermal anomalies and fire products) may prove useful for detecting change in the future, but lack sufficient length at this time ($\sim$10 years) to distinguish between natural variability and climate change-induced trends. Documenting changes in fire activity is also complicated by changes in human land use, land cover, and human ignitions. These uncertainties can be reduced by repeated studies in a variety of ecological settings, across cultures and land uses, but will require paleoenvironmental data where observational records are missing, short, or incomplete.

IV Fire history studies

Paleoecological records can place current variability in the context of the past, particularly prior to major land modifications or anthropogenic climate change. Paleoecological records are especially valuable where long records of historical fire do not exist or are of insufficient spatial extent or duration. These long-term studies may also yield insights into the rate and direction of vegetation change given altered disturbance and climate regimes (Clark, 1996; Gavin et al., 2007; Whitlock et al., 2003). Three paleoecological methods, based on tree-rings, sedimentary charcoal, and soil charcoal, are often used for reconstructing fire regimes both as ecological benchmarks and for understanding the relationship between fire and climate. Fire scars and age structure analysis use tree-rings to date the location and extent of past fires (Farris et al., 2010; Heinselman, 1973; Hemstrom and Franklin, 1982; McBride, 1983). Heat from low and moderate severity fires often kill only a portion of the cambium of living trees, leaving a scar that can be identified in cross-section. The year of the fire generating each scar can be identified and cross-dated using a master chronology of tree-ring widths for the region. Individual trees can record a large number of surface fires, preserving the history of fire at a particular point in space (Farris et al., 2010; Hessl et al., 2007; Niklasson and Granstrom, 2000). In regions experiencing moderate to high severity fire, the age of trees that established following fire can be used to estimate fire frequency (Heinselman, 1973; Kipfmueller and Baker, 2000). Variations in charcoal abundance or influx (particles cm^{-2} $year^{-1}$) in lakes and ponds provide a record of past trends in biomass burning (Ali et al., 2009b; Clark, 1990; Gavin et al., 2007; Higuera et al., 2007; Whitlock and Millspaugh, 1998) and when combined with pollen, relationships between fire and vegetation change can be inferred. Charcoal may also be deposited in soils and other depositional environments where it can persist for thousands of years. Soil charcoal studies are useful in regions that lack lake sediments, but because of mixing, transport, and the cost of radiocarbon dates, it may be difficult and expensive to assess fire frequency.

Numerous studies have reported associations between drought and wildfire occurrence based on both tree-ring (Brown, 2006; Brown and Wu, 2005; Brown et al., 2008; Donnegan et al., 2001; Grissino-Mayer and Swetnam, 2000; Hessl et al., 2004; Heyerdahl et al., 2002, 2008; Kitzberger et al., 2001, 2007; Norman and Taylor, 2003; Swetnam, 1993; Swetnam and Betancourt, 1992; Taylor, 2000; Veblen, 2000; Veblen et al., 1999) and sedimentary charcoal records of past fire (Clark, 1990; Colombaroli and Gavin, 2010; Marlon et al., 2008, 2009; Meyer et al., 1992; Umbanhowar, 2004; Umbanhowar et al., 2009; Whitlock et al., 2003). Overwhelmingly, increases in the duration, frequency, and severity of past droughts

Figure 1. Photograph of Solongotyn Davaa, in the Tarvagatay Mountains of Mongolia, taken in the summer of 2010. A high severity fire recently burned this tree-line stand of *Pinus sibirica* (Siberian pine) where previous research (D'Arrigo et al., 2001; Jacoby et al., 1999) documented 450-year-old trees and relict wood >1700 years old. The presence of relict wood with no charcoal indicates this site had not burned for at least 1700 years.

have lead to increased frequency and extent of wildfire. In some regions, where drought occurrence is mediated by synoptic scale drivers of climatic variability, fire has also been related to these large features of atmospheric-ocean circulation (Heyerdahl et al., 2008; Kitzberger et al., 2001, 2007; Norman and Taylor, 2003; Roman-Cuesta et al., 2003; Swetnam and Betancourt, 1990; Yocom et al., 2010) via systematic variations in temperature, precipitation, air pressure, humidity, wind patterns, and lightning occurrence (Girardin et al., 2006; Trouet et al., 2009). The mechanisms linking drought and fire may be variable depending on the ecological system studied as well as the timescale of the study. In tree-ring studies, particularly those in closed-canopy forests, increased fire activity during droughts may have resulted from altered fuel condition (Donnegan et al., 2001). However, those studies performed in pine woodlands with a grassy understory may reflect changes in fuel volume (Swetnam and Betancourt, 1990). Millennial-length records from sediment charcoal may reflect slow changes in vegetation cover, fuel density, and fuel continuity rather than seasonal changes in fuel condition (Whitlock and Millspaugh, 1998).

Fewer studies have explored the effect of temperature on fire history (Clark, 1990; Heyerdahl et al., 2002, 2008; Marlon et al., 2008; Morgan et al., 2008; Swetnam, 1993; Veblen et al., 1999). However recent studies indicate a strong link between increased temperature and biomass burning on millennial timescales (Marlon et al., 2008; Power et al., 2008; Prentice, 2010; Wang et al., 2010). Increased temperatures could indirectly affect fire regimes by controlling the volume of fuel available to burn or by controlling the condition of fuels. Higher temperatures in boreal or alpine ecosystems might lead to a longer growing season, higher rates of productivity, and more continuous fuels. Increased temperatures at tree-line, independent of changes in precipitation, could lead to a longer dry season and greater fire activity. For example, high elevation, tree-line sites that rarely burned in the past because of a long snow season may now be exposed to high severity fires more typical of middle-elevation forest (Figure 1). Results from tree-ring-based studies suggest that increased temperatures in the past have lead to a longer snow-free season, drier fuels, and larger burned areas (Heyerdahl et al., 2008). However, in parts of Canada and northern Europe, fire frequency has decreased since about 1850 despite a warming trend (Bergeron, 1991; Bergeron and Archambault, 1993; Flannigan et al., 1998), possibly as a result of increased precipitation.

While many areas of the world are expected to dry in future decades, some regions, such as eastern North America, Europe, and tropical Africa, may experience increased precipitation (Piao et al., 2006) particularly during the fire season. Increased moisture may reduce fire frequency, extent, or severity or alter seasonality either through changes in fuel condition or fuel volume. Similar to model-based studies, fire history studies have mostly been conducted in North America and have been largely focused on aridity as a driver of fire regimes. Clearly, we need more studies in moist temperate forests and non-forested areas outside of North America. Fire history studies directed at understanding the mechanisms responsible for change are also required if past variability is to be applied to future climate change projections (Ali et al., 2009a). In particular, what temperature and moisture changes in the past were required to increase fuel volumes sufficient to shift fire regimes from low to high severity? What has been the relative contribution to area burned by human versus lightning ignitions in different regions and vegetation types? In what systems did increased aridity reduce fuel volume or continuity thereby reducing fire activity?

V Uncertainties in detecting changes in fire regimes

Although long fire history data sets will be required to validate models and determine whether fire regimes have experienced a change of state, these data are difficult to collect, are limited in occurrence, and inferences are restricted by the spatial and temporal resolution of the data. As previously noted, few regions of the world maintain long observational records of past fire activity, and satellite records are currently too short to detect change. Climatic variability and human activities are also strong drivers of fire activity, therefore studies of anthropogenic climate change and fire must take these variables into account. While fire history data have the potential to address some of these challenges, inferences remain somewhat limited.

Fire scar and stand age data are only available where species of trees reliably produce fire scars or where forests or other woody vegetation respond to severe fires with episodic recruitment. This limits tree-ring-based records to forests and woodlands. Sedimentary charcoal data are best collected from lakes, ponds, and hollows and these may have limited distributions in some regions and, often, low temporal resolution. Soil charcoal may be more widely available, but uncertainty is introduced by mixing and disturbance of soil as well as uncertainty caused by the tree age at the time of fire (Gavin et al., 2007). In addition, reconstructions of past fire derived from tree-ring and sediment charcoal records suffer from the ‘fading record problem’, where the sample replication decreases back in time (Bowman, 2007). These age-related uncertainties make inferences, such as fire frequency, challenging. Even for fire-scar data, fire intervals and associated statistics are problematic. Fire intervals decrease with increasing sample area and increasing sample size (Hessl et al., 2004). As a result, estimates of fire intervals are affected by changes in sample depth over time and must be standardized to adjust for this effect. Further, fire history derived from fire scars may not reconstruct long enough periods to identify change. For example, where fire intervals are long, it may be statistically impossible to identify a change in fire interval given the length of available data. However, extreme events that are not represented in the paleoenvironmental record may be sufficient evidence of threshold changes in a fire regime (Hu et al., 2010). Estimating past fire severity is difficult and data intensive, particularly for tree-ring studies since it requires an estimate of mortality. For sedimentary charcoal records, severity may be conflated with extent (Ali et al., 2009b; Higuera et al., 2007), although at some sites erosional layers following charcoal layers serve as an indicator of severity (Colombaroli and Gavin, 2010). Regardless of these challenges, paleoenvironmental data are the best long-term data available from many regions of the world where observational records are short, incomplete, or non-existent.

Human land use and behavior can be strong drivers of wildfire variability (Bowman et al., 2009; Burney et al., 2003) and anthropogenic climate change is coincident with a host of human developments throughout the world (i.e. fire suppression, urbanization, agricultural abandonment, invasive species, etc.). The problem of attribution then is critical and non-trivial. I would argue that expanding fire history, empirical, and model-based studies to regions of the world with variable histories of land use and human behavior would allow us to better predict how human actions might overwhelm or interact with changes in climate. Data from regions without a history of fire suppression or with well-documented patterns of human ignitions would help constrain models of fire activity under climate change.

VI Pathways of climate-altered fire regimes

Given the historical and present variability in vegetation, fuels, and human activities, identifying a limited set of pathways through which climate change might alter fire regimes could help focus and guide future research. Climate, vegetation change, and human activities can influence fuels across a wide range of spatial and temporal scales resulting in several pathways of possible change in fire regimes. Temperature, relative humidity, precipitation, and wind speed all influence how fires burn on short timescales by both influencing the condition of fuels and the amount of heat transfer required for combustion of those fuels (Albini, 1976; Anderson, 1982; Rothermel, 1983). On the timescale of weeks to months, meteorological variables may influence the duration of the fire season, frequency of lightning ignitions, and the abundance of fine fuels (Goldammer and Price, 1998; Wotton and Flannigan, 1993). On the scale of years to decades, climate may influence fire regimes by altering net primary productivity, decomposition, vegetation structure, vegetation composition, density, fuel loading, and fuel connectivity across a landscape (Meyn et al., 2007). Based on these general principles, I propose three pathways through which climate change might alter fire activity:

1. **Alteration of fuel condition.** This pathway might occur where ignition sources and fuels are plentiful but fuel moisture is high, such as moist temperate and boreal forests (Meyn et al., 2007). Changes in the length of the fire season (e.g. a longer or shorter

snow-free season) (Westerling et al., 2006), a shift in the fire season (Turetsky et al., 2011), higher frequency or longer duration of drought/pluvial events (Gedalof et al., 2005), or increased/decreased frequency of fire weather conducive to fire spread (Podur and Wotton, 2010) could all alter fuel condition.

2. **Changes in fuel loading.** Episodic or incremental increases in fuel loading as a result of other disturbances (e.g. insect outbreaks or mortality events) or changes in the density or connectivity of fuels as a result of warmer and/or wetter conditions are likely to occur in many regions. In systems dominated by fine fuels (grasslands, shrublands, or woodlands), this pathway could develop in a matter of months or seasons (Meyn et al., 2007). Future aridity and associated decreases in productivity might lead to reduced fire activity in places where fuel continuity is already limited, particularly semi-arid forest or woodland environments. In systems dominated by coarse woody fuels (continuous forests), increases in fuel volume would take decades but could lead to increased fire severity and increased emissions as larger volumes of biomass are consumed. This transition to higher fuel loads is likely to occur in semi-arid forests where precipitation is projected to increase or areas subjected to widespread mortality events (Allen and Breshears, 1998; van Mantgem et al., 2009). Fuel loads may change as a result of climate change altering species composition, vegetation structure, age class, density, and decomposition rates, or as a result of changing fire regimes themselves (de Groot et al., 2003, 2009; Malanson and Westman, 1991; Soja et al., 2007). Similar changes are possible in the absence of climate change, for example as a consequence of land-use change or invasive species. Disentangling these mechanisms is a major challenge to understanding the role of climate change in altered fire regimes.

3. **Changes in ignitions.** Where ignitions are limiting, for example semi-arid forest environments with little convective activity, fuels are dry enough to carry a fire but ignitions are relatively infrequent. Projected warmer temperatures and increased convective activity may translate into increased lightning activity and increases in wildfire (Price and Rind, 1994). However, changes in human ignitions could also alter the fire regime in these regions, making it difficult to separate direct human influences via ignitions versus indirect influences caused by anthropogenic climate change.

Although these pathways are not completely independent (e.g. fire in the forests of the coastal Pacific Northwest are likely limited by both ignitions and fuel condition), I argue that these are the primary trajectories likely to occur given climate change. Future empirical- and model-based research should identify the most likely pathway of change in the system of interest in order to develop the most appropriate hypotheses and methods. For example, studies of area burned in regions experiencing increases in fire severity might observe no change in fire activity when in fact major changes affecting the atmosphere and biosphere could be occurring. Model-based studies projecting large increases in area burned as a result of a more arid climate may deviate from actual conditions as vegetation density and composition shift with a changing climate or due to increased fire activity. Most empirical- and model-based studies to date have focused on pathway 1 (altered fuel condition). Although this is critical for understanding immediate effects of altered climate on fire regimes, we need additional studies focused on pathways 2 (changes in fuel loading) and 3 (changes in ignitions). Careful consideration of potential pathways and mechanisms will allow for reduced uncertainty and greater ability to generalize results across ecosystems especially where data are lacking.

VII Critical research needs

Critical research needs in many parts of the world include developing fire history records of not just area burned and fire frequency, but also fire severity and fire seasonality. These records could address potential changes in fuel volume (pathway 2) and condition (pathway 1). With respect to modeling, critical needs include next-generation models that go beyond fire weather to include changing vegetation, fuels, and human activities. Long-term fire history records could be used to help parameterize and validate model projections of fire activity. One method is hindcasting – models of vegetation and fire during past climates that can be compared to paleoecological records (Gavin et al., 2007). Some developing countries did not have the resources to actively suppress fires, allowing fires to continue to be recorded by trees after many developed countries experienced fire cessation. In locations with a fire-scar record that continues to the present, model hindcasts could be validated with fire-scar evidence during the 20th century, when instrumental climate data are also available. This approach would allow for significant improvements of fire-climate models, particularly when applied across vegetation types and land-use histories.

Humans are the primary agent of fire across the globe (Bowman et al., 2009; Flannigan et al., 2009) and considerable uncertainty lies in projecting changes in human behavior and land use. Introduced species, for example, have increased the frequency of fires in portions of the Intermountain West of North America where increased abundance of exotic grasses such as cheat grass (*Bromus tectorum*) and buffelgrass (*Pennisetum ciliare* = *Cenchrus ciliaris*) have resulted in greater areas burned (Esque et al., 2004; Knapp, 1998). In some locations, increases in fine-fuel productivity from invasive species (pathway 2) may be more important for altering fire regimes than climate change. Changes in fire-related policy, including development in the wildland-urban interface, fire management, forest management, and human behavior and attitudes will also have large effects on fire regimes coincident with global climate change (Moritz and Stephens, 2008; Podur and Wotton, 2010; Schoennagel et al., 2004; Wotton et al., 2010). It is not unreasonable to expect that human activities may overwhelm climate change effects on fire regimes in some locales. Consequently, empirical and model-based studies need to better define the impact of humans on fuel volume, connectivity, and ignitions.

The complexities engendered by interactions between climate, human activities, vegetation dynamics, and fire necessitate that relationships be generalized if we are to effectively predict global responses of fire to climate change. The three pathways I propose in this progress report operate on timescales relevant to human activities and responses. The first pathway, altered fuel condition, has received the most attention because empirical relationships between weather, fuel moisture, and fire activity are well established and occur on short timescales. The second pathway, altered fuel volume, may prove to be of the greatest concern since increased fuel volume can lead to the greatest feedbacks to the biosphere and atmosphere through changes in fire severity. The last pathway, changing ignitions, has received the least attention from the perspective of understanding future trends in lightning and human ignitions. As DGVMs continue to develop, observational and fire history data will be critical in providing long-term records to validate and improve these models. However, fire history data must include long records of not just area burned and fire frequency but also fire severity and seasonality. These records must span a variety of ecological settings including those areas where we might expect reduced fire activity. Finally we need more fire history records from locations with variable land use to help us disentangle the interactions between human activities and climate change. Projections of extreme fire activity associated with climate change will certainly attract the public's attention, but these projections must be grounded in the complexities of changing vegetation and human activities, as well as a changing climate.

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