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EDITORIAL

Focus on changing fire regimes: interactions with climate, ecosystems, and society

Brendan M Rogers[1] , Jennifer K Balch[2], Scott J Goetz[3] , Caroline E R Lehmann[4,5] and Merritt Turetsky[6]

[1] Woods Hole Research Center, Falmouth, MA, United States of America
[2] Department of Geography, University of Colorado, Boulder, CO, United States of America
[3] School of Informatics, Computing, and Cyber Systems, Northern Arizona University, Flagstaff, AZ, United States of America
[4] School of Geosciences, University of Edinburgh, Edinburgh, United Kingdom
[5] Royal Botanic Garden, Edinburgh, United Kingdom
[6] Institute of Arctic and Alpine Research, University of Colorado, Boulder, CO, United States of America

E-mail: brogers@whrc.org

Abstract

Fire is a complex Earth system phenomenon that fundamentally affects vegetation distributions, biogeochemical cycling, climate, and human society across most of Earth's land surface. Fire regimes are currently changing due to multiple interacting global change drivers, most notably climate change, land use, and direct human influences via ignition and suppression. It is therefore critical to better understand the drivers, patterns, and impacts of these changing fire regimes now and continuing into the future. Our review contributes to this focus issue by synthesizing results from 27 studies covering a broad range of topics. Studies are categorized into (i) Understanding contemporary fire patterns, drivers, and effects; (ii) Human influences on fire regimes; (iii) Changes in historical fire regimes; (iv) Future projections; (v) Novel techniques; and (vi) Reviews. We conclude with a discussion on progress made, major remaining research challenges, and recommended directions.
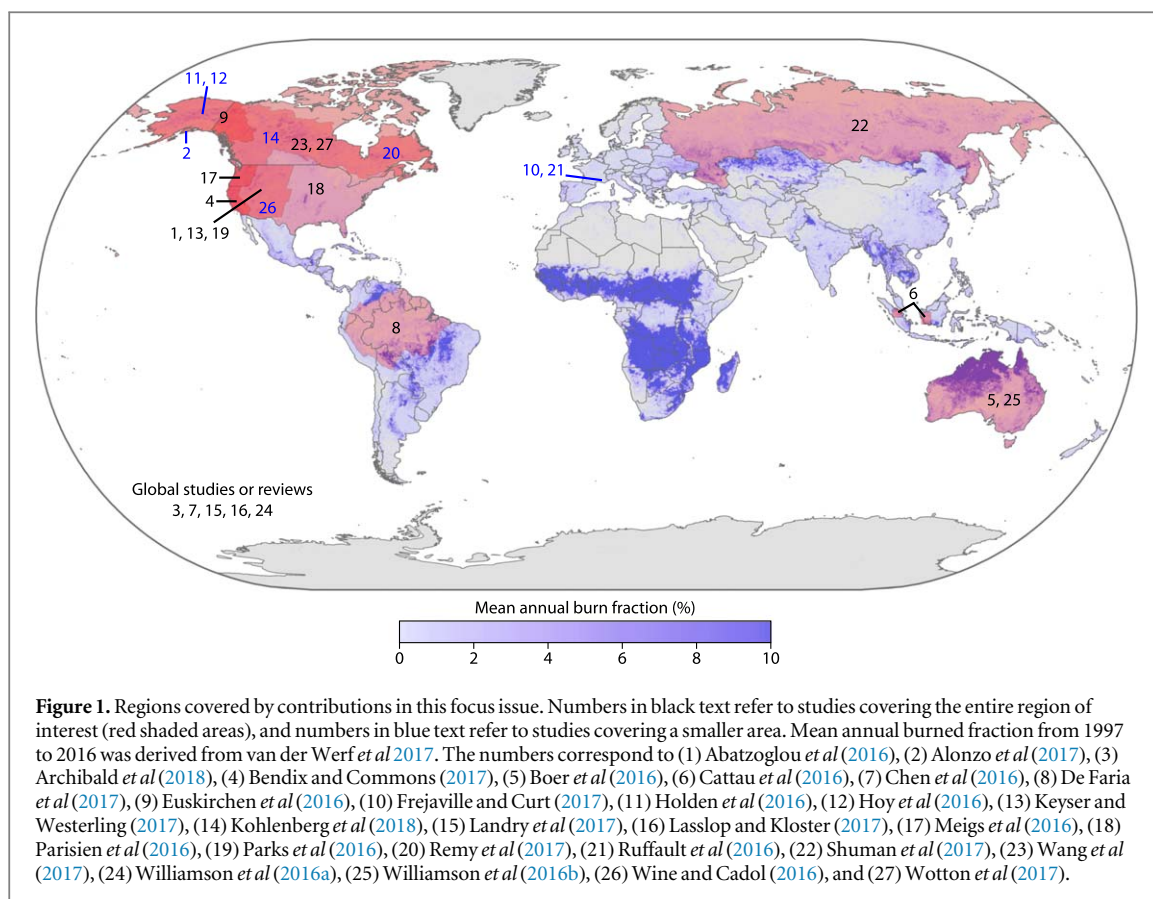
1. Introduction

Fire is a fundamental and inevitable Earth system process. Throughout geologic history, fire has played a major role in regulating atmospheric O_2 (Lenton 2001, 2013, Belcher *et al* 2010), driving plant evolution (Pausas and Keeley 2009, Keeley *et al* 2011, Archibald *et al* 2018), and determining the distribution of biomes and plant communities (Bond *et al* 2005). The ability to control fire represented a turning point in our own human evolution, and later allowed us to disperse across the continents and transform landscapes in ways optimal to human survival (Burton 2011). Yet today we have a polarized relationship with fire. Fires are necessary for the persistence of key ecosystems, continue to be used as a land management tool, and are not going away. But with an ever-increasing human population, continued expansion into wildlands, and changing climate, fires are an acute and increasing danger to our infrastructure, natural and cultural resources, human health, ecosystem resilience, and climate itself (Johnston *et al* 2012, Ward *et al* 2012, Bowman and

Johnston 2014, Thomas *et al* 2017). It has never been more important for us to understand the patterns, drivers, and effects of fires across Earth's diverse biomes.

Understanding and predicting fire has proven an extremely challenging endeavour because of the multi-dimensional and coupled nature of its drivers (Williams and Abatzoglou 2016). Fire occurrence and behavior depend on the convergence of fuel conditions, weather patterns, and ignition sources. Fuel conditions are determined by vegetation amount, chemical composition, structure, and continuity. Climate has a major influence on fuel properties, and finer-scale weather patterns determine fuel moisture and physical conditions necessary for fire spread. Even with optimal burning conditions, fires require an ignition source, provided either by lightning or humans. The temporal and spatial scales that determine fire cover many orders of magnitude and scientific disciplines.

Today, roughly 3% of the Earth's surface burns annually (van der Werf *et al* 2017). Current fire

Figure 1. Regions covered by contributions in this focus issue. Numbers in black text refer to studies covering the entire region of interest (red shaded areas), and numbers in blue text refer to studies covering a smaller area. Mean annual burned fraction from 1997 to 2016 was derived from van der Werf *et al* 2017. The numbers correspond to (1) Abatzoglou *et al* (2016), (2) Alonzo *et al* (2017), (3) Archibald *et al* (2018), (4) Bendix and Commons (2017), (5) Boer *et al* (2016), (6) Cattau *et al* (2016), (7) Chen *et al* (2016), (8) De Faria *et al* (2017), (9) Euskirchen *et al* (2016), (10) Frejaville and Curt (2017), (11) Holden *et al* (2016), (12) Hoy *et al* (2016), (13) Keyser and Westerling (2017), (14) Kohlenberg *et al* (2018), (15) Landry *et al* (2017), (16) Lasslop and Kloster (2017), (17) Meigs *et al* (2016), (18) Parisien *et al* (2016), (19) Parks *et al* (2016), (20) Remy *et al* (2017), (21) Ruffault *et al* (2016), (22) Shuman *et al* (2017), (23) Wang *et al* (2017), (24) Williamson *et al* (2016a), (25) Williamson *et al* (2016b), (26) Wine and Cadol (2016), and (27) Wotton *et al* (2017).

regimes are greatly influenced by humans through ignition sources, suppression, and changes in land cover and fuels (Bistinas *et al* 2013, Kelley *et al* 2019). Fire regimes are also rapidly changing, a function of changing climate patterns, extreme weather, land use, human population, and vegetation distributions (Jolly *et al* 2015, Andela *et al* 2017, Veraverbeke *et al* 2017). These changes are expected to continue during the coming years and decades, with potentially wide-ranging impacts on ecosystems, biodiversity, habitat, biogeochemical cycling, climate, and society.

This focus issue brings together 27 studies that collectively aim to better understand Earth's changing fire regimes from varied angles. Due to the multi-dimensional nature of fire, the studies use analytic tools ranging from charcoal records in lake sediments, field observations of recent fires, laboratory burn experiments, airborne remote sensing, satellite remote sensing, and a variety of statistical and mechanistic modeling techniques. The authors focused on fires across Australia, Indonesia, the Amazon, Siberia, temperate and boreal North America, and the entire globe (figure 1). Here, we synthesize key findings of each study and place them in a broader context of evolving wildfire research. We organize the studies into six general sections, and conclude by discussing current progress, research challenges, and suggesting future research priorities.

2. Understanding contemporary fire patterns, drivers, and effects

The theme of contemporary fire dynamics runs throughout this focus issue collection, and can be tied directly or indirectly to every study. In this section, however, we highlight studies that have the specific aim of better understanding fire patterns, drivers, and effects in current conditions. In a global analysis, Chen *et al* (2016) developed simple but powerful seasonal predictive relationships between large-scale sea surface temperature patterns and regional burned area. The authors found that 48% of global burned area can be forecast using models built from a single ocean climate index at least three months prior to peak burning. Including two ocean climate indices substantially improved this predictive power. This method builds on previous fire forecasting methods for the Amazon (Chen *et al* 2011) and has the potential to provide valuable information for aligning fire management resources in advance of the fire season. Looking at the other side of the fire-climate feedback loop, Landry *et al* (2017) provide a global modeling analysis of the impact of fire-emitted aerosols on radiative forcing, surface forcing, surface temperature, and land carbon stocks. Top of the atmosphere and surface forcings were negative (-0.1 and -1.3 W m^{-2}) and resulted in small increases in globall-averaged carbon stocks (<6 Pg C). This work is particularly important given

the highly uncertain but potentially large influence of aerosols on climate, now and continuing into the future (e.g. Jacobson 2004, Ward *et al* 2012, Rap *et al* 2013).

One of the regions with the largest increases in wildfire globally is the western US (Dennison *et al* 2014, Westerling 2016, Balch *et al* 2017). The combination of climate change, history of aggressive suppression in systems adapted to frequent low-severity fires, and expansion of the wildland urban interface have created conditions for increasingly dangerous fires. As a result, there has been contentious debate surrounding wildfire management and policy strategies (e.g. North *et al* 2015, Schoennagel *et al* 2017, Hurteau *et al* 2019, Schultz and Moseley 2019). One research challenge is to separate the influence of climate and lightning ignitions on burned area patterns. Lightning-ignited fires account for roughly 2/3rds of the burned area in the western US (Pyne *et al* 1996, Stephens 2005), yet most 'wet' lightning and does not generate ignition and climate is often assumed to be the dominant top-down environmental control on burned area. Abatzoglou *et al* (2016) provide a much more nuanced view of this issue, separating the effects of wet and dry lightning on fire frequency and burned area in the western US using newly-available fire, lightning, and meteorological data sets. Although largely coming to the same conclusion, i.e. that climate is the dominant control on interannual burned area, they present distinct geographic patterns where, for example, burned area in coastal regions and the Pacific Northwest is tightly tied to lightning strikes. This is consistent with recent analysis in the North American boreal showing the influence of lightning on increasing wildfires (Veraverbeke *et al* 2017). Another key reserch challenge in the western US involves the influence of increasing insect outbreaks on fire, which has often been assumed to increase fire likelihood and severity. These assumptions have formed the basis of policy and fuel reduction activities (Agricultural Act of 2014), but are not necessarily supported by research on fire probality. The issue of fire severity, however, had not been studied at large scales. Meigs *et al* (2016) provide a novel assessment of this interaction, focusing on wildfire severity following outbreaks of a common bark beetle and defoliator species. The authors conclude that by reducing live vegetation, these insect outbreaks actually reduce subsequent fire severity. The conclusions have implications for disturbance interactions and management planning.

In many US western states, the impact of fires on streamflow is important for urban and agricultural water supply. Studies focusing on specific fire events have documented increases in streamflow due to reduced transpiration and soil infiltration capacity (e.g. Larsen *et al* 2009, Kinoshita and Hogue 2011), but the effect of longer-term fire frequency on large-scale watershed water yield has not been investigated. Wine and Cadol (2016) conducted such an analysis on three watersheds in New Mexico, separating the effects of fire and climate variability. They found a significant increase in runoff in two of the three watersheds studied, attributing between 12% and 22% of total annual discharge to observed fires, and suggested such increases will be detected if at least one fifth of a large watershed burned in a period of three to five years. The state within the western US that receives the most attention, however, is California, mostly because of the often large societal damages. Nevertheless, one ecosystem type that remains under-studied are riparian systems. Although riparian areas are generally wetter and less likely to burn, they can serve as a 'wick' to carry wildfire across otherwise nonflammable landscapes (North 2012) and are home to a disproportionate share of the state's biodiversity (Holstein 1984). Understanding fire frequency and its variability across these diverse riparian systems is therefore important for landscape planning and conservation. In an effort to provide new baseline information, Bendix and Commons (2017) use spatial data to quantify fire return intervals in riparian systems across California. The authors document the substantial geographic variation in fire return intervals, seasonal variation, and relationship with climatic variables.

From a global perspective, Australia is one of the highest burning regions (figure 1), with ecosystems ranging from closed-canopy forests to savannas and grasslands to xeric shrublands and desert. Similar to California, Australia has been experiencing increasingly destructive wildfires (Burrows 2019, Pickrell 2019). Nonetheless, interannual variability in climate is extremely high, making it challenging to define fire regime baselines and detect trends. To that end, Williamson *et al* (2016b) provide a comprehensive analysis of fire season characteristics across Australia, classified into 61 climate regions and three broad climate zones (monsoon tropics, arid, and temperate). The authors documented clear regional differences in fire seasons, relationships with fire weather, influence of management, and relationships with sea surface temperature anomalies. They also placed Australian fire regimes in a global context, highlighting the unusually long and variable fire season compared to other continents. The analysis by Williamson *et al* (2016b) is largely consistent with that of Boer *et al* (2016), who undertook a more physical approach to define Australian fire regimes as limited by either fuel productivity or fuel dryness. The authors accomplished this by modeling fire activity as a function of actual and potential evapotranspiration. They found the vast majority of the continent to be productivity-limited, with the fuel dryness-limited systems occuring close the coasts and falling within Williamson *et al*'s monsoon tropical and temperate zones.

Moving to northern latitudes, fires in boreal forests contribute only roughly 2% of global annual burned area (Giglio *et al* 2013) but represent roughly 9% of annual global fire carbon emissions due to their

relatively high severity and deep organic soils (van der Werf *et al* 2017). Because of the long period for forest regrowth to re-sequester lost carbon, and the amplified effects of fire aerosols and surface albedo in snow-covered systems, boreal forest fires exert a disproportionate influence on climate (Randerson *et al* 2006, Ward *et al* 2012, Oris *et al* 2013). With polar amplification, temperature increases have been most rapid in high latitudes, contributing to intensifying fire regimes across the biome (e.g. Gillett *et al* 2004, Soja *et al* 2007, Kasischke *et al* 2010, Turetsky *et al* 2011, Ponomarev *et al* 2016). Several papers in this focus issue provide key insights into carbon cycle feedbacks and fire emissions in these boreal systems.

Linking two scientific communities that rarely work together, Holden *et al* (2016) provide a novel analysis of the impact of fire severity (measured by satellite remote sensing) on microbial composition and dynamics in interior Alaska. The authors found a continuum of reduced microbial biomass and basal respiration with increasing severity. They also identified differential tolerance between soil microbial taxa, with mycorrhizae and basidiomycetes fungi being the most vulnerable to high severity fires. This carries implications for newly-identified carbon cycle feedbacks, including positive (slower post-fire recruitment from reductions in mycorrhizal fungi) and negative (reduced post-fire soil respiration from reductions in saprotrophic fungi). Across the landscape, most fires in boreal North America occur in mature black spruce (*Picea mariana*) stands (Rogers *et al* 2015). Nonetheless, with an increasing frequency of severe fire weather and large fire years, younger and more deciduous-dominated or mixed stands are tending to burn, yet the impacts and implications for carbon cycling are much less understood. Two studies in this focus issue addressed this knowledge gap. Taking advantage of pre-fire airborne lidar acquisitions (see section 6 for the novelty of this approach), Alonzo *et al* (2017) used repeat lidar and Landsat imagery to estimate fire effects in different forest types in Alaska's Kenai Peninsula. The authors found that mixed forests experienced substantially smaller reductions in canopy volume reduction and surface elevation (i.e. burn depth) than black spruce forests, especially those in the flat lowlands. This generally confirms previous observations (Rogers *et al* 2014), but covers a much larger sampling domain. Using a ground-based approach, Hoy *et al* (2016) analyzed fire effects in the organic soils of recently-burned black spruce forests of different ages in interior Alaska. They found that, compared to the typical mature black spruce stands (70–120 years old), intermediate-aged stands (37–52 years old) emitted less carbon to the atmosphere but displayed significantly greater percent depth reductions and much less remaining carbon in their organic soils. As these systems experience more frequent wildfires, this implies they will experience a continued reduction of their soil layers and combustion of older 'legacy' carbon (Walker *et al* 2019), with negative impacts on permafrost

preservation and potential switches to more deciduous-dominated forests (Johnstone *et al* 2010) or even shrub-lands and grasslands (Kukavskaya *et al* 2016). Fires in boreal peatlands are also a major concern because of the carbon they contain and the emissions associated with smouldering combustion, particularly CH_4 for its climate impacts and Hg for its nervous system toxicity and downstream impacts on food chains (Turetsky *et al* 2006). Using controlled laboratory burn experiments, Kohlenberg *et al* (2018) calculated emission factors for CO, CO_2, CH_4, and gaseous and particulate Hg in peat samples from northern Alberta. The authors found generally higher emission ratios than typically used in large-scale modeling, especially for CH_4, and documented the sensitivity of these emissions to combustion temperature and fuel moisture content. For all of boreal fire effects studied in this collection of papers, as the scientific community's techniques for understanding, mapping, and modeling improve, we can better place these systems in a global context, predict system responses, and optimize fire management to limit the most deleterious impacts on climate, ecosystem services, and human health.

Finally, the Amazon is one of Earth's most critical biomes in terms of carbon storage, biodiversity, and planetary stability (Cox *et al* 2000, Foley *et al* 2007, Davidson *et al* 2012). Fires in the Amazon rainforest typically indicate deforestation, bringing the region closer to a potential tipping point (Lenton *et al* 2008, 2019). Fires are typically started by humans for agriculture or land clearing (Soares-Filho *et al* 2012) and are exacerbated by episodic drought conditions. To understand the implications of these droughts, De Faria *et al* (2017) modified a dynamic vegetation model to include the direct and indirect (i.e. leaf and branch shedding) effects of drought on fire intensity in the Amazon. They found substantial increases in fire intensity during the 2005 and 2010 Amazon droughts, and suggest indirect effects of drought through fuel loading may be more important than the direct meteorological effects. This research adds to our understanding of the inter-related and compunding impacts of drought in the Amazon, stressing the need for better forest protection and fire prevention mechanisms.

3. Human influences on fire regimes

The research highlighted here investigates the influence of humans on fire regimes. Although these studies utilize different techniques over different domains, there is a collective consensus of profound human impacts on historical and modern fire regimes. Hence, it is nearly impossible to consider and predict fire patterns across the globe without including human influence. Lasslop and Kloster (2017) diagnose human impacts by implementing regionally-varying human ignition and suppression algorithms based on population density and

cropland cover within a global dynamic vegetation and fire model. The resulting model matched observed global burned area patterns quite well, and suggested a dominant pattern of increased burning in the tropics due to humans, decreases in temperate latitudes, and little influence in the boreal. This pattern is mostly consistent with that found by Parisien *et al* (2016), who analyzed the influence of humans on contemporary fire occurrence over North America using a statistical approach. The authors found that while climate was the dominant control, anthropogenic influences measured by population density, a human footprint index, and roadless volume were a close second and considerably more important than landscape features such as topographic indices and non-fuel fractions. Regional influences and patterns varied to some degree, but humans consistently exerted a negative influence on burned area across a range of ecosystem types, fire regimes, and population densities, including remote locations and the boreal forest.

This general pattern of humans decreasing burned area was confirmed by two papers in this issue focused on the Mediterranean fire regimes of southern France. Mediterranean fire regimes tend to consist of a complex mixture of fuel- and dryness-limited systems dominated by human ignitions and suppression. Frejaville and Curt (2017) teased apart the influence of climate and humans on fire frequency and burned area using a statistical temporal de-coupling approach. Models showed that fire patterns have diverged from climatic expectations in ways consistent with changing fire suppression policies in the mid-1990s. The authors suggest changes in land use and suppression have exceeded the strength of climate change on fire regimes in southern Europe. Ruffault *et al* (2016) used a somewhat similar approach but first clustered fires into three distinct fire weather types based on meteorological variables at varying time lags. They found that most fires could be classified as either heat-driven (warm anomalies), wind-driven (higher winds but cooler temperatures), or occurring during near-normal atmospheric conditions. Despite relatively stable climatic drivers, the wind-driven and near-normal fire types decreased over the time period in concert with changes in fire suppression policies. In contrast, the conditions for and occurrence of heat-driven fires increased. This suggests the effectiveness of fire suppression varies by fire type, with implications for further climate change. Both of these studies are broadly consistent with Chen *et al* (2016), who found that climatic indices had the lowest explanatory power for burned area in Europe.

Finally, Cattau *et al* (2016) investigated whether or not recent certification schemes from the Roundtable on Sustainable Palm Oil (RSPO) were effective in reducing fire occurrence in oil palm concessions in Indonesia, and specifically on cleared peatlands. Fires for oil palm plantation clearing and maintenance are particularly problematic when occurring on peatlands from a carbon, air quality, and biodiversity perspective. The RSPO certification program does not allow the use of fire except when it can be demonstrated to be the least damaging option. The authors found that certifications appeared to be effective in limiting fire occurrence on oil palm plantations, but only during wet years of low fire probability and only on non-peatland plantations. Additional mechanisms are needed to combat fire occurrence in fire-prone years and on peatland systems.

4. Changes in historical fire regimes

This focus issue is particularly interested in changes to Earth's fire regimes, which are affected most by climate change and land use. Several studies leveraged a growing and now sufficiently long set of observational records to diagnose changes over the last several decades. In the western US, both climate change and previous fire suppression policies have been widely implicated in the recent rise in fire occurrence, size, and severity (Dennison *et al* 2014, Westerling 2016, Balch *et al* 2017). Nonetheless, changes in severity across the entire domain has yet to be investigated. Keyser and Westerling (2017) do so by modeling the probability of high severity fire occurrence across the western US as determined by vegetation, topographic variables, and a suite of climate predictors. The authors highlighted the importance of including inter-annual climate for prediction, and although their results confirmed substantial increases in the number of fires across the domain, they did not find an increasing fraction of high severity fires. This may be due to temporal limitations, as fire suppression began over 70 years before the start of this analysis period. In southern France, Frejaville and Curt (2017) documented a changing fire regime in Southern France that has increasingly diverged from climatic expectations due to humans, and Ruffault *et al* (2016) suggested these decreases are due to fires associated with high winds and near-normal climatic conditions, yet are somewhat offset by an increasing trend in fires associated with hot and dry conditions.

One can greatly extend the time period of inference for changing fire regimes, albeit with larger uncertainty, by employing models and paleoecological data. Using an updated global fire vegetation model, Lasslop and Kloster (2017) were able to recreate the global decreases in burned area during the 19th and 20th centuries. Yet they were only able to do so when including human ignition and suppression patterns, thereby supporting the idea that humans were the primary cause of this trend (Marlon *et al* 2008, Wang *et al* 2010, Marlon *et al* 2013). Taking a paleoecological approach, Remy *et al* (2017) investigated changing fire dynamics, including proxies for biomass burning, fire frequency, and derived fire size, across a transect in eastern Canada. The authors found the largest fire

sizes to occur between approximately 3000 and 1000 years before present. By combining this with climate data simulated by a general circulation model, they also inferred different drivers between the west/central regions (fires controlled by spring and summer temperatures) and the eastern region (fires controlled by precipitation variability).

5. Future projections

Building on the knowledge and models derived from observational data, it is extremely important to develop robust projections of future fire regimes, as these will have a large influence on future ecosystems, society, and the climate system. A number of studies in this focus issue provide such projections, and collectively highlight the depth and complexity of fire modeling with both intuitive and counter-intuitive results. The studies come to a general consensus that in dryness-limited systems (e.g. forests), fire frequency and severity will increase, as has been documented globally over the last two decades (Andela *et al* 2017). In fuel-limited systems, the opposite may become true with increasing aridity and fuel limitations.

Starting in boreal North America, Wang *et al* (2017) and Wotton *et al* (2017) investigated the potential intensification of fire regimes across Canadian forests. As opposed to previous projections using climate data with a resolutoin of monthly or longer, or focused exclusively on fire weather indices, Wang *et al* (2017) utilized daily meteorological data from stations and high-resolution modeling to derive fire spread days, or days when wildfires spread rapidly across the landscape. To do so, the authors developed an index of potential and realized spread days based on simulated ignitions, meteorological data, and observed patterns of daily fire progression. Future projections showed substantial increases in fire spread days across forested Canada with more severe climate change, including a greater than 50% increase in western Canada and two-to-three fold increases in eastern Canada. This metric of fire spread days is particularly important from a fire management perspective, as seemingly small changes in the number of spread days may have a major influence on fire containment and thus overall burned area. Focusing even more on metrics relevant for fire management, Wotton *et al* (2017) used the Canadian Forest Fire Behavior Prediction System to project crown fire initiation, number of days with active fire growth potential, and three fireline intensity thresholds known to be important for suppression activities: $2\,\mathrm{MWm}^{-1}$, signifying the limits of ground resources without aerial support; $4\,\mathrm{MWm}^{-1}$, indicating the limit of aerial suppression effectiveness; and $10\,\mathrm{MWm}^{-1}$, a level at which even heavy water bombers become ineffective. Projections suggested that despite increases in precipitation, fuel dryness will increase on average due to increases in temperature and evaporative demand.

This resulted in a consistent pattern of intensifying fire regimes and potential for unmanageable fires, including a doubling or more of these metrics in Canada's northern and eastern boreal forests. These projected increases in fire occurrence and intensity in boreal forests are consistent with those in tropical closed-canopy forests. For example, De Faria *et al* (2017) projected substantial increases in combustion levels (up to 90%), or carbon emitted per unit burned area, across the Amazon during the 21st century.

Turning towards the impact of these increasing fires on climate, Euskirchen *et al* (2016) employed a land and vegetation model with energy budgets parameterized from regional flux towers to investigate future changes in atmospheric heating across Alaska and Northwest Canada due to changes in vegetation, snow dynamics, and wildfire. Model projections suggested an overall increase in future atmospheric heating (0.8–$2.7\,\mathrm{W\,m}^{-2}$ per decade). This was primarily a function of decreased snow cover in the spring, which was only partially offset by increases in land surface albedo from more fires and thereby more snow exposure beneath tree canopies. This result is in contrast to work showing the magnitude of atmospheric heating from snow cover loss to be roughly equal to that from post-fire albedo cooling in Alaska between 2000 and 2011 (Ueyama *et al* 2014), but consistent with projections of a reduced cooling impact from post-fire albedo due to earlier snowmelt (Potter *et al* 2019). Overall, these studies suggest the biophysical cooling effect of boreal fires will decrease in magnitude, and be more than offset by atmospheric heating from declining snow cover in spring. Euskirchen *et al* (2016) also projected mild increases in ecosystem carbon under future climates, which is consistent with Shuman *et al* (2017)'s model projections of aboveground biomass and species distributions across Russia. Using an updated forest 'gap' model that simulates individual trees growing and competing, the authors found fire acted to increase the prevalence of larch (*Larix* spp.) across future Russian forests, as larch tend to be more fire tolerant than spruce (*Picea* spp.) or fir (*Abies* spp.). Somewhat counterintuitively, this resulted in higher average levels of aboveground biomass due to larch's relatively high productivity compared to other species. It should be noted, however, that this model did not consider the impacts of fire on carbon stored in organic soil layers or permafrost, which is often the largest source of fire carbon emissions in boreal forests (Boby *et al* 2010, Rogers *et al* 2014, Walker *et al* 2018), and that observational data may support a pattern of continued biomass accumulation during the transition from larch to spruce and fir when wildfire is excluded from Siberian forests (Schulze *et al* 2012). Nonetheless, this work highlights the complexities, nonlinearities, and importance of including ecosystem dynamics and species competition when projecting future fire regimes and carbon budgets in boreal forests.

Moving to systems with both fuel- and dryness-limited fire regimes, Boer *et al* (2016) projected an overall increase in fire activity but relatively little changes in the type of fire regime across Australia. In the western US, Parks *et al* (2016) looked exclusively at the issue of fire severity, measured by the Composite Burn Index on the ground and the differenced Normalized Burn Ratio from satellites. The authors statistically modeled fire severity as a function of 30-year climate normals, and projected decreases in fire severity across the domain by the mid-21st century. This pattern, however, was due mainly to the fact that fuel-limited systems (warmer and drier open forests and drylands) exhibited lower severity than dryness-limited systems, such as closed canopy forests, and that future climate became warmer and drier. Other research has suggested fire severity will increase before dryland systems replace closed canopy forests in warmer and drier climates of the region (Rogers *et al* 2011).

6. Novel techniques

Several studies in this focus issue highlighted how more sophisticated modeling, increasingly available data sets, and appropriate data coverage in space and time can transform our knowledge of particular fire dynamics, and potentially inform fire management and policy. Here we summarize these novel techniques and their potential applicability.

In boreal forests, depth of burn in the organic soils is a critical metric of fire severity in the context of carbon emissions, permafrost degradation, and post-fire regeneration. Yet depth of burn is extremely challenging to observe and model at spatial scales larger than a field site, and even ground observations of burn depth can have large uncertainties (Rogers *et al* 2014), mainly due to the fact that pre-fire soils are typically not sampled. Taking advantage of pre-fire airborne lidar acquisitions, Alonzo *et al* (2017) showed depth of burn can be estimated with high accuracy when using airborne lidar acquired before and after a fire. If this type of pre- and post-fire lidar data were available across larger areas, it would transform our ability to estimate burn depth and thereby a multitude of other fire effects. The recent lidar instrument installed on the International Space Station, the Global Ecosystem Dynamics Investigation (GEDI), as well as the NASA ICESat-2 mission both provide novel data on surface topgraphy and vegetation structure that will allow for better estimates of pre- and post-fire vegetation structure, and may also have utility for estimating burn severity associated with changes in topography.

Forecasting seasonal burned area and fire intensity is a critical management need in terms of aligning resources and optimizing suppression strategies. Yet existing methods to do so in many regions are severely limited. The simple but powerful predictive models of burned area based on sea surface temperatures offered

by Chen *et al* (2016) have the potential to transform regional prediction services, offering forecasts several months in advance of the fire season. Future steps should be taken to improve and operationalize these models for specific regions of interest. Along similar lines, forecasts of meteorological data could be translated into management-relevant suppression thresholds given techniques used in Wotton *et al* (2017).

In terms of better understanding fire regime types and recent changes, several techniques developed in this focus issue could have broad applicability. For example, the categorization of fire types by limiting factor (fuel or dryness) by Boer *et al* (2016), and the fire weather types developed by Ruffault *et al* (2016), could be extended to other systems and even globally in order to improve our understanding and definintion of 'pyromes' (Archibald *et al* 2013). The decomposition of annual versus decadal patterns employed by Frejaville and Curt (2017) could be used in other regions to disentangle the impact of climate and humans on recent fire trends. And finally, the linkage between satellite remote sensing of fire severity and post-fire microbial dynamics made by Holden *et al* (2016) could be extended to other regions and biomes to better understand interactions between fires, soil microbes, and post-fire ecosystem dynamics.

7. Reviews

Two important review articles in this focus issue synthesized information from nearly opposite ends of the Earth system-society spectrum. Together they constitute valuable sources of information on interconnected fire processes, societal impacts, and recommendations for future research priorities.

Archibald *et al* (2018) provide a sweeping, comprehensive, and novel review of fire in the Earth system through the lens of plant traits and geophysical feedbacks. Compiling recent research across a breadth of topics, the authors provide compelling evidence that fire has acted as a strong selective force and evolutionary filter, and that selected functional plant traits in turn influence fire regimes through flammability and fire tolerance strategies. The authors offer examples of 'biogeographic conundrums' that highlight both convergent and divergent evolution of plant-fire regime feedbacks. These coupled relationships are generally underappreciated but critical for understanding and modeling Earth's fire regimes. The authors also discuss geophysical feedbacks between fire (as mediated by plant traits) and Earth's climate and atmospheric composition on different time scales. At shorter time scales (i.e. immediate to decades), fire regimes influence climate primarily through their impacts on atmospheric concentrations of radiatively active gases (e.g. CO_2, CH_4, N_2O), aerosol loads, surface energy budgets, and nutrient redistribution. At longer geologic timescales (i.e. millions of years),

however, fires are thought to regulate atmospheric O_2. When O_2 levels increase much above modern levels, ecosystem flammability sharply increases and widespread fires reduce vegetative phosphorous weathering. This, in turn, ultimately inhibits geological sequestration of organic matter and therefore net release of O_2 to the atmosphere. The authors conclude with research challenges and recommendations to the community, mostly focused on upscaling and integrating fire-plant evolution and functional traits into models.

Looking towards our modern challenge of both adapting to and actively managing fire regimes, Williamson *et al* (2016a) provide a timely review on the health impacts of prescribed and wild fires. The human health impacts of fire smoke are increasingly recognized (Johnston *et al* 2012, Bowman and Johnston 2014, Reid *et al* 2016, Cascio 2018), a fact that can dramatically increase the estimated economic burden of landscape fires (Jones and Berrens 2017, Thomas *et al* 2017). Prescribed fires are designed to reduce fuel loads and thus the severity of uncontrolled fires, but can also have negative consequences on human health in downwind regions. A 'catch 22' can arise when planning prescribed fires: strong winds and an unstable atmosphere can lead to uncontrollable fires, but light winds and a stable atmosphere can lead to inadequate smoke dispersion and thus undesirable levels of PM2.5 and air pollution in downwind population centers. Williamson *et al* (2016a) introduce a conceptual framework to consider the causes, impacts, and uncertainties of this phenomenon, suggesting smoke impacts and prescribed fire 'leverage' (i.e. the ratio of wildfire burned area that is saved by conducting prescribed burns over a given area) should be combined into a quantifiable 'smoke regime', which can be operationalized for planning purposes.

8. Concluding remarks and future research priorities

Fire is an extremely complex phenomenon whose drivers and impacts span vast ranges in time and space. It has never been more important to understand these dynamics as fire regimes are changing, and in many instances intensifying, due to climate change, land use, and other global change drivers. In just the last several years we have witnessed extreme fire events in Alaska (Mooney 2015, Veraverbeke *et al* 2017), Canada (Parker 2016, Walker *et al* 2018, 2019), Siberia (Ayres 2019), the Western US (Balch *et al* 2018, Zak 2019), Europe (Elbein 2019, Smith 2019), Indonesia (Alisjahbana and Busch 2017, Rusmana 2019), Australia (Gunia 2019), and the Amazon (Krauss 2019, Symonds 2019), among others. These fires generate a multitude profound impacts on society; when quantified in economic terms, the damages can be extraordinary (IAWF 2015, Thomas *et al* 2017).

The fire science community has made exceptional gains recently, especially with focused collections of research papers such as this issue. This progress is in large part due to the growing archive of field observations and remote sensing imagery, computation and technological advancements, and increasingly detailed and robust models. Yet much more is needed to accurately represent fire in projections of our biosphere and society. Particularly challenging and important directions include fire-permafrost interactions in high latitudes, changing vegetation distributions and flammability, fine-scale heterogeneity in fuels and connectivity, and capturing ignitions and suppression in different geopolitical contexts. Much work also remains to be done to translate fire science into operational, management, and policy contexts where it is desperately needed for adaptation and mitigation.

Based on this focus issue, and the broader state of fire science generally, we offer specific recommendations for future research priorities. For one, better geographic representation and coverage of Earth's pyromes (Archibald *et al* 2013) is needed. Studies in this focus issue included a definitive bias towards western North America, with little coverage of Africa and tropical savannas and grasslands more generally (i.e. dryness-limited systems, figure 1), a pattern that is not atypical in the literature despite these regions contributing the majority of global burned area. Given the importance of models in all fire science disciplines, we also strongly recommend the continued development and refinement of 'high resolution' models, both in terms of spatial and temporal resolution as well as process (e.g. physical fire spread and intensity, fire effects, and human influence). Models should strive to leverage the growing number of available data products from field observations, airborne imagery, and satellite remote sensing. Traditionally disparate modeling communities (e.g. operational fire management versus Earth system process modelers) should also strive to work together more closely, as a large potential for synergies remains largely untapped. The same applies to data products, for example by merging historical government records with modern satellite imagery. Model progress, in turn, will be aided by the growing archives of observations and rapid advances in computation power (e.g. Google Earth Engine). Fire scientists should continue to harness this data and computation revolution, as well as utilize advanced statistical techniques such as machine learning. One particular recommendation is to use these new tools to advance fire severity and mapping beyond simplistic indices such as the differenced Normalized Burn Ratio, which is widespread but contains well-documented limitations (e.g. Murphy *et al* 2008, Veraverbeke *et al* 2012, Rogers *et al* 2014). We also recognize that feedbacks between fire regimes and climate are critical for global climate projections (Ward *et al* 2012, Landry *et al* 2017, Rabin *et al* 2017, Archibald *et al* 2018), yet contain large uncertainties. In some instances the feedbacks may not

yet be known (e.g. Holden *et al* 2016). Further work to identify and quantify these can assist global modeling as well as international policy targets and agreements. Finally, the profound ways in which fires interact with human society are beginning to be recognized more broadly. We recommend an increased emphasis on understanding these interactions, including the ways in which humans influence fire regimes, the full economic costs of wildfires, and an increased emphasis on attribution, especially for large and damaging wildfire seasons. These research avenues would greatly benefit from more trans-disciplinary studies between physical scientists, social scientists, and economists. Doing so can also lead to beneficial societal outcomes via altered management and policies.

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ORCID iDs

Brendan M Rogers ⬡ https://orcid.org/0000-0001-6711-8466
Scott J Goetz ⬡ https://orcid.org/0000-0002-6326-4308
Merritt Turetsky ⬡ https://orcid.org/0000-0003-0155-8666

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