Advanced Review

Climate–vegetation–fire interactions and feedbacks: trivial detail or major barrier to projecting the future of the Earth system?

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Fire is a complex process involving interactions and feedbacks between biological, socioeconomic, and physical drivers across multiple spatial and temporal scales. This complexity limits our ability to incorporate fire into Earth system models and project future fire activity under climate change. Conceptual, empirical, and process models have identified the mechanisms and processes driving fire regimes, and provide a useful basis to consider future fire activity. However, these models generally deal with only one component of fire regimes, fire frequency, and do not incorporate feedbacks between fire, vegetation, and climate. They are thus unable to predict the location, severity or timing of fires, the socioecological impacts of fire regime change, or potential non-linear responses such as biome shifts into alternative stable states. Dynamic modeling experiments may facilitate more thorough investigations of fire–vegetation–climate feedbacks and interactions, but their success will depend on the development of dynamic global vegetation models (DGVMs) that more accurately represent biological drivers. This requires improvements in the representation of current vegetation, plant responses to fire, ecological dynamics, and land management to capture the mechanisms behind fire frequency, intensity, and timing. DGVMs with fire modules are promising tools to develop a globally consistent analysis of fire activity, but projecting future fire activity will ultimately require a transdisciplinary synthesis of the biological, atmospheric, and socioeconomic drivers of fire. This is an important goal because fire causes substantial economic disruption and contributes to future climate change through its influence on albedo and the capacity of the biosphere to store carbon. © 2016 Wiley Periodicals, Inc.

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INTRODUCTION

The temporal and spatial patterns and ecological effects of fire in a region (the fire regime) are determined by interactions between the biosphere and atmosphere. The atmospheric drivers of fire, at both macro and microclimate scales, are relatively well known, with precipitation, temperature, wind and lightning playing important roles in fuel drying, ignition, spread and extinction of fires (reviewed by Ref 1–3). However, quantifying the biological and socioeconomic drivers of fire remains a major challenge, even under current climate conditions, because of the interactions and feedbacks between fire, vegetation, human intervention, and climate. Consequently, projecting changes in vegetation growth and fuel dynamics under future climatic conditions, necessary to predict future fire activity, is an even more challenging problem.[4,5]

This challenge is important, firstly because the ability to predict future fire activity could greatly reduce the impacts of fire on human and natural systems. But future fire activity also has the potential to drive climate change by impacting vegetation, the surface radiative balance, terrestrial water cycle, and cloud distributions. If such effects occur at the continental scale, they could result in planetary wide change, including a significant change in the capacity of the biosphere to store carbon. If this is the case, fire has the potential to reframe our understandings of the global carbon cycle, and needs to be better represented in climate models.

Fire activity is inextricably linked to the fire regime. The fire regime can be described simply in terms of the intensity, frequency, seasonality, and type of fire at a site,[6] but it also encompasses a range of time periods and scales (past, present, or future; a single fire or many fires over years, decades or centuries); different spatial scales affected (e.g. a single ecosystem or vegetation type, a particular geographical area); and whether a fire is of natural or anthropogenic origin. Additionally, the fire regime incorporates the variability of fire intensity, frequency, and seasonality across space and time, the conditions that affect fire occurrence (e.g. fuel type, fire weather), and the ecological impact of the fire.[7] Attempts have been made to develop a global assessment of fire regimes, but a wide variation in the state of knowledge about the drivers of fire regimes in different geographic regions remains. Generalizations are difficult, because the density, duration, and variability of fire activity within global groupings of fire regimes, or pyromes, do not directly relate to different global vegetation units (biomes).[8,9] Since a single biome can contain several different fire regimes, and, alternatively, very different biomes can belong to the same pyrome, the development of future fire regimes in response to changes in climate and human activity is likely to be difficult to predict.[9]

This review aims to identify those aspects of fire activity that can be understood or modeled in the context of climate change, and those which represent unpredictable responses and feedbacks. In order to achieve this, we firstly outline the challenges that exist in projecting fuel loads under future climatic conditions. We do not consider one particular time frame or scenario of future emissions, because the challenges exist regardless of the extent of change. These include the uncertainties inherent in predicting biological responses to future change, uncertainties in the many biological, socioeconomic, and physical drivers, and difficulties in measuring, let alone predicting, the multiscale interactions and feedbacks that exist amongst all drivers. We then assess the contributions that conceptual, empirical, and process models of fire have made towards our understanding of the evolving nature of fire activity in a warming world. And finally, we conclude with recommendations on how progress could be made and future research directions.

CHALLENGES IN PROJECTING FUEL LOADS UNDER FUTURE CLIMATE CONDITIONS

It has been claimed that predictions of 'the outcomes of climate interactions with future fire regime(s) are almost pure conjecture' (Ref 10, p. 254). While this claim was made in relation to one forest type in Australia, it is likely to be just as applicable to other biomes around the world. Moving beyond conjecture requires an appreciation of what elements can be projected into the future, which elements cannot, and which could be better understood with more research. Identifying those aspects able to be controlled or modified by humans and those that cannot is also important.

Biological Drivers

Biological responses to increased temperature, carbon dioxide (CO_2), extreme events, and changes to rainfall patterns, as well as shifts in species distributions and interactions, represent one of the greatest challenges to predicting future fire regimes. However, some generalizations are possible. Increased tree mortality is expected in response to drought, increased temperatures and interactions with other climate-mediated processes such as insect outbreaks.[11,12] Large trees in particular exhibit reduced growth and biomass production at high temperatures.[13,14] Fuel loads may increase in the short term as a result of drought responses such as leaf and bark shedding, or, alternatively, compensatory responses such as decreased productivity with decreased rainfall could lead to reduced fuel loads. Increased leaf longevity in response to elevated CO_2[15] may also have consequences for fuel accumulation. Changes in ecosystem processes such as water use, photosynthesis, growth and regeneration, mortality, and litter decomposition are likely to occur in response to changing temperature and precipitation.[16] Increased temperature and CO_2 are expected to increase plant growth through the 'fertilization' effect[17,18] in ecosystems where rainfall and temperature are not limiting.[19,20] Alternatively, reduced rainfall may have the opposite effect, although improved water use efficiency with elevated CO_2 could counteract to some extent the reduction in water availability, by reducing water demand and soil drying due to reductions in total transpiration.[17,21,22] This compensatory effect may be particularly important in water limited systems.[23] These changes have the potential to affect the flammability of forests and fuel loads by changing vegetation structure, species abundance, and species attributes such as wood density or leaf nutrient status, in turn affecting herbivory and decomposition.

Many generalizations, however, have been found to be overly simplistic when scrutinized closely within different ecosystems (e.g. Ref 16,24). Plant growth and regeneration following fire can be affected by disturbance regime,[25] competition,[26,27] or nutrient and water availability. The fertilization effect under elevated CO_2 may not apply in nutrient limited ecosystems, because plants are unable to match the increased carbon with equivalent concentrations of nitrogen. This causes a decline in C:N ratio and a subsequently greater reduction in photosynthesis when nutrient availability is low.[17,28] Changes to the C:N content of leaves may alter rates of decomposition[29–32] and palatability to herbivores,[33–35] with consequent effects on fuel accumulation. Free air enrichment experiments (FACE) have made strong contributions to understanding the range of whole plant responses to atmospheric CO_2 enrichment across diverse ecosystems around the world.[21,36] Contrasting responses and mechanisms have been demonstrated in different forest types and regions.[21] Extensive comparative research is therefore still required to develop general models of plant physiological responses and how they influence ecosystems processes and fire activity amongst global vegetation types.

Changes to the extent and species composition of vegetation types are likely to occur[37] as species' distributions shift in response to changing climate conditions[38–40] and human assisted migration or accidental introductions.[41,42] Changes to vegetation structure may lead to microclimatic changes that can substantially affect fire behavior and severity. Novel ecosystems may emerge, with previously unseen species assemblages and interactions, and new responses to fire. For instance, the spread of invasive species is expected to increase in the future, as the productivity of native species declines,[43] and the invasive potential of species changes.[44–47] Such changes have the potential to alter fuel continuity and flammability across the landscape.[48–50]

Extensive debate has focused on the competitive interactions between C4 grasses and C3 woody plants under climate change, because invasive C4 species such as Gamba Grass (*Andropogon gayanus*) now drive grass fire cycles in many woody ecosystems around the world.[51] In general, it is expected that climate change will increase the dominance of C4 grasses, because they have higher water use efficiency, greater drought tolerance, and greater persistence in warmer climates compared to C3 species.[52,53] However, the combined effect of elevated CO_2 and competitive interactions between C4 and C3 plants under different nutrient conditions and seasonality is not well understood, and can lead to idiosyncratic responses.[52,54] C3 trees, for example, may come to dominate in savannahs under the combination of increasingly frequent fires and elevated CO_2, because they are able to store more non-structural carbohydrate in underground storage organs than grasses, and recover to fire-resistant sizes faster under high CO_2 conditions.[25]

Positive feedbacks can in some cases cause ecosystem-level transformations, with shifts in fire regime into alternative stable states. One mechanism by which this can occur is if the spread of an invasive species increases flammability and fire spread, excluding fire sensitive native species, and promoting further increases in fire frequency and intensity.[48] For example, Gamba Grass (*A. gayanus*) and Buffel Grass (*Cenchrus ciliaris*) are very successful invaders in semiarid and savannah ecosystems in Australia, Mexico, Hawaii and the western United States,[55] forming dense monocultures that exclude native species, causing huge increases in fuel loads and altering the fire regime and functioning of the system.[56–59] Alternatively, fire may be suppressed when invasive species out-compete dense understory species with lower fuel moisture.[48] Frequent fire in tropical forests, interacting with climate, resources and species traits, can cause a shift towards savannah, radically changing fire regimes.[60,61] This represents a dramatic transformational change, from the most carbon dense and least flammable of all biomes, to the most frequently burnt biome with substantially lower carbon storage capacity. However, biome switching is not always a gradual process. In forests dominated by obligate seeders adapted to fire regimes with relatively long fire return intervals and low intensity fires, for example, increased frequency of severe fire can cause a change in vegetation state following population collapse.[62,63]

All of these biological responses have the potential to cause a change in the fire regime in different regions. Changes to the fire regime not only affect fuel accumulation, but can have long-term effects on the vegetation structure, composition, and flammability. In combination with demographic changes such as reduced seed production under warmer and drier conditions, more frequent fire may result in 'interval squeeze,' leading to greater extinction risk for woody plants, and changed ecosystem structure, composition, and carbon storage.[64] These unpredictable responses and interactions limit our ability to predict whether fuel loads will increase or decrease at a particular point, let alone predict how fire regimes and fuel loads may change across the landscape or in different ecosystems or regions of the world.

Socioeconomic Drivers

Fire management by humans is a major driver of global fire regimes,[65–67] and the extent and impact of the sociopolitical drivers of fire is increasing.[68] Land use change is a key driver of changes to fire activity.[69] Anthropogenic changes to the frequency, intensity, and timing of fire may lead to shifts in vegetation structure, composition, and flammability. Increased fire frequency is associated with agriculture, afforestation as well as deforestation, arson and prescribed burning to protect biodiversity, infrastructure and population centers.[70–72] The relationship between humans and fire activity is non-linear, with the highest frequency of fire and largest area burned occurring at intermediate levels of population density and urbanization, declining beyond certain thresholds of ignition rates.[73] The impacts of anthropogenic burning are likely to be greatest in systems where fire is naturally rare, fuel load is high, and vegetation is poorly adapted to fire.[74] Fire suppression to protect assets or resulting from land use change, habitat fragmentation, and artificial barriers (e.g. roads, fuel breaks) leads to vegetation and fire regime changes.[66] For example, it has been suggested that long-term exclusion of fire from forests has contributed to the very high intensity and severity of recent wildfires[70,75] (although this is not accepted by all in all ecosystems[76,77]). Changes to historical trends in fire suppression and ignition is likely to increase in the future as populations increase and land conversion continues.

As with the biological and climatic drivers of fire, the socioeconomic drivers vary across regions and with time, and may interact with other drivers not controlled by humans.[78] Fire weather and fuel availability affect the timing and impact of different sources of anthropogenic ignitions (e.g. cigarettes, welding sparks, campfires, and arson).[73,79,80] Fuel reduction burns have been shown to reduce the severity of wildfires in many regions (e.g. Ref 81), and demands to increase prescribed management burning to reduce fire risk are likely in fire-prone areas as fire frequency rises under climate change. However, under warmer conditions the fire season is projected to occur earlier in the year, and last longer,[82–86] so quotas for increased prescribed burning may be constrained by a narrowing window of opportunity with suitable weather conditions for controlled burning. Resources available for such management will also be stretched as greater areas require treatment.[19,87] In many regions prescribed burning is limited by the negative effects of smoke-related particulate matter on human health.[88–91] Additionally, controlled burning has been shown to be ineffective at reducing fire spread or severity under extreme weather conditions,[92,93] which are projected to increase with climate change.[94] Nor is controlled burning always effective at reducing the area burned by unplanned fires.[93,95–97] An increase in the frequency of prescribed burning may also increase flammability in some vegetation types, a human-induced positive feedback effect.[63,98,99] In subalpine and alpine forests of south-eastern Australia, for example, Zylstra[100] demonstrated that frequent burning (up to a 14-year cycle) led to changes in forest structure that more than doubled the average size of fires, which spread faster and were more difficult to suppress. Other management options to reduce fuel loads, such as grazing or mechanical removal, may therefore become more important in the future.

Deforestation and increased burning in 'fire frontiers' such as high-biomass tropical rainforests, which would not historically have supported fire,[68] may exacerbate climate change, firstly by releasing carbon stocks, but also by inhibiting regional rainfall through the production of tropospheric smoke layers[101,102] and the reduction of evaporation,[103] in turn encouraging more fires.[104,105] Similarly, combustion of the massive stores of carbon in both tropical and boreal organic forest soils represents a substantial risk to amplifying atmospheric CO_2 concentrations.[106]

Climate Drivers

Several recent reviews provide detailed overviews of the climate drivers of fire (e.g. Ref 1,107). Here we highlight the interactions and feedbacks that exist with the biological and human dimensions that pose challenges in projecting future fire regimes.

Feedbacks, both positive and negative, also exist between macro climate and large-scale fires.[10] Positive feedbacks include the CO_2 emitted,[105] increased lightning caused by smoke contributions to convection,[108] and changes to surface albedo.[109] Changes to albedo can occur within burn perimeters following a single intense fire,[110] and as the result of more gradual vegetation change with increased fire frequency in response to drier conditions (e.g. the conversion of boreal forest to tundra[109]), but will differ across vegetation types and regionally due to interactions with other drivers.[111] Carbon and energy exchange is affected immediately after fire, with the release of carbon stores and when productivity and CO_2 sequestration rates are reduced. On longer time scales, the exchange is affected through impacts on soils, drainage, decomposition and vegetation composition.[106,112,113]

In addition to CO_2, fires emit aerosol particles, which are one of the largest sources of change in the earth's radiation budget.[114] Ash and soot from fires affect the global radiation budget directly by scattering and absorbing radiation (the albedo effect), and indirectly by serving as nuclei for cloud formation.[111,115] Aerosols therefore have a cooling effect on the troposphere,[116] a negative feedback that is further strengthened by the increased albedo and biophysical cooling associated with regrowth after high intensity fires.[109] Although improvements have been made in new generations of global climate model (GCM), the effect of smoke aerosols on clouds and the earth's radiation balance remains one of the larger uncertainties in projections of future climate and estimates of anthropogenic effects on climate.[117]

Ignitions are the ultimate barrier to prediction of future fire. Non-anthropogenic lightning activity appears to have increased with recent warming,[118] and, assuming the observed relationship between surface temperatures and lightning activity holds into the future,[1] it is projected to increase further with continuing climate change.[119–121] It has been estimated, for example, that there may be 10% more lightning for every 1°C of warming.[122] However, whether a strike results in a fire event requires many factors to coincide, including the type of lightning event (dry vs wet lightning; positive vs negative lightning strokes), vegetation type, and fuel moisture and condition at the time of the strike, determined by antecedent drought, fuel availability and weather.[1,123]

Multiscale Interactions

Fire research in the past has tended to concentrate on one spatial or temporal scale at a time,[124] while the important interactions and feedbacks occur across scales, from the scale of a leaf to global and atmospheric levels, and seconds to centuries[1,107] (Table 1, Figure 1). Much of our understanding of the interactions between fire, climate and vegetation is based on experimental data at scales that are inappropriate for understanding fire regimes. For example, flammability experiments at the leaf scale have limited relevance to fire behavior at the landscape scale, which is determined by the arrangement, size distribution and ratio of living to dead components of the fuel load and fuel moisture.[127] Similarly, short-term (from seconds to weeks) physiological responses to elevated CO_2 and temperature at the leaf level are well understood,[21] but there are fewer data on longer-term CO_2 acclimation responses, which can reverse the increase in photosynthesis and growth seen in short-term studies.[128] While short-term experiments may overestimate the direct effects of climate change because they do not consider acclimation, they may also underestimate community effects, particularly in ecosystems that respond slowly.[129] The Free Air Enrichment Experiments (FACE) contributed important information about long-term, ecosystem-level responses to CO_2,[15,21,130] but there are few data on vegetation responses to CO_2 at larger spatial scales, so there is high uncertainty about how CO_2 enrichment could affect fuel production and amplify or counteract climate variability. Likewise, beyond small plots such as Harvard Forest (http://harvardforest.fas.harvard.edu/research/LTER), there have been no studies to investigate the response of forest ecosystems to warming, or changes to precipitation, over the timescale of decades.[131] Scaling up from physiological experiments at small spatial and temporal scales therefore remains a major challenge.[131]

While modeling and macro ecological inferences may identify some generalizations about fire–climate interactions at the global scale, they do not always hold at the regional or local scales. For example, plant productivity, and therefore fuel production, is strongly linked to temperature and

TABLE 1 | The Properties and Drivers of Fire Regimes Characterizing the Temporal and Spatial Patterns and Impacts of Fire in a Region (Adapted from Falk et al.[124]).

Property	Drivers			
	Climate/Weather	Biological	Terrain	Social
Spatial characteristics				
Extent—size and spatial homogeneity of burning	Climatic influences on vegetation type, fuel accumulation, and condition Daily and seasonal weather conditions (temperature, humidity, wind) determining fire spread	Fuel type, structure, flammability, vertical continuity, landscape connectivity	Physical barriers to fire spread (e.g. water, gullies)	Suppression capability (accessibility); proximity to valued assets
Intensity—amount and rate of surface fuel consumption	Seasonal weather conditions determining fuel moisture; daily fire weather	Fuel type, structure, flammability, and connectivity (landscape and vertical)	Slope and aspect effects on fuel moisture and fire behavior	Pattern of management burning
Heterogeneity—pattern of burning	Atmospheric instability, wind	Patchiness of flammable fuels across the landscape	Topographic influence on wind (roughness, slope)	Location of built environment; ignition patterns
Severity—impact of fire on biotic and abiotic ecosystem properties	Daily fire weather	Fuel volume, condition, connectivity	Slope and aspect effects on fuel moisture and fire behavior	Suppression capability
Temporal characteristics				
Frequency—number of fires per unit time in an area	Teleconnections, drought, dry lightning frequency and intensity, fire weather	Fuel type and accumulation, regeneration after fire		Frequency of management burns, other human ignitions
Seasonality—timing of fires	Length of fire season	Community composition and structure, phenology (e.g. timing of leaf fall, greenup)	Slope and aspect effects on soil moisture	Timing of management burns, other human ignitions
Duration—length of burn period	Length of fire season	Fuel structure, continuity		Suppression capability

precipitation at the global scale.[132] However, at the regional scale, diverse socioeconomic drivers (e.g. fire suppression and land use and land cover change) result in complex patterns in fire activity.[133] Furthermore, local site factors affect biomass and fuel accumulation, with steep slopes and coarser soils generally being less productive than flatter and finer-textured soils.[134] Similarly, empirical models of fire activity at different temporal scales provide different understanding of fire–climate–vegetation relationships. For example, models using annually updated climate and land-cover variables characterize the relationship differently to models based on climatological means.[135] Annual models are able to capture short-term variation in climate whereas averaged models define broad climate envelopes within which flammable vegetation and fire-conducive climate conditions overlap.

Given the above spatiotemporal constraints on models it follows that the accuracy and precision with which the drivers of fire can be projected under future conditions is also scale dependent (Figure 2). At the continental and global scales, the statistical distribution of key climate variables (precipitation, temperature, wind) is known, and spatial data exist to describe broad vegetation types and ecosystem productivity, so it is possible to model the 'niche' of fire.[68] However at landscape and regional scales

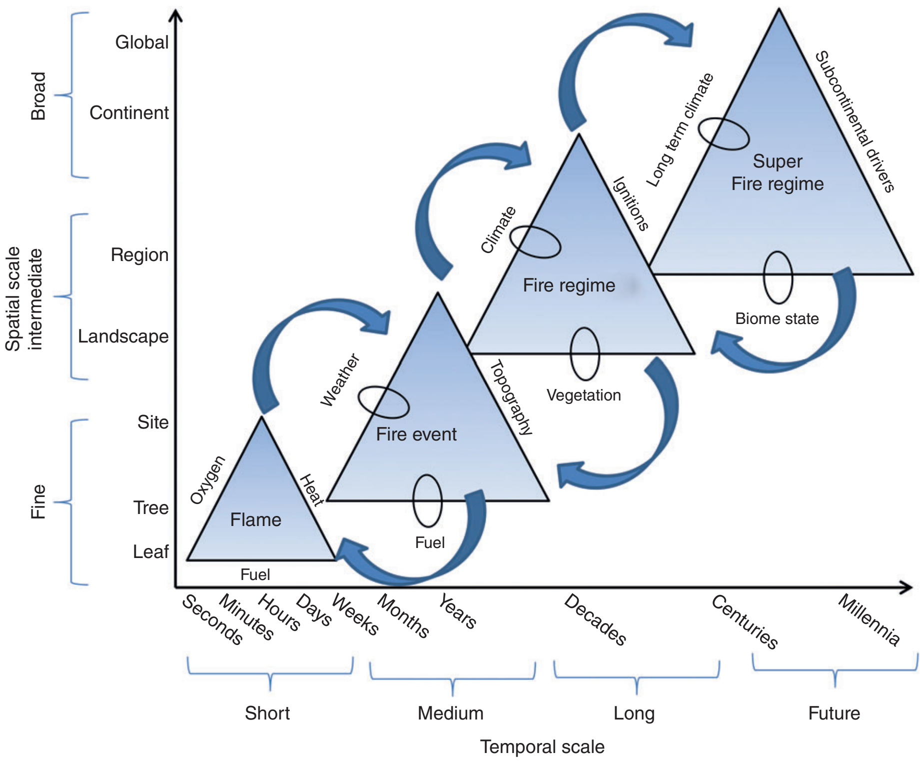

FIGURE 1 | The drivers of fire across multiple temporal and spatial scales. This is an adaptation of the diagram first presented by Moritz et al.,[125] in which the fire triangle concept was extended to incorporate the feedbacks between fire drivers (small loops) and processes (arrows) at different scales. Whitlock et al.[126] added the super-fire regime triangle to include the long-temporal perspective supported by paleo-ecological studies. The dominant drivers at each scale are represented by the side of each triangle.

predictability often declines[136] because accurate mapping of vegetation and fire history (and hence fuel loading), soils and climate is generally lacking. This reduces the ability to capture the influence of natural variability in these drivers. One exception is that recent land management (forestry, agriculture, urbanization) is often available at these intermediate spatial scales, although this does not improve predictability if the impact of management decisions is not monitored. Productivity and vegetation structure can be precisely mapped using surrogate indices based on satellite data, although accuracy is compromised because understorey biomass and structure are not resolved in these measurements. Key microclimatic variables that often help maintain abrupt vegetation boundaries (e.g. wind, precipitation, temperature, and humidity) are not well represented in forecasts or climate models, but with appropriate investment of human and scientific resources very accurate measurements at a single point are possible if the research question warranted that level of detail.[137] This is also the case for other drivers such as CO_2, biomass, vegetation type and structure, and soil. Although regions with a high incidence of lightning and human ignitions are broadly known,[138] prediction of ignition remains a barrier to accurate predictive models of fire occurrence. The importance of anthropogenic ignitions relative to natural ignitions differs around the world,[139,140] as does our understanding of the factors driving ignitions and our ability to predict them.

Similarly, the ability to project the drivers of fire varies across temporal scales. Fire activity and behavior of an ignited fire can be reasonably well predicted over the scale of days across the landscape using short-term weather forecasts and fire behavior models correctly parameterized for dominant vegetation types. In contrast, estimates of future levels of CO_2 and temperature can only be broadly bounded by scenarios of future emissions. Long-term climate projections are not designed to provide predictions of future conditions, but probabilistic statements of what the future climate could look like if certain conditions are met (see Box 1). Projections of change to fire activity in the near-term are simpler than longer-term projections of changes to fire regimes, because the long term will be determined by global greenhouse gas mitigation and may include non-linear fire regime shifts and unpredictable adaptive response of fire managers. For other drivers, such as wind and precipitation, the accuracy of projections quickly

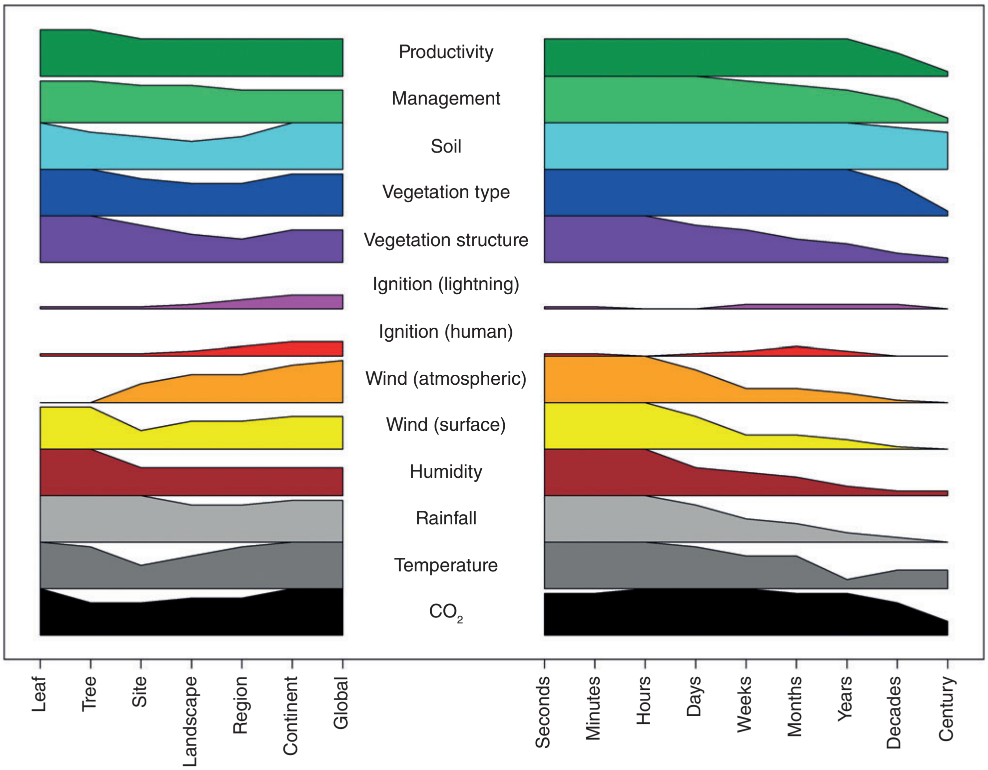

FIGURE 2 | A qualitative assessment of the certainty associated with projections of the drivers of fire across temporal and spatial scales. Thicker wedges indicate greater accuracy in measurements or projections of the driver at each scale. Scores are relative and unit-less. Spatial scale was scored on the ability to predict the variable under current conditions, while temporal scale was scored for one point in space, assuming best available knowledge. Further details are provided in Supporting Information.

degrade over time, either because the underlying physical mechanisms are not fully understood, or the mechanisms operate at a much finer resolution than that of general circulation models.[141] Land cover and associated fire activity can be predicted relatively accurately in the short term, but become less predictable at longer time scales due to the influence of social and political demands, which could shift in response to changes in area burnt and perceptions of fire risk to unburnt areas (discussed in *Conceptual Models*). Soil type is relatively static up to the scale of decades, so accurate predictions of soil moisture flux and eco-hydrological dynamics are possible, although landscape scale fires can have dramatic impacts on catchments, resulting in substantial shifts in hydrology and wide scale erosion and soil loss.[142] Sudden changes in soil can also occur when fires consume peatlands[143] or generate debris flows.[144] At time scales beyond decades, vegetation structure, condition and even type are unpredictable because of the interactions and feedbacks discussed above.

Overall, there are substantial gaps in our ability to project the biophysical drivers of fire, even when each driver is considered in isolation (as in Figure 2). The 'cascade of uncertainties' from the uncertainty associated with future emissions, carbon-cycle modeling and climate modeling[145] drives an even larger range of uncertain climate impacts, which is further compounded by interactions between the drivers of fire across scales of time and space.

APPROACHES RELEVANT TO UNDERSTANDING FUTURE FIRE ACTIVITY

There are three main approaches that can be used to inform our thinking about fire activity under future climate conditions. They were not designed to answer the same questions about fire activity or fire regimes, and are applicable at different scales, but each approach contributes information relevant to the challenge of projecting future fire activity.

Conceptual Models

Several conceptual models have been used to describe fire activity under current climate conditions, and

BOX 1

PREDICTION VERSUS PROJECTION

The challenges in understanding the complex and heterogeneous interactions between vegetation, fire, and climate require clarity in research objectives and an understanding of the available tools, climate models and projections. The most basic approach is to describe systems based on analyses of existing spatial and temporal data, to illuminate potential mechanisms. These mechanisms form the basis of models attempting to *predict* or *project* fire activity under a given climate or plausible future climates.

Fire activity *predictions* seek to describe a very complex response to specific changes in climatic conditions in specific areas, by a particular period in time. For example, fire managers may want to know the changing return interval of large wildfires on the urban fringe so they can best allocate scarce resources to protect lives and property. Climate predictions are generally only available for short-term forecasts (from 30 days to 2 years). They are initialized with observations, and attempt to produce an estimate of the actual evolution of the climate in the future. By contrast, climate *projections* are not predictions of future conditions, but probabilistic statements of what the future climate could look like if certain conditions are met. Their intention is not to make accurate predictions regarding the future state of the climate system at any given point in time, but to represent the range of plausible possible futures climates under a given set of scenarios of climate forcings and model-derived estimates of climate sensitivity (the temperature change resulting from increases in CO_2).[146]

provide a basis for thinking about future fire. All acknowledge the importance of climate and weather, operating at a range of temporal scales, in determining fire activity mediated through fuel effects.

The fire regime triangle reflects the three dominant factors influencing fire in different regions of the world.[147] These are the vegetation characteristics, fire weather climatology, and ignition patterns, all of which vary in importance spatially and temporally. This model identifies gradients in fire probabilities that are controlled by long-term environmental norms in addition to the spatial variation in probabilities driven by inter-annual fluctuations in environmental conditions (climate vs weather).

The intermediate-fire-productivity model, also known as the varying constraints hypothesis,[148] suggests that fire activity peaks at intermediate levels of aridity and productivity, reflecting the changing roles of fuel availability and drought as fire drivers along the productivity gradient.[132,149,150] In moist, productive regions there is an abundance of fuel, and fire activity is determined by the frequency of dry conditions, while in dry, unproductive regions fire activity is limited by fuel availability. Examples of the former are the Mediterranean-type ecosystems of California in the United States, the Mediterranean Basin of southern Europe and North Africa, the Western Cape region of South Africa and southwest and south Australia. Desert regions around the world belong to the latter, fuel limited type, while the savannahs of northern Australia and Africa represent an intermediate type in which high productivity and very dry conditions alternate between wet and dry seasons.

The four switch model[151] integrates many of the processes from the previous concepts, but adds greater understanding of the temporal dimension. It describes fire activity in terms of four factors that must be fulfilled simultaneously (switched 'on') for fire to occur. There must be fuel available (biomass); it must be dry enough to burn (availability to burn); weather conditions must be conducive to fire spread (fire weather), and there must be an ignition source (ignition). The four switches operate at very different temporal scales. The fuel switches develop over years to centuries, the weather switch operates over weeks to months and the ignition switch occurs in seconds.[152]

These conceptual models have contributed to our understanding that fire regimes will change in step with climate change and provide a framework for understanding the mechanisms of change in fire regimes at a global scale. All models suggest that climate change will affect fire activity differently in different biomes or ecosystems, so that fire may increase in some systems and decrease in others. For example, an increase in the frequency of droughts with climate change might increase fire activity in productive forest environments, but reduce fire activity in dry ecosystems where plant growth may be limited and fuel loads reduced.[132] Identifying the factor limiting fire in different ecosystems is a step forward because climate change will affect the limiting factors in different ways.

However, since these conceptual models were not designed to answer questions about fire activity under future climate conditions, they have some limitations when applied to this question. One constraint is that they deal with only one component determining fire regimes, the frequency of fire, and ignore other components such as the seasonality, intensity, and severity of fire.[152] Although fire frequency tends to be correlated with other characteristics of fire regimes, leading to relatively few combinations of broad fire regime types (or pyromes) globally,[9] relying solely on them risks underestimating widely differing ecological responses to climate change. Additionally, since equilibrium in the climate-vegetation-fire relationship is an underlying assumption of these models, they are unable to resolve the transient dynamics involved in ecological change. Finally, because feedbacks between fire, vegetation, climate, and socioeconomic drivers are not incorporated, they cannot predict the location, the timing or the impact of changes in fire regime, and are unable to consider the possibility of non-linear responses such as biome shifts into alternative stable states.[5]

Empirical Models

Empirical models attempt to build statistical models of fire based on fire activity and the prevailing climate conditions. Based on the assumption that the relationship between fire activity and climate remains unchanged into the future, they can be used to project into future climate conditions. Empirical models have been used to relate historical climate and fire activity inferred from paleoecological records of charcoal sediments, fire-scarred trees, and tree growth rings.[153–155] Such studies have identified shifts in the drivers of the global fire regime over time (from precipitation in preindustrial times, to anthropogenic drivers during the Industrial Revolution, to temperature under future climate conditions), and project the development of an unprecedentedly fire-prone global environment in the future.[156]

Empirical modeling approaches have been used to document the role of weather and climate on fire activity (e.g. Ref 157–160), validate the importance of productivity (e.g. Ref 68,147), and identify other environmental and social factors determining fire activity (e.g. Ref 161–163). Importantly, they have highlighted the substantial changes in fire activity in some regions that can result from relatively small changes in climatic drivers of fire, such as annual precipitation (e.g. Ref 164).

However, empirical models are often limited by the short observational records and limited temporal resolution available from observations, so they are unable to characterize fire activity in systems with very long fire return intervals. They can only identify patterns with those environmental and climatic variables included in the analyses, and they are unable to capture the potential for the relationships and interactions between key drivers to fundamentally change under future climate conditions. As with the conceptual models considered above, the ability of statistical models to predict climate change impacts on fire activity is fundamentally limited by the simplification required to reduce the complexity of fire regimes to a single variable such as fire frequency.[152]

Additionally, correlative models based on mean annual conditions will never capture the extreme events that are associated with the large, high intensity wildfires in biomass rich forests that have severe impacts on ecological and human communities, such as those in south-eastern Australia and California. While the models could be improved by using the extremes of the distribution such as the 99th percentile of fire danger indices,[152] the extremes are often not well simulated in projections of future climate.[165–167] Extreme fire weather is associated with specific synoptic-scale meteorological conditions and broader-scale oscillations,[168,169] which can be represented in dynamic climate models,[170,171] but are not captured by many commonly used climate projections, such as statistically downscaled products.[172,173] Similarly, extreme winds, which can drive fires under otherwise moderate weather conditions and create heavy fuel loads, are not currently well represented in climate models.[174]

Process Models

Process models attempt to quantify the understandings provided by conceptual and empirical models, and can incorporate projections of future climate to predict fire activity across landscapes and time.

Fire Behavior Models

Wildfire behavior models are generally used to inform operational fire management, by predicting the behavior of fire in response to changes in topography and fuel under particular weather conditions.[175] Examples include the Coupled Atmosphere-Wildland Fire-Environment (CAWFE),[176] FARSITE-Fire Area Simulator,[177] and PHOENIX RapidFire.[178] They require accurate data about topography, vegetation and fuel, in addition to weather predictions. Since they are designed to predict fire behavior at the landscape scale over the course of several days, they are not applicable to long-term projections of future fire activity. However, output from behavior models could be used to validate or adjust longer-term projections of fire activity.[179]

Landscape Fire Succession Models

Landscape fire succession models have been developed to simulate the interactions between fire and vegetation, by quantifying fuel accumulation and transitions between vegetation states or successional stages. These models have been used to investigate the relative importance of climate, weather and fuel characteristics on fire dynamics at the landscape scale.[180] Examples include FireBGCv2,[181] FIRESCAPE,[182,183] LAMOS-FATE-HS,[87] EMBYR,[184] and LANDSUM.[185]

This approach has demonstrated that the interaction between succession and fire alter landscape composition and structure enough to influence coarse-scale simulations, and these changes are amplified under future climate warming.[180] Detailed representations of vegetation succession are therefore necessary to realistically simulate interactions between fire and vegetation under future climate conditions.

However, the general application of landscape fire succession models is limited because their parameterization requires extensive empirical data (e.g. fuel accumulation and fire spread in particular forest types). They are therefore not readily transferable across different vegetation types (e.g. grassland vs temperate forest) or hemispheres (although there are exceptions[186]), and it is not possible to scale predictions of fire activity up to continental or global scales.

Dynamic Global Vegetation Models

Dynamic global vegetation models (DGVMs) simulate the long-term response of vegetation to climate processes at a global scale. Processes such as photosynthesis, competition, disturbance and mortality are modeled. Many DGVMs now include fire sub-models, in addition to the vegetation, carbon and water models (e.g. Ref 187–190). The latest generation of models (earth system models) also incorporate feedbacks between atmospheric and land processes so that changes in vegetation, carbon and hydrological cycles affect the climate.

DGVMs have been used to simulate global vegetation in the absence of fire, contributing to our understanding of the evolution of fire regimes and current vegetation patterns.[191] By evaluating the mismatch between climate potential and actual vegetation distribution, such experiments have highlighted the importance of fire as a global control of vegetation structure. Coupled with GCMs, DGVMs are the only way currently available to achieve a globally consistent analysis of future fire activity.

However, to achieve global applicability, DGVMs have to use simplified representations of landscapes, vegetation, and fire. Currently, most DGVMs describe vegetation in terms of broad functional types and physiognomic groups, rather than as individual plant species or vegetation communities.[192,193] This limits the ability of these models to simulate the responses of communities at regional scales, so that even the most advanced models fail to represent the seasonal and geographic distribution of fire activity globally.[194] Future improvements are likely, as demonstrated by Scheiter and Higgins,[195] who developed an individual-based model that simulates a heterogeneous tree population, with the biomass, carbon status, phenology and fire response of each tree being tracked over time.

There are several additional factors limiting the ability of DGVMs to accurately project vegetation dynamics and fire activity, particularly in intensively human-managed landscapes.[180,192] DGVMs do not dynamically simulate anthropogenic disturbance or land management decisions.[196,197] Some models assume that vegetation composition and structure are static, and only simulate climate effects on biogeochemistry and ecophysiology.[198,199] Others, such as state- and- transition and equilibrium biogeographical models, are based on the assumption that vegetation will change instantaneously when climate thresholds are crossed (e.g. Ref 200,201). Importantly, they are not initialized with current vegetation, which would enable the effects of past fire activity to be incorporated, and they lack realistic rates of vegetation growth and replacement affecting successional change (e.g. time lags to capture tree longevity).[192] Addressing these deficiencies requires information about vegetation at a fine spatial scale, which is lacking for most of the world.

Integrated Fire-vegetation Models

Integrated fire-vegetation models (IFVMs) are similar to DGVMs, in that they attempt to model the interacting effects of climate and other drivers on fuel availability and fire regimes. However, they differ slightly in terms of their focus. IFVMs integrate fire and vegetation models to study shifts in fire regimes resulting from changing conditions, while DGVMs model changing vegetation dynamics.[179] When coupled with GCMs, IFVMs are powerful tools for understanding future climate interactions with vegetation dynamics and fire, although the same limitations in the parameterisation of mechanisms apply. Examples include

Global FIRe Model (GlobFIRM)[202] and The Large-fire Simulator (FSim).[203]

FUTURE RESEARCH DIRECTIONS

The conceptual, empirical and process models discussed here all help direct thinking about feedbacks between vegetation, climate and fire, but quantifying these feedbacks demands better integration of the different model approaches[204] (Figure 3). Without better consideration of the underlying processes, existing empirical models will never be able to discriminate cause from effect, while process models could be improved with greater experimental validation,[205] particularly exploring feedbacks amongst system components. Improved empirical and process models provide the architecture for more nuanced conceptual models, which in combination with narratives of future societies can highlight research areas requiring refinement and quantification. Research is required to refine each of the approaches, but the development of plausible scenarios of future fire activity depends on the integration and synthesis of all approaches to inform dynamic experiments and improve simulations of future responses.

The concept of the pyrome is useful for describing patterns in current fire regimes,[9] but projecting potential changes to future fire regimes requires knowledge of the underlying mechanisms controlling fire at the biome level. Further historical reconstructions, longitudinal studies, and long-term monitoring should focus on filling in the knowledge gaps that exist in different biomes around the world. The state of knowledge remains highly skewed, with research being focused on ecosystems that are currently fire-prone, such as savannahs in Australia and Southern Africa, or the temperate forests of Australia and California and the rainforest of the Amazonia. In contrast, there is little knowledge about ecosystems such as the temperate grasslands of Central Asia and dry forests of southeast Asia, and those systems with a very close coupling between humans and fire, such as the rainforests of Asia. These gaps prevent comparative analyses which could identify testable hypotheses to direct future research.

More appropriate scale-dependent research questions are required to fill in the gaps that remain between the broad continental patterns and these regional or biome specific responses.[136] Different patterns, relationships, and mechanisms will be identified at different scales. If research questions are not applied at the appropriate scale to address specific objectives, artifacts of scale are likely to obscure actual patterns and processes. This is particularly important in studies of biological responses, where

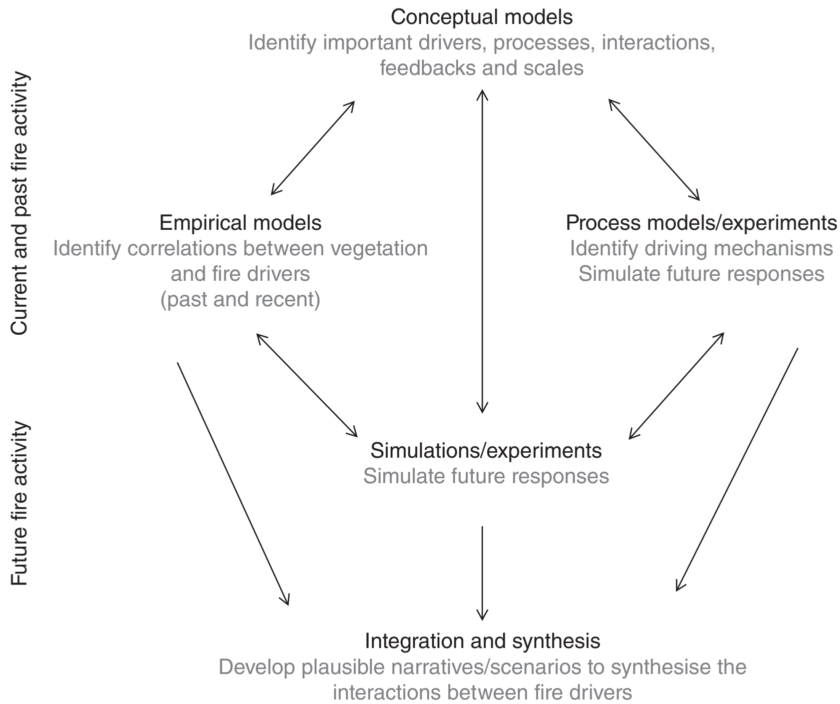

FIGURE 3 | The key approaches relevant to understanding fire danger under climate change (Adapted from Bowman et al.[204]).

interactions and feedbacks can appear to decouple responses from climate drivers, or introduce temporal lags. The identification of 'domains of scale,'[206] within which patterns or responses are similar, or scale in a predictable manner, would improve the ability to generalize across systems.

A better understanding of fire regimes across multiple scales would also improve predictions of fire activity.[124,207] Analyses performed at multiple spatial and temporal scales are necessary to identify the relative importance of the drivers of fire and identify times and places when broad-scale processes may be more or less important than fine-scale processes.[208,209] This would highlight cross-scale interactions which may lead to non-linear responses, such as occurs when catastrophic weather conditions over-ride the importance of fuel condition.[207] Related to this is the need for a better appreciation of the role that inter-annual and internal variability (e.g. ENSO, Pacific Decadal Oscillation) may play in determining fire regimes and activity,[210] particularly in regions such as Australia and Africa with large inter-annual climate variability.[86]

Satellite-based datasets are increasingly being used to inform empirical models, and show great potential to improve the models and our understanding of long-term vegetation change, landscape fire feedbacks on climate change and fire processes. The LANDSAT earth observation satellite program has operated for four decades now, and recent advances in computational power have enabled significant advances in cataloging long-term global vegetation and land use change.[211] Vegetation structural characteristics such as cover and life form are also being mapped at increasing resolution,[212] and technologies such as space borne LIDAR are providing global vegetation forest height fields.[213] Climate feedback drivers from landscape fire, such as aerosol emissions, are being captured in more detail from satellites,[214] and new geostationary satellites with a high temporal resolution, such as GOES-R and Himawari-8, are allowing us to gain information on intra-fire dynamics and intensity[215] in different vegetation types, as well as lightning strike density.[216] Improved global surveillance at high resolution will reduce the uncertainty that remains around the drivers of fire at the landscape, regional and continental scales (Figure 2), and will enable the spatial variation and temporal patterns, including switches to fire season, to be integrated into dynamic models.[217]

Dynamic modeling experiments will facilitate more thorough investigations of fire–vegetation feedbacks and interactions, but their success will depend on the inclusion of more complex biological, ecological, and social relationships in DGVMs.[218] The incorporation of current vegetation, improvements in plant functional types and the representation of vegetation growth and mortality is essential. This may be achieved by linking to other models, such as landscape succession models. For example, Yospin et al.[192] developed a climate-sensitive vegetation state-and-transition simulation model (CV-STSM). States were characterized based on assessments of both current and projected future vegetation from a DGVM. The model was integrated with an agent-based model of land use decisions and a mechanistic model of fire behavior and spread. They concluded that DGVMs alone will not be able to provide realistic projections of vegetation dynamics and disturbance. However, by combining DGVMs with state-and-transition models incorporating management decisions and land use change the interactions between disturbance and climate-change effects on vegetation can be simulated at a scale relevant to management.

Projections of future fire activity are only possible within a scenario framework, because fire activity is not solely a climate phenomenon. Models of fire activity based only on climate drivers are likely to be gross oversimplifications, and this will become more so as the influence of human drivers increases over time.[197] Recent DGVMs have started to incorporate decision-making for land use change scenarios,[219] but research is required to identify the socioeconomic and political mechanisms driving changes in fire policy.[197] Only by including the biological, atmospheric, and socioeconomic drivers of fire, and their interactions and feedbacks across spatial and temporal scales will we improve our understanding of fire under changing climate conditions. Global pyrogeography, the study of the spatial distribution of fire across large scales, has been suggested as one way to synthesize the biological, physical, and social science relevant to understanding the drivers of fire and define fire regimes.[5] The development of plausible scenarios should be informed by comparative analyses of contrasting approaches to fire management, land use changes and future greenhouse gas emissions to help improve fire management and carbon storage.

CONCLUSIONS

Conceptual, empirical, and process models have contributed to our understanding of the interactions and feedbacks between vegetation, fuel, and fire regimes, and provide a useful basis to consider future fire activity under climate change. These approaches, informed by greatly improved satellite data, have identified patterns and some of the mechanisms and processes driving fire regimes across temporal and spatial scales. Collectively, they suggest that climate change will affect fire activity differently in different biomes. However, there are many aspects of fire regimes, across the globe and at regional and landscape scales, which cannot be projected into the future using currently available tools. Until they are better represented in earth system models and projections of climate change, fire will remain a major barrier to our understanding of the future of the Earth system.

FURTHER READING

Scott AC, Bowman DMJS, Bond WJ, Pyne SJ, Alexander ME. *Fire on Earth: An Introduction*. John Wiley & Sons, Australia; 2014, 476 pp.

REFERENCES

1. Fauria MM, Michaletz ST, Johnson EA. Predicting climate change effects on wildfires requires linking processes across scales. *WIREs Clim Change* 2011, 2:99–112.
2. Potter BE. Atmospheric interactions with wildland fire behaviour – I. Basic surface interactions, vertical profiles and synoptic structures. *Int J Wildland Fire* 2012, 21:779–801.
3. Potter BE. Atmospheric interactions with wildland fire behaviour – II. Plume and vortex dynamics. *Int J Wildland Fire* 2012, 21:802–817.
4. Hennessy KJ, Lucas C, Nicholls N, Bathols J, Suppiah R, Ricketts J. Climate change impacts on fire-weather in south-east Australia; 2005, 91 pages.
5. Bowman DMJS, Murphy BP, Williamson GJ, Cochrane MA. Pyrogeographic models, feedbacks and the future of global fire regimes. *Glob Ecol Biogeogr* 2014, 23:821–824.
6. Gill AM. Fire and the Australian flora: a review. *Aust For* 1975, 38:4–25.
7. Krebs P, Pezzatti GB, Mazzoleni S, Talbot LM, Conedera M. Fire regime: history and definition of a key concept in disturbance ecology. *Theory Biosci* 2010, 129:53–69.
8. Chuvieco E, Giglio L, Justice C. Global characterization of fire activity: toward defining fire regimes from Earth observation data. *Glob Chang Biol* 2008, 14:1488–1502.
9. Archibald S, Lehmann CER, Gomez-Dans JL, Bradstock RA. Defining pyromes and global syndromes of fire regimes. *Proc Natl Acad Sci USA* 2013, 110:6442–6447.
10. Adams MA. Mega-fires, tipping points and ecosystem services: managing forests and woodlands in an uncertain future. *For Ecol Manage* 2013, 294:250–261.
11. Allen CD, Macalady AK, Chenchouni H, Bachelet D, McDowell N, Vennetier M, Kitzberger T, Rigling A, Breshears DD, Hogg EH, et al. A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. *For Ecol Manage* 2010, 259:660–684.
12. Logan JA, Regniere J, Powell JA. Assessing the impacts of global warming on forest pest dynamics. *Front Ecol Environ* 2003, 1:130–137.
13. McDowell NG, Allen CD. Darcy's law predicts widespread forest mortality under climate warming. *Nat Clim Change* 2015, 5:669–672.
14. Prior LD, Bowman DMJS. Big eucalypts grow more slowly in a warm climate: evidence of an interaction between tree size and temperature. *Glob Chang Biol* 2014, 20:2793–2799.
15. Duursma RA, Gimeno TE, Boer MM, Crous KY, Tjoelker MG, Ellsworth DS. Canopy leaf area of a mature evergreen Eucalyptus woodland does not respond to elevated atmospheric [CO2] but tracks water availability. *Glob Chang Biol* 2016, 22:1666–1676.
16. Keenan RJ. Climate change impacts and adaptation in forest management: a review. *Ann For Sci* 2015, 72:145–167.
17. Stokes C, Ash A, Tibbett M, Holtum J. OzFACE: the Australian savanna free air CO_2 enrichment facility and its relevance to carbon-cycling issues in a tropical savanna. *Aust J Bot* 2005, 53:677–687.
18. Wang X. Effects of species richness and elevated carbon dioxide on biomass accumulation: a synthesis using meta-analysis. *Oecologia* 2007, 152:595–605.
19. Williams RJ, Bradstock RA, Cary GJ, Enright NJ, Gill AM, Liedloff AC, Lucas C, Whelan RJ, Andersen AN, Bowman DMJS, et al. Interactions between climate change, fire regimes and biodiversity in Australia: a preliminary assessment. Report to the Department of Climate Change and the Department of the Environment, Water, Heritage and the Arts; 2009.

20. Brant AN, Chen HYH. Patterns and mechanisms of nutrient resorption in plants. *Crit Rev Plant Sci* 2015, 34:471–486.
21. Norby RJ, Zak DR. Ecological lessons from free-air CO_2 enrichment (FACE) experiments. In: Futuyma DJ, Shaffer HB, Simberloff D, eds. *Annual Review of Ecology, Evolution, and Systematics*, Annual Reviews, California vol. 42. 2011, 181–203.
22. Penuelas J, Canadell JG, Ogaya R. Increased water-use efficiency during the 20th century did not translate into enhanced tree growth. *Glob Ecol Biogeogr* 2011, 20:597–608.
23. Polley HW, Johnson HB, Derner JD. Soil- and plant-water dynamics in a C3/C4 grassland exposed to a subambient to superambient CO(2) gradient. *Glob Chang Biol* 2002, 8:1118–1129.
24. Morgan JA, Pataki DE, Korner C, Clark H, Del Grosso SJ, Grunzweig JM, Knapp AK, Mosier AR, Newton PCD, Niklaus PA, et al. Water relations in grassland and desert ecosystems exposed to elevated atmospheric CO_2. *Oecologia* 2004, 140:11–25.
25. Bond WJ, Midgley GF. Carbon dioxide and the uneasy interactions of trees and savannah grasses. *Philos Trans R Soc Lond B Biol Sci* 2012, 367:601–612.
26. Polley HW, Jin VL, Fay PA. Feedback from plant species change amplifies CO_2 enhancement of grassland productivity. *Glob Chang Biol* 2012, 18:2813–2823.
27. Polley HW, Johnson HB, Tischler CR. Woody invasion of grasslands: evidence that CO(2) enrichment indirectly promotes establishment of Prosopis glandulosa. *Plant Ecol* 2003, 164:85–94.
28. de Graaff MA, van Groenigen KJ, Six J, Hungate B, van Kessel C. Interactions between plant growth and soil nutrient cycling under elevated CO2: a meta-analysis. *Glob Chang Biol* 2006, 12:2077–2091.
29. Gong SW, Guo R, Zhang T, Guo JX. Warming and nitrogen addition increase litter decomposition in a temperate meadow ecosystem. *PLoS One* 2015, 10: e0116013.
30. Henry HAL, Cleland EE, Field CB, Vitousek PM. Interactive effects of elevated CO_2, N deposition and climate change on plant litter quality in a California annual grassland. *Oecologia* 2005, 142:465–473.
31. Talhelm AF, Pregitzer KS, Zak DR. Species-specific responses to atmospheric carbon dioxide and tropospheric ozone mediate changes in soil carbon. *Ecol Lett* 2009, 12:1219–1228.
32. Top SM, Filley TR. Effects of elevated CO_2 on the extractable amino acids of leaf litter and fine roots. *New Phytol* 2014, 202:1257–1265.
33. Ziska LH, Reeves JB, Blank B. The impact of recent increases in atmospheric CO_2 on biomass production and vegetative retention of Cheatgrass (Bromus tectorum): implications for fire disturbance. *Glob Chang Biol* 2005, 11:1325–1332.
34. Zvereva EL, Kozlov MV. Consequences of simultaneous elevation of carbon dioxide and temperature for plant-herbivore interactions: a metaanalysis. *Glob Chang Biol* 2006, 12:27–41.
35. Mattson WJ, Kuokkanen K, Niemelä P, Julkunen-Tiitto R, Kellomäki S, Tahvanainen J. Elevated CO_2 alters birch resistance to Lagomorpha herbivores. *Glob Chang Biol* 2004, 10:1402–1413.
36. Ainsworth EA, Long SP. What have we learned from 15 years of free-air CO2 enrichment (FACE)? A meta-analytic review of the responses of photosynthesis, canopy. *New Phytol* 2005, 165:351–371.
37. Dowdy AJ, Mills GA. Atmospheric and fuel moisture characteristics associated with lightning-attributed fires. *J Appl Meteorol Climatol* 2012, 51:2025–2037.
38. Root TL, Price JT, Hall KR, Schneider SH, Rosenzweig C, Pounds JA. Fingerprints of global warming on wild animals and plants. *Nature* 2003, 421:57–60.
39. Parmesan C, Hanley ME. Plants and climate change: complexities and surprises. *Ann Bot* 2015, 116:849–864.
40. Parmesan C. Ecological and evolutionary responses to recent climate change. *Annu Rev Ecol Evol Syst* 2006, 37:637–669.
41. Hellmann JJ, Byers JE, Bierwagen BG, Dukes JS. Five potential consequences of climate change for invasive species. *Conserv Biol* 2008, 22:534–543.
42. Walther GR, Roques A, Hulme PE, Sykes MT, Pysek P, Kuhn I, Zobel M, Bacher S, Botta-Dukat Z, Bugmann H, et al. Alien species in a warmer world: risks and opportunities. *Trends Ecol Evol* 2009, 24:686–693.
43. Zhao MS, Running SW. Drought-induced reduction in global terrestrial net primary production from 2000 through 2009. *Science* 2010, 329:940–943.
44. Nagel JM, Huxman TE, Griffin KL, Smith SD. CO_2 enrichment reduces the energetic cost of biomass construction in an invasive desert grass. *Ecology* 2004, 85:100–106.
45. Sasek TW, Strain BR. Efects of CO_2 enrichment on the growth and morphology of a native and an introduced honeysuckle vine. *Am J Bot* 1991, 78:69–75.
46. Smith SD, Huxman TE, Zitzer SF, Charlet TN, Housman DC, Coleman JS, Fenstermaker LK, Seemann JR, Nowak RS. Elevated CO_2 increases productivity and invasive species success in an arid ecosystem. *Nature* 2000, 408:79–82.
47. Ziska LH, Sicher RC, George K, Mohan JE. Rising atmospheric carbon dioxide and potential impacts on the growth and toxicity of poison ivy (Toxicodendron radicans). *Weed Sci* 2007, 55:288–292.
48. Brooks ML, D'Antonio CM, Richardson DM, Grace JB, Keeley JE, DiTomaso JM, Hobbs RJ,

Pellant M, Pyke D. Effects of invasive alien plants on fire regimes. *Bioscience* 2004, 54:677–688.

49. Mack RN, Simberloff D, Mark Lonsdale W, Evans H, Clout M, Bazzaz FA. Biotic invasions: causes, epidemiology, global consequences and control. *Ecol Appl* 2000, 10:689–710.
50. McGranahan DA, Engle DM, Miller JR, Debinski DM. An invasive grass increases live fuel proportion and reduces fire spread in a simulated grassland. *Ecosystems* 2013, 16:158–169.
51. Rossiter-Rachor NA, Setterfield SA, Douglas MM, Hutley LB, Cook GD. Andropogon gayanus (Gamba grass) invasion increases fire-mediated nitrogen losses in the tropical savannas of northern Australia. *Ecosystems* 2008, 11:77–88.
52. Sage RF, Kubien DS. Quo vadis C-4? An ecophysiological perspective on global change and the future of C4 plants. *Photosynth Res* 2003, 77:209–225.
53. Pau S, Edwards EJ, Still CJ. Improving our understanding of environmental controls on the distribution of C-3 and C-4 grasses. *Glob Chang Biol* 2013, 19:184–196.
54. Wand SJE, Midgley GF, Jones MH, Curtis PS. Responses of wild C4 and C3 grass (Poaceae) species to elevated atmospheric CO2 concentration: a meta-analytic test of current theories and perceptions. *Glob Chang Biol* 1999, 5:723–741.
55. Weber E. *Invasive Plant Species of the World: A Reference Guide to Environmental Weeds*. Wallingford: CABI Publishing; 2003.
56. Martin TG, Murphy H, Liedloff A. Invasive species and climate change: a framework for predicting species distribution when data is scarce. CSIRO Climate Adaptation Flagship Working Paper No. 13G, Canberra; 2012. Available at: https://research.csiro.au/climate/wp-content/uploads/sites/54/2016/03/13G_CAF-Working-Paper-13G.pdf (accessed February 15, 2016)
57. Parr CL, Ryan BJ, Setterfield SA. Habitat complexity and invasive species: the impacts of Gamba Grass (Andropogon gayanus) on invertebrates in an Australian tropical savanna. *Biotropica* 2010, 42:688–696.
58. Rossiter NA, Setterfield SA, Douglas MM, Hutley LB. Testing the grass-fire cycle: alien grass invasion in the tropical savannas of northern Australia. *Divers Distrib* 2003, 9:169–176.
59. Setterfield SA, Rossiter-Rachor NA, Douglas MM, Wainger L, Petty AM, Barrow P, Shepherd IJ, Ferdinands KB. Adding fuel to the fire: the impacts of non-native grass invasion on fire management at a regional scale. *PLoS One* 2013, 8:e59144. doi:10.1371/journal.pone.0059144.
60. Murphy BP, Bowman DMJS. What controls the distribution of tropical forest and savanna? *Ecol Lett* 2012, 15:748–758.
61. Hoffmann WA, Geiger EL, Gotsch SG, Rossatto DR, Silva LCR, Lau OL, Haridasan M, Franco AC. Ecological thresholds at the savanna-forest boundary: how plant traits, resources and fire govern the distribution of tropical biomes. *Ecol Lett* 2012, 15:759–768.
62. Bowman DMJS, Murphy BP, Neyland DLJ, Williamson GJ, Prior LD. Abrupt fire regime change may cause landscape-wide loss of mature obligate seeder forests. *Glob Chang Biol* 2014, 20:1008–1015.
63. Lindenmayer DB, Hobbs RJ, Likens GE, Krebs CJ, Banks SC. Newly discovered landscape traps produce regime shifts in wet forests. *Proc Natl Acad Sci USA* 2011, 108:15887–15891.
64. Enright NJ, Fontaine JB, Bowman D, Bradstock RA, Williams RJ. Interval squeeze: altered fire regimes and demographic responses interact to threaten woody species persistence as climate changes. *Front Ecol Environ* 2015, 13:265–272.
65. Bowman DMJS, Balch J, Artaxo P, Bond WJ, Cochrane MA, D'Antonio CM, DeFries R, Johnston FH, Keeley JE, Krawchuk MA, et al. The human dimension of fire regimes on Earth. *J Biogeogr* 2011, 38:2223–2236.
66. Bowman DMJS, O'Brien JA, Goldammer JG. Pyrogeography and the global quest for sustainable fire management. *Annu Rev Environ Resour* 2013, 38:57–80.
67. Archibald S, Staver AC, Levin SA. Evolution of human-driven fire regimes in Africa. *Proc Natl Acad Sci USA* 2012, 109:847–852.
68. Krawchuk MA, Moritz MA, Parisien MA, Van Dorn J, Hayhoe K. Global pyrogeography: the current and future distribution of wildfire. *PLoS One* 2009, 4: e5102.
69. Butsic V, Kelly M, Moritz MA. Land use and wildfire: a review of local interactions and teleconnections. *Land* 2015, 4:140–156.
70. Bryant BP, Westerling AL. Scenarios for future wildfire risk in California: links between changing demography, land use, climate, and wildfire. *Environmetrics* 2014, 25:454–471.
71. Liu ZH, Yang J, Chang Y, Weisberg PJ, He HS. Spatial patterns and drivers of fire occurrence and its future trend under climate change in a boreal forest of Northeast China. *Glob Chang Biol* 2012, 18:2041–2056.
72. Romero-Calcerrada R, Novillo CJ, Millington JDA, Gomez-Jimenez I. GIS analysis of spatial patterns of human-caused wildfire ignition risk in the SW of Madrid (Central Spain). *Landsc Ecol* 2008, 23:341–354.
73. Syphard AD, Radeloff VC, Keeley JE, Hawbaker TJ, Clayton MK, Stewart SI, Hammer RB. Human influence on California fire regimes. *Ecol Appl* 2007, 17:1388–1402.

74. McWethy DB, Higuera PE, Whitlock C, Veblen TT, Bowman DMJS, Cary GJ, Haberle SG, Keane RE, Maxwell BD, McGlone MS, et al. A conceptual framework for predicting temperate ecosystem sensitivity to human impacts on fire regimes. *Glob Ecol Biogeogr* 2013, 22:900–912.
75. Stephens SL, Martin RE, Clinton NE. Prehistoric fire area and emissions from California's forests, woodlands, shrublands, and grasslands. *For Ecol Manage* 2007, 251:205–216.
76. Baker WL. Are high-severity fires burning at much higher rates recently than historically in dry-forest landscapes of the Western USA? *PLoS One* 2015, 10: e0136147.
77. Keeley JE, Zedler PH. Large, high-intensity fire events in southern California shrublands: debunking the fine-grain age patch model. *Ecol Appl* 2009, 19:69–94.
78. Moritz MA, Batllori E, Bradstock RA, Gill AM, Handmer J, Hessburg PF, Leonard J, McCaffrey S, Odion DC, Schoennagel T, et al. Learning to coexist with wildfire. *Nature* 2014, 515:58–66.
79. Plucinski MP. The timing of vegetation fire occurrence in a human landscape. *Fire Saf J* 2014, 67:42–52.
80. Penman TD, Bradstock RA, Price O. Modelling the determinants of ignition in the Sydney Basin, Australia: implications for future management. *Int J Wildland Fire* 2013, 22:469–478.
81. Waltz AEM, Stoddard MT, Kalies EL, Springer JD, Huffman DW, Meador AS. Effectiveness of fuel reduction treatments: assessing metrics of forest resiliency and wildfire severity after the Wallow Fire, AZ. *For Ecol Manage* 2014, 334:43–52.
82. Fox-Hughes P, Harris RM, Lee G, Grose M, Bindoff NL. Future fire danger climatology for Tasmania, Australia, using a dynamically downscaled regional climate model. *Int J Wildland Fire* 2014, 23:309–321.
83. Flannigan M, Cantin AS, de Groot WJ, Wotton M, Newbery A, Gowman LM. Global wildland fire season severity in the 21st century. *For Ecol Manage* 2013, 294:54–61.
84. Liu YQ, Stanturf J, Goodrick S. Trends in global wildfire potential in a changing climate. *For Ecol Manage* 2010, 259:685–697.
85. Westerling AL, Hidalgo HG, Cayan DR, Swetnam TW. Warming and earlier spring increase western US forest wildfire activity. *Science* 2006, 313:940–943.
86. Jolly WM, Cochrane MA, Freeborn PH, Holden ZA, Brown TJ, Williamson GJ, Bowman D. Climate-induced variations in global wildfire danger from 1979 to 2013. *Nat Commun* 2015, 6:7537. doi: 10.1038/ncomms8537.
87. Bradstock RA, Cary GJ, Davies I, Lindenmayer DB, Price OF, Williams RJ. Wildfires, fuel treatment and risk mitigation in Australian eucalypt forests: insights from landscape-scale simulation. *J Environ Manage* 2012, 105:66–75.
88. Haikerwal A, Akram M, Del Monaco A, Smith K, Sim MR, Meyer M, Tonkin AM, Abramson MJ, Dennekamp M. Impact of fine particulate matter (PM2.5) exposure during wildfires on cardiovascular health outcomes. *J Am Heart Assoc* 2015, 4:e001653.
89. Hurteau MD, Westerling AL, Wiedinmyer C, Bryant BP. Projected effects of climate and development on California wildfire emissions through 2100. *Environ Sci Technol* 2014, 48:2298–2304.
90. Johnston F, Bowman D. Bushfire smoke: an exemplar of coupled human and natural systems. *Geogr Res* 2014, 52:45–54.
91. Johnston FH, Henderson SB, Chen Y, Randerson JT, Marlier M, DeFries RS, Kinney P, Bowman D, Brauer M. Estimated global mortality attributable to smoke from landscape fires. *Environ Health Perspect* 2012, 120:695–701.
92. Reinhardt ED, Keane RE, Calkin DE, Cohen JD. Objectives and considerations for wildland fuel treatment in forested ecosystems of the interior western United States. *For Ecol Manage* 2008, 256:1997–2006.
93. Price OE, Bradstock RA, Keeley JE, Syphard AD. The impact of antecedent fire area on burned area in southern California coastal ecosystems. *J Environ Manage* 2012, 113:301–307.
94. IPCC. Managing the risks of extreme events and disasters to advance climate change adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change; 2012, 582 pp.
95. Boer MM, Sadler RJ, Wittkuhn RS, McCaw L, Grierson PF. Long-term impacts of prescribed burning on regional extent and incidence of wildfires—Evidence from 50 years of active fire management in SW Australian forests. *For Ecol Manage* 2009, 259:132–142.
96. Price OF, Pausas JG, Govender N, Flannigan M, Fernandes PM, Brooks ML, Bird RB. Global patterns in fire leverage: the response of annual area burnt to previous fire. *Int J Wildland Fire* 2015, 24:297–306.
97. Price OF, Penman TD, Bradstock RA, Boer MM, Clarke H. Biogeographical variation in the potential effectiveness of prescribed fire in south-eastern Australia. *J Biogeogr* 2015, 42:2234–2245.
98. Fernandes PM, Botelho HS. A review of prescribed burning effectiveness in fire hazard reduction. *Int J Wildland Fire* 2003, 12:117–128.
99. Blackhall M, Raffaele E, Veblen TT. Is foliar flammability of woody species related to time since fire and herbivory in northwest Patagonia, Argentina? *J Veg Sci* 2012, 23:931–941.

100. Zylstra P. The historical influence of fire on the flammability of subalpine Snowgum forest and woodland. *Victorian Nat* 2013, 130:232–239.

101. Zhang Y, Fu R, Yu HB, Qian Y, Dickinson R, Dias M, Dias PLD, Fernandes K. Impact of biomass burning aerosol on the monsoon circulation transition over Amazonia. *Geophys Res Lett* 2009, 36: L10814.

102. Rosenfeld D. TRMM observed first direct evidence of smoke from forest fires inhibiting rainfall. *Geophys Res Lett* 1999, 26:3105–3108.

103. Sheil D, Murdiyarso D. How forests attract rain: an examination of a new hypothesis. *Bioscience* 2009, 59:341–347.

104. Bowman DMJS, Balch JK, Artaxo P, Bond WJ, Carlson JM, Cochrane MA, D'Antonio CM, DeFries RS, Doyle JC, Harrison SP, et al. Fire in the earth system. *Science* 2009, 324:481–484.

105. van der Werf GR, Randerson JT, Giglio L, Collatz GJ, Mu M, Kasibhatla PS, Morton DC, DeFries RS, Jin Y, van Leeuwen TT. Global fire emissions and the contribution of deforestation, savanna, forest, agricultural, and peat fires (1997–2009). *Atmos Chem Phys* 2010, 10:11707–11735.

106. Page SE, Siegert F, Rieley JO, Boehm HDV, Jaya A, Limin S. The amount of carbon released from peat and forest fires in Indonesia during 1997. *Nature* 2002, 420:61–65.

107. Stavros EN, McKenzie D, Larkin N. The climate-wildfire-air quality system: interactions and feedbacks across spatial and temporal scales. *WIREs Clim Change* 2014, 5:719–733.

108. Altaratz O, Koren I, Yair Y, Price C. Lightning response to smoke from Amazonian fires. *Geophys Res Lett* 2010, 37:L07801.

109. Beck PSA, Goetz SJ, Mack MC, Alexander HD, Jin YF, Randerson JT, Loranty MM. The impacts and implications of an intensifying fire regime on Alaskan boreal forest composition and albedo. *Glob Chang Biol* 2011, 17:2853–2866.

110. Rocha AV, Loranty MM, Higuera PE, Mack MC, Hu FS, Jones BM, Breen AL, Rastetter EB, Goetz SJ, Shaver GR. The footprint of Alaskan tundra fires during the past half-century: implications for surface properties and radiative forcing. *Environ Res Lett* 2012, 7:044039.

111. Randerson JT, Liu H, Flanner MG, Chambers SD, Jin Y, Hess PG, Pfister G, Mack MC, Treseder KK, Welp LR, et al. The impact of boreal forest fire on climate warming. *Science* 2006, 314:1130–1132.

112. Chambers SD, Beringer J, Randerson JT, Chapin FS. Fire effects on net radiation and energy partitioning: contrasting responses of tundra and boreal forest ecosystems. *J Geophys Res Atmos* 2005, 110:D09106.

113. Liu HP, Randerson JT. Interannual variability of surface energy exchange depends on stand age in a boreal forest fire chronosequence. *J Geophys Res Biogeosci* 2008, 113:G01006.

114. Myhre G, Samset BH, Schulz M, Balkanski Y, Bauer S, Berntsen TK, Bian H, Bellouin N, Chin M, Diehl T, et al. Radiative forcing of the direct aerosol effect from AeroCom Phase II simulations. *Atmos Chem Phys* 2013, 13:1853–1877.

115. Urbanski SP, Hao WM, Baker S. Chemical composition of wildland fire emissions. In: *Developments in Environmental Science*, vol. 8. Amsterdam: Elsevier B.V.; 2009, 79–107.

116. Lohmann U, Lesins G. Stronger constraints on the anthropogenic indirect aerosol effect. *Science* 2002, 298:1012–1015.

117. Myhre G, Shindell D, Bréon F-M, Collins W, Fuglestvedt J, Huang J, Koch D, Lamarque J-F, Lee D, Mendoza B, et al. Anthropogenic and natural radiative forcing. In: Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM, eds. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge and New York: Cambridge University Press; 2013.

118. Woolford DG, Dean CB, Martell DL, Cao J, Wotton BM. Lightning-caused forest fire risk in Northwestern Ontario, Canada, is increasing and associated with anomalies in fire weather. *Environmetrics* 2014, 25:406–416.

119. Price C, Rind D. The impact of a 2-X-CO_2 climate on lightning-caused fires. *J Climate* 1994, 7:1484–1494.

120. Price C, Rind D. Possible implications of global climate change on global lightning distributions and frequencies. *J Geophys Res Atmos* 1994, 99:10823–10831.

121. Krause A, Kloster S, Wilkenskjeld S, Paeth H. The sensitivity of global wildfires to simulated past, present, and future lightning frequency. *J Geophys Res Biogeosci* 2014, 119:312–322.

122. Price C. Thunderstorms, lightning and climate change. In: Betz HD, Schumann U, Laroche P, eds. *Lightning: Principles, Instruments and Application*. Netherlands: Springer; 2009, 521–535.

123. Krawchuk MA, Moritz MA. Burning issues: statistical analyses of global fire data to inform assessments of environmental change. *Environmetrics* 2014, 25:472–481.

124. Falk DA, Miller C, McKenzie D, Black AE. Cross-scale analysis of fire regimes. *Ecosystems* 2007, 10:809–823.

125. Moritz MA, Morais ME, Summerell LA, Carlson JM, Doyle J. Wildfires, complexity, and highly optimized

tolerance. *Proc Natl Acad Sci USA* 2005, 102:17912–17917.

126. Whitlock C, Higuera PE, McWethy DB, Briles CE. Paleoecological perspective on fire ecology: revisiting the fire regime concept. *Open Ecol J* 2010, 3:6–23.

127. Fernandes PM, Cruz MG. Plant flammability experiments offer limited insight into vegetation–fire dynamics interactions. *New Phytol* 2012, 194:606–609.

128. Leakey ADB, Ainsworth EA, Bernacchi CJ, Rogers A, Long SP, Ort DR. Elevated CO_2 effects on plant carbon, nitrogen, and water relations: six important lessons from FACE. *J Exp Bot* 2009, 60:2859–2876.

129. Langley JA, Hungate BA. Plant community feedbacks and long-term ecosystem responses to multi-factored global change. *AoB Plants* 2014, 6:plu035.

130. Gimeno TE, Crous KY, Cooke J, O'Grady AP, Ósvaldsson A, Medlyn BE, Ellsworth DS. Conserved stomatal behaviour under elevated CO_2 and varying water availability in a mature woodland. *Functional Ecology* 2015, 30:700–709.

131. Way DA, Oren R, Kroner Y. The space-time continuum: the effects of elevated CO_2 and temperature on trees and the importance of scaling. *Plant Cell Environ* 2015, 38:991–1007.

132. Pausas JG, Ribeiro E. The global fire productivity relationship. *Glob Ecol Biogeogr* 2013, 22:728–736.

133. Costa L, Thonicke K, Poulter B, Badeck FW. Sensitivity of Portuguese forest fires to climatic, human, and landscape variables: subnational differences between fire drivers in extreme fire years and decadal averages. *Reg Environ Change* 2011, 11:543–551.

134. Cyr D, Gauthier S, Bergeron Y. Scale-dependent determinants of heterogeneity in fire frequency in a coniferous boreal forest of eastern Canada. *Landsc Ecol* 2007, 22:1325–1339.

135. Parisien M-A, Parks SA, Krawchuk MA, Little JM, Flannigan MD, Gowman LM, Moritz MA. An analysis of controls on fire activity in boreal Canada: comparing models built with different temporal resolutions. *Ecol Appl* 2014, 24:1341–1356.

136. Wiens JA. Spatial scaling in ecology. *Funct Ecol* 1989, 3:385–397.

137. Little JK, Prior LD, Williamson GJ, Williams SE, Bowman D. Fire weather risk differs across rain forestusavanna boundaries in the humid tropics of north-eastern Australia. *Austral Ecol* 2012, 37:915–925.

138. Zhang YJ, Ma M, Lu WT, Tao SC. Review on climate characteristics of lightning activity. *Acta Meteorologica Sinica* 2010, 24:137–149.

139. Marlon JR, Bartlein PJ, Carcaillet C, Gavin DG, Harrison SP, Higuera PE, Joos F, Power MJ, Prentice IC. Climate and human influences on global biomass burning over the past two millennia. *Nat Geosci* 2008, 1:697–702.

140. Power MJ, Marlon J, Ortiz N, Bartlein PJ, Harrison SP, Mayle FE, Ballouche A, Bradshaw RHW, Carcaillet C, Cordova C, et al. Changes in fire regimes since the Last Glacial Maximum: an assessment based on a global synthesis and analysis of charcoal data. *Climate Dynam* 2008, 30:887–907.

141. Field CB, Barros V, Stocker TF, Qin D, Dokken DJ, Ebi KL, Mastrandrea MD, Mach KJ, Plattner G-K, Allen SK, et al. *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change*. Cambridge and New York: Cambridge University Press; 2012.

142. Bowman DMJS, Boggs GS. Fire ecology. *Prog Phys Geogr* 2006, 30:245–257.

143. Kettridge N, Turetsky MR, Sherwood JH, Thompson DK, Miller CA, Benscoter BW, Flannigan MD, Wotton BM, Waddington JM. Moderate drop in water table increases peatland vulnerability to post-fire regime shift. *Sci Rep* 2015, 5:8063.

144. Parise M, Cannon SH. Wildfire impacts on the processes that generate debris flows in burned watersheds. *Nat Hazards* 2012, 61:217–227.

145. Schneider SH. What is 'dangerous' climate change? *Nature* 2001, 411:17–19.

146. IPCC. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change 2007.

147. Moritz MA, Parisien MA, Batllori E, Krawchuk MA, Van Dorn J, Ganz DJ, Hayhoe K. Climate change and disruptions to global fire activity. *Ecosphere* 2012, 3:UNSP 49. doi:10.1890/es1811-00345.00341.

148. Krawchuk MA, Moritz MA. Constraints on global fire activity vary across a resource gradient. *Ecology* 2011, 92:121–132.

149. Pausas JG, Bradstock RA. Fire persistence traits of plants along a productivity and disturbance gradient in mediterranean shrublands of south-east Australia. *Glob Ecol Biogeogr* 2007, 16:330–340.

150. van der Werf GR, Randerson JT, Giglio L, Gobron N, Dolman AJ. Climate controls on the variability of fires in the tropics and subtropics. *Global Biogeochem Cycles* 2008, 22:GB3028.

151. Bradstock RA. A biogeographic model of fire regimes in Australia: current and future implications. *Glob Ecol Biogeogr* 2010, 19:145–158.

152. Murphy BP, Williamson GJ, Bowman D. Fire regimes: moving from a fuzzy concept to geographic entity. *New Phytol* 2011, 192:316–318.

153. McKenzie D, Gedalof Z, Peterson DL, Mote P. Climatic change, wildfire, and conservation. *Conserv Biol* 2004, 18:890–902.

154. Marlon JR, Bartlein PJ, Daniau AL, Harrison SP, Maezumi SY, Power MJ, Tinner W, Vanniere B. Global biomass burning: a synthesis and review of Holocene paleofire records and their controls. *Quaternary Sci Rev* 2013, 65:5–25.

155. Scott AC. Charcoal recognition, taphonomy and uses in palaeoenvironmental analysis. *Palaeogeography Palaeoclimatology Palaeoecology* 2010, 291:11–39.

156. Pechony O, Shindell DT. Driving forces of global wildfires over the past millennium and the forthcoming century. *Proc Natl Acad Sci USA* 2010, 107:19167–19170.

157. Westerling AL, Gershunov A, Brown TJ, Cayan DR, Dettinger MD. Climate and wildfire in the western United States. *Bull Am Meteorol Soc* 2003, 84:595–604.

158. Swetnam TW, Betancourt JL. Fire-southern oscillation relations in the southwestern United States. *Science* 1990, 249:1017–1020.

159. Gedalof Z, Peterson DL, Mantua NJ. Atmospheric, climatic, and ecological controls on extreme wildfire years in the northwestern United States. *Ecol Appl* 2005, 15:154–174.

160. Barbero R, Abatzoglou JT, Kolden CA, Hegewisch KC, Larkin NK, Podschwit H. Multiscalar influence of weather and climate on very large-fires in the Eastern United States. *Int J Climatol* 2015, 35:2180–2186.

161. Archibald S, Roy DP, van Wilgen BW, Scholes RJ. What limits fire? An examination of drivers of burnt area in Southern Africa. *Glob Chang Biol* 2009, 15:613–630.

162. Ager AA, Preisler HK, Arca B, Spano D, Salis M. Wildfire risk estimation in the Mediterranean area. *Environmetrics* 2014, 25:384–396.

163. Chuvieco E, Martinez S, Roman MV, Hantson S, Pettinari ML. Integration of ecological and socioeconomic factors to assess global vulnerability to wildfire. *Glob Ecol Biogeogr* 2014, 23:245–258.

164. Batllori E, Parisien MA, Krawchuk MA, Moritz MA. Climate change-induced shifts in fire for Mediterranean ecosystems. *Glob Ecol Biogeogr* 2013, 22:1118–1129.

165. Alexander LV, Tapper N, Zhang XB, Fowler HJ, Tebaldi C, Lynch A. Climate extremes: progress and future directions. *Int J Climatol* 2009, 29:317–319.

166. Zhang XB, Alexander L, Hegerl GC, Jones P, Tank AK, Peterson TC, Trewin B, Zwiers FW. Indices for monitoring changes in extremes based on daily temperature and precipitation data. *WIREs Clim Change* 2011, 2:851–870.

167. Perkins SE. A review on the scientific understanding of heatwaves—Their measurement, driving mechanisms, and changes at the global scale. *Atmos Res* 2015, 164–165:242–267.

168. Hasson AEA, Mills GA, Timbal B, Walsh K. Assessing the impact of climate change on extreme fire weather events over southeastern Australia. *Climate Res* 2009, 39:159–172.

169. Amraoui M, Pereira MG, DaCamara CC, Calado TJ. Atmospheric conditions associated with extreme fire activity in the Western Mediterranean region. *Sci Total Environ* 2015, 524:32–39.

170. Grose MR, Pook MJ, McIntosh PC, Risbey JS, Bindoff NL. The simulation of cutoff lows in a regional climate model: reliability and future trends. *Climate Dynam* 2012, 39:445–459.

171. Grose MR, Timbal B, Wilson L, Bathols J, Kent D. The subtropical ridge in CMIP5, and implications for projections of rainfall in southeast Australia. *Aust Meteorol Oceanogr J* 2015, 65:90–106.

172. Harris RM, Grose M, Lee G, Bindoff NL, Porfirio LL, Fox-Hughes P. Climate projections for ecologists. *WIREs Clim Change* 2014, 5:621–637. doi:10.1002/wcc.1291.

173. Ekström M, Grose MR, Whetton PH. An appraisal of downscaling methods used in climate change research. *WIREs Clim Change* 2015, 6:301–319.

174. Kumar D, Mishra V, Ganguly A. Evaluating wind extremes in CMIP5 climate models. *Climate Dynam* 2015, 45:441–453.

175. Scott AC, Bowman DMJS, Bond WJ, Pyne SJ, Alexander ME. *Fire on Earth: An Introduction*. Chichester: Wiley-Blackwell; 2014.

176. Coen JL. Modeling Wildland Fires: A Description of the Coupled Atmosphere-Wildland Fire Environment Model (CAWFE). 2013, 38 Pages.

177. Finney MA. FARSITE: FireaArea Simulator-Model Development and Evaluation. 2004, 47 pages.

178. Chong D, Tolhurst K, Duff T, Cirulis B. Sensitivity Analysis of PHOENIX RapidFire. Technical Report prepared by the Bushfire CRC 2013.

179. Herawati H, Gonzalez-Olabarria JR, Wijaya A, Martius C, Purnomo H, Andriani R. Tools for assessing the impacts of climate variability and change on wildfire regimes in forests. *Forests* 2015, 6:1476–1499.

180. Keane RE, Cary GJ, Flannigan MD, Parsons RA, Davies ID, King KJ, Li C, Bradstock RA, Gill M. Exploring the role of fire, succession, climate, and weather on landscape dynamics using comparative modeling. *Ecol Model* 2013, 266:172–186.

181. Keane RE, Loehman RA, Holsinger LM. The FireBGCv2 landscape fire and succession model: a research simulation platform for exploring fire and vegetation dynamics. General Technical Report RMRS-GTR-255 2011.

182. Cary GJ, Keane RE, Gardner RH, Lavorel S, Flannigan MD, Davies ID, Li C, Lenihan JM, Rupp TS, Mouillot F. Comparison of the sensitivity

of landscape-fire-succession models to variation in terrain, fuel pattern, climate and weather. *Landsc Ecol* 2006, 21:121–137.

183. King KJ, de Ligt RM, Cary GJ. Fire and carbon dynamics under climate change in south-eastern Australia: insights from FullCAM and FIRESCAPE modelling. *Int J Wildland Fire* 2011, 20:563–577.
184. Hargrove WW, Gardner RH, Turner MG, Romme WH, Despain DG. Simulating fire patterns in heterogeneous landscapes. *Ecol Model* 2000, 135:243–263.
185. Keane RE, Holsinger LM, Pratt SD. Simulating historical landscape dynamics using the landscape fire succession model LANDSUM version 4.0. General Technical Report RMRS-GTR-171CD 2006, 73 pages.
186. Yospin GI, Wood SW, Holz A, Bowman DMJS, Keane RE, Whitlock C. Modeling vegetation mosaics in sub-alpine Tasmania under various fire regimes. *Model Earth Syst Environ* 2015, 1:1–10.
187. Pfeiffer M, Spessa A, Kaplan JO. A model for global biomass burning in preindustrial time: LPJ-LMfire (v1.0). *Geosci Model Dev* 2013, 6:643–685.
188. Fosberg MA, Cramer W, Brovkin V, Fleming R, Gardner R, Gill AM, Goldammer JG, Keane R, Koehler P, Lenihan J, et al. Strategy for a fire module in dynamic global vegetation models. *Int J Wildland Fire* 1999, 9:79–84.
189. Arora VK, Boer GJ. Fire as an interactive component of dynamic vegetation models. *J Geophys Res Biogeosci* 2005, 110:G02008.
190. Spessa A. Modeling vegetation fires and fire emissions. In: Goldammer JG, ed. *Vegetation Fires and Global Change. Challenges for Concerted International Action. A White Paper directed to the United Nations and International Organizations*. Germany: Global Fire Monitoring Center (GFMC); 2013.
191. Bond WJ, Woodward FI, Midgley GF. The global distribution of ecosystems in a world without fire. *New Phytol* 2005, 165:525–537.
192. Yospin GI, Bridgham SD, Neilson RP, Bolte JP, Bachelet DM, Gould PJ, Harrington CA, Kertis JA, Evers C, Johnson BR. A new model to simulate climate-change impacts on forest succession for local land management. *Ecol Appl* 2015, 25:226–242.
193. Bachelet D, Neilson RP, Lenihan JM, Drapek RJ. Climate change effects on vegetation distribution and carbon budget in the United States. *Ecosystems* 2001, 4:164–185.
194. Kelley DI, Prentice IC, Harrison SP, Wang H, Simard M, Fisher JB, Willis KO. A comprehensive benchmarking system for evaluating global vegetation models. *Biogeosciences* 2013, 10:3313–3340.
195. Scheiter S, Higgins SI. Impacts of climate change on the vegetation of Africa: an adaptive dynamic vegetation modelling approach. *Glob Chang Biol* 2009, 15:2224–2246.
196. Scheller RM, Mladenoff DJ. An ecological classification of forest landscape simulation models: tools and strategies for understanding broad-scale forested ecosystems. *Landsc Ecol* 2007, 22:491–505.
197. Ruffault J, Mouillot F. How a new fire-suppression policy can abruptly reshape the fire-weather relationship. *Ecosphere* 2015, 6:199.
198. Running SW, Nemani RR. Regional hydrological and carbon balance responses of forests resulting from potential climate change. *Clim Change* 1991, 19:349–368.
199. Neilson RP, Running SW. Global dynamic vegetation modelling: coupling biogeochemistry and biogeography models. In: *Global Change and Terrestrial Ecosystems*. New York: Cambridge University Press; 1996, 451–465.
200. Halofsky JE, Hemstrom MA, Conklin DR, Halofsky JS, Kerns BK, Bachelet D. Assessing potential climate change effects on vegetation using a linked model approach. *Ecol Model* 2013, 266:131–143.
201. Strand EK, Vierling LA, Bunting SC, Gessler PE. Quantifying successional rates in western aspen woodlands: current conditions, future predictions. *For Ecol Manage* 2009, 257:1705–1715.
202. Thonicke K, Venevsky S, Sitch S, Cramer W. The role of fire disturbance for global vegetation dynamics: coupling fire into a Dynamic Global Vegetation Model. *Glob Ecol Biogeogr* 2001, 10:661–677.
203. Finney MA, McHugh CW, Grenfell IC, Riley KL, Short KC. A simulation of probabilistic wildfire risk components for the continental United States. *Stoch Environ Res Risk Assess* 2011, 25:973–1000.
204. Bowman DMJS, Perry GLW, Marston JB. Feedbacks and landscape-level vegetation dynamics. *Trends Ecol Evol* 2015, 30:255–260.
205. Finney MA, Cohen JD, McAllister SS, Jolly WM. On the need for a theory of wildland fire spread. *Int J Wildland Fire* 2013, 22:25–36.
206. Wiens JA, Bachelet D. Matching the multiple scales of conservation with the multiple scales of climate change. *Conserv Biol* 2010, 24:51–62.
207. Peters DPC, Pielke RA, Bestelmeyer BT, Allen CD, Munson-McGee S, Havstad KM. Cross-scale interactions, nonlinearities, and forecasting catastrophic events. *Proc Natl Acad Sci USA* 2004, 101:15130–15135.
208. Parisien MA, Parks SA, Krawchuk MA, Flannigan MD, Bowman LM, Moritz MA. Scale-dependent controls on the area burned in the boreal forest of Canada, 1980–2005. *Ecol Appl* 2011, 21:789–805.
209. Parks SA, Parisien MA, Miller C. Multi-scale evaluation of the environmental controls on burn

probability in a southern Sierra Nevada landscape. *Int J Wildland Fire* 2011, 20:815–828.

210. Grant JW, Lynda DP, Jolly WM, Mark AC, Brett PM, David MJSB. Measurement of inter- and intra-annual variability of landscape fire activity at a continental scale: the Australian case. *Environ Res Lett* 2016, 11:035003.
211. Hansen MC, Potapov PV, Moore R, Hancher M, Turubanova SA, Tyukavina A, Thau D, Stehman SV, Goetz SJ, Loveland TR, et al. High-resolution global maps of 21st-Century forest cover change. *Science* 2013, 342:850–853.
212. Sexton JO, Song XP, Feng M, Noojipady P, Anand A, Huang CQ, Kim DH, Collins KM, Channan S, DiMiceli C, et al. Global, 30-m resolution continuous fields of tree cover: Landsat-based rescaling of MODIS vegetation continuous fields with lidar-based estimates of error. *Int J Digit Earth* 2013, 6:427–448.
213. Simard M, Pinto N, Fisher JB, Baccini A. Mapping forest canopy height globally with spaceborne lidar. *J Geophys Res Biogeosci* 2011, 116:G04021.
214. Kahn RA, Chen Y, Nelson DL, Leung FY, Li QB, Diner DJ, Logan JA. Wildfire smoke injection heights: two perspectives from space. *Geophys Res Lett* 2008, 35:L04809.
215. Schmit TJ, Gunshor MM, Menzel WP, Gurka JJ, Li J, Bachmeier AS. Introducing the next-generation Advanced Baseline Imager on goes-R. *Bull Am Meteorol Soc* 2005, 86:1079–1096.
216. Goodman SJ, Blakeslee RJ, Koshak WJ, Mach D, Bailey J, Buechler D, Carey L, Schultz C, Bateman M, McCaul E, et al. The GOES-R Geostationary Lightning Mapper (GLM). *Atmos Res* 2013, 125:34–49.
217. Laris PS. Spatiotemporal problems with detecting and mapping mosaic fire regimes with coarse-resolution satellite data in savanna environments. *Remote Sens Environ* 2005, 99:412–424.
218. Scheiter S, Langan L, Higgins SI. Next-generation dynamic global vegetation models: learning from community ecology. *New Phytol* 2013, 198:957–969.
219. Arneth A, Brown C, Rounsevell MDA. Global models of human decision-making for land-based mitigation and adaptation assessment. *Nat Clim Change* 2014, 4:550–557.

