



Towards a comprehensive look at global drivers of novel extreme wildfire events

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Abstract

Extreme wildfire events in recent years are shaking our established knowledge of how fire regimes respond to climate variables and how societies need to react to fire impacts. Albeit fires are stochastic and extreme in nature, the speed, intensity, and extension of new extreme fires that have occurred during the last years are unprecedented. Here, we identify common features of these emerging novel extreme wildfire events characterized by very high fire intensity and rapid rates of spread, and we review the major mechanisms behind their occurrence. We then point to the major challenges that extreme wildfire events pose to science and societies worldwide, both today and in the future. Climate change and other factors are contributing to more flammable landscapes and the promotion of unstable atmospheric conditions that ultimately promote wildfire development. Anticipating these novel conditions is a key scientific challenge with paramount implications for present and future fire management, ecosystems, and human well-being.

Keywords Climate change · Extreme wildfire event · Pyrocumulonimbus · Land-use change · Socioecological system · Fire management

Wildfire activity across the globe emerges as a complex interplay between landscape patterns, vegetation type and structure, climate, and human activities. In general, fire regime drivers are well understood (Krawchuk et al. 2009; Bowman et al. 2009; Archibald et al. 2013, 2017; Syphard et al. 2017; McLauchlan et al. 2020). Climate gradients control vegetation structure, productivity, and flammability (through plant traits, Archibald et al. 2017), and weather patterns (mostly wind and relative humidity) and topographical variables act as more local

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fire activity drivers (Mermoz et al. 2005; Archibald et al. 2009; Parisien and Moritz 2009; Bradstock 2010; Povak et al. 2018). Ignitions trigger fire combustion when both fuel and weather factors allow it. Anthropogenic influences restrict or enhance the ignition and spread of fire in the landscape, in a complex and dynamic mix of social and biophysical factors (Bowman et al. 2009, 2017; Archibald 2016; Syphard et al. 2017), changing fire regimes and in some cases pushing them outside the range of variability (McLauchlan et al. 2020).

Current global change is accelerating changes in wildfire regimes (Brotons et al. 2013; Abatzoglou and Williams 2016; Di Virgilio et al. 2019; Williams et al. 2019). Recent human activity overlaps with climate change effects inducing rapid changes in fire regimes worldwide, resulting in a range of ecosystem impacts and increasing threats to human societies including goods and lives, but also to investments, and planning or future economic activities (Bowman et al. 2017; McLauchlan et al. 2020). Albeit many fire regimes have been historically characterized by rare, large, and impacting wildfires (as the 1910 *Big Burn* in the Northern Rockies in the USA that burnt 121,000 ha in 2 days, but also older registers in North America boreal forests 1000 years before present; Ali et al. 2012), recent global events (2016 Canada, 2017 Chile, USA, and Portugal, 2018 Northern Europe, South Africa and the USA, 2019 Bolivia, 2020 Australia and USA) point to the emergence of novel extreme wildfire events not reported previously and associated, in many areas, to a higher frequency of events than expected (Sharples et al. 2016; Boer et al. 2017; Tedim et al. 2018; Nolan et al. 2020). Although researchers have gained deep knowledge on wildfire activity over time, this knowledge falls short in predicting the speed, intensity, and extension of recent fires, with most of them breaking records in terms of fatalities, material losses, burnt area, or fire speed. Understanding and predicting wildfires have proven an extremely challenging endeavor, and fire researchers need to reevaluate existing knowledge and develop new paradigms to fully understand and be able to predict these events (Moreira et al. 2020; Rogers et al. 2020).

Here, we aim at identifying and describing major mechanisms behind the emergence of extreme wildfire events (EWE) occurring across the globe in recent years and to point out some of the main challenges they pose to science and societies worldwide when looking at future fire regimes and their impacts. We use the definition of EWE proposed by Tedim et al. (2018) based on fire behavior and impacts, and we broaden it with an extreme wildfire season, which includes a high number of fires that leads to the unprecedented burnt area in a single season. We analyze some of the main illustrative EWE occurring between 2016 and 2020 (Fig. 1) that have shaken our current understanding of wildfire phenomena and can be categorized as novel fire events because of the lack of similar records (18 EWE described in Supplementary material 1). Specifically, most of these novel EWE were associated with extreme rates of spread, extreme burnt area, or extreme impacts. Through the review and analyses of official reports and research papers, we identify, sort, describe, and conceptualize the major mechanisms that characterize these novel EWE and proceed to disentangle the relative roles of climate and socioecological factors. We also provide some insights about possible future global trends of these mechanisms. This could assist scientists and fire planners to develop adequate tools to predict where EWE will be more likely to develop in the future.

1 Drivers of novel extreme wildfire events

We describe below the main mechanisms explaining the causes of extreme wildfire behavior or extreme burnt area in a season. For the different mechanisms, we describe the phenomenon,

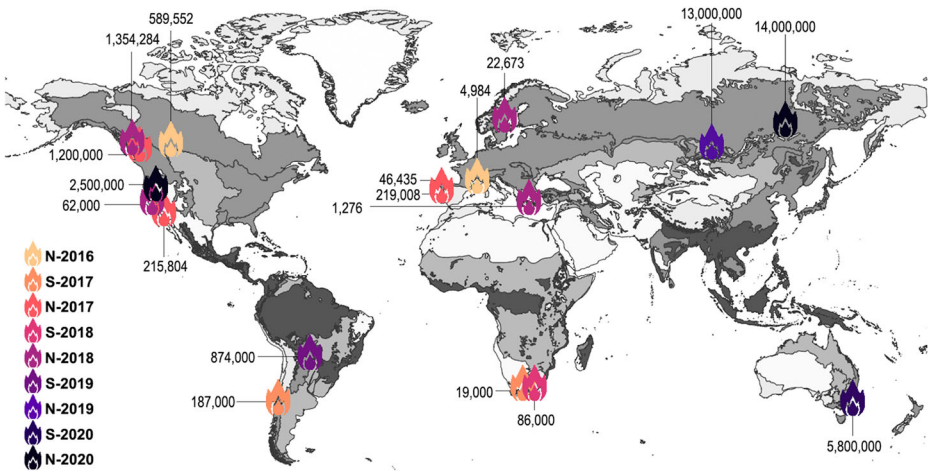


Fig. 1 Location of illustrative extreme wildfire events or episodes reviewed in this study from May 2016 to December 2020. The different flame colors indicate the temporality of the events (legend). N indicates fire season in the Northern hemisphere (~ May–October), and S fire season in the Southern hemisphere (~ November previous year–February). Numbers indicate the burnt area in each EWE according to the sources indicated in Table S1. Region limits correspond to Olson et al.'s (2001) ecoregions classification colored in 5 levels according to a productivity gradient (from darker (moister) to lighter (drier): Tropical and subtropical moist broadleaf and coniferous forests, mangroves, flooded grasslands, and savannas. Tropical and subtropical dry broadleaf forests, boreal forests/taiga, temperate conifer, broadleaf, and mixed forests. Tropical, subtropical and temperate grasslands, savannas, and shrublands. Mediterranean forests, woodlands and scrub, montane grasslands and shrublands, and tundra. Deserts and xeric shrublands, inland water, and rock and ice)

the relation with wildfire activity, and its potential evolution to the future. We finally also try to derive predictions on where extreme events are more likely to develop in the near future.

1.1 Weather and climatic mechanisms

1.1.1 Unstable atmospheres and pyroconvection

Wildfire behavior can become extreme when cumulus flammagenitus or cumulonimbus flammagenitus clouds are generated (more known as pyrocumulus (PyroCu) or pyrocumulonimbus (PyroCB) respectively, terms used in this work). These types of clouds are formed by convection forced by the same wildfire: hot smoke from the fire rises in the air that ends up condensing water vapor and forming clouds (Lareau and Clements 2016; Fig. 2). PyroCu may become PyroCb that can trigger local storms and thunderstorms, and they develop when the upward plume is reinforced by instability in middle levels of the troposphere such that a very deep convective cloud forms. Pyrocumulonimbus can also inject aerosols into the stratosphere and be transported globally (Bowman et al. 2020). If thunderstorms are generated, two opposite processes impacting the wildfire might occur: rain, which might reduce fire intensity and spread, and lightning, which might originate new fires at long distances from the main fire (Dowdy et al. 2017). Beyond the effects of lightning, the formation of pyroconvection (known here as the capacity to form either PyroCu or PyroCb) has far-reaching consequences for wildfire behavior and intensity: although the microphysics are not fully understood, hot air rises rapidly (air that is warmer and moister than its surrounding environment at the same pressure is less dense and subject to an upward buoyant force) and it

is replaced by cold air, rich in oxygen that feeds the fire and increases fire activity, which at the same time increases hot rising air and makes a feedback dynamic (Lareau and Clements 2016). Below the rising parcel a void is created, leading to lower pressure at the base and attracting surrounding air to compensate for the displaced parcel (indrafts, Fig. 2). Even though this activity can happen in many types of fires, instability characterized during pyro-cloud formation exacerbates this process. The smoke plumes and pyro-clouds can act as chimneys and create interactions with the atmosphere that change wildfire behavior in an unpredictable way nowadays (Finney et al. 2015). When a cloud is massive enough that the gas pressure is insufficient to support it, it will collapse and the updraft will turn into a downdraft (Fig. 2). The descendent bursts can carry cinders and other ignited material (“ember showers”) that cause massive spotting ahead of the fire. Convective behaviors cause emergency and response forces to struggle with strong difficulties in predicting fire spread direction (Duane et al. 2015;

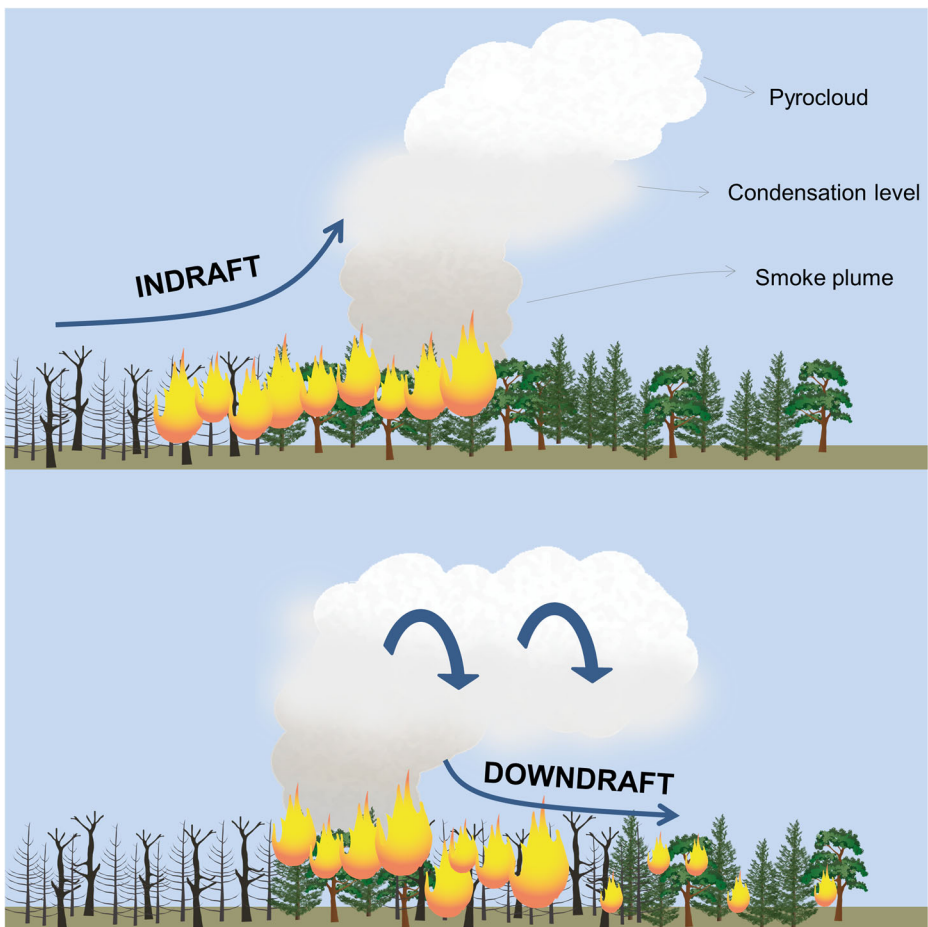


Fig. 2 Conceptual scheme of the main air currents affecting wildfires during pyroconvection. The upper panel shows the formation of a pyro-cloud during a wildfire, with the three main stages in the vertical column of the fire: the smoke plume, the condensation level, and the formed pyro-cloud (PyroCu or PyroCb). The vertical development of the pyro-cloud creates a pressure gradient that forces indraft currents influencing and exacerbating fire runs. The lower panel shows the moment when the pyro-cloud collapses because it lacks enough buoyancy to support it, and it creates downdrafts and spotting that cause erratic and quick fire propagation

Sharples et al. 2016). The wildfire spread algorithms and models are based on surface weather data and are usually not able to reproduce current wildfire behaviors and predict future spreads. Under this situation, even prevention, management and pre-emergency planning get lost on how to reduce fire hazards and impacts.

Pyroconvection formation is strongly influenced by a range of environmental factors including atmospheric stability and surface fire weather conditions (Dowdy and Pepler 2018). Atmospheric stability is the resistance of the atmosphere to the vertical or upward movement of air that has been heated nearer to the surface. Unstable atmospheres are characterized by strong temperature decreasing profiles (Peterson et al. 2016) and by humid low-level air masses that are able to reach the condensation level (height at which an air parcel cooled by dry adiabatic will reach 100% humidity saturation and can be both the convective condensation level: CCL or the lifted condensation level: LCL; Fig. 3). This condensed parcel will not rise anymore if it is not forced (e.g., because of the wildfire), unless it reaches the level of free convection (LFC; level at which the air parcel is warmer than the environment). When the condensed cloud reaches the LFC, it can freely rise until the equilibrium level (EL; level at which a parcel becomes again the same temperature as the environment). The potential energy available for free convection (CAPE) is the region between the LFC and the EL. However, to develop free convection, the parcel first needs to reach the LFC, and the convective inhibition index (CIN) indicates this effort. CIN represents the vertical area where a parcel is colder than the environment, and it is defined as the amount of energy beyond the normal work of expansion needed to lift a parcel from the surface to the LFC. Reaching the condensation level through a thermal balance with the surrounding air can occur (1) in summer days, in which high-intensity fires provide the extra convective heating, moisture and buoyancy needed to break a capping inversion or (2) with the supply of moisture in the lower atmosphere, such as at the beginning of the night or during spring conditions (more humid environments). However, it is more common that LCL and LFC are reached when other processes are helping to lift the heated and humid air: (1) with the entry of cold air fronts that raise warmer air; (2) in convergent air mass zones; and (3) due to orographic air rise. In any case, wildfire combustion processes provide extra heat and moisture at the base of the plume that help to reach the areas of free convection (Cunningham and Reeder 2009; Potter and Anaya 2015).

Pyroconvection is not new. Rothermel (1991) already classified fires into three typologies, one of them representing fires driven by plume behavior. Several fires developing pyroconvection have been recorded in the last decades, especially in the USA and Australia (Fromm et al. 2006; Werth et al. 2011). However, their frequency, extension, and impacts might be increasing during recent years (Dowdy and Pepler 2018; Bowman et al. 2020) and be related to increases in vegetation stress (Nolan et al. 2020) and changing atmosphere conditions (Dowdy et al. 2017). Additionally, the uncertainty and unknowns related to their process and behavior, together with a deficiency in current simulation models to include them, make them specially challenging for suppression decision-making and locate them in the spotlight of current wildfire research. A good example of the human and ecological crisis caused by PyroCb wildfires is the Australia 2019/2020 outbreak with over 35 fire pyrocumulonimbus that caused unprecedented burnt area amid dry vegetation and very high temperatures (Boer et al. 2020; Bowman et al. 2020; Nolan et al. 2020) (Fig. 4). There have been various attempts to characterize an index able to predict convective activity related to wildfires. The Haines Index (Haines 1988) is a good predictor of atmosphere stability (Tatli and Türkes 2013; Dowdy and Pepler 2018). However, this index sometimes fails in predicting pyroconvection activity since high values may not necessarily correspond to a high risk of pyroconvection in

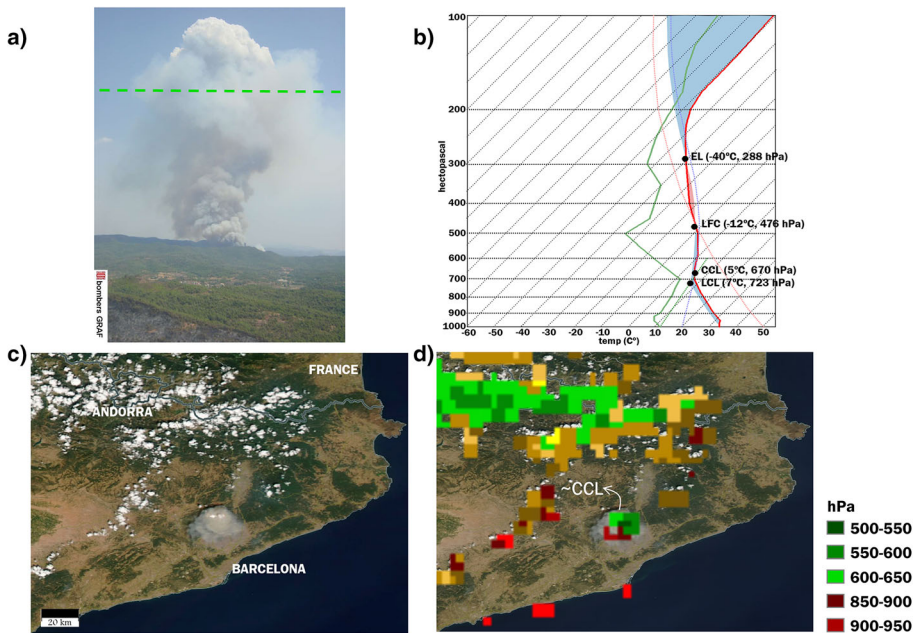


Fig. 3 Pyroconvection formation in an iconic fire (Sant Llorenç Fire, 11 August 2003, Spain). Panel **a** shows a picture of the smoke plume and the PyroCu formed during the fire. The green line shows the condensation level. Panel **b** shows the vertical profile (Skew-T diagram) for the same fire the day of the pyro-cloud. The green and red lines show the dew point temperature and the temperature vertical profile respectively. Blue polygons show negative buoyancy and the red polygon shows positive buoyancy. Four levels relevant for pyroconvection are marked: the LCL, the CCL, the LFC, and the EL (see main text for further explanation). Panel **c** shows a satellite view (true color reflectance composite detected by Aqua MODIS sensor) from the same fire and its regional location. The smoke plume and pyro-cloud can be observed at the center of the image. Panel **d** shows the same image as in **c** but with information about the pressure level of the top clouds (Aqua/MODIS sensor). This allows to see that the cloud tops correspond approximately to a level between the CCL and LFC identified in panel **b**. Credits: **a** Bombers de la Generalitat de Catalunya. **b** GWIS information facility. **c** and **d** Worldview Earth Data

cases with very wet fuels and weak near-surface wind speeds, and also because it does not represent the heat and moisture released from the fire itself (Dowdy et al. 2017). Specifically, the index saturates very quickly, and an extended index has been proposed and could be more useful (Mills and McCaw 2010). Yet, recent research advances are fine-tuning the use of the Haines Index by adjusting its value in relation to additional factors such as relief complexity or ground fuel characteristics that are increasing their potential explanation (Di Virgilio et al. 2019). The use of the CAPE (potential energy for convection) and DCAPE (maximum energy available to a descending parcel of air) value has also been proposed as an indicator of pyroconvection, but their use also shows difficulties to predict it (Potter and Anaya 2015). These two indexes usually fail since they do not consider the changes in the air that allows the smoke to rise and overcome the free convection layer (Potter and Anaya 2015).

The frequency and evolution of unstable atmospheres and their probable evolution under climate change have been poorly studied. Studies of possible future changes in the Haines Index suggested that atmospheres more conducive to pyroconvection activity will occur in the future in the USA (Tang et al. 2015). In a combined approach in Australia, Di Virgilio et al. (2019) found an increment of PyroCb conditions in the future,

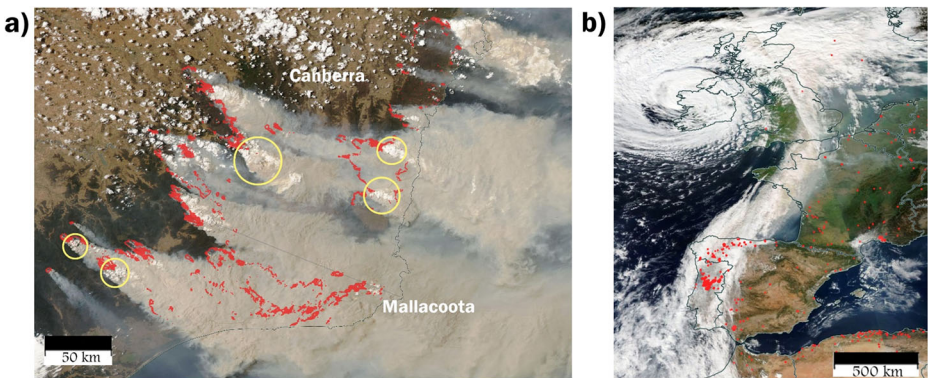


Fig. 4 Satellite images of iconic extreme wildfire episodes. Red points show active fires detected by Suomi NPP/VIIRS and the background image corresponds to a true color reflectance composite detected by the Aqua MODIS sensor. **a** Pyro-clouds outbreak on January 4, 2020, in Southeastern Australia. Some pyro-clouds formation can be observed next to the fires (yellow circles). **b** Massive wildfire episode occurred in western Iberian Peninsula (Portugal and NW Spain) on the 15–16th of October 2017 after hurricane Ophelia struck (located offshore Ireland in the image). All information is retrieved from Worldview Earth Data

especially in the spring. The mechanisms by which climate change will increase PyroCB are based on vapor content dynamics in future atmospheres. The capacity of an air parcel to be buoyant enough to reach the condensation level increases with moisture in the lower troposphere (Haines 1988). While global air temperature is increasing (Dentener et al. 2013) and thus the saturated vapor content, there is also an increment in specific humidity of the lower troposphere (Dentener et al. 2013) that increases atmosphere energy and instability. Concurrently, Haines Index future estimations indicate that air at medium troposphere is projected to be drier at the end of the century (Di Virgilio et al. 2019), and this will foster air parcel buoyancy and thus conditions conducive to PyroCb development. All these predictions, if combined with increasing evidence of longer and more intense droughts that increment fuel availability, forecast a likely future with an increase of pyroconvection probability. But, we face the challenge to predict not only when but also where this pyroconvection activity will be more prone to occur under global change conditions. The main factors promoting pyroconvection are atmosphere characteristics and large amounts of vegetation available to burn (McRae et al. 2015; Peterson et al. 2016). These extreme fires depend upon large fuel accumulations that release enough energy to interact with tropospheric dynamics (Artés and Castellnou 2019), regardless of the species present (Fernandes et al. 2019). Convective activity (usually linked to storm activity) has long been characterized, and factors such as continentality, frequency of cold low-pressure systems, and presence of foehn winds have been often related to it (Dial et al. 2010; Bechtold 2019; Taszarek et al. 2019). Places with complex or rolling relief (uneven slopes, abundant ridges, etc.) are also more prone to develop pyroconvection (Werth et al. 2011; Di Virgilio et al. 2019) because air mixing is promoted and orographic lifting can occur. The vicinity of water bodies at a mesoscale (~ 100 km) may also be involved in favoring convective activity: moisture supply at the ground level can promote pyroconvection (Bechtold 2019). Additionally, some studies have identified the potential for pyroconvection by assessing the distribution of the Haines Index across continents (Tatli and Türkeş 2013; Dowdy and Pepler 2018). This information can be used to forecast the capacity to form pyroconvection in

the future, fed with the capacity of the landscape to generate high-intensity fires as a function of vegetation loads.

1.1.2 Novel climates: new interactions between drought, hot environments, and novel wind situations (e.g., hurricanes)

High temperatures, low humidity, and strong wind are major wildfire climatic drivers of wildfires, together with previous weather conditions that predispose fuel available to burn (Bradstock 2010). In fact, well-known indices as the Fire Weather Index or the Forest Fire Danger Index gather together all these weather variables to build unique index risk information and have been widely proven to explain wildfire annual variability (de Groot et al. 2015), especially when using anomalies or percentiles rather than the raw values. However, global fire evidence points to a new situation in which a mix of novel conditions might be driving EWE. In a recent study, Ruffault et al. (2018) identified that extreme fires occurring in France in 2003 and 2016 were related to two distinct shifts in the fire weather space towards fire weather conditions that had not been explored before and resulted from specific interactions between different types of droughts and different fire weather types, one especially linked to an extreme heatwave (2003) and the other linked to an extreme wind episode (2016). The extreme fire season in Australia 2019–2020 is also a good example since EWE reported were mostly related to a severe drought lasting for more than 1 year that made available all fine and coarse fuels in a highly continuous landscape, together with extreme fire weather conditions exacerbating fire behavior (Boer et al. 2020).

Climate change is predicted to alter global circulation patterns (Raible et al. 2010; Grams et al. 2017; Wang et al. 2020). Novel wind patterns associated with changing circulation phenomena might increase wildfire hazards (Duane et al. 2019). Another good example of this is Hurricane Ophelia (category 3) in October 2017, the first Atlantic tropical storm on record that reached Europe (Stewart 2018). While Atlantic hurricanes do sometimes take a circuitous route westward across the ocean and loop back again towards Europe in low intensity, this one took a shortcut. This sudden behavior is explained by a creation of the low-pressure area on a relatively northern latitude (usually, storms are generated in warmer waters in southern latitudes), and by the position and strength of the mid-latitude jet stream, which guided the hurricane towards Europe, reaching the continent weakened as a tropical storm. On October 15, 2017, hundreds of fires ignited in Portugal and NW Spain, amid long-standing drought and heat records, but simultaneously occurring as Hurricane Ophelia passed offshore the Iberian Peninsula (Fig. 4). In fact, the strong humid winds that originated by the hurricane promoted pyroconvection activity that worsened the situation (CTI Comissão Técnica Independente 2017).

Climate change thus might mean not only rising mean temperatures but also creating new emerging conditions—with no analog in observed records—that can shift fire regimes as we know them today. This, combined with uncertain changes in climate modes, such as the El Niño Southern Oscillation (ENSO), the North Atlantic Oscillation (NAO), or the Indian Ocean Dipole (IOD) that have been related to wildfire activity in different regions of the world (Trigo et al. 2002; Kitzberger et al. 2007; Cai et al. 2013; Chen et al. 2016; Drobyshev et al. 2016), points to a future with strong uncertainty in novel climate situations. New configurations within the climate space might have more severe consequences on fire behavior than the ones predicted by models built with observed records. The mechanisms of how these novel climates will in fact influence fire regimes are currently being investigated but not yet fully understood (Ruffault et al. 2018; Duane et al. 2019).

How exactly climate change may disrupt historical circulation patterns is uncertain, but sudden and new phenomena can be expected because of the already observed changes in the tropical belt, the jet streams, and the northern polar vortex that alters atmospheric circulation in many instances (Dentener et al. 2013). Novel wind circulation patterns related to hurricanes or other meteorological phenomena are beyond our predictive capacity in the short term. However, historical areas little affected by strong winds should become more aware of the possibility of experiencing new circulation patterns. Additionally, attention must be paid when strong winds interact with steep and heterogeneous reliefs since vorticity-driven lateral spread can occur and show extreme behavior difficult to predict by fire suppression bodies (Sharples and Hilton 2020). In these situations, fire propagates fast across steep leeward slopes, and it has been associated with the generation of deep flame zones and massive spotting (McRae et al. 2015; Rodrigues et al. 2019; Sharples and Hilton 2020). Nonetheless, projections indicate that average wind speeds might not change by more than a few percent by the end of the century, particularly in summer, with similar changes expected for extreme wind speeds (Sharples et al. 2016). But, areas that have been historically affected by wind can also see a shift in fire activity in relation to the changing fire niche. France, Greece, Spain, California or Southeast Australia, among others, can experience an increase in the likelihood of extreme wildfire events if the occurrence of extremely hot temperatures, severe drought and intense wind episodes concur. In fact, recent exceptional fires in Europe (Torre de l'Espanyol, Catalonia, NE Spain, 2019) have propagated with warm winds blowing from the South or Southeast, during a synoptic weather condition not usually associated with strong wind-driven fires (Duane and Brotons 2018).

1.1.3 New fuel available: more vapor pressure deficit increases vegetation stress

Plants' ability to grow is closely related to vapor deficit pressure (VPD; Resco de Dios 2020), with some authors asserting that VPD limits tree growth even before soil moisture begins to lessen (Sanginés de Cárcer et al. 2017). The increase of this deficit leads to a decline in leaf and canopy photosynthetic rates due to stomata closure, reduced growth, widespread drought-related forest mortality, and decline of ecosystem productivity (Williams et al. 2013; Konings et al. 2017). Increasing plant stress can lead to a rise in available fuel to burn in both dead and live fuels (available fuels are the ones with low moisture, i.e., with 14% for dead and 70–100% for live fuels; Resco de Dios 2020). Some observations suggest that litterfall rates increase with VPD growth and may lead to increments in crown fire vulnerability (De Faria et al. 2017). How VPD is currently changing and how it will evolve in the future needs to be studied to forecast changes in available fuel and the likelihood of wildfires linked to huge fuel loads (Resco de Dios 2020).

Vapor pressure deficit is the difference between the water vapor pressure at saturation and the actual water vapor pressure for a given temperature. Global air temperature is increasing (Dentener et al. 2013) and thus the saturated vapor content, and observations have also reported an increment in the specific humidity of the lower troposphere (Dentener et al. 2013). Regarding the latter, climate change is intensifying atmosphere energy because warmer air can be moister: the atmosphere can hold about 7% more water vapor for each degree Celsius of warming. However, during recent years, the near-surface air moistening has receded, and changes in global evaporation rates are not clear (Dentener et al. 2013; Rhein and Rintoul 2013). Thus, although holding more water vapor in the atmosphere, the water vapor deficit might be increasing if the growth of specific water vapor is not proportional to the

saturated vapor pressure. In this sense, Yuan et al. (2019) have shown an increase in VPD at the global scale causing a widespread decrease in vegetation growth. Warmer air is increasing atmospheric energy (that can promote pyroconvection) but not enough to override plant water deficit (which results in an increase in available fuel to burn).

Ecosystems worldwide are becoming more stressed due to warmer climates (Yuan et al. 2019), so the increase in available fuel might be occurring at a global scale. However, climate change scenarios predict a more severe temperature increase in some regions, such as the Arctic or Mediterranean biomes (Collins et al. 2013; Lionello and Scarascia 2018), where this temperature escalation can promote large-scale increases in fuel availability leading to a rise in the likelihood of higher-intensity fires.

1.1.4 New fuel available: shifts in aridity push weather-limited fire regions to increased fire activity

Global biome's fire regimes have been described to shift along an aridity-productivity gradient following a humped relationship (Fig. 5; Krawchuk and Moritz 2011; Pausas and Paula 2012): fuel shapes the fire-climate relationship, limiting fire activity in very arid conditions. In contrast, in wet regions with well-developed vegetation, fire activity is limited by the occurrence of dry and hot conditions. In the middle of the gradient, hot and rainy ecosystems such as the savannas hold the major rate of fire activity.

Under a climate change context and before vegetation adapts to novel climate conditions, an increase in hot, dry conditions will extend fire activity in areas that were historically weather limited (Fig. 5). Rapid climate change will create mismatches between productivity gradients and climate fire windows (Archibald et al. 2009). EWE may progressively shift to fuel-rich areas in which fire has been, so far, strongly climate limited. This disruption may be progressive in nature if climate changes are slow or abrupt if shifts occur associated with drought or heatwave events.

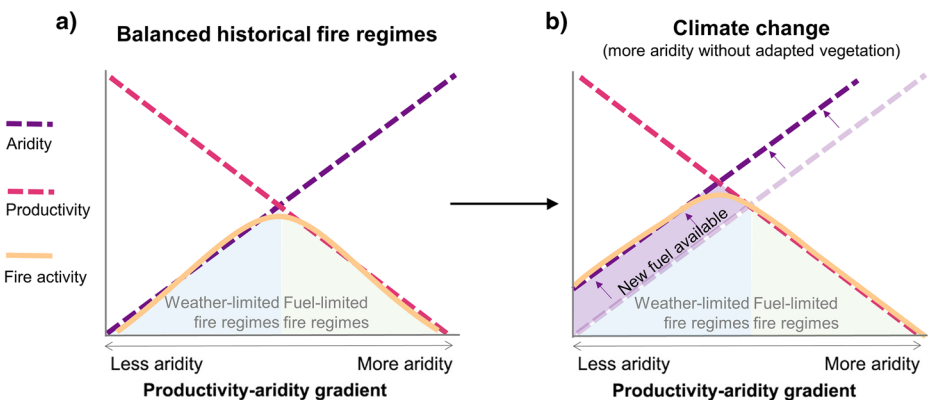


Fig. 5 Climate space of wildfires. **a** Classical humped fire-aridity relationship. In humid areas, fuel is available and the frequency of arid conditions drives fire activity (weather-limited fire regimes). In contrast, in arid areas, arid conditions limit the development of wildfires, and it is vegetation growth that prompts fire activity (fuel-limited fire regimes). **b** Effects of climate change in the fire-aridity relationship. Climate change will increase the frequency of hot and dry conditions. Before vegetation changes and re-balances to these climate shifts, there will be a period in which historical weather-limited areas will be available to burn more frequently under novel aridity conditions

Biomes with high fuel amounts and near arid areas are the most likely candidates to suffer from the pushing of weather-limited regimes. Studies show that fire regime shifts with increasing fire activity will most likely occur in transition zones, where large and continuous fuel loads are ready to burn (Boer et al. 2017). Examples of these areas include humid Mediterranean regions closely affected by arid desert areas (Bowman et al. 2017). High loaded temperate forests, as in North America, Central Europe, and southeastern Australia, are predicted to increase in fire weather conditions in the future (Millar and Stephenson 2015; Dowdy and Pepler 2018), and some of them are starting to show this pattern (Sommerfeld et al. 2018). Subtropical areas of the southern hemisphere, including the Atlantic coast of Brazil, southern Africa, and eastern Australia will see a decrease in rainfall conditions (i.e., an increase in aridity) that will promote fire activity in well forest-fueled landscapes before vegetation adapts to harsher conditions (Cardoso et al. 2003; Miles et al. 2004; Pitman et al. 2007; Bowman et al. 2017). In addition, boreal forests are forecast to extend their share of stand-replacing fires (Gauthier et al. 2015). Southern latitudes of the boreal forest are expected to increase fire activity (Flannigan et al. 2009), which can push ecosystems to tipping points ravaging forest resilience, as is already happening in places in southern Siberia boreal forests (Kukavskaya et al. 2016).

1.1.5 New fuel available: lengthening of the fire season is increasing vegetation stress

Historical fires occur during a specific period of the year, different among ecosystems. Usually, the fire season is related to periods in which vegetation is available because moisture decreases (i.e., high temperature, low precipitation, or after snow melting) and atmospheric conditions promote the fire environment (Boer et al. 2017). The fire season may follow a bimodal pattern if fuel dryness does so.

Climate change can extend the period over which fuel is dry enough to burn (Jolly et al. 2015). Longer fire seasons can increase plant stress at the end of the season and aggravate the likelihood of EWE by adding low-moisture fuel. In addition, an advance of the fire season has uncertain consequences on wildfire behavior. If fires are to occur under a more humid environment such as the one predominating during spring in many ecosystems, such as in the Mediterranean, boreal, or temperate forests, pyroconvection activity might take place more easily (Di Virgilio et al. 2019). Future fire seasons can in fact be extended to such a degree that, in some regions, the fire could become active all year around. Out-of-season fires are likely to exert novel pressures and impacts on vegetation if fires occur, for instance, during the growing or the dormant seasons, or in other words, the seasons in which vegetation is not adapted to fire effects (Le Fer and Parker 2005; Valor et al. 2017).

The lengthening of the fire season is already occurring in many places (Jolly et al. 2015) with consequences for fire activity (e.g., Portugal 2017; Sánchez-Benítez et al. 2018). Jolly et al. (2015) revealed that 25.3% of the Earth's vegetated surfaces have seen their fire season increase in the period 1979–2013, specifically in the eastern coast of Southern Hemisphere continents, western North America, and central Asia. Places where climate model projections forecast earlier snowmelt timing, changes in variability of spring and autumn precipitation, and a general strong warming context, will be the most likely to experience expansions of the fire season.

1.2 Socioecological mechanisms

Other global change drivers such as changes in land use and the reshaping of fuel patterns are likely to interact with climate and increase the impact of EWE occurrence in relation to

historical trends. Large wildfires and extreme wildfires are usually associated with weather conditions, but fuel composition, landscape-level fuel connectivity, and spatial fuel patterns are also related to large wildfires (Fernandes et al. 2016). Here, we introduce a number of human-driven changes in fuel amount and composition occurring at the landscape scale that can ultimately escalate the frequency of extreme wildfire events.

Land abandonment is playing a very important role in European Mediterranean countries by adding available fuel at the landscape scale and sometimes pushing the system from fuel limited towards weather-limited fire regimes (Pausas and Fernández-Muñoz 2011; Pausas and Paula 2012). Afforestation leads to a higher frequency and more devastating fire regimes in many places (Ursino and Romano 2014). Farmland abandonment has occurred primarily in developed countries in Europe and North America (Li and Li 2017), especially in mountainous and hilly areas, due to their unfavorable farming conditions. Afforestation due to land abandonment can reshape fire-climate-vegetation relationships in coming decades. In Europe, due to ongoing social processes, regions with a higher risk of farmland abandonment in the near future are Mediterranean and Scandinavian countries (Terres et al. 2015). Moreover, due to China's rapid urbanization, studies predict a high probability of an increase in the abandonment rate during coming years (Li and Li 2017). Global scenarios diverge in the future use of land for croplands or pastures according to population dynamics and agricultural efficiency (Stehfest et al. 2019).

The presence of foreign flammable, large-scale plantations (e.g., *Pinus radiata* and *Eucalyptus* sp. in Chile, *Eucalyptus* sp. in Portugal) can increase fine flammable fuels at the landscape scale. The resins of the most common planted species are highly flammable, reinforcing rates of spread, and enhancing large wildfire likelihood (McWethy et al. 2018, but see also Fernandes et al. 2019, who stated that eucalyptus plantation expansion is not related to increases in the burnt area in Portugal). Yet, what especially enhances large wildfire likelihood of forest plantations is the homogenization in terms of fuel load and structure at the landscape scale. The area of planted forests around the world increased from 167.5 to 277.9 million hectares from 1990 to 2015 (Payn et al. 2015). The increase was faster in the temperate biome, and regionally in East Asia, followed by Europe, North America, and Southern and Southeast Asia. The pace of expansion of tree plantations in the coming decades is predicted to highly impact South America (Jobbágy et al. 2012) and Africa, with some experts suggesting that Africa will be the center of tree plantation expansion globally (Kroger 2012). Economics dictate a preference for fast-growing trees such as eucalyptus and coniferous species, which have shown to be usually more flammable than native vegetation (McWethy et al. 2018). The relation between plantations and fire hazard has important consequences when broad-scale forest restoration programs are planned, such as the Bonn Challenge that aims to “restore forest landscapes” in Africa by 2030 (International Union for Conservation of Nature 2020) or the Biodiversity Strategy of the European Union (European Commission 2020) that proposes to plant 3 billion trees by 2030. Several voices are warning of the lateral implications these programs will have beyond their intended goals, and especially regarding increases in fuel availability and landscape connectivity, and ultimately fire risk (Bond et al. 2019; Anderegg et al. 2020; Gómez-González et al. 2020). Nonetheless, logging primary forests becomes the alternative to these plantations, and although it can be done under sustainable and ecological prescriptions, it also implies other ecological impacts, mostly according to the ecosystem considered. Under a climate change situation and given the era of extreme wildfire events the earth is witnessing, these caveats need to be fully evaluated to consider all the nuances and side effects they pose.

Afforestation and forest restoration are the other side of the coin of fragmentation. Landscape-scale fragmentation can cause fire spread to cease due to non-flammable cover types, but it also can cause fire to increase in two main ways: by increasing anthropogenic ignitions near remote forests and increasing edge flammability. Whether fragmentation increases or not fire activity depends mostly on ecosystem type and geographic region. For instance, in the Amazon, fire events occur directly after recent deforestation (Cardil et al. 2020). In Siberia, evidence shows that forest fires are mostly related to the proximity to roads and agricultural fires (Kovacs et al. 2004), indicating a positive effect of fragmentation on wildfire occurrence. However, in Mediterranean ecosystems, landscape fragmentation has been usually related to impeding wildfire spread (McWethy et al. 2018).

Strong fire suppression strategies in some areas are contributing to fuel accumulation at the landscape scale (the so-called fire paradox) ultimately promoting the occurrence of extreme wildfire events (Schoennagel et al. 2017; Roos et al. 2020). This is especially affecting areas such as the western US, where first the European settlement ceased indigenous fire burning, and then, a strong fire suppression policy derived from big fires in 1910 has changed historical fire return intervals. For millennia, low and frequent surface fires reduced fuel accumulation in dry forests of south and western North America. In southern Oregon for instance, forests burned every 8 years on average (Metlen et al. 2018), and in northwestern Mexico, fire return intervals were smaller than 15 years (Stephens et al. 2003). But, after fire suppression and other land-use changes, these forests have experienced gradual fuel build-up (especially in ladder fuels) (Fry et al. 2014) such that recent wildfires have tended to be larger and more severe (Schoennagel et al. 2017). Fire suppression is thus escalating the wildfire issue to a greater extent in fuel-limited ecosystems that were historically fire managed than in forests adapted to low-frequency high severity fires, such as boreal forests.

Invasive species can cause frequent and often large fires (e.g., as with pines and acacias in South Africa) changing fire regime dynamics and promoting large wildfires in cases where these species are more flammable and add more fine fuels to the landscape than native ones (Van Wilgen 2009; te Beest et al. 2012). Invasive species often alter fire regimes to suit themselves leading to more invasions and more fires (Brooks et al. 2004). Otherwise, insect outbreaks linked to human-driven climate change are usually related to an increase in fire likelihood (Agne et al. 2016; James et al. 2017). Several studies from western North America point to insect-induced fire increases because of increments of crown fuel accumulation, needle flammability, vertical continuity, or wind penetration (Matt Jolly et al. 2012; Agne et al. 2016; Candau et al. 2018). However, other studies show reductions in fire severity after these insect outbreaks (Meigs et al. 2016), indicating a lack of consensus in such relationships (Harvey et al. 2018).

Human settlements can also alter fire regimes and promote the occurrence of EWE. Fast, intense wildfire events can intersect with human settlements and modify suppression tactics and burn patterns in such a way that increases fire intensity (Schoennagel et al. 2017; Radeloff et al. 2018). Wildland urban interfaces might influence fire spread and provide feedback to the burning process since the heterogeneous structure and the presence of flammable exotic ornamental species increment fire propagation within these zones (Fernandez et al. 2018; Ganteaume 2018). Additionally, when a flammable dwelling burns up during a wildfire, it can become part of the active fuels being able to increment fire intensity (Gollner et al. 2015). Besides, changing fire ignitions (up to 99.7% of human-caused individual fires in Chile (CONAF 2020), 95% in Europe (San-Miguel-Ayanz et al. 2012), 87% in Australia (Collins et al. 2015), 85% in Africa (Archibald 2016), 84% in the USA (Balch et al. 2017), and 40% in Canada (Camp and Krawchuk 2017)) can enhance EWE occurrence if they coincide with more recurrent extreme severe weather conditions.

2 Implications for the anticipation and reduction of novel extreme wildfire events

Our conceptual review discusses the main mechanisms behind the occurrence of extreme events in recent years (2016–2020) to better understand global causes of wildfire extreme events. We suggest that novel extreme wildfire events are ultimately a consequence of climate processes brought upon by climate change. In some cases, these climate processes are coupled with new fuel configurations leading to extreme behaviors. Global change is modifying ecological systems in a very complex way that makes it difficult to make predictions based on historical records (Brotons and Duane 2019). Complex atmospheric-fire relationships are still being explored with big unknowns (Lareau and Clements 2016; Miller et al. 2018; Sharples and Hilton 2020). The capability to predict extreme behaviors is, at present, strongly limited and includes high degrees of uncertainty. However, here we provide new insights on how these relationships might be acting and how we all, scientists, first responders, and managers can act to approach future research and management.

How this knowledge can be transformed into management guidelines aimed at the reduction of extreme wildfire event risk is a challenge, and it mostly depends on how the different mechanisms rely on the landscape, fuel, and human variables or not. For wildfires relying on these types of variables, we have space for fire prevention and extreme fire behavior reduction. But for wildfires occurring under extreme weather conditions, our role in their prevention is minor. However, we can play an important role in wildfire anticipation, preparedness, response, and recovery. Fire management needs thus to improve our current understanding of the frequency of weather conditions affecting each region and apply fuel reduction plans that correctly weigh the effect of fuel in fire spread (Duane et al. 2015). For instance, in areas recurrently affected by strong wind events, investments have to change towards landscape planning, civil protection, and risk management since fire hazard reduction can be hard to achieve. In fact, we must be careful when applying forest management for risk reduction to not be funding “frustration” instead of “safety” in places in which fire spread is likely to be mostly related to other factors than fuel, such as prevailing wind conditions. New methodologies for risk mitigation should be implemented to get the social and political incentives right.

Relying on an actual capacity to impact EWE through landscape and fuel management (i.e., EWE depend mostly on fuel variables), there is long path to improve decision-making and understand, anticipate, and prevent extreme wildfire events. Several works are claiming for a return of fire indigenous practices to ensure a sustainable way of letting wildfires to burn and eventually reduce fueled landscapes (both as a consequence of fire suppression policies or rural abandonment processes; Schoennagel et al. 2017; Kelly et al. 2020; Moreira et al. 2020). In addition, fuel treatments aimed to prevent wildfires and help suppression maneuvers need to strategically count on evidence of their efficiency and on a plan to maintain them economically in the long term. Some countries are considering the promotion of economic value chains of forest products and nature-based solutions as a way to incentivize sustainable forest management (Verkerk et al. 2018), while other regions advocate for an agricultural landscape mosaic and silvopasture practices as a way to reduce the risk of large, intense fires (Moreira et al. 2020). Adaptive management seems to be strongly encouraged in an unstable climate context: vegetation needs to readapt to changing climates and we can help ecosystems and species to new conditions in which they will be better adapted and less likely to release massive energy during wildfires (Schoennagel et al. 2017).

The implications of the surge of extreme wildfire events are of paramount concern for ecosystems and human well-being. Extreme wildfire events can burn all types of fuels, including

recently burnt ones (Price and Bradstock 2010), affect huge extensions (Boer et al. 2020), and alter severity patterns (Ndalila et al. 2018). Changes in the recurrence and severity of wildfires can threaten species resilience (interval squeeze hypothesis; Enright et al. 2015; Kelly and Brotons 2017), and an utmost wildfire extension can hamper species recolonization and push some species close to extinction (Pickrell and Pennisi 2020; Victoria State Government 2020; Wintle et al. 2020). But, the biggest concerns of extreme wildfire events nowadays are the implications for emergency management organizations, human safety, economic losses, and long-term impacts on communities (Sharples et al. 2016; Schoennagel et al. 2017; Tedim et al. 2018). We are still surpassed by extreme behaviors and we need to importantly focus on increasing preparedness, response, and prevention for these global novel threats (European Commission 2018), while we work on understanding EWE and the biophysical drivers according to integrated new knowledge.

Global change with climate changes at its forefront is causing a rate of change not experienced before by many ecosystems. Anticipating these novel responses is a key scientific challenge with paramount implications for the future of society and present strategic planning. The basis and grounds for fire management in a dawning “era of megafires” should shift towards accepting the risk of fire (Moritz et al. 2014; Schoennagel et al. 2017; Moreira et al. 2020). Similar to other ever-present risks such as earthquakes, floods, or typhoons, societies should find strategies to cope with the ever-present (and the increasing frequency) of extreme wildfires. Fire is likely to play an increasingly large and uncertain role in this dangerous game and we need to be prepared.

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Declarations

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