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Wildfires and global change

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No single factor produces wildfires; rather, they occur when fire thresholds (ignitions, fuels, and drought) are crossed. Anomalous weather events may lower these thresholds and thereby enhance the likelihood and spread of wildfires. Climate change increases the frequency with which some of these thresholds are crossed, extending the duration of the fire season and increasing the frequency of dry years. However, climate-related factors do not explain all of the complexity of global fire-regime changes, as altered ignition patterns (eg human behavior) and fuel structures (eg land-use changes, fire suppression, drought-induced dieback, fragmentation) are extremely important. When the thresholds are crossed, the size of a fire will largely depend on the duration of the fire weather and the extent of the available area with continuous fuels in the landscape.

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We live on a flammable planet, with wildfires occurring nearly everywhere there is sufficient biomass (Archibald *et al*. 2013). Fires are an ancient phenomenon (Pausas and Keeley 2009; Scott 2018), and many plant species have acquired adaptive traits that help them survive and reproduce under recurrent fire events (Keeley *et al*. 2011; Lamont *et al*. 2019). Wildfire regimes vary across ecosystems, especially in relation to productivity (Keeley and Zedler 1998; Pausas and Ribeiro 2013), and also as a consequence of human activities (Balch *et al*. 2017; Syphard *et al*. 2017; Keeley and Pausas 2019) and other global changes. While temperature and atmospheric carbon dioxide (CO_2) concentrations are increasing worldwide, other global change drivers (eg population growth, land use and management, rainfall, invasive species) have differential impacts on global fire activity (Krawchuk and Moritz 2011; Pausas and Paula 2012; Keeley and Syphard 2019). In addition, global change drivers have differing effects depending on the ecosystem vegetation structure and dominant fuel types (grass, litter, or standing wood). Understanding all of these complexities is not always straightforward, yet is key for the sustainable management of ecosystems in a changing world. Global warming is often implicated as the primary driver of accelerated wildfire activity (eg Williams *et al*. 2019), but anthropogenic factors other than climate change can be as, if not more, important than climate change. However, in many ecosystems, the relative role of climate may be increasing as warming escalates. Here, we present and discuss the complexities of the role of global change drivers in modifying fire regimes (Table 1) and provide a mechanistic understanding of this topic that is applicable to any region worldwide (although many of our examples are drawn from Mediterranean climate regions [MCRs], given that they are among the most well documented).

In a nutshell:

- Climate change alone is insufficient to explain current fire-regime changes for wildfires
- Wildfires require the confluence of at least four factors: ignitions, continuous fuels, droughts, and appropriate weather conditions
- Climate change increases drought frequency, extending the fire season and increasing the frequency of dry years
- Human factors apart from those associated with climate change modify ignition patterns and landscapes in such a way that they increase the probability of ignitions coinciding with extreme weather in landscapes with contiguous fuel beds
- The relative role of climate is increasing as warming continues, but on some landscapes its importance may be outweighed by other global change drivers

The occurrence of wildfires in an ecosystem requires the confluence of at least four factors: ignitions, continuous fuels, droughts, and appropriate weather conditions (wind, high temperatures, and low humidity). Wildfires result from the nexus of these factors, all of which are potentially affected by global changes. Thus, fire regimes are changing in many ecosystems, but often for different reasons. Because fire is a spatial process based on connectivity, it is unlikely that the relationship between wildfire drivers and wildfire activity will be linear (Abades *et al*. 2014; Pausas and Keeley 2014; van Nes *et al*. 2018). For this reason, abrupt shifts in fire regimes are possible even with small changes in the drivers, making prediction difficult. Fire drivers can therefore be considered as switches: that is, wildfires occur when the four primary drivers (ignitions, fuel, drought, and fire weather) are "switched on" (sensu Bradstock 2010). However, the level at which a driver switches on (or off) may not be fixed; moreover, fire weather acts at a different spatiotemporal scale from the other three drivers (Moritz *et al*. 2005). Here, we

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Table 1. Main effects of different global change drivers on fire-regime parameters in ecosystems with different types of fire regimes

	Crown-fire ecosystems	Surface-fire ecosystems	
Global change driver	***Woody-fueled fires***	***Grass-fueled fires***	***Litter-fueled fires***
Drought	+flammability +FI, +FS, –FRI	–biomass –FI	+litter fall, –litter decomposition +FI
Urban population growth	+ignitions –FRI	+fire exclusion +FRI, +FI	+fire exclusion +FRI, +FI
Rural population growth	+fragmentation –FS, +FRI	+(over)grazing and +ignitions	+fragmentation, +openings, +ignitions
Atmospheric CO_2	Minor effect	Encroachment +FI	+litter production, +C/N, –decomposition +FI
Invasive grasses	–FRI, –FI	+biomass +FI	+biomass +FI
Heatwaves	+flammability +FI, +FS	+flammability +FI, +FS	+flammability +FI, +FS
Unnatural fuel loads (fire exclusion, tree plantations)	+FI	+FI	+FI
Examples	*Mediterranean shrubland, boreal forests*	*Tropical grasslands, savannas, open woodlands*	*Pine woodlands, some closed forests*

Notes: + indicates positive effect of the global change driver; – indicates negative effect. FI: fire intensity; FS: fire size; FRI: fire return interval.

propose that wildfires be viewed through a threshold approach: that is, wildfires occur when three thresholds are crossed (ignition, continuous fuel, and drought), and fire weather shifts these thresholds to lower values, triggering the occurrence and spread of wildfires (Figure 1). Through this lens, we evaluate how global change affects wildfire drivers (ignition, fuel, drought, and weather) and emphasize the interactions that drive wildfires across the world.

Factors affecting wildfire regimes

Ignition patterns

The primary natural source of fire ignition is lightning. Volcanoes and falling rocks are of secondary importance, and spontaneous ignitions may be considered where there is a high accumulation of organic matter (such as peat). In a world undergoing marked alterations in climate and weather patterns, the spatial and temporal distribution of lightning activity may be changing (Romps *et al*. 2014), with unforeseen implications for the fire regime.

However, the main causes of changes in fire ignitions are anthropogenic factors (Balch *et al*. 2017; Syphard *et al*. 2017; Cattau *et al*. 2020). Humans cause ignitions directly by accident (eg cigarettes; campfires; sparks from engines, powerlines, and welding equipment) or deliberately (ie arson), but also indirectly by altering fuels in such a way that increases their susceptibility to ignitions. Openings created by humans (through construction of roads and buildings, logging activities, and so forth) in formerly vegetated landscapes increase the availability of fine dry fuels for both anthropogenic and natural ignitions (Figure 1). Consequently, ignitions, including those by lightning, are often associated with roads and exotic grasslands, which are more flammable than natural forest vegetation (Calef *et al*. 2008; Veldman *et al*. 2009; Barlow *et al*. 2020). Overall, the number of people living in the wildland–urban interface (WUI) may be an indicator of potential ignition points (although under very high population densities fire activity decreases due to quick detection, proximity to suppression resources, and fuel fragmentation) (Syphard *et al*. 2007). For rural populations in highly developed landscapes (such as Eurasia), this association may be weaker, given that rural activities (eg grazing, farming, wood gathering; see below) often reduce fuels, making ignitions less likely. However, agricultural fires in less developed landscapes can also ignite adjacent wildlands and produce wildfires if the other thresholds (Figure 1) have been crossed, as currently occurs in some tropical ecosystems (Barlow *et al*. 2020). Furthermore, the increase of the rural population in those ecosystems also tends to result in higher levels of burning to convert forests to farmland. In many ecosystems, the number of people living in the WUI has increased in recent decades, and as with many spatial processes, this number tends to increase exponentially. For instance, the population of California has increased by six million since 2000, and most fires in this region are ignited by a diversity of anthropogenic factors (Syphard and Keeley 2015), including powerline failures that have been the cause of fires over ~200,000 ha since 2000 (ie five times the amount over the previous 20 years; Keeley and Syphard 2018, 2019). The "California lifestyle" model, in which development is spread widely across the landscape instead of being contained within more concentrated settlements, is becoming increasingly common around the world, especially in other highly populated MCRs.

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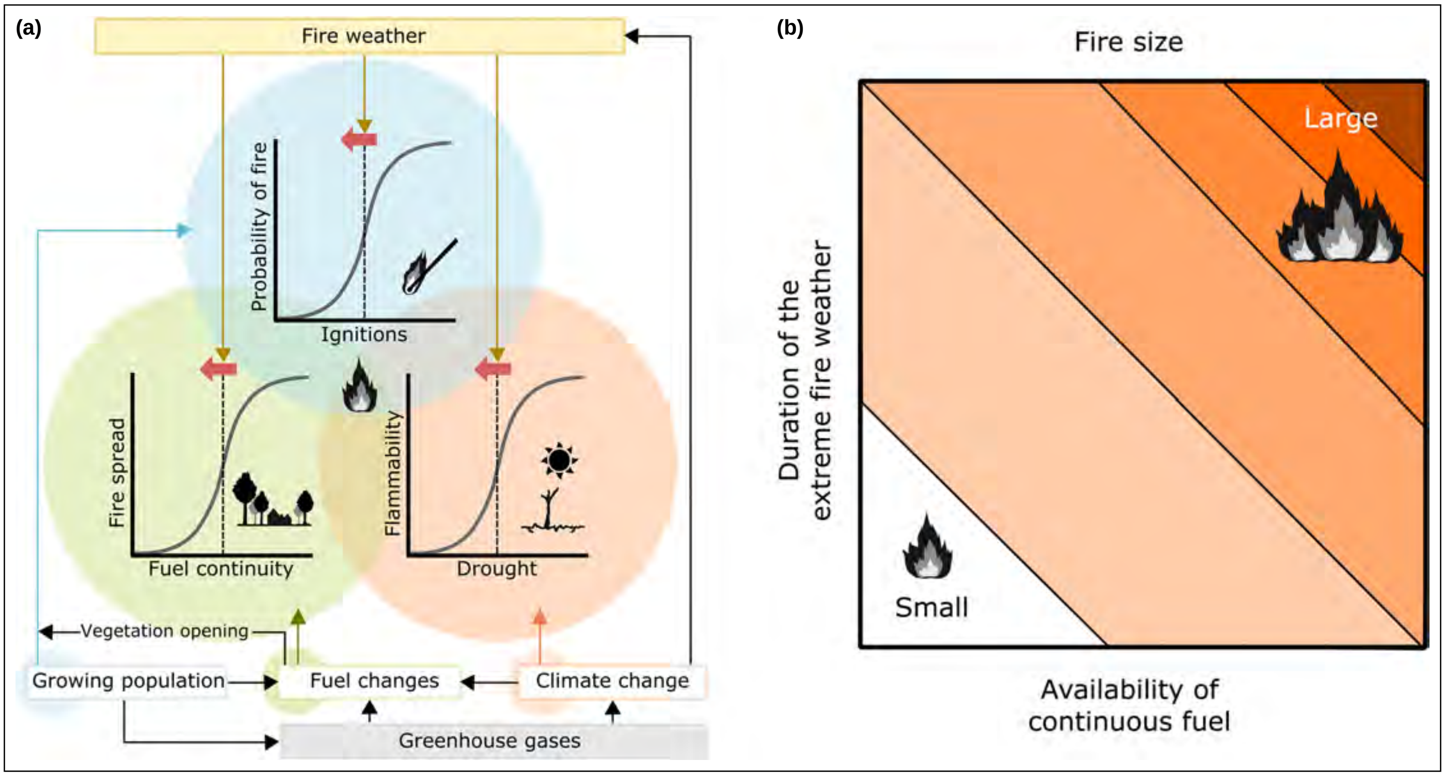

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Figure 1. Conceptual model of relationships between fire parameters and their drivers. (a) Probability of fire occurrence versus ignitions, fire spread versus landscape fuel continuity, and fuel flammability versus drought. In these graphs, dashed vertical lines indicate thresholds. In all cases, fire weather (strong wind, high temperature, or low humidity) shifts the curve and the threshold toward lower values (thick red arrows; ie saturation is reached at lower values along the x-axis), consequently increasing the probability of an ignition resulting in a fire, fire spread (for a given landscape configuration), and vegetation flammability (fuel dries faster). The flow chart shows the main factors affecting the fire drivers, including human population growth in or near wildlands, altered fuel loads (fragmentation, oldfields, fire exclusion, among others), and climate change. Arrows indicate positive interactions, with the exception of changes in fuel, which can increase or decrease fuel continuity depending on the system (eg fragmentation versus fire exclusion or increasing oldfields). (b) Once all thresholds have been crossed, the size of the fire is determined by the duration of the extreme fire weather and the availability of continuous fuels in the landscape.

The relationship between the number of ignitions and the occurrence of wildfires is likely to follow a saturation curve (Figure 1a): that is, if the weather conditions are not severe, few ignitions are unlikely to generate a wildfire, but there is a level of ignitions in which the probability of a wildfire increases abruptly (Bradstock 2010). Some ecosystems may therefore be limited by natural ignition (flammable ecosystems that do not burn because of the lack of ignitions; central Chile may be an example; Keeley *et al*. 2012). Others are saturated by ignitions (eg areas with large human population densities or frequent lightning strikes), in which case a small reduction in ignitions may not reduce fire activity. However, even a relatively small number of ignitions, if coupled with extreme fire weather (which reduces the threshold value; Figure 1), can generate large wildfires. For instance, anthropogenic ignitions have been declining in recent decades in many MCRs, yet the few ignitions that occur during severe wind events generate large wildfires (Curt and Frejaville 2018; Keeley and Syphard 2018, 2019).

Increasing human population growth enhances the probability of ignitions during severe fire weather; in MCRs, due to urban sprawl into landscapes with dangerous fuels, it also increases the number of people and properties at risk. For example, the area burned in the 2017 Tubbs Fire in northern California, which was caused by a powerline failures, largely coincided with the area burned by the 1964 Hanly Fire in the same area. Yet there were no fatalities in the Hanly Fire despite the fact that it was substantially larger than the Tubbs Fire, and only 84 structures were destroyed; in comparison, there were 22 fatalities in the 2017 Tubbs Fire, and more than 5600 structures were destroyed (Keeley and Syphard 2019). The Tubbs Fire was far more devastating simply because the regional population had increased fivefold over the intervening 53 years between the two fires, and the electrical grid system had been greatly expanded across the landscape, with a consequent increase in the potential for wind-driven powerline failures.

Fuel continuity

The rate at which wildfires spread through plant communities depends on their structure and the flammability of neighboring plants. Fuel continuity and its load are critically important, and both vary with productivity across ecosystems (Pausas and Paula 2012), as productivity controls plant growth and decomposition. However, human activities strongly influence fuel patterns. For instance, agriculture and urban infrastructure increase ecosystem fragmentation and reduce landscape fuel continuity. In highly populated areas (eg southern Europe), large fires often cease when they reach farmland. Indeed, a global reduction of fire activity has been detected in recent decades (Marlon *et al.* 2008; Andela *et al.* 2017), partially due to increased farming (mainly in tropical areas). Other factors, however, increase fuel continuity and fire activity in many regions of the world.

Fire exclusion is an example of a driver that has enhanced fuel buildup in many ecosystems. For instance, many western US coniferous forests that were once subject to frequent surface fires have experienced a marked increase in understory fuels as a consequence of a successful fire suppression policy. This has caused a widespread increase in vertical connectivity (ladder fuels) and in the susceptibility to high-intensity crown fires (Covington and Moore 1994; Allen *et al.* 2002; Swetnam *et al.* 2016). Similar fire-exclusion policies are altering fuel structure in other ecosystems worldwide (eg Baker and Catterall 2015; Johansson *et al.* 2019). In Mediterranean Europe, aggressive fire suppression is currently the primary policy; although this approach reduces the number of fires, it increases fuel loads and consequently the susceptibility of the landscape to ignitions and droughts (Pausas and Fernández-Muñoz 2012; Curt and Frejaville 2018).

Forestry plantations are another potential source of increasing fuel amount and continuity. They are on occasion established in natural nonforest ecosystems, such as Mediterranean shrublands and savannas (Bosch and Hewlett 1982), which greatly increases fuel loads in these systems. Other plantations are established in native forest ecosystems, but tree density and the degree of homogeneity are usually much higher in plantations (such as on evenly aged plantations, which maximize wood production) than in the native forests they replace and thus they increase fuel continuity (Keeley and Syphard 2019). Fuel management can alleviate several of these problems by generating vertical discontinuities and reducing tree density (Knapp *et al.* 2017), but this is not always practiced because of cost, limitations due to air-quality restrictions (eg prescribed burns), and topographic constraints (eg mechanical treatments); in addition, silvicultural management is often based on the climate of the 20th century. As a result, massive fires have become increasingly common in exotic tree plantations, such as in Chile and Portugal (Gómez-González *et al.* 2018).

In many regions, rural abandonment of agriculture (including livestock grazing and wood gathering) has driven increases in early successional (flammable) plant communities, enhancing fuel loads and continuity (homogenization of landscape). This trend has been occurring in part because rural abandonment has not been accompanied by the reintroduction of native herbivores. Examples have been documented in Mediterranean Europe (Pausas and Fernández-Muñoz 2012) and the former Soviet Union (Dubinin *et al.* 2011). However, this process is occurring in many other regions where urbanization rates are increasing, and it is likely to become more relevant in areas where tourism provides an alternative economic income to traditional rural livelihoods (Chergui *et al.* 2018).

Invasive plants are also changing fuel patterns, most typically by increasing the amount and continuity of herbaceous fuels, with consequences for the fire regime (Brooks *et al.* 2004; Pausas and Keeley 2014). For example, the Great Basin Sage Scrub ecosystem in the US is threatened due to exotic grass invasion and subsequent changes in a natural mosaic of patchy burns toward large, continuous burns that threaten recovery of the native ecosystem (eg the 2020 Dome Fire in California's Mojave Desert; Keeley and Pausas 2019).

Increased atmospheric CO_2 enhances plant growth and litter production, and is therefore likely to be contributing to increasing fuel load and continuity; a substantial proportion of Earth greening (Piao *et al.* 2020) and savanna encroachment (Buitenwerf *et al.* 2012) has been linked to atmospheric CO_2 fertilization. Given that CO_2 increases water use efficiency (ie reduced stomata openings for fixing a given amount of carbon), the greater biomass promoted by higher concentrations of atmospheric CO_2 may be more important in dry ecosystems, although evidence for this remains limited (Van der Sleen *et al.* 2015).

Independent of the mechanism that increases fuels, greater fuel continuity clearly enhances the probability of fire spread, a pattern that is not linear but rather associated with thresholds (Figure 1) due to the spatial nature of the processes associated with fire spread (that is, a contagious process; Abades *et al.* 2014; Pausas and Keeley 2014; van Nes *et al.* 2018). In other words, there is a level of fuel continuity from which fires can easily "percolate" through the landscape, and this percolation threshold is modified by fire weather (Figure 1).

Under very high and continuous fuel loads as well as extreme fire weather, fires not only cross the fuel threshold very easily but can generate enormous heat and a tall plume of hot air that drives convection columns (pyrocumulonimbus; Panel 1; Figure 2). In some extreme cases, the heat may be so great that the convection column extends through the tropopause and enters the stratosphere (Figure 2; Dowdy *et al.* 2019). In such instances, fire–atmosphere feedbacks produce complex, rapid, and unpredictable fires (see "firestorm" in Panel 1). The intensity of these fires is such that flammable material some distance ahead of the fire front is desiccated and easily ignited by embers, enabling the fire to jump fuel breaks. These types of fires can also burn forests that have been traditionally considered resistant to wildfire.

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Panel 1. Key concepts

Crown fire: fires in woody-dominated ecosystems that affect all vegetation including crowns (woody-fueled fires). They are typically high intensity. Examples include fires in some Mediterranean-type forest and shrublands and in closed-cone pine forests.

Fire regime: the characteristic wildfire activity that prevails in a given area at a particular time. It is typically determined by its frequency, intensity, seasonality, size distribution, and type of fuels consumed, and depends on the frequency which all fire thresholds are crossed (Figure 1). Two common fire regimes that represent extremes are surface-fire regimes and crown-fire regimes.

Fire weather: refers to the prevailing weather conditions affecting fire behavior; extreme (or severe) fire weather refers to strong winds, high temperatures, and low humidity.

Firestorm: a generic term used to describe wildfires with extreme, at times erratic behavior driven by high winds. The term has been used to describe wind-driven fires (eg Santa Ana wind firestorms in California) or pyrocumulonimbus plume fires (the 2019–2020 fires in Southeast Australia).

Flammable: a general term for fuels that easily ignite and contribute to fire spread. Quantifying the propensity to burn (flammability) is complex, as it encompasses several processes and depends on plant traits and structure, weather conditions, and the scale of reference (Pausas *et al*. 2017).

Megafire: wildfires at the extreme of the frequency size distribution for a given ecosystem; typically megafires are outliers (in the statistical sense) in relation to the historical fire size distribution. They are often driven by strong winds and/or high and continuous fuel loads (ie wind-driven or fuel-driven wildfires). Sometimes the term refers to several fires that burn simultaneously in a specific region, and then merge as they grow. The size of megafires is determined by the duration of the fire weather and by landscape characteristics (Figure 1b); for example, fires in Alaskan boreal forests often extend over 500,000 ha or more, but in other landscapes, continuous fuels are insufficient to carry fires of this size. The social impacts of a fire are not included in this definition (but see Stephens *et al*. 2014), as not all megafires are necessarily catastrophic.

Pyrocumulonimbus: a dense, towering, vertical cloud carried by powerful upward air currents generated by the heat of a wildfire (Figure 2; also known as plume-dominated fires, superheated wildfires, and wildfire-driven thunderstorms). This phenomenon is typically linked to very high and continuous fuel loads and extreme fire weather that produces great heat and strong convection currents. In most cases, it remains in the troposphere, but when heat produced by a fire is extremely high, it can cross the tropopause and inject a large amount of smoke into the stratosphere. These plumes often collapse at altitude due to colder temperatures, and create extreme winds. As such, these plumes generate feedback processes between the atmosphere and the fire that can produce strong surface winds, tornadoes, and even pyrogenic lightning ignitions that further expand the fire (firestorms).

Surface fire: fires that spread in the herbaceous (grass-fueled fires) or litter (litter-fueled fires) layer, such as the understory of some forests (understory fires) and in savannas and grasslands. These fires are usually of relatively low intensity and high frequency.

Droughts

Droughts occur in all ecosystems but the average severity and duration of drought events, including anomalous drought events, differ markedly among systems. The impact of a drought is largely due to deviation from the long-term average, as this is what drives plant adaptations. In MCRs and savanna ecosystems, droughts occur frequently, and as a result these landscapes are typically fire prone. Globally, however, droughts may occur with less regularity and are often dependent on decadal-scale events. These differing patterns of drought have important effects on wildfire frequency and intensity.

On a global scale, climate warming is expected to greatly affect fuels, whereas changes in rainfall patterns are more variable; even on landscapes where rainfall is not declining, however, warming increases evapotranspiration rates, leading to both a drier climate and fuels. Drought has contrasting effects between woody and grassy ecosystems (Table 1). In woody-dominated ecosystems (eg Mediterranean, temperate, and boreal ecosystems), drought not only increases the likelihood of fire, it also creates more standing dead biomass, and increases plant mortality and litter, further enhancing fuel connectivity. All of these factors exacerbate ignition success and fire spread. In

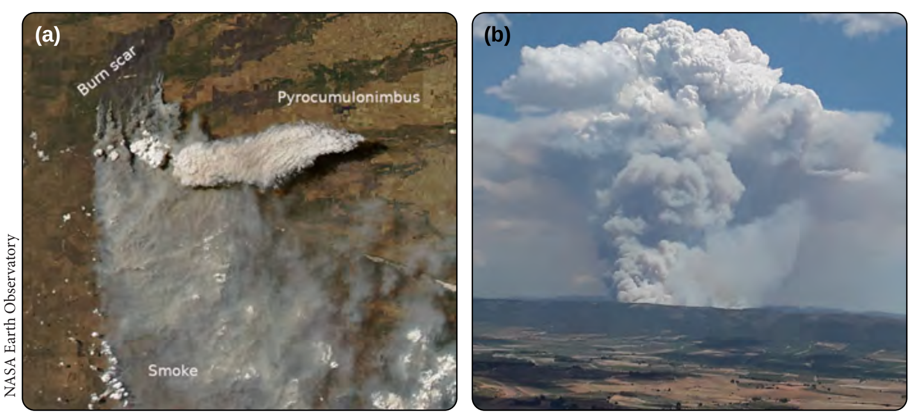

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Figure 2. Pyrocumulonimbus (a) in La Pampa Province, Argentina, as seen from a satellite (29 Jan 2018) and (b) in Beneixama, Spain, as seen from the ground (15 Jul 2019). In (a), note that the dynamics of the smoke at lower levels (moving toward the south) differs from that at higher levels (pyrocumulonimbus moving west).

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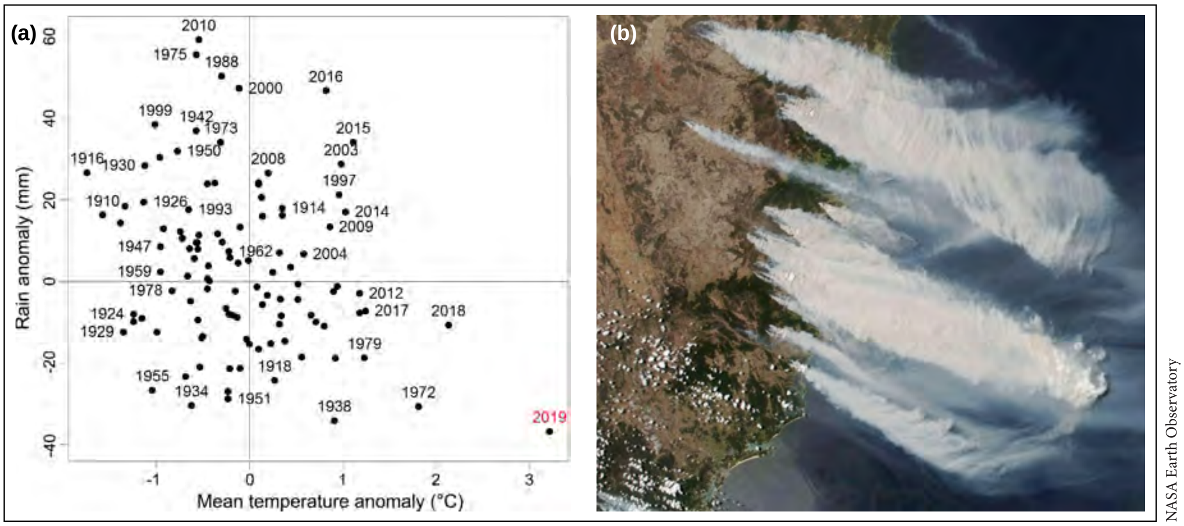

Figure 3. The 2019–2020 bushfires in southeastern Australia were driven by the combination of an extended drought and severe fire weather conditions. (a) Mean temperature anomaly and rainfall anomaly in Australia for the month of December for all years with available climatic records (1910–2019). (b) Smoke plumes showing the importance of wind in driving multiple fires (8 Nov 2019). Graph in (a) elaborated from data by the Australian Bureau of Meteorology.

consequence, fire seasons are becoming longer (Westerling *et al.* 2006; Flannigan *et al.* 2013), and this increases the annual frequency of weather conditions appropriate for fire spread. In many forest ecosystems where past climatic conditions were rarely conducive to fire, the frequency of dry years (that is, years with appropriate conditions for fire spread) is now higher.

Although drought is often a good indicator of the probability of fire spread in woody-dominated ecosystems, this relationship is not linear, as there is a drought threshold from which fire spread increases abruptly (Figure 1; Westerling and Bryant 2008; Pausas and Paula 2012). This threshold is not universal, and the degree of drought necessary for it to be crossed (ie to switch from a nonflammable to a flammable state) depends on the vegetation type (ie landscape fuel amount and continuity). For example, the drought threshold in productive ecosystems (where fuels are more dense) is associated with conditions that are less dry, as compared to the threshold in dry ecosystems (where fuels are more sparse) (Pausas and Paula 2012).

In contrast, in seasonal grassy communities (note that grass-fueled fires account for most burned area globally; Van der Werf *et al.* 2006), drought is associated with reduced (rather than increased) fire activity. This is because grasses become highly flammable each year during the dry season, and fire activity is dependent mainly on grass biomass and continuity; in such ecosystems, drought reduces fuel continuity and subsequently fire activity. Indeed, grass biomass and continuity are affected positively by the previous year's rainfall (antecedent climate). The contrasting effect of drought between woody and grassy communities was evident after the particularly long and severe 2019 drought in Australia (Figure 3a), which resulted in greatly increased areal extent burned in forests but decreased areal extent burned in savannas (Bowman *et al.* 2020). A positive effect of antecedent rainfall has also been detected in some ecosystems dominated by woody species, suggesting that drought prior to onset of the fire season may to some extent reduce fire spread in the herbaceous or litter layer (Swetnam and Betancourt 1998; Pausas 2004; Keeley and Syphard 2017).

Fire weather

Fire weather refers to the weather conditions directly affecting fire behavior (ie conditions that lower fire thresholds in a given ecosystem and make them easier to cross) (Figure 1a). In addition, the duration of fire weather can contribute to fire size (Figure 1b); as examples, the longer-than-average Santa Ana wind event during 2017 contributed to the massive Thomas Fire in California, and the very long and intense heat wave in that state during August–September of 2020 led to the highest annual burned area on record.

Wind is a critically important fire weather factor and facilitates the crossing of all three fire thresholds; generally, wind (1) increases the chances of successful ignition of a fire because it supplies oxygen for combustion; (2) affects flame length and depth, as well as the dispersal distance of embers, and therefore greatly influences fire spread rate and the degree to which a fire can bridge fuel discontinuities; and (3) increases evapotranspiration rates, exacerbating vegetation dryness (and therefore enhancing its flammability). Wind can shift fire thresholds downward (Figure 1), and may offset or overwhelm all other factors (eg wind-driven fires). In addition, changes in wind direction determine the shape of the fire, and the duration of wind events may determine the size of the fire (Figure 1b). The importance of wind is conspicuous in many fire-prone

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ecosystems (Figure 3b; Keeley *et al.* 2012); for instance, in California's chaparral, the largest fires typically occur in autumn, when foehn winds – dry, warm winds that blow downslope in the lee of a mountain range – blow more frequently (eg Santa Ana and North winds; Keeley and Syphard 2019). Notably, these severe wind events do not usually accompany extreme fires, because other thresholds must be crossed simultaneously to generate those fire events. In fact, large wind-driven fires in MCRs are typically ignition-limited and require a combination of extreme wind conditions and human-caused ignition (see "Ignition patterns" above; Keeley and Syphard 2019).

The location and direction of topographically determined winds (eg foehn winds) are unlikely to be affected by global change, although there is evidence of shifts in seasonal peaks, frequency, and intensity (Guzman-Morales and Gershunov 2019). However, windstorms that are linked to ocean temperatures could be more susceptible to change (Elsner *et al.* 2008); the unprecedented approach of Hurricane Ophelia toward western Europe in 2017, where it fueled fires in Portugal and Spain and transported the smoke to the UK, is one prominent example (Figure 4). Although difficult to predict, new wind regimes may be key for future fire activity in many regions.

High temperature and low atmospheric humidity are the other key factors of fire weather; they exacerbate evapotranspiration rates and warm and dry fuels, which shift ignition and fuel thresholds downward (that is, warm and dry fuels ignite and burn faster because they require less heat energy to reach ignition temperature; Figure 1). Foehn winds are usually very hot and dry, and can therefore greatly enhance ignitions, flammability, and fire spread even when they are not especially strong. High temperatures can also contribute to the formation of strong convections, which typically develop when fuel loads are very high (but not often in wind-driven fires), increasing the probability of generating pyrocumulonimbus clouds and severe fire behavior (Panel 1). More frequent heatwaves (Figure 3; Wang *et al.* 2020) resulting from climate warming may increase the occurrence of these events. The recent massive wildfires in Southeast Australia (2019–2020) and California (2020) were both driven by extreme weather conditions consisting of strong winds and high temperatures after extraordinarily dry years (Figure 3).

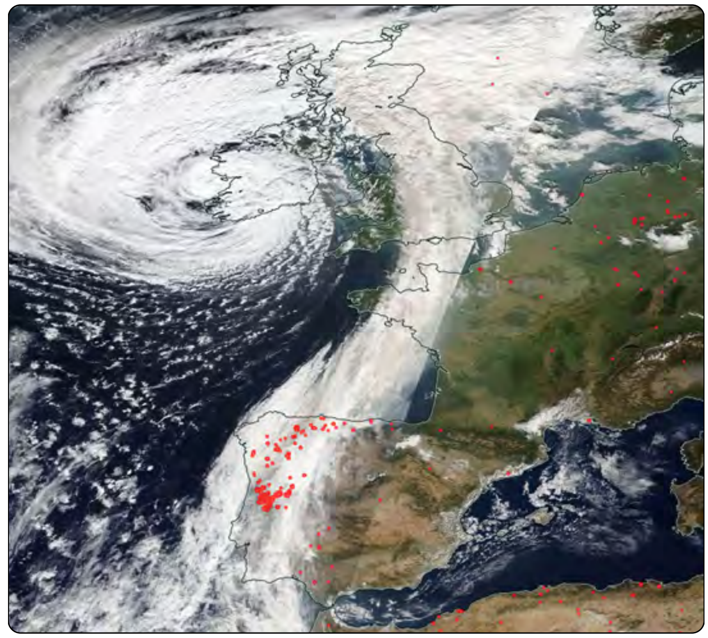
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Figure 4. Hurricane Ophelia originated in the Caribbean and eventually reached Europe, where it fueled fires in Portugal and Spain, and covered the UK with smoke from those fires (16 Oct 2017). It is considered the easternmost Atlantic hurricane on record. Red circles are fires as detected by the Visible Infrared Imaging Radiometer Suite (VIIRS).

Conclusions

Although none of the factors mentioned above generate wildfires in and of themselves, combinations of these factors – ignition, drought, continuous fuels, and suitable fire weather – typically act in concert to produce wildfires under certain conditions. The fire regime of an ecosystem is determined by the frequency with which all thresholds are simultaneously crossed, and its current variations depend on how global change factors affect the various fire drivers (Table 1; Figure 1). When these thresholds are crossed, the size and duration of a fire will largely depend on how long the fire weather lasts and the extent of the area containing suitable fuel material (Figure 1b). The former can be influenced by climatic change, whereas the latter largely depends on landscape constraints (including topography) and human activities (eg fragmentation, rural abandonment, fire exclusion, tree plantations). Wildfires in Spain, for example, are typically smaller than those in Australia or Canada not because of differences in climate and weather conditions but rather because of the lower availability of extensive natural vegetation. Large wildfires (see "megafire" in Panel 1) are not necessarily novel events in many ecosystems, but they may be increasing in occurrence as thresholds are more frequently crossed due to higher numbers of ignitions (Syphard and Keeley 2015), as well as landscape modifications (eg Covington and Moore 1994; Pausas and Fernández-Muñoz 2012) and more severe drought conditions (Figure 3; eg Boer *et al.* 2020).

Human factors drive many of these changes in fire regime (Figure 1). One of these factors is climate change, which increases the frequency of conditions conducive to fire: that is, it increases the fire season (in fire-prone ecosystems) or the frequency of fire-prone years (in typically non-fire-prone ecosystems). However, climate-related factors do not explain all the complexity of the changes in global fire regimes, as altered ignition patterns (eg human behavior) and fuel structure (eg land-use changes, fire suppression, fragmentation) are also important. For instance, in many Mediterranean ecosystems, the drought threshold is crossed annually, and vegetation cover is usually high enough for fire spread; as such, ignitions are a key factor. Larger populations of humans in the WUI will likely lead to increased ignition rates, and consequently higher probability of ignitions coinciding with extreme weather events to generate wildfires. In other ecosystems, changes to forest management (through policies, rural depopulation, and so forth) may be more relevant for fire activity than changes in climate. Overall, with respect to climate-change-associated increases in fire activity (eg due to increasing drought frequency), cold and moist ecosystems and fuel-driven fire regimes are likely to be more susceptible than warm and dry ecosystems and wind-driven fire regimes; however, other drivers may outweigh climate in controlling fire regimes.

Thresholds can be quantified for each system with statistical models constructed from empirical data (Westerling and Bryant 2008; Pausas and Paula 2012), but this approach can be challenging because estimations of one threshold requires controlling for the others. An alternative approach is to use simulation models and sensitivity analysis (Abades *et al*. 2014; Pausas and Keeley 2014; van Nes *et al*. 2018). Further research is also required for using thresholds and early warnings for fire risk management, as has been done previously for other natural hazards. Because wildfires require the crossing of several thresholds simultaneously (Figure 1), managing with the goal of preventing any single threshold from being crossed could potentially reduce fire activity considerably. Although the occurrence of weather conditions conducive to fire may be increasing as a result of climate change, managing ignitions and fuel loads have been shown to be effective tools for maintaining fires within an acceptable regime. Application of these tools will vary across ecosystems, however; for instance, areas in which fuel-driven fires dominate require very different management approaches from those dominated by wind-driven fires (fuel versus ignition control, respectively; Keeley and Syphard 2019). Likewise, grassy and woody ecosystems respond in different ways and therefore require distinct management strategies (Table 1). In areas where management is likely to be ineffective, the primary option should be to delimit danger zones in which human activities are minimized, in much the same way as is done in areas at risk of flooding or volcanic activity.

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