Universitat Autònoma de Barcelona

Assessing global change impacts on fire regimes in Mediterranean ecosystems

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Memòria presentada per

Andrea Duane Bernedo

per a optar al grau de Doctora

Amb el vist-i-plau de

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Programa de Doctorat en Ecologia Terrestre

Centre de Recerca Ecològica i Aplicacions Forestals

Universitat Autònoma de Barcelona

Barcelona, Juliol de 2018

Per a tota la gent meravellosa que m’envolta

The worst decision is indecision

Benjamin Franklin

AGRAÏMENTS

Com que se que és el primer que us llegireu d'aquesta tesis, intentaré esmerçar-me en incloure a tota la gent que crec que és mereix unes línies. I el més fort és que no és poca… i si sense voler em deixo algú, el meu més humil perdó.

Vull començar per tota la gent que m'ha ajudat a les meves estades internacionals. De la meva estada a Canadà, en especial agrair l'ajuda de la Mélanie Desrochers i la Aurélie Terrier. Van ser capaces de transformar el fred boreal en caliu mediterrani. De la meva estada a Austràlia m'agradaria agrair tota l'ajuda rebuda per tot el grup del CEED, però en especial a la Kate Giljohann, el Mick McCarthy i el Luke Kelly. La seva excel·lència recercadora és proporcional amb les ganes de fer que la gent es senti com a casa. I sobretot al David i la Belinda, que van fer-me sentir com un membre més de la seva família. Tan de bo tothom pogués trobar a l'estranger una hospitalitat com la seva.

És molt important per a mi mencionar tot el cos del GRAF-Bombers de la Generalitat de Catalunya. Gràcies a en ells crec haver ampliat exponencialment els meus coneixents de l'ecologia del foc, i a més m'han deixat tastar la passió pel foc, que la veritat és que és additiva. En especial m'agradaria agrair al Jordi Pagès, per fer créixer a tothom que té a prop a partir de la més pura humilitat. I com no, al Marc Castellnou, una de les persones que més m'ha inspirat i ensenyat, no només de focs, sinó de prendre decisions i d'afrontar la vida.

Vull agrair al CREAF la seva qualitat humana i científica per a donar paraigües a en aquesta tesis. Els tres membres del meu tribunal de seguiment han sigut capaços de seguir les meves cabòries, i crec que entendre-les. A en Jordi Vayreda li vull agrair el recolzament constant i la capacitat racional de veure tot allò que fem, juntament amb una profunda il·lusió. A més, vull agrair a l'Anselm Rodrigo i al Joan Pino la oportunitat de créixer al seu costat a nivell docent, i també per totes les converses compartides a Prades, Montcada, Callús... la seva visió crítica i teòrica han enriquit sempre els meus pensaments. També del CREAF vull agrair al Paco Lloret la seva incondicional manera de donar-me suport, des de l'àmbit més personal que ens uneix, a la confiança professional, que ens ha portat a fer alguns treballs junts. Intueixo que no seran els últims. I com no, agrair a l'Enric el seu constant suport, la seva hospitalitat yankee i els seus enormes coneixements (que ell no es creu) en l'ecologia i el foc.

Com no, vull agrair a tota la gent del CTFC tot el suport donat durant aquests cinc anys. Crec que tots coincidiran en que la noia tímida roja dels primers mesos ha aconseguit empoderar-se laboralment, i gran part és gràcies a en ells i la seva confiança. Vull donar especial gràcies al Lluís Coll, Aitor Ameztegui, Martina Sanchez, Jaime Coello, Edu Busquets, Míriam Piqué, Rut Domènech, Eduard Plana, Marc Font, Marta Serra, Victor Granda, Josera Gonzalez, Laura Cardador, Adrian Regos, Antoine Cabon, Edu Setas, Marc Taull, Ana Sanz, Jordi Camprodon, Laura Recoder, Carla Fuentes, Javier de Dios, Ángela Blazquez, Mónica Lanzas, Víctor Sazatornil, Nicolas Titeux, Pere Casals, Pere Rovira, i un llarg etcètera!. A la Laia Ximenis també li vull agrair especialment la professionalitat en la gestió dels meus expedients. Entendre el contingut dels correus amb el Ministerio en relació a la FPU suposa un exercici de mindfulness lloable. Lògicament, no m'oblido de tots els meus companys d'àrea. Vull agrair als Davids, amb els quals esmorzar a Can Mascaró significa sempre un esmorzar de qualitat. A la Núria Pou, que tot i que fa molta por al principi, resulta que és un tros de pa, i porta la feina a uns nivells de compromís i seriositat difícilment igualables. Al Gerard Bota, la passió del qual em fa tremolar, però del qual aprenc dia a dia. La Magda Pla i el Dani Villero, que m'han ajudat a entendre les eines quantitatives com a mètode de recerca des d'un punt de vista simple i engrescador. Al Francesc Sardà, del qual he après que la recerca és compatible amb ser un catxondo i un fiestero, cosa que m'encanta. Al Virgilio Hermoso, que sempre m'ha servit com a referent ambientòleg d'èxit professional. A l'Alejandra Moran, a la qual admiro per la seva capacitat d'afrontar-ho tot amb un somriure, i que alhora et fa sentir brillant. Al Quim Canelles, a qui li agraeixo ser la persona més autosuficient del món, i que a més hagi aconseguit entendre les meves bogeries. A l'Assu Gil, que m'ha ajudat tantíssim en alguns detalls de la tesis, i sense la qual aquesta tesis no seria igual.

Especialment li vull dedicar un paràgraf a la persona amb la que crec que més m'agrada treballar en aquest món, la Núria Aquilué. Amb ella aquesta tesis ha estat molt més efectiva, dinàmica, profunda, lògica. I gràcies a la seva amistat la meva vida ha estat molt més efectiva, dinàmica, profunda, lògica i divertida. Gràcies per totes les hores de bogeria, riure, codi-model, plor, desesperació, amistat.

També vull posar especial èmfasi en els agraïments cap al meu director de tesis, el Lluís Brotons. Crec que hem fet un team molt bo, que ens hem entès perfectament, i que podem fer tantíssimes coses. Li agraeixo tot el que he après sobre ecologia, dinàmica del paisatge, ecologia del foc, pertorbacions, escenaris, presa de decisions, transferència, drons, mapes, objectius, estratègia i tot allò que és clau. A més, és una persona encantadora, amb un cor enorme i amb ganes de fer que tothom al seu voltant sigui feliç. Crec que a la recerca és difícil trobar gent d'aquesta qualitat humana.

A Solsona no només hi he trobat companys de feina i un poble acollidor, sinó amigues d'aquelles que no es perdran. Vull agrair en especial a la Carla Bellera la seva alegria, intel·ligència, passió, feminisme, esperit de lluita, valentia i amor que sempre m'ha donat. Estic segura que les nostres passes seguiran creuant-se. I també vull agrair a la Gemma Estany la seva amistat, per liar-nos juntes a totes les mogudes varies que se'ns ocorrien. Amb ella, tot és fàcil. La seva valentia i humilitat fan que el seu nom sigui el primer en aparèixer per a qualsevol projecte.

Aquesta tesis no hagués estat possible sense el suport dels Rangers. Han sigut la meva família Solsonina. Els inicis van suposar una troballa profunda. Hem passat per tot tipus de moments però sento que sempre els tindré a prop pel que faci falta. L'Ana ha posat color i alegria a les nostres vesprades. La Laura, sempre m'ha ensenyat a lluitar per allò just. El Miquel va ser tot un repte: distant, calculador, analitzador. Ara s'ha convertit en un dels meus pilars a Solsona: les converses amb ell traspassen sempre l'expectativa. A més, a nivell de recerca, sempre m'ajuda a desencallar en 5 minuts allò amb el que porto bloquejada 3 setmanes. Té una capacitat que no sap ni ell. Al Mario li vull agrair la seva incondicionalitat. Sempre ha estat al meu costat, i ha aconseguit demostrar els valors reals de l'amistat. A més, no puc deixar de sorprendre'm a diari de totes les seves capacitats de memòria i coneixement. I com no, encantada amb la nostra passió per la muntanya, que sempre ens uneix.

A més a més, vull agrair a les persones més importants de la meva tot el suport i amor rebut durant aquests anys. A la Mariona, la Maria, l'Ester, la Brobia, la Girona i les nenis d'ambientals, que són indiscutiblement les que em donen a diari ganes de viure la vida intensament, i les que han servit d'espatlla en moments de frustració. Com no, haig d'agrair grandíssima part d'aquesta tesis al Mikel, que va estar sempre en tot moment donant-me suport amb un somriure enorme amb totes les meves incerteses i indecisions. Gràcies a en ell he pogut aprendre tantes coses de la vida, a la vegada que feia la tesis. Gràcies.

Agraeixo de tot cor tot el suport rebut per la meva família. Al meu germà Lucas i a la Caro, que tot i sovint no entendre res del que faig, mai no han gosat fer-ho veure, i sempre m'han ajudat a sentir-me segura i empoderada dels meus avenços. En fer la tesis coincidint amb el temps, amb el Lucas hem pogut compartir (una altra vegada a la vida). totes les emocions al voltant de la tesis. Al meu pare (Dad) li agraeixo tota la confiança amb la meva feina (de vegades massa incondicional), i també ser la única persona que sense conèixer el tema entén perfectament tots els meus models. No és fàcil. A més, s'ha currat la revisió de l'anglès de bona part de la tesis, que agraeixo profundament. Estic profundament agraïda de tot el seu suport. I agraeixo moltíssim a la meva mare (Marona) la seva visió crítica i realista, i alhora admiradora, de tota la meva feina. El teu suport sempre ha estat clau per a fer-me sentir forta. Gràcies per ser-hi, sempre.

I ja per acabar, vull donar-li les gràcies a la persona que més m'ajuda des de ben a prop, a l'Oscar (ideòleg de la portada, gràcies bú!). Aquests mesos no només ha sabut donar-me el suport que necessitava, sinó ha sabut capgirar la situació i fer que cada dia fos alegre, mogut, divertit, desafiant. És el maremoto que remou els meus pilars per a convertir-me cada dia en millor persona. Gràcies.

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PREFACE

The present thesis is the result of the work carried out by Andrea Duane Bernedo. All the ideas, data compilation, methods, analyses and inference of results has been done by the candidate. From the work derived from her thesis, the following articles have been published or are about to be published in international scientific journals:

Duane A, Piqué M, Castellnou M, Brotons L (2015) Predictive modelling of fire occurrences from different fire spread patterns in Mediterranean landscapes. International Journal of Wildland Fire 24:407–418. doi: http://dx.doi.org/10.1071/WF14040

Duane A, Aquilué N, Gil-Tena A, Brotons L (2016) Integrating fire spread patterns in fire modelling at landscape scale. Environmental Modelling and Software 86:219–231. doi: 10.1016/j.envsoft.2016.10.001

Duane A, Brotons L (2018) Synoptic weather conditions and changing fire regimes in a Mediterranean environment. Agriculture and Forest Meteorology 253–254:190–202. doi: 10.1016/j.agrformet.2018.02.014

Duane A, Kelly L, Giljohann, K, Batllori E, McCarthy M, Brotons L. Climate-fuel feedbacks drive fire activity in dynamic Mediterranean landscapes. Under Review in Ecosystems.

Duane A, Aquilue N, Canelles Q, Moran-Ordoñez A, De Caceres M, Brotons L. Adapting fire management to future climate change. To be submitted in Science of the Total Environment.

ABSTRACT

Fire regimes are changing or are expected to do so under global change, with potentially adverse impacts on ecosystems and societies. The main objective of this thesis is to gain a better understanding on the processes influencing fire dynamics at large scales, and to integrate them in modelling tools that help us to predict global change impacts and eventually design strategic management plans. The approach followed is based on disentangling the mechanisms driving different fire spread patterns and assessing the dynamism in fire activity. Then, I integrate these drivers in a landscape modelling tool that allows us to estimate the impact of future climate and fire management strategies on fire regimes. All these questions are tested in Catalonia, a highly dense populated Mediterranean region (~32,000 km^2) that deals with a period of high uncertainty in the face of global change.

The results of this thesis provide new evidence of the underpinning processes that drive wildfire dynamics in Catalonia. By using fire spread patterns, a common classification used by operational services, I have promoted a paradigm shift in how environmental processes are being integrated in landscape assessments, since fire spread patterns unravel fire regime mechanisms operating at these scales. I have found that they rely upon different environmental and anthropic factors, and that future changes will impact the different fires in idiosyncratic manners. Increasing fuel accumulation due to rural abandonment and hotter temperatures has promoted in the 90s the emergence of new 'convective' fires, characterized by extreme behaviors. However, fire suppression in the last decade has managed to control wildfires occurring under hot and dry situations, but not under windy ones, which provides key insights into how future planning needs to be conceived. In addition, this thesis also identifies the dynamic role of weather on fire regimes; past fires create time periods in which fuel-limitation becomes the main fire driver. Fire suppression is thus pushing the system towards weather-dependent, highly uncertain conditions. By analyzing future climate conditions in Catalonia, I have also found that novel climates may induce extreme wildfires. Finally, I show that the application of prescribed burning plans under reasonable efforts (~15,000 ha/year) can offset negative fire effects associated with climate change and maintain desired ecological states. All these results reveal that climate change, land-use changes, forest abandonment and fire suppression are simultaneously modifying fire regimes in Catalonia towards a critical situation, and that strategic management plans are needed to override extreme fire impacts associated with climate change. Fire management should shift from a 'fire suppression' era to a 'fire regime management' era. This thesis provides quantitative evidence to apply efficient science-based fire management policies that may eventually lead to a sustainable coexistence with fire.

RESUM

Els règims d'incendis estan canviant o s'espera que ho facin sota la influència del canvi global, amb impactes potencialment adversos per als ecosistemes i la societat. L'objectiu principal d'aquesta tesis és incrementar el coneixement que tenim sobre els processos que influencien les dinàmiques del foc a gran escala, i integrar-los en eines de modelització que ens ajudin a predir els impactes del canvi global amb la intenció de dissenyar plans estratègics de gestió. L'aproximació que s'ha seguit es basa en desxifrar els mecanismes que governen diferents tipologies de patrons de propagació del foc i avaluar el dinamisme en l'activitat dels incendis. Un cop identificats, s'integren tots aquests factors en una eina de modelització del paisatge la qual permet estimar els impactes del futur canvi climàtic i de diferents estratègies de gestió sobre el règim d'incendis. Totes aquestes qüestions es testen a Catalunya, una regió Mediterrània (~32,000 km^2) densament poblada i que afronta un període de gran incertesa davant del canvi global.

Els resultats d'aquesta tesis proporcionen noves evidències dels processos subjacents que governen la dinàmica dels incendis a Catalunya. Amb l'ús de patrons de propagació d'incendis, una classificació àmpliament utilitzada en el món operatiu de l'extinció, he promogut un canvi de paradigma de com els processos ambientals són integrats en les avaluacions de paisatge, ja que els patrons de propagació de foc permeten explicar els mecanismes del règim d'incendis que operen a escala de paisatge. He trobat que la seva ocurrència i propagació depenen de diferents factors ambientals, i que els canvis futurs impactaran de manera idiosincràtica als diferents incendis. L'increment en l'acumulació de combustible degut a l'abandonament rural i unes temperatures més altes, han promogut en els anys 90 l'aparició de nous incendis 'convectius', caracteritzats per comportaments extrems. No obstant, els bombers han pogut controlar en l'última dècada els incendis associats a situacions càlides i seques, però no als associats a situacions de vent, fet que ha de servir com a base pels futurs plans de gestió. A més, en aquesta tesis també demostro que el paper de la meteorologia en l'activitat dels incendis és dinàmic: els incendis del passat poden crear períodes de temps on el principal factor limitant per a l'ocurrència d'incendis és la manca de combustible. Si es redueixen els incendis amb l'extinció, allò que realment s'està fent és dependre cada vegada més de fenòmens meteorològics altament incerts. Mitjançant l'anàlisi de les condicions climàtiques futures a Catalunya, també he trobat unes condicions climàtiques noves que podran induir a incendis extrems. Finalment, demostro que l'aplicació de plans de cremes prescrites amb quantitats raonables (15,000 ha/any) pot contrarestar els impactes negatius del foc associats al canvi climàtic i mantenir estats ecològics pre-definits. La gestió dels incendis, doncs, ha de canviar de l'era de l'extinció a l'era de la gestió del règim. Aquesta tesis proporciona evidències quantitatives per a aplicar polítiques de gestió d'incendis eficaces, les quals poden portar-nos cap a una coexistència sostenible amb el foc.

INTRODUCTION

INTRODUCTION

Fire as an evolutionary pressure in Mediterranean ecosystems

Fire represents a major disturbance in many ecosystems worldwide (Bond and Keeley, 2005; Bowman et al., 2009; Keeley et al., 2012; Krawchuk et al., 2009). It differs from other abiotic disturbances (as wind storms or floods) in that it relies on organic materials to develop (Bond and Keeley, 2005) and therefore its activity depends on vegetation. Fire has shaped the diversity of life on Earth for millions of years (Pausas and Ribeiro, 2017), and it profoundly influences the current composition and structure of ecosystems (Archibald et al., 2013; Bowman et al., 2009). Many plant species have acquired adaptive mechanisms to resist and regenerate after fires (Bond and Van Wilgen, 1996), demonstrating plants' capacity to cope with fire (Hanes, 1971; Keeley, 1986; Trabaud, 1994). Fire has acted as an evolutionary pressure leading to the current biodiversity to be adapted to particular temporal and spatial patterns of fire (Kelly and Brotons, 2017; Pausas and Keeley, 2009). Species are then not adapted to fire per se, but to specific fire regimes (Keeley et al., 2011). The term fire regime (Gill, 1973) is used to define fire activity in a region in a specific period, and it includes several attributes related to its patterns and ecological effects, such as frequency, intensity, extension, seasonality and severity. Characterizing and understanding fire regimes in a region enhances the knowledge behind species requirements and can eventually help to apply conservation decisions.

Mediterranean-type ecosystems (MTE) encompass a biome on earth characterized by hot and dry summers and strong seasonality (Olson et al., 2001). Cool wet winters promote biomass growth and extended summer droughts favor the regular occurrence of wildfire (Batllori et al., 2013). Historically, fires started with lighting during wet or dry storms, which can be very common in many MTE (Pineda and Rigo, 2017). The geographic location of Mediterranean regions also benefits from the frequency of strong wind events that further exacerbate fire activity. MTE are dominated by fire-adapted vegetation resulting from a long evolutionary association with fire (Pausas and Keeley, 2009), where usually crown and high-intensity fires largely prevail (Keeley et al., 2012).

Changing fire regimes

Ever since prehistoric times, natural fire regimes have been altered by human activity in a multitude of ways, by modifying fuel structure, igniting new fires and extinguishing wildfires (Bowman et al., 2011; Keeley et al., 2012). In highly populated areas such as the Mediterranean Basin, it makes little sense to refer to a "natural" fire regime because the footprint of human dynamics has interacted with natural factors to mould fire regimes in time and space, and makes the characterization of a 'baseline' fire regime near impossible (Gil-Romera et al., 2010; Lloret, 2003; Vallejo et al., 2006). However, although humans have been using fire to manage the environment for millennia, rapid and intense human-related impacts are sharply changing fire patterns specially in the last decades with increasing impact on both natural values and society assets (Bowman et al., 2011; Fréjaville and Curt, 2017; Gill et al., 2013). The alteration of ecosystems at unprecedented rates may lead to unidentified changes, making natural systems unable to persist within their natural variability regimes (Vitousek et al., 1997), potentially reaching non-return ecological states during this century (Batllori et al., 2017; FAO, 2013).

The present escalation of environmental changes is modifying fire regimes and producing new challenges for conservation management. The alteration of habitats through land-use and land-cover changes is among the most significant and immediate threat to biodiversity (Titeux et al., 2016), and it directly impacts fire regimes (Oliveira et al., 2014), both by increasing forest continuity in places where fire regimes were constrained by this driver (Pausas and Fernández-Muñoz, 2011), or by an increasing fuel fragmentation that limits fire spread in places where high-recurrence fires were common (Archibald, 2016). In MTEs from European countries of the Mediterranean Basin, afforestation linked to rural abandonment that occurred during last decades has shifted the systems to weather-limited fire regimes (Moreira et al., 2001; Pausas and Fernández-Muñoz, 2011), in which the occurrence of fire-weather conditions drives fire activity (Pausas, 2004) increasing the uncontrollability of fire events. The increase of adverse weather events associated with a warming climate has stimulated an unsustainable fire regime that threats both ecosystem and societies. Urbanization of rural areas during the second half of the 20st century has further modified fire dynamics, aggravating fire hazards both because the increase of ignition sources in these areas and an increased exposure of human activities to fire effects (Lampin-Maillet et al., 2011).

Direct human fire actions have also altered fire regimes (Bowman et al., 2011; Brotons et al., 2013; Chergui et al., 2017; Costafreda-Aumedes et al., 2017; Loepfe et al., 2011; Oliveira et al., 2012). Not only by changing fuel spatial arrangement, humans have also directly affected fire regimes by boosting anthropic ignitions and by suppressing fires with investments in huge fire-fighting structures. In European Mediterranean countries fire management policies basically rely on fire suppression, and the increasing effort made in this direction has strongly modified fire regimes (Brotons et al., 2013; Moreno et al., 2014; Otero and Nielsen, 2017; Turco et al., 2013).

Climate change is argued to become the most important environmental problem that societies face nowadays, and most of its consequences are not fully understood yet because they interact with a wide range of environmental impacts (Aponte et al., 2016; Flannigan et al., 2009; Millar et al., 2007). Climate change in the Mediterranean Basin is predicted to increase summer heat-waves events, extend fire seasons, increase yearly average temperatures and increase precipitation irregularities (IPCC, 2014). How these switches will impact wildfires is still under research (Batllori et al., 2013; Westerling et al., 2011). While a warmer climate will upsurge fire activity by increasing water demand and decreasing fuel moisture, this increase on temperatures may also decline ecosystem productivity and lead to an overall reduction of fuel biomass (Batllori et al., 2013; Flannigan et al., 2009), which can counteract warming effects on fire activity. Climate change might also promote the occurrence of other disturbances (forest outbreaks, windstorms, invasive species, etc.) that result in new drivers of fire regime change. There is still an important gap in the understanding and prediction of future climate shifts and their impacts on ecosystems (Schoennagel et al., 2017).

Available evidence from last decades show a steady increase of extreme wildfire events escaping from fire-fighting efforts, reaching acute fire intensities and often burning very large areas (San-Miguel-Ayanz et al., 2013). Extreme wildfires have worst consequences for societies and ecosystem properties than small fires (Adams, 2013; San-Miguel-Ayanz et al., 2013; Tedim et al., 2013),. In European countries from the Mediterranean Basin, the appearance of these wildfires has been related to an expansion of forests interacting with increasingly hotter and drier weather conditions (Tedim et al., 2013). The high fuel loads accumulated in forests have resulted in intense fire behaviors (high flames, fire spotting capacity) that make them very difficult to control by fire suppression brigades. Moreover, suppression systems often collapse in protecting dispersed human assets which leads to diminished fire suppression effectiveness. Under a climate change context, these extreme wildfires are predicted to increase (Amatulli et al., 2013).

The fire situation has become a global problem facing most European, North-American and Australian governments (Boer et al., 2009; San Miguel and Camia, 2009; Schoennagel et al., 2017). The year 2017 has been called one of the worst years in terms of human fatalities, burnt houses and massive evacuations linked to wildfires. Portugal experienced the worst number of civil deaths in their history (66 in June and 45 in October, with fires burning 45,000 and 54,000 hectares respectively). In January 2017, Chile experienced the worst wildfire ever recorded, with 500,000 hectares burnt, killing 11 people and burning thousands of houses. California, a region used to wildfire occurrence, has undergone through the most destructive wildfire on record, burning more than 9,000 houses and killing 46 people, with a total affected area of 559,000 ha. Italy experienced 1,000 wildfires on the same day, on 17th July, amid high temperatures and drought, with a collapse on the suppression system. Extreme wildfires are becoming more usual (Fernandes et al., 2016; San-Miguel-Ayanz et al., 2013) despite the huge efforts dedicated to fire suppression.

Inappropriate fire regimes are now one of the most significant threats to biodiversity in places such as the Mediterranean Basin (Pausas et al., 2008). The current challenge is to understand fire regime changes, anticipate their interactions with different global change components such as climate changes and move to a proactive mode of decision making that minimizes adverse impacts (IPBES, 2016). A deeper comprehension of fire dynamics is therefore needed to enhance possibilities of successful biodiversity conservation strategies at the ecosystem level. The analysis of historical fire regimes is a key step towards a better understand of biodiversity trends, threats and opportunities. The prediction of fire regime evolution to the future can bring light on the threats that ecosystems will face and the actions that can help to override undesired states. Since vegetation is a key determinant of fire regimes, and ignition occurrence may be limiting fire occurrence, management of fire regimes is an option open to either reduce fire risk or improve environmental quality. Ecology research and biodiversity conservation require a deeper knowledge on fire regime dynamics in a global change context.

In addition, a comprehensive understanding of fire regime patterns and processes will help to transform our societies within the resilience paradigm (Tedim et al., 2016). During the last decades, a rise in urbanizations located in wildland-urban interfaces has led to an increasing number of fatalities (Moritz et al., 2014) and the political response has been directed to try to eliminate fire from the system, without a total success in any place in the world (Archibald, 2016; Moritz et al., 2014; San-Miguel-Ayanz et al., 2013; Tedim et al., 2016). There is a claim to promote societies in which people are less vulnerable and more resilient to fire impacts.

The understanding on how the different drivers of change can further impact fire regimes is still undergoing (Flannigan et al., 2009; Regos et al., 2014; Westerling et al., 2011). Yet, there is no clear consensus on future land-cover changes because they rely upon more local economical drivers with high uncertainty in their long term predictions (Rounsevell et al., 2006). In addition, the complex interactions of drivers, the cascading effects of sequential disturbances (Batllori et al., 2017), and the uncertainty of future conditions (Thompson and Calkin, 2011), make the projection of future changes a major challenge. Fire research requires further tools and approaches that help to understand ongoing changes and provide solutions to help to make effective decisions.

Fire management: state of the art and future challenges

Fire management includes the decisions that directly affect fire regimes: fuel treatments, prescribed burning, fire suppression, fire prevention, awareness campaigns, etc., and that can help to achieve a desired fire regime. There are many other landscape decisions that can also indirectly modify fire regimes, such as urban planning or agricultural recipes, that can be synergistically considered to achieve fire regime goals (Loepfe et al., 2012). Fire management policies, as well as many other conservation environmental decisions, have historically been based on reactive actions after a disaster has already taken place: focusing on ignition prevention campaigns or fire suppression investments. Some modest changes to wildfire policies have included long-term preventive actions, but fire management is still primarily centered on fire suppression (Moritz et al., 2014).

Fire suppression has evolved during the last decades (Brotons et al., 2013; Costa et al., 2011; Curt and Frejaville, 2017; Otero and Nielsen, 2017; Ruffault and Mouillot, 2015). Current technologies and knowledge have shifted from a local-scale simple decision-making process to a complex fire event holistic approach. In the early stages of the fire management development, flame suppression represented the simplest action aimed to control wildfires, from using the most rudimentary water bucket to the most sophisticated fire aircrafts. The local spatial scale of the action is limited, and the temporal scale of flame suppression is also restricted to present actions. This strategy seemed effective for low intensity fires occurring in fragmented low fuel dominated landscapes, and nowadays it is continuously being used to control these kinds of fires. However, as fires are getting larger and more intense, direct flame attack becomes insufficient to control current harsh wildfires in worsening conditions (Castellnou et al., 2010).

The evolution of fire behavior and spread understanding led to the establishment of a fire spread pattern classification (Castellnou et al., 2009; Costa et al., 2011) that allowed suppression brigades to anticipate fire spread behavior and introduce strategic anticipation to the fire-fighting toolkit. They became capable to foresee decisions during the same fire event based on previously studied fires, and thus winning extinction-time and enhancing fire suppression effectiveness. The capability to predict fire behaviour led to the use of the opportunity concept, in which conditions for fire suppression are optimal and results on the suppressed area or intensity reduction are significant. When anticipatory firefighting governs fire suppression strategies, both temporal and spatial scales are combined to incorporate future likely states of fire development. Anticipatory actions based on different fire spread patterns have become the main strategy followed by firefighter brigades in some Spanish regions (Catalonia), and have shown to be effective in most of the cases (Brotons et al., 2013; Otero and Nielsen, 2017). However, given an extreme fire weather event, firefighter brigades can become unable to stop fires.

Nowadays, in the European countries of the Mediterranean Basin, current fire management policies rely basically on fire suppression, and do not sufficiently address the socio-economic and land management issues behind the wildfire phenomena (Fernandes, 2013; Tedim et al., 2016). Fire suppression is generally based on a suppression apparatus organized according to a military structure with huge investments in equipment which enjoy widespread political, institutional, and public support. But, in a counterintuitive way, suppression policies might have contributed to promote extreme wildfire events by homogenizing and increasing forest surface. Known as the fire paradox, a high suppression effort can eliminate natural fire breaks, which hold back large wildfires under extreme weather conditions (Minnich, 1983; Moritz et al., 2014). However, the fire paradox does not necessarily happen in all ecosystems. The capability of fire suppression to affect future fires depends on fire frequency, vegetation recovery rate and landscape fuel cover. That is to say, if fire frequency is very low and/or vegetation recovery is fast, new fires might not usually encounter past fires breaks (since vegetation will have already grown), so reducing fires with suppression will not modify future fires. Instead, in ecosystems with scarce vegetation, new fires will be restricted due more to low fuel areas than by past fires, so reducing fires with suppression will not mean an impact on future fires. Most probably, ecosystems with enough fuel cover and rather fire frequency will be the ones with higher probability of displaying the fire paradox. More research should delve into the actual effects of fire suppression according to biomes characteristics.

Fire suppression requires a paradigm change which integrates complementary fire management tools to control fire activity. Under the ongoing changing situation and the impossibility to control all fires, new strategic foresights are needed to control adverse wildfires. Worse climatic weather conditions can exacerbate extreme wildfires and only by profiting from landscape opportunities fire intensity can decrease and firefighters can act to content the fire. Thus, fire regime control involves the creation of low-fuel landscapes that force fuel to be the limiting driver for fire activity rather than climate. Achieving low-fuel landscapes is closely reliant on landscape planning and fire management. With landscape planning, wildfire risk can be integrated as a land management factor, creating landscapes as dynamic meshes formed by society, policies, economics, environment and culture.

Currently, investments in fire solutions are based on the handling of threats and avoid a long-term strategic foresight. Future uncertainties explain why policies focus on the suppression phase, which offers immediate, tangible and politically defendable short-term results, down weighting prevention or initiatives aimed to modify the human system in more profound ways with longer term sustained effects. Fire suppression strategies need a shift to a new age in fire management in which the object of decision is not each isolated fire but rather is aimed at promoting sustainable fire regime as a whole. Anticipatory fire suppression should move one step ahead and shift to wider temporal and spatial scales to give birth to a new strategy based on decreasing large fires' devastating impacts and move to approximations that look more into longer-term policies (Birot, 2009). Likewise, fire management needs to be implemented under a scientific evidence based basis, and requires the quantitative assessment of its effectiveness to be sure that a desired fire regime is achievable or that the vast sums of public money spent on treatment are being used wisely (Addison et al., 2013; Driscoll et al., 2010).

Fire spread patterns – a classification linking natural and anthropogenic influences at the landscape scale

Fire is a disturbance acting at multiple scales (Parisien and Moritz, 2009). At micro scales, the chemistry reactions determine the capacity to sustain a flame (Quintiere, 2006). At small scales, the input of fuel, oxygen and heat drives fire behavior (Rothermel, 1972). At the landscape scale, the interaction between topography, weather and vegetation influences fire spread (Rothermel, 1983). At the biome scale, the relation between ecosystem productivity and aridity constitutes the basis of fire activity (Archibald et al., 2009; Bradstock, 2010; Krawchuk and Moritz, 2011; Pausas and Ribeiro, 2013).

Of the fire mechanisms acting at the landscape scale, little research has been conducted to characterize fires conforming to the propagation they display at this scale (Cardil et al., 2016; Lecina-Diaz et al., 2014). Fires can be classified according to their fire spread pattern, a common classification used in operational services, which helps to understand fire evolution (Castellnou et al., 2009; Costa et al., 2011). Wildfires present analogous patterns under similar weather and terrain conditions, which means that they can be classified into typologies (i.e. wind-driven, topographic, etc.). Attributing a fire spread pattern to a fire enables one to predict fire movement over the landscape, and thus anticipate the landscape changes that might suppose an opportunity for suppression (changing slopes, ravine junctions, etc.). That is the reason why operational firefighter services have commonly used this knowledge to improve the effectiveness of their operations (i.e. instead of attacking directly the flames, the attack is focused in strategic locations that suppose a change in fire spread). Synergistically, fire management at the landscape scale can also use the concept of fire spread pattern to effectively apply management actions in strategic points that suppose a change in fire spread capacity, according to the most common type of fire that a region can experience. In fact, fire spread patterns can provide a reliable way of understanding fire dynamics at the landscape scale without needing to deepen in the complex flame behavior. The sizes and behaviors that fires can achieve, together with the interaction with suppression capabilities, differs between the different kinds of spread patterns, and opens the possibility to foster fire regime predictability through their characterization.

The occurrence of the different types of fire patterns is hypothesized to depend on the interaction between weather, topography and fuel (Costa et al., 2011). The influence of weather at the landscape scale has been argued to be related to synoptic weather situations (Paschalidou and Kassomenos, 2016; Pereira et al., 2005; Ruffault et al., 2016). Synoptic weather situations are depictions of continental scale atmospheric configurations at short time intervals (hours to days) that result in specific weather variables at a regional scale (Skinner et al., 2002). Characterizing synoptic weather conditions of days in which fires occur allows one to capture underlying weather processes of regional areas at a simple data resolution (Taklel et al., 1994). For instance, the widely known phenomena of the 'Santa Ana Winds' in California, consist of the location of a high-pressure system in the Great Basin of the United States that leads to strong hot and dry down slope winds in the mountain channels in southern California (Abatzoglou et al., 2013). This situation has broadly been documented to produce the largest and strongest fires in the area (Jin et al., 2014; Keeley et al., 1999; Keeley and Fotheringham, 2001; Moritz, 2003). Understanding the atmospheric configurations that can lead to the development of large fires constitutes a potentiality to explain fire regime dynamics.

However, the same synoptic weather situation may cause different fire spread patterns according to topographic and fuel features where the fire is developing (Costa et al., 2011). In fact, the relative role of the drivers affecting the different fire spread patterns is unknown. Quantifying drivers' contributions on the occurrence and spread of fire spread patterns will lead us to increase our ability to accurately predict fire regimes at large scales.

A landscape modelling framework

Working at the landscape scale implies a system framework in which it is difficult to anticipate responses using experimental approaches. Models here become an appealing alternative to deal with these challenges. Models support decision-making in complex and dynamic environments by offering a systematic, rational and transparent platform for synthesizing existing knowledge, forecasting the consequences of management alternatives and evaluating uncertainty (Addison et al., 2013). Mathematical tools integrating ecological processes and social and climate scenarios are key tools to help fire regime understanding and environmental decisions at such scales and under long-term planning.

Fire regime modelling and typification can help to identify, control and manage the limiting factors of fire spread. Namely, a region could become less flammable if processes are identified, actions are planned and fuel is managed. Noteworthy is that at the fire level, climate cannot be managed, but it can be forecasted within different extreme scenarios. Accordingly, policymakers could consider the different landscape scenarios resulting from the application of the climate change scenarios and fire regime modelling, to conclude in science-based policies considering a holistic wildfire-social approach.

Long term decision making should incorporate not only expert opinions but also quantifying models. And models should rely on ecological processes more than on historical registers, to eventually allow the emergence of novel situations not recorded in the past. In fact, climate change might entail cause ‘novel’ or ‘no analogue’ environmental conditions that can present new challenges for management, policy and planning. So there is an increasing consensus that the use of model projections under different scenarios is a key step for understanding a system’s evolution, for reducing uncertainty and for aiding in the decision-making process (Addison et al., 2013; IPBES, 2016; Thompson and Calkin, 2011).

Catalonia: an iconic Mediterranean-type ecosystem

Changes in fire regimes have been widely reported in many MTE ecosystems (Fréjaville and Curt, 2017; Moreno et al., 2014; Pausas and Fernández-Muñoz, 2011; Syphard et al., 2009; Úbeda and Sarricolea, 2016). For this thesis, the evaluation of global change impacts is focused in Catalonia, a Mediterranean region of about ~32,000 km^2 located in NE Spain (Fig. 1). Catalonia is a very densely populated region (with 232 inhabitants per km^2 in 2016; it is only surpassed by four Italian regions within the European regions of similar size; Fig. 2), and it’s the third region of Europe in terms of forest surface (up to 60%; Fig. 3). This, together with fire-prone weather conditions governing its summers, makes Catalonia an extremely vulnerable region to wildfires.

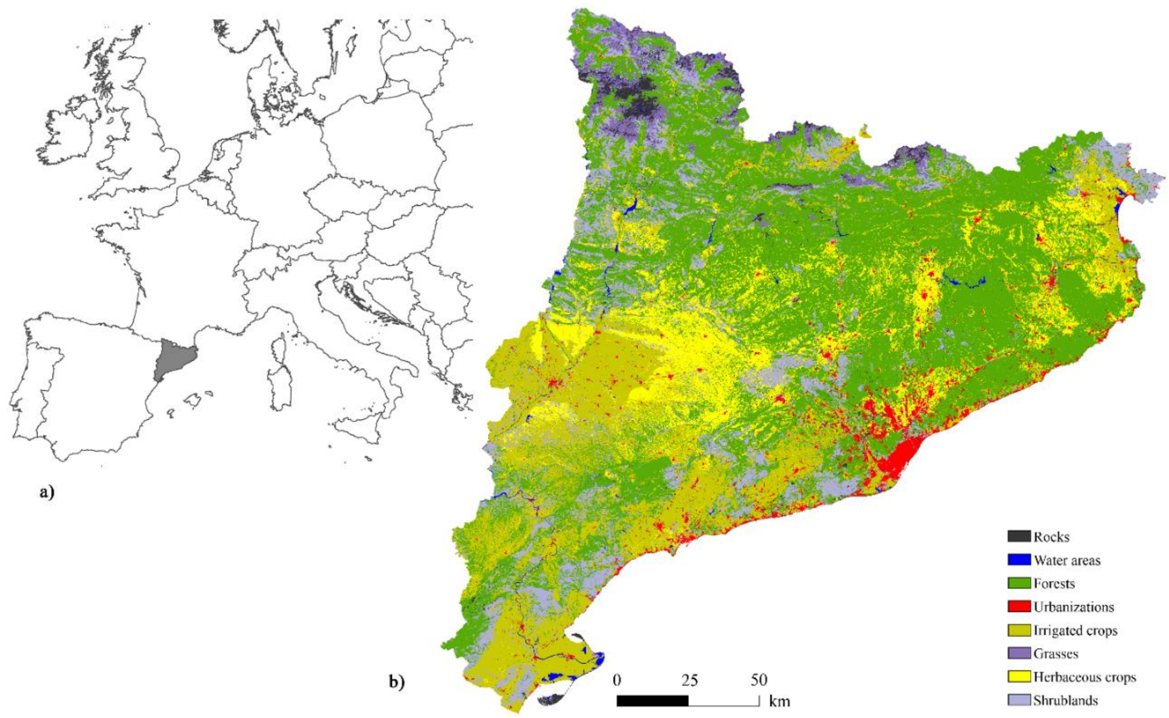

Figure 1. Situation of Catalonia in Europe (a) and Land Cover Mapin Catalonia from 1989 (b).

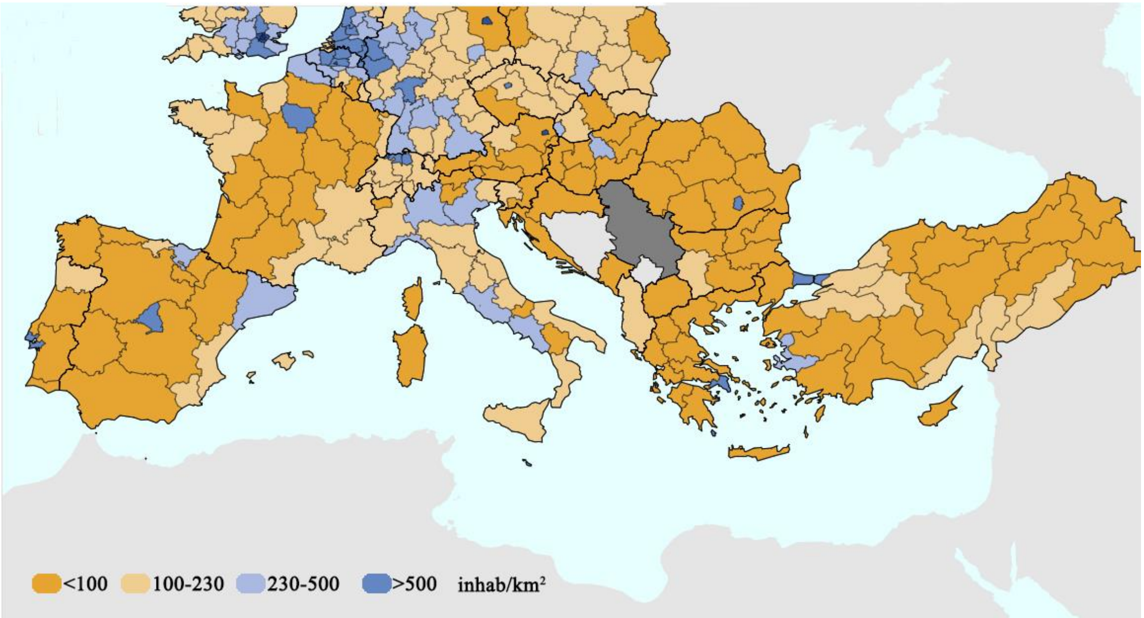

Figure 2. Population density in the EU regions (level NUTS-2) (source: Eurostat).

The relief in Catalonia is highly heterogeneous. The Pyrenees, the major mountain range in Catalonia, separates the north from France, and most of the other mountain ranges follow the east–west orientation. The topography of Catalonia greatly influences climate, weather dynamics and vegetation patterns. Precipitation and temperatures are closely related to distance-to-sea and altitude. Mean annual temperature ranges from 17.3ºC in the south to 0ºC in the north-west at high altitude, and, similarly, precipitation varies from 335 mm in the south to 1500 mm in the high altitude areas of the north-west region (Ninyerola et al., 2000). Average wind speeds vary significantly over the region, with average wind speed in the northern and southern Catalonia higher than in the center (Gencat, 2004), and the strongest winds can gust at 200 km/h (Liberato et al., 2011).

Catalonia landscapes encompass diverse mosaics of agricultural plans, pine-oak forests and mountainous shrublands (Fig. 1). Sixty percent of the area is covered by forests and shrublands according to the 2009 land cover map of Catalonia (Ibàñez and Burriel, 2010). Dominant tree species are pines (*Pinus halepensis, Pinus nigra, Pinus sylvestris, Pinus uncinata* and *Pinus pinea*) and Holm oaks (*Quercus ilex* and *Quercus suber*). Vegetation distribution over the Catalan landscape also coincides with the north–south gradient, similarly to temperature and precipitation, as well as with historic land-use changes (Puerta-Piñero et al., 2012) and forest management. The understory is highly heterogeneous and usually rich in helioxerophytic species including *Quercus coccifera*, *Rosmarinus officinalis*, *Erica multiflora*, *Cistus sp*., etc. (Villanueva, 2005). Shrublands are dominated by *Rosmarinus officinalis*, *Thymus vulgaris*, *Globularia alypum* and *Quercus coccifera* (Vigo et al., 2005).

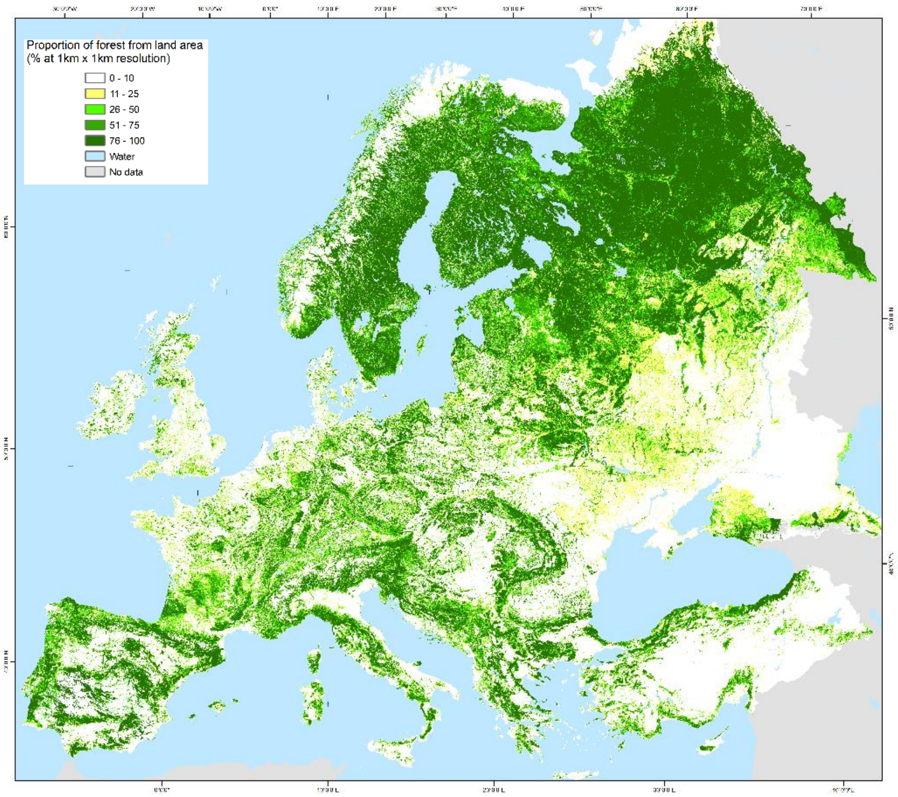

Figure 3. Forest cover map and percentage of forest land area at 1 km x 1 km in 2011 in Europe (source: EFI, JRC and Kempeneers et al., 2011).

The area occupied by forests in Catalonia has been increasing from the beginning of the 20th century, with this increase considerably accelerating since the middle of the last century due to the crisis of rural societies leading to abandoned farmland that is subsequently and gradually being recolonized by forests (Puerta-Piñero et al., 2012). Socioeconomic changes moving from a rural dominated to a globalized industrial/service driven society have also profoundly altered ignition patterns and uses of forest dominated landscapes. In terms of forest management, the heterogeneity, instability and low income that characterize Mediterranean forests together with the small extension of forest ownership (among other factors) have led to a lack of management in most of the Catalan forests. The net result is that Catalan forests tend to be very dense, with high fuel accumulation and slow growth.

Simultaneously with rural abandonment, Catalonia has experienced significant urban development in or near forest areas from a non-rural population, creating large extensions of the so called wildland-urban interfaces. These areas also induce a shift on fire regimes, both because fires can spread through them and because the attraction of suppression brigades for house protection weakens resources targeted to suppress fires. These areas suppose a challenge for management with impacts in the whole fire regime system.

Catalonia is a European region with quite high fire activity, with a lower number of fires than the western Iberian Peninsula, and similar to other regions as south-eastern France or Sicilia (Fig. 4; San Miguel and Camia, 2009). Fire return intervals in Catalonia for the period 1980-2000 vary widely in time and space but range from 60 to > 400 years for homogeneous fire regions of around 45,000 ha (Pique et al., 2011). Annual burnt area is highly variable, with the largest areas burnt in 1986 (65,000 ha) and 1994 (82,000 ha). Most of the burnt area is caused by a few large fires and most fires occur in summer (June-September). Stand-replacing fires are the most widespread type of fire in Catalonia, with >85% of the burnt area being affected by crown fires (Rodrigo et al., 2004). Some very large fires and with short recurrence periods have triggered radical shifts in vegetation eventually leading widespread non-reversible tipping points from coniferous to oak and scrubland dominated landscapes.

Wildfires are a major concern in the region, as demonstrated by the vision society has of the situation (Gordi Serrat, 2011; Otero and Nielsen, 2017). The dominance of private forest ownership, and the vision of fire as a threat and an alien for a rural society in crisis increasingly dominated by urban visions, have led public administrations to have targeted investments on fire suppression assets, which is the most directly visual product that administrations can provide the society in terms of wildfire management. The prevalent fire management strategy in Catalonia is fire suppression, and firefighting investment has increased six-fold since the early 1980s. The strategy generally applied, justified by the high values at risk in this highly populated country, is based mainly on a fast and aggressive attack on all ignition points, at every place and under all weather conditions. The forestry department has also tried to mobilize forest regional planning to incentivize forest productivity and prevent wildfires, with poor results.

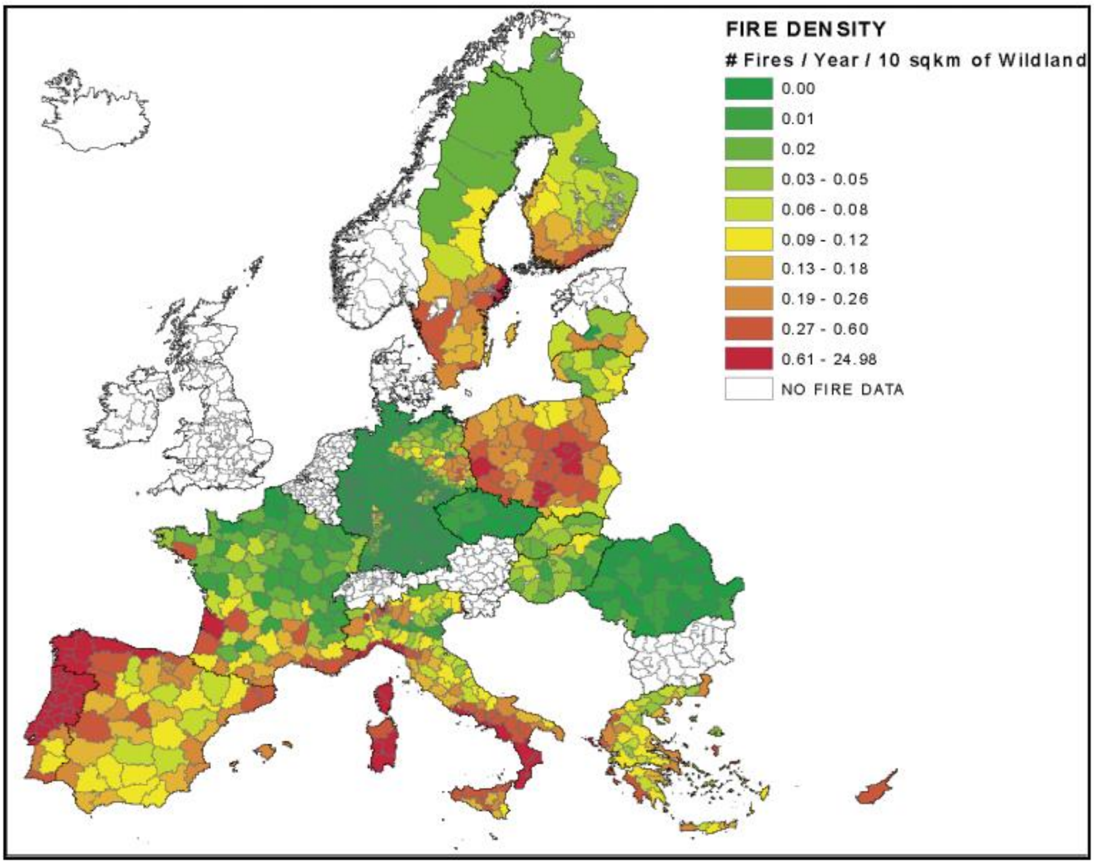

Figure 4. Average annual distribution of the number of fires by 10 square km of wildland area in EU regions (level NUTS-3) from 1980-2006 (source: San Miguel and Camia, 2009).

A decreasing trend in the number and size of fires has been observed after the big fires of 1986 and 1994, mainly explained by an increasing effort on fire prevention and suppression (Brotons et al., 2013; Turco et al., 2013). However, large wildland fires have not decreased to the same degree. Catalan firefighters are now able to stop 97% of the fires, succeeding in their initial attacks and hold fires to not bigger than 50 ha (San Miguel and Camia, 2009). However, there is still a small percentage that overcome firefighters capacity (usually associated to very bad weather conditions, with low humidity, high temperature and strong winds), and become large wildfires, threatening human lives and goods.

Furthermore, fire conditions are expected to worsen in the future (Batllori et al., 2013; IPCC, 2014) and budgets might drop due to economic crisis events (Costafreda-Aumedes et al., 2015). In the Spanish recent past (1998-2009), budget was not supposed to be a constraint to forest firefighting. All available firefighting resources were used to minimize the damages, whatever the costs, even if these exceeded any budgetary limit (Vélez

Muñoz, 2009). However, although 90% of budgetary resources assigned to fires have been committed to suppression (Fig. 5), wildfires are still surpassing suppression capacities in many instances and trigger social and ecological negative impacts. The increment of suppression budgets applied during the first half of 2010 decade was not translated into a larger control of wildfires in Catalonia.

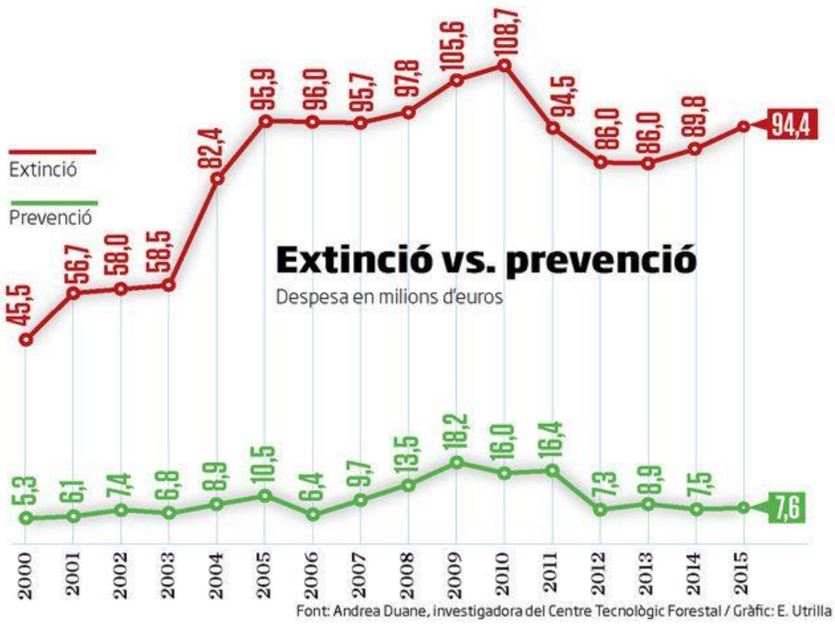

Figure 5. Investments on fire suppression and prevention in Catalonia from 2000 to 2015 in millions of euros. Ninety percent of budgets are committed to suppression (red line), and 10% to prevention (green line). The edition of the figure is the same as presented in the regional newspaper 'ARA' from 24th July of 2016, and it is in Catalan.

This Mediterranean region provides an excellent case study to explore interactions between wildfires, climate, fire policies and landscape dynamics, and be representative of potential changes in other Mediterranean regions.

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OBJECTIVES AND THESIS STRUCTURE

OBJECTIVES AND THESIS STRUCTURE

The impact of climate change and other anthropogenic factors on fire regimes are still largely uncertain. Here, I want to test sound and novel questions that can help to improve fire dynamic's understanding and assess global change influences on fire regimes. My aim is to offer a new vision on fire regime dynamics and to stimulate the creation of scientific-based fire management policies at large scales and long-time effects.

Main objective

The main goal of this thesis is to gain a better understanding on the factors that underpin fire regime dynamics to then integrate them in landscape fire succession models and provide evidence on the impacts of global change into future fire regimes.

The specific objectives of this thesis are the following:

1) To analyze main landscape features behind the occurrence and spread of different fire spread patterns.

2) To evaluate and operationalize a methodology to classify the synoptic weather situations that lead to the development of large wildfires.

3) To assess the relationship between climate, fuel and fire in determining dynamic fire regimes, and evaluate the fire paradox existence in a MTE.

4) To quantify the impacts of climate change in future fire regimes.

5) To appraise how different fire management strategies can modulate fire regimes under the climate change.

Structure

This thesis has been structured in five chapters that aim to respond to these questions (Fig.1.). After the five chapters, I present a discussion on the main findings and contributions of this thesis. The main concluding remarks are exposed in the last section. Each of the five chapters of the thesis has the following objectives and methodology:

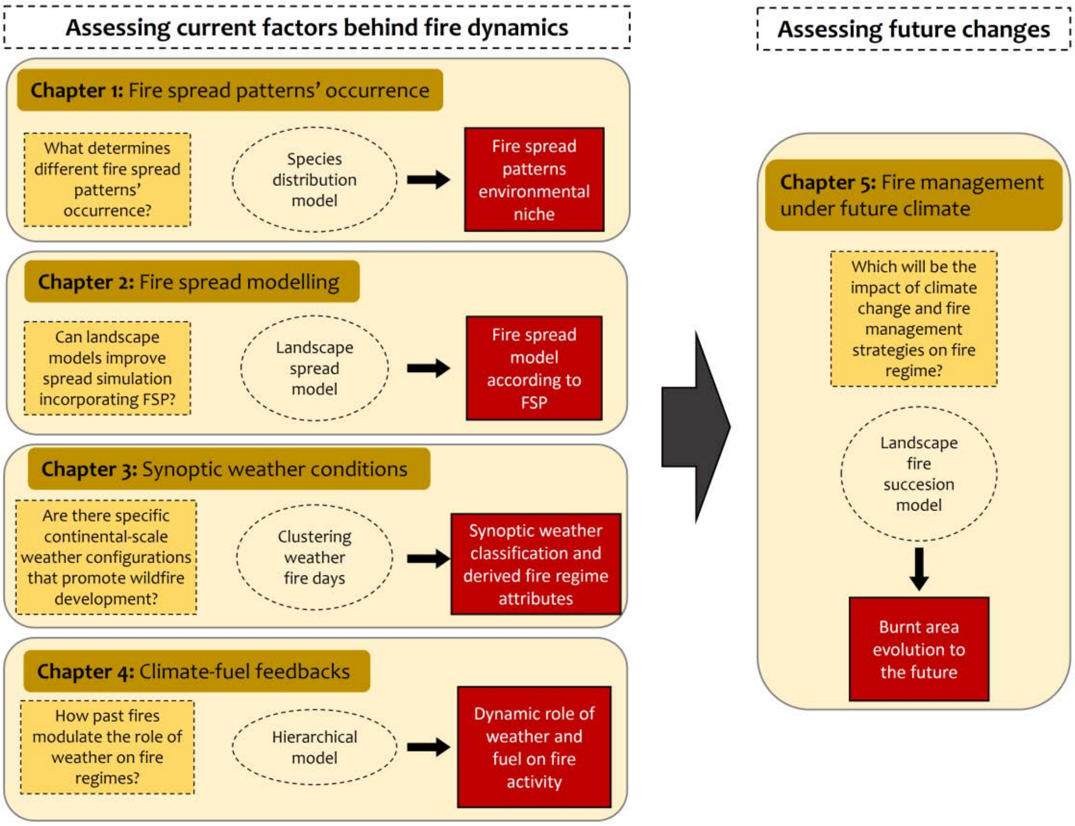


Figure 1. Structure of the present thesis with the five presented chapters. FSP refers to Fire Spread Pattern.

Chapter 1.

In the first chapter of this thesis, I investigate the environmental niche of the occurrence of three different kinds of fire spread pattern. Fires in Catalonia from 1989 to 2012 were previously classified into three different fire spread patterns. I use the MaxEnt algorithm, which allows to build logistic models of fire occurrences with environmental data. A model for the decade 1989-1999 is firstly built and then validated for the decade 2000-2012, and vice versa. Then, I apply variation partitioning analyses to estimate the relative contribution of the driving factors affecting the occurrence of each fire spread pattern. **(Objective 1)**

Chapter 2.

In this chapter, I develop a model that simulates fire spread at the landscape scale according to five environmental factors (wind direction, slope, fuel load, species flammability and aspect). I seek to capture the combination of variables that determine the spread of the three different fire spread patterns present in Catalonia **(Objective 1).** In this chapter, I assume that each typified weather condition leads to the development of one kind of fire spread pattern. Additionally, I attempt to demonstrate that fire spread modelling in landscape fire succession models improve when separating fires by fire spread pattern, and that this may involve an enhancement on our capacity to predict global changes on future landscapes.

Chapter 3.

Evaluating weather conditions that lead to the development of large wildfires at regional scales requires from the incorporation of processes explaining fire activity at these scales. In this chapter, I classify fire days into groups according to continental-level atmospheric configurations (Synoptic Weather Conditions) **(Objective 2)**. I use fire days from 1980 to 2015 in Catalonia, and wind, pressure and temperature data at different atmospheric altitudes covering the whole of Western Europe (25-70ºN and 20ºW-40ºE) to characterize weather conditions. I also analyze fire regime attributes derived from these groups. Unlike previous chapters, this work does not specifically assess a relation with fire spread patterns.

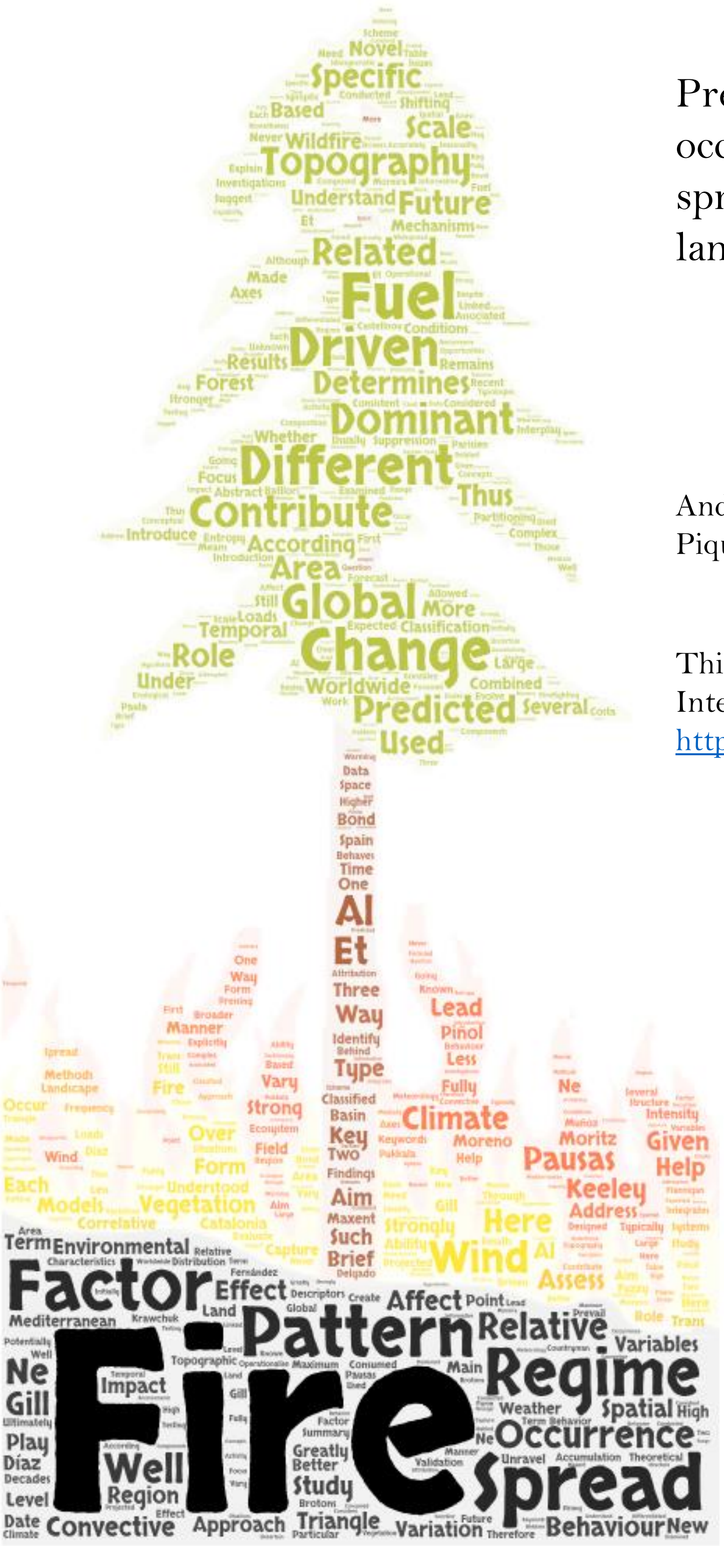
Chapter 4.

In this chapter, I investigate the dynamic role of climate and fuel in fire activity in a Mediterranean region **(Objective 3)**. I build a hierarchical model to evaluate the variations in annual burnt area in relation to weather, fire management and past fires. Past fires include the sum of burnt area in different intervals of time. The model also allows to quantify the modulating effect of region attributes (mean annual wind and vegetation aggregation) on the relations between past fires and burnt area. Furthermore, if past fires result in a negative effect on burnt area, outcomes allow to explore the fire paradox effect in Catalonia. I use data for nine homogeneous fire regions in Catalonia for the last 35 years. In this chapter, I do not use the fire spread pattern classification, but I center on dynamism of primary drivers.

Chapter 5.

In this last chapter, I gather all the findings from the four first chapters in a model that simulates fire regime to the future under different drivers of change. The model simulates emergent properties such as annual burnt area, fire size, fire intensity and fire shapes, by the interaction of climate, landscape features and fire management strategies. I firstly evaluate climate change impacts (RCP 8.5 scenario) on potential burnt areas in relation to a business as usual scenario **(Objective 4)**. I then apply four different management strategies under climate change and discuss the implications and resulting impacts of each different strategy **(Objective 5)**.

CHAPTER 1



Predictive modelling of fire occurrences from different fire spread patterns in Mediterranean landscapes

Andrea Duane, Marc Castellnou, Míriam Piqué and Lluís Brotons

This chapter has been published in International Journal of Wildland Fire (doi: http://dx.doi.org/10.1071/WF14040)

ABSTRACT

Fire regimes are shifting worldwide because of global changes. The relative contribution of climate, topography and vegetation greatly determines spatial and temporal variations in fire regimes, but the interplay of these factors is not yet well understood. We introduce here a novel classification of fires according to dominant fire spread pattern, an approach considered in operational firefighting, to help understand regional-scale spatial variability in fire regimes. Here, we studied whether climate, topography and fuel variables allowed the prediction of occurrences from different fire spread patterns in Catalonia, NE Spain. We used a correlative modelling approach based on maximum entropy methods, and examined, through variation partitioning, the relative contribution of different factors on determining their occurrence. Our results accurately predicted the occurrence of different fire spread patterns, and the results were consistent when temporal validation was conducted. Although forest fuel factors made a higher contribution to the occurrence of convective fires, wind-driven fires were strongly related to topographic and climate factors. These findings may have a strong impact on investigations into how fire regimes may be projected into the future under forecast global change as they suggest that future environmental changes may affect different fire spread patterns in an idiosyncratic manner.

Keywords

Fire behavior triangle, MaxEnt, Variation partitioning, Global change, Catalonia

Brief summary

Fire regimes are changing worldwide. Here we introduce a novel approach for assessing changes in fire regimes in a Mediterranean area from the modeling of different fire typologies according to their dominant spread pattern. This can help us to better understand fire impacts and it can lead to new ways of predicting global change effects on fire regimes.

INTRODUCTION

Fire regimes play a key role in ecosystem composition and distribution (Bond and Keeley 2005; Pausas and Keeley 2009) and they are shifting worldwide because of global changes (Keeley et al. 2012; Moritz et al. 2012; Moreno et al. 2014). The term 'fire regime' integrates several concepts related to temporal and spatial patterns of fire occurrence in a specific area as well as its ecological effects (Gill 1973), and it is typically determined by the frequency, intensity, seasonality and type of fuels consumed by wildfires in a given area.

The relative roles of weather, topography and vegetation on fire regimes are not fully understood, but their contributions are well known to vary in time and space (Pausas and Keeley 2009). One way to capture the spatial variability of fire regimes is to focus on the conditions ultimately leading to specific fire spread patterns in a given area. Dominant fire spread patterns are usually linked to specific synoptic weather conditions, topography, or vegetation patterns, determining fire behaviour and thus fire suppression opportunities (Castellnou et al. 2009; Costa et al. 2011). The attribution of a given fire spread pattern to a particular fire can be potentially used to unravel the mechanisms determining fire characteristics and thus contribute to our understanding of how fire regimes can change. Dominant fire spread patterns are differentiated based on the relative contribution of the factors forming the 'fire behaviour triangle' (Countryman 1972; Parisien and Moritz 2009), because the most informative environmental factors that can explain fires (occurrence and spread) at a landscape level are those captured by the axes of this triangle. The fire behaviour triangle is a conceptual, theoretical scheme of how a wildfire behaves and it is composed of three factors: topography, meteorology and fuel. Thus, fires can be classified into three different fire spread patterns according to whether the dominant factor affecting spread is related to topography (topography-driven fires), meteorology (wind- driven fires) or fuel accumulation (convective fires). Nonetheless, this fire-spread classification has never been quantitatively assessed and therefore the relative contribution of different factors other than the dominant fire spread factor remains unknown, as well as the predictive ability of the approach to identify future fire occurrences of the different spread patterns.

Data over recent decades in different regions of the Mediterranean Basin point to large-scale changes in fire recurrence, intensity and severity (Piñol et al. 1998; Díaz-Delgado et al. 2004; González and Pukkala 2007) associated with widespread land abandonment and fuel accumulation (Moreira et al. 2001; Pausas and Fernández-Muñoz 2011), global warming (Piñol et al. 1998; Pausas 2004) and fire suppression activity (Brotons et al. 2013; Moreno et al. 2014). However, it is still uncertain how the fire regime is going to evolve according to all these changes in such complex systems. Despite investigations into the effect of future climate change on fire regimes (Flannigan et al. 2009; Batllori et al. 2013), the specific contribution of the different climate components to fire regime remains fuzzy (Keeley et al. 2012; Pausas and Paula 2012). Several studies have addressed the question of how factors affect fire regimes (Krawchuk et al. 2009), but no work to date has focussed on explicitly addressing the role of the different components of fire behaviour using fire spread patterns in a predictive manner. The complexity of wildfire impacts at a landscape scale combined with expected future global change create a pressing need to identify and operationalise the mechanisms by which different environmental factors mediate changes in fire regimes.

This study was designed to address two main issues: (1) first, we aimed to evaluate the predictive capability of the fire spread pattern classification by means of correlative models in a Mediterranean region affected by large fires. Fires were classified in the field according to their dominant spread pattern, which is theoretically related to different combinations of weather, topography and vegetation (the fire behaviour triangle); (2) we then attempted to assess the relative contribution of these environmental factors to each type of fire spread pattern with the aim of testing the hypothesis that each spread pattern is associated with specific combinations of these factors. According to the dominant mechanisms behind fire spread patterns, we expected that convective fires would be more strongly related to forest structure descriptors, whereas wind-driven fires would be more strongly related to wind descriptors (Table 1). We also predicted that topography-driven fires would be related to topographic factors, and they should occur over a broader range of environments where stronger fire spread determinants such as fuel loads or strong winds are not greatly inducing the occurrence of the other fire spread patterns, because wind or high vegetation loads can overcome topography effects and trans- form an initially topography-driven fire into a convective or wind-driven fire. Consequently, topography-driven fires are more likely to occur under less specific situations where the other stronger drivers do not prevail.

Table 1. Hypothetical effect of factors on fire spread patterns

Type of factors	Convective Fires	Topography-driven fires	Wind-driven fires
Topographic factors	No	Yes	Yes
Climate factors	Yes	Yes	Yes
Landscape fuel factors	No	Yes	?
Forest fuel factors	Yes	?	No

STUDY AREA AND REGIONAL FIRE CONTEXT

Our study area was Catalonia, a region in the north-eastern Iberian Peninsula (Fig. 1). The climate is Mediterranean, with hot dry summers, rainy springs and autumns, and cold winters. Continental and Pyrenean influences are found, with precipitation and temperature variations related to distance to sea and altitude. Mean annual temperature ranges from 17.3ºC in the south to 0ºC in the north-west at high altitude, and, similarly, precipitation varies from 335 mm in the south to 1500 mm in the high altitude areas of the north-west region (Ninyerola et al. 2000). Average wind speeds vary significantly over the region, with higher mean annual wind speed in northern and southern Catalonia and the high Pyrenees than in the centre. The strongest winds can gust at 150 km h-1 in north and north-west synoptic meteorological events.

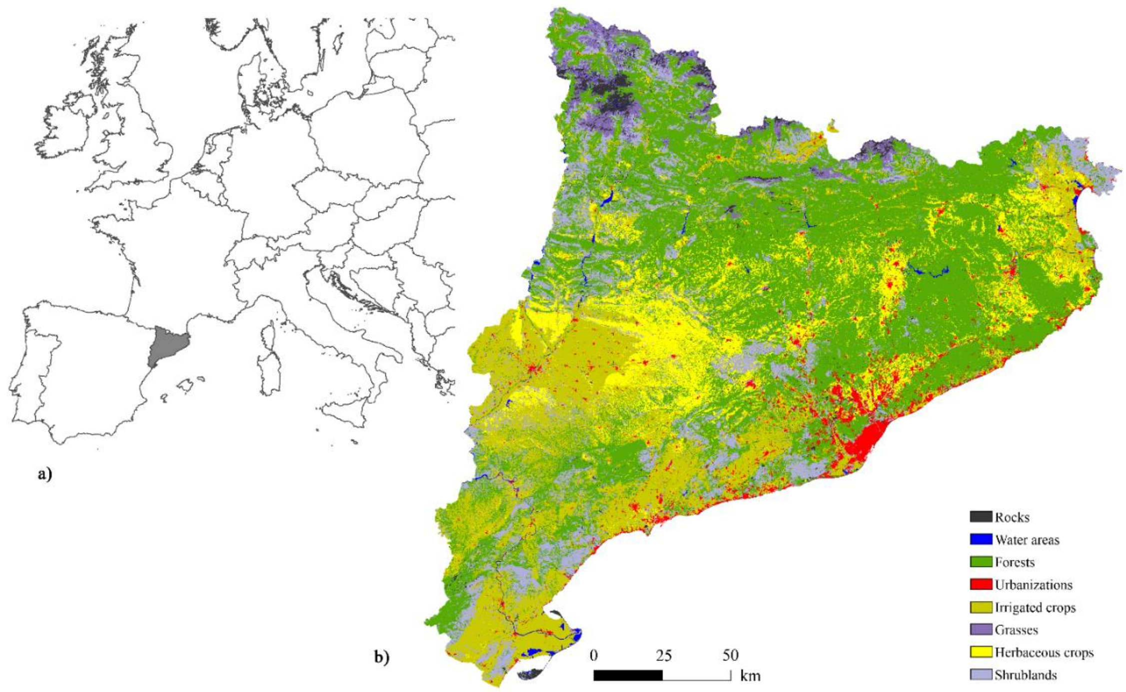


Figure 1. Situation of Catalonia in Europe (a) and Land Cover Map from 1989 (b).

Relief in Catalonia is highly heterogeneous. The eastern area is defined by the coast whereas the northern area is defined by the Pyrenean mountain range separating the Iberian Peninsula from France. The mean altitude of the region is 637 m above mean sea level (a.m.s.l.) and mean slope is 128. Most of the mountain ranges are orientated east–west, although some mountain chains near the sea follow the coast direction south-west to north-east. There are also flat areas near big river basins in the west and south of the region.

According to the 2005 land-cover map of Catalonia (Ibañez et al. 2002), 60% of the area is covered by shrublands and forests, 36.7% of which is forest, mainly evergreen (60% coniferous, 40% deciduous; Gracia et al. 2000). Dominant tree species are pines (*Pinus halepensis, Pinus nigra, Pinus sylvestris, Pinus uncinata* and *Pinus pinea*) and Holm oaks (*Quercus ilex* and *Quercus suber*), followed by other oaks (*Quercus faginea, Quercus humilis* or *Quercus petraea*) plus *Abies alba* and *Fagus sylvatica*. Vegetation distribution over the Catalan landscape also coincides with the north–south gradient similarly to temperature and precipitation, as well as with historic land-use changes (Puerta-Piñero et al. 2012) and forest management. The understorey is highly heterogeneous and usually rich in helioxerophytic species. The area occupied by forests in Catalonia has considerably increased since the middle of last century, mostly owing to abandoned farmland subsequently being recolonised with trees (Poyatos et al. 2003). In terms of forest management, the heterogeneity, instability and low income that characterise Mediterranean forests together with the small extension of forest ownership (among other factors) have led to a lack of management in most of the Catalan forests, resulting in fuel accumulation. Both the increase in forest area and fuel accumulation can contribute to increases in fire frequency and severity (Pausas and Fernández-Muñoz 2011).

In the 1942–2002 period, Catalonia recorded 8121 wildfires, which burned 477 982 ha of forest land. The mean annual area burnt was 8000 ha year-1, corresponding to 0.75% of the Catalan wildland area. Most of the burnt area (67%) was caused by 152 fires (2% of fires) larger than 500 ha (González and Pukkala 2007), and most of the fires (67%) occurred in the summer (June–September; Piñol et al. 1998). Stand-replacing fires appeared to be the most common in the area, with a large proportion of the area burnt being affected by crown fires (.85%; Rodrigo et al. 2004). The total number of fires and total burned area have both increased in the past few decades (Lloret et al. 2002; Díaz-Delgado et al. 2004; González and Pukkala 2007), with high annual variability depending on each year's climate characteristics (Piñol et al. 1998). The prevalent fire management strategy in Catalonia is fire suppression, and investment in it has increased six-fold since the early 1980s. Although several studies (Minnich 1983; Minnich and Chou 1997) have argued for effects of fire suppression practices on small fires enhancing the homogenisation of fuels across the landscape and promoting large fires, in Catalonia the specific role of fire suppression efforts on determining fire regimes is still under debate (Piñol et al. 2007; Brotons et al. 2013).

METHODS

Fire data

We used 1987 to 2012 fire data provided by regional govern- ment and firefighter services. The exact ignition point and the dominant spread pattern that the wildfire described were recorded. We used fires over 50 ha for two reasons: (1) the aim was to identify factors driving incidence of large wildfires, and (2) it is usually impossible to determine dominant fire spread patterns for old small fires. Location of recorded ignitions was not always available, and fire spread pattern could not be determined for all fires;

therefore, our final sample size for each fire spread pattern ranged over ~ 20–30 fires (Table 2). Fires had already been assessed by Castellnou et al. (2009) who classified old fires (before 2007) in relation to fire perimeter shape and synoptic weather conditions when the fire burnt. Modern fires were classified in situ (according to main spread rate and direction) by fire analysts (official firefighter reports). According to the fire behaviour triangle, the following spread patterns were identified (Rothermel 1991; Castellnou et al. 2009):

Topography-driven fires

Fire is dominated by local atmospheric air movement, mainly caused by local slopes heating and cooling during the day (i.e. sea breeze, land breeze, and valley and slope winds).

Wind-driven fires

Wind brings the flame closer to fresh fuel, thus accelerating spread in the wind direction (Rothermel 1983) owing to radiation and forced convection heat transfer (Anderson 1969). The fire spreads through understoreys and canopies, often reaching high intensities.

Convective fires (or plume-driven or fuel-driven)

These are considered to be dominated by airstreams created through convection caused by the fire (Rothermel 1991). A convective fire environment arises as a consequence of the particular combinations of high fuel loads and specific atmospheric conditions, usually related to atmospheric stratification, low moisture content and specific general wind circulation (Quílez 2009). The hot air mass situated on top of the fire rises by convection, and new cold drafts enter the fire area, reactivating fire activity and increasing fire intensity. The wildfire advances by massive spotting independently of topography or prevailing wind. The fire spreads through understoreys and canopies, achieving high intensity.

Table 2. Fire data available

Fire Type	Decade	Number of fires	Mean area burnt (hectare)
Topography-driven	1989-1999	21	261.9
	2000-2012	18	249.1
Wind-driven	1989-1999	30	907.9
	2000-2012	30	867.0
Convective	1989-1999	25	4336.2
	2000-2012	19	546.9

Environmental fire predictor data

Environmental descriptors used to explain the different types of fire spread patterns were selected based on the factors contributing to the fire behaviour triangle: topography, vegetation and climate factors as a surrogate of weather patterns. We considered that integrating climate spatial variability in the modelling of fire spread patterns could be used to produce both spatial and temporal projections and explain likely weather events. Factors were introduced into the model in raster format covering the full extent of the study area at 250-m resolution (Table 3, additional details on variable descriptions in Appendix S1 available as Supplementary Material online only at http://www.publish. csiro.au/?act=view_file&file_id=WF14040_AC.pdf). Correlated variables were considered when Spearman rho $ 0.80, and the one with the lowest degree of spatial variability was discarded. We included for each pixel the information of the pixel itself and its surroundings to account for the characteristics of the factors in the initial fire conditions that might influence the spread and area burnt. Thus, all grids were reprocessed using a 1-km-radius moving window average. If we had only used the information from the pixel itself, we would not have been modelling fire spread but instead just ignition occurrence. A radius of 1 km was chosen because it includes the mean area of an average large wildfire (500 ha) in Catalonia.

Table 3. Description of predictors

Main group classes	Variable	Source	Units	Description and units
Topographic factors	Slope	DEM[a]	º	Mean slope around the ignition
	Slope standard deviation	DEM	º	Mean slope standard deviation around the ignition
	Ravine junction	Topographic maps	n	Number of ravine junctions around the ignition
	Main ridge direction	DEM	%	Percentage of area with ridge directions oriented N-S or E-W around the ignition
	Elevation dominance	DEM	m	Elevation difference between the ignition and its surroundings
Climate factors	Mean annual wind speed	Wind Map	km h^{-1}	Mean annual wind speed around the ignition
	Solar radiation and temperature	DCAC[b]		Sum of the standardizations of mean solar radiation and mean annual temperature around the ignition
Landscape fuel factors	Shrub-lands	LCMC[c] and historic fire perimeters	%	Percentage land cover of shrublands around the ignition (regenerated from fires or from crop abandonment)
	Herbaceous crops	LCMC	%	Percentage land cover of herbaceous crops around the ignition
	Irrigated crops	LCMC	%	Percentage land cover of irrigated lands around the ignition
	Grasses	LCMC	%	Percentage land cover of grasses around the ignition
Forest fuel factors	Forest cover	LCMC	%	Percentage land cover of forests around the ignition
	Forest canopy cover	FM and NFI[d]	%	Canopy recovery of the forest cover around the ignition
	Basal area	FM and NFI	m^2 ha^{-1}	Area occupied by the cross-section of tally trees around the ignition (conifers or broadleaves)
	Trees per hectare	FM and NFI	trees ha^{-1}	Number of trees per hectare around the ignition (conifers or broadleaves)
	Understory recovery	FM and NFI	%	Percentage of forest area occupied by understory around the ignition
	Maximum understory height	FM and NFI	dm	Maximum understory height around the ignition
	Mean understory height	FM and NFI	dm	Mean understory height around the ignition

[a] DEM: Digital Elevation Model
[b] DCAC: Digital Climatic Atlas of Catalonia
[c] LCMC: Land Cover Map of Catalonia
[d] FM and NFI: Spanish Forest Map and National Forest Inventory

Land cover and forest maps

We searched for available spatial land-cover and forest information matching the time period over which the fire database had been collected. We therefore proceeded to generate land-cover and forest maps for two time windows: one from the early 1990s and the other from the early 2000s. This is for two main reasons:

(1) As wildfires have significant effects on landscape and our fire data are sequential, we cannot base all fires on an old map because this would fail to reflect the influence of the first fires affecting later fires. We considered that a one- decade time-window was long enough to base all ignition points in a single map and avoid spatial fire effects of one fire on the others.

(2) Although different land-cover maps were available for the region since the early 1980s, only two forest inventories were available (1989 and 2000). As forest structure data were required, we adapted our models to the timing of the forest inventories.

Based on Brotons et al. (2013), we used different land-cover maps of Catalonia (Ibañez et al. 2002), the 2000 Spanish Forest Map (Vallejo Bombin 2005) and the National Forest Inventory (Villaescusa and Díaz 1998; Villanueva 2005) with data avail- able for Catalonia. Spatial distribution of forest structure in the two decades was derived from National Forest Inventory data by applying kriging interpolation techniques (Gunnarsson et al. 1998), generating continuous layers of forest information.

Modelling approach

We used the ignition point of each fire classified according to its spread pattern as the dependent variable. In the present approach, we were only taking into account one aspect of fire regimes: occurrences of fires, excluding other assessments related to size, severity, etc.

We then built models using a presence-only method based on the maximum entropy approach (MaxEnt software; Phillips et al. 2006). MaxEnt is machine-learning software that uses an algorithm based on the maximum entropy to model geographic species distribution. Here, ignition fire points were similar to species presence sites commonly used in species distribution modelling (Moritz et al. 2012). Because it cannot be determined whether other areas were also suitable to burn at a given time, it is appropriate to assume the data represent presence-only as some of these other areas may in fact experience wildfire if they share environmental characteristics with other wildfire-prone locations (Parisien et al. 2012; Peters et al. 2013). In addition, previous findings from species distribution modelling suggested that machine-learning algorithms are specially flexible in handling heterogeneous data given that they do not require normally distributed data (e.g. wildfire ignitions; Bar Massada et al. 2013).

MaxEnt works by estimating the probability distribution of maximum entropy taking into account the set of constraints that reflects our incomplete information on the species distribution (Phillips et al. 2006). MaxEnt model units show habitat suitability indexes built by contrast between the areas where the species is present and the whole landscape.

High values indicate that the place is predicted to have suitable conditions for that species. During the modelling process, the algorithm performs a gain defined as the increase in the ignition probability in the training locations (Bar Massada et al. 2013), which is analogous to deviance in generalised additive and linear models (Phillips 2005). We used default model parameters (convergence thresh- old of 10-5, maximum iteration value of 1000 and automatic regularisation with a value of 10-4). These default settings have been shown to perform well (Phillips and Dudík 2008). According to our data, we constrained our model to linear, quadratic and hinge response curves. Despite the small size of the calibration sample (Table 2), MaxEnt has been shown to be robust and perform well with small sample sizes (Wisz et al. 2008).

We measured the predictive accuracy of the models by using the area under the receiver operating characteristic curve (AUC; (Fielding and Bell 1997)). The AUC provides a single measure of model performance, independently of any particular choice of threshold. The AUC was calculated for both test data (k-fold data splitting: averaging AUC values from cross-validation analyses, sequentially removing blocks of 15% of the data used for model calibration), and for independent projection data (Araújo et al. 2005) corresponding to data from another time- period (see Temporal model validation). Despite more conservative criteria, we considered AUC values between 0.7 and 0.8 to denote a fair model, between 0.8 and 0.9 to denote a good model, and larger than 0.9 to denote excellent model performance. Significance of the AUC was assessed by confidence intervals (CI95%), testing whether model values were higher than 0.5 (which corresponds to a random distribution value). CIs were calculated by bootstrapping for each run of the model, and then their limits were averaged between the k-fold models. Bootstrapping (non-parametric resampling bootstrap) was repeated 100 times, and confidence limits were calculated through a basic non-parametric method (Davison and Hinkley 1997).

Relative contributions of environmental factors to the final models

We aimed to identify the relative contribution of the variables explaining the occurrence of different fire spread patterns. However, the correlations between variables were substantial because vegetation largely reflects both climatic and topographic conditions. The possible correlated information or the compensated effects between variables can hide pure contributions of variables, making the response curve of each single variable hard to interpret and thus its individual contribution difficult to assess. In order to avoid such misinterpretations, we aimed to assess the independent contribution of different groups of variables by variation partitioning (Borcard et al. 1992). We considered the same group of variables as in the fire behaviour triangle, but separating vegetation contributions between land- scape fuel factors and forest fuel factors. Therefore, by considering forest structure, it was possible to differentiate the effects of fuel amount with respect to the variables expressing only land-cover information. At the same time, and to make the models easier to read, we pooled topography and climate information into a single variable called 'Unmanageable', as these factors are commonly beyond human control.

To this end, we developed several models, obtaining the gain of the model of each group of variables (MaxEnt's 'Regularised Training Gain' value) as a relative percentage of the gain of the full model. Similarly to Legendre (2008), we determined what amount of the total gain was explained by each group of variables separately or via the correlation between groups: the combined gain of two groups was considered as information that could not be assigned to one group and that was shared by the two groups. Relative contributions are shown in a proportional Venn diagram built using Micallef and Rodgers (2012).

Temporal model validation

Two models were first built for each fire spread pattern with the observed data (1989–99 and 2000–12). Then, for each decade model, we built a projection to the other decade. Validation between decades was conducted in order to test whether the models could explain similar distributions and processes. Between-decade differences in AUC were assessed by CI95% comparisons, testing whether the average AUC values of one decade overlapped with the AUC values of the other decade. CIs were calculated as described in the Modelling approach section.

Finally, to assess if the models were built using the same information and thus explaining the same processes, we evaluated whether the contributions of each group of variables were similar in the two decades. We compared the contributions of each factor group (forest fuel factors, landscape fuel factors and unmanageable factors) from the two decades through CI95% comparison testing whether average contribution values of one decade overlapped with the contribution of the other decade.

RESULTS

Predictive modelling of fire spread patterns

Statistical models developed for fire spread patterns ranged from having fair to excellent predictive ability (Fig. 2). These results held both for the k-partitioning test but also for the independent projection datasets, thus suggesting very good independent model adjustments. Fitted models were all better than a random distribution (AUC > 0.5; CI95%; dark boxes, Fig. 3). Topography-driven fires from 2000 to 2012 showed the lowest predictive accuracy. All models, except for convective 2000–12 and wind-driven 1989–99, showed higher values in their projection validation than in the original calibration data.

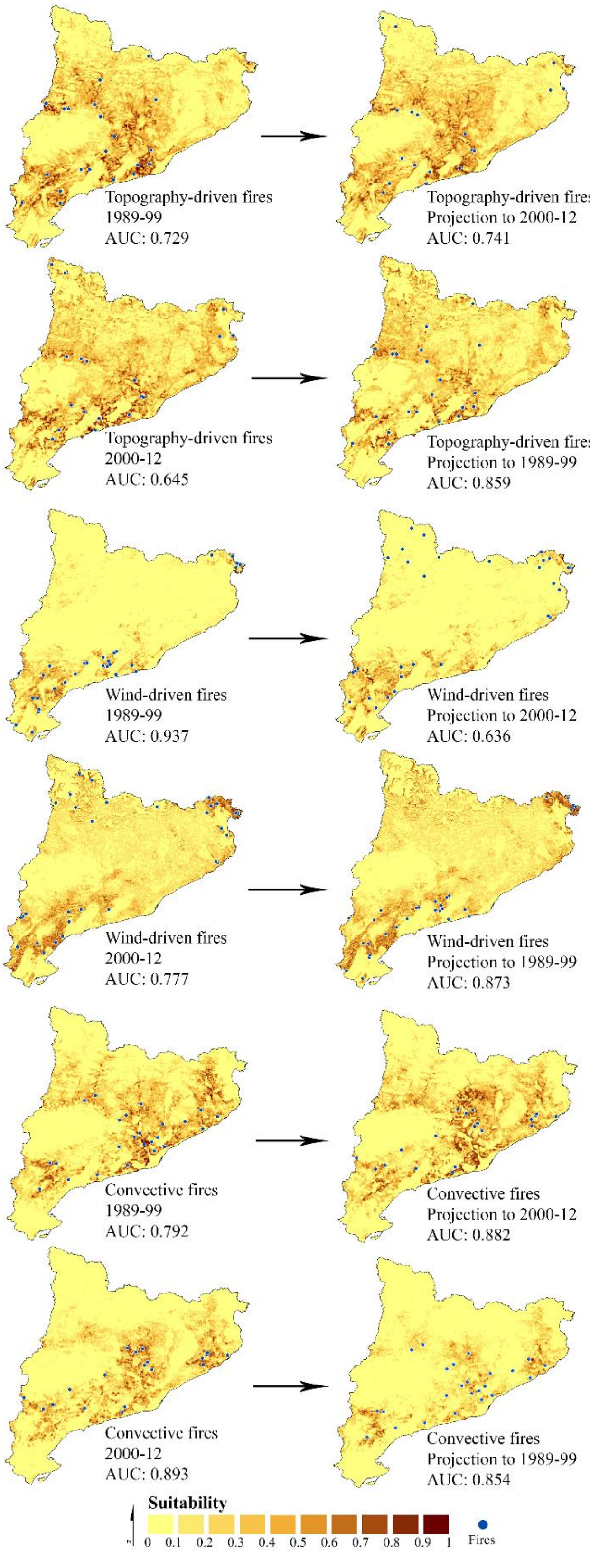


Figure 2. Predicted habitat suitability maps. The figure illustrates the predicted habitat suitability maps for the model of each decade and its projection to the other decade for each kind of fire based on AUC.

Relative contributions of environmental factors to the final models

In topography-driven fire models, the relative weight of unmanageable factors and landscape fuel factors on model predictive ability differed between decades (Fig. 4; see Appendix S2). Model results basically differed owing to the weight of the landscape fuel factor in the model, which was 11% in 1989–99 but jumped to 39% in 2000–12. In turn, unmanageable factors had a consistently lower contribution. The contribution from forest fuel factors was ~15%. Fuel variables together (landscape and forest) accounted for ~ 60–80% of the total model gain, whereas unmanageable factors explained ~20–40% of this gain.

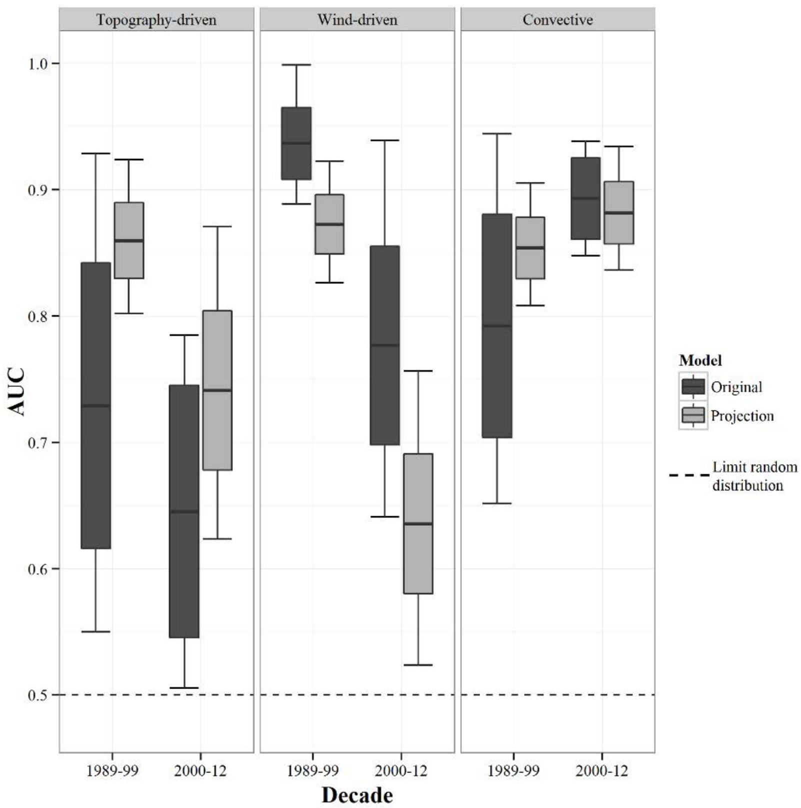


Figure 3. Comparison of the mean, standard error and 95% CI for AUC values between the two decade models. The box plot shows the statistics for the AUC values from k-partitioning tests and the projection of the other decade model to the same decade per fire spread pattern. Confidence intervals were calculated using non-parametric methods and averaged for k-model performances.

Wind-driven fires showed between-decade differences in terms of the portion of total gain shared by different factors. In 1989–99, the groups' independent contributions were low and essentially explained by unmanageable factors (22%), but in 2000–12, these contributions were higher, explaining 47% of model gain. Forest fuel factors showed low contributions in both decades (~6%). Fuel variables together (landscape and forest) accounted for ~50–70% of total model gain, whereas unmanageable factors explained ~30–50% of this gain.

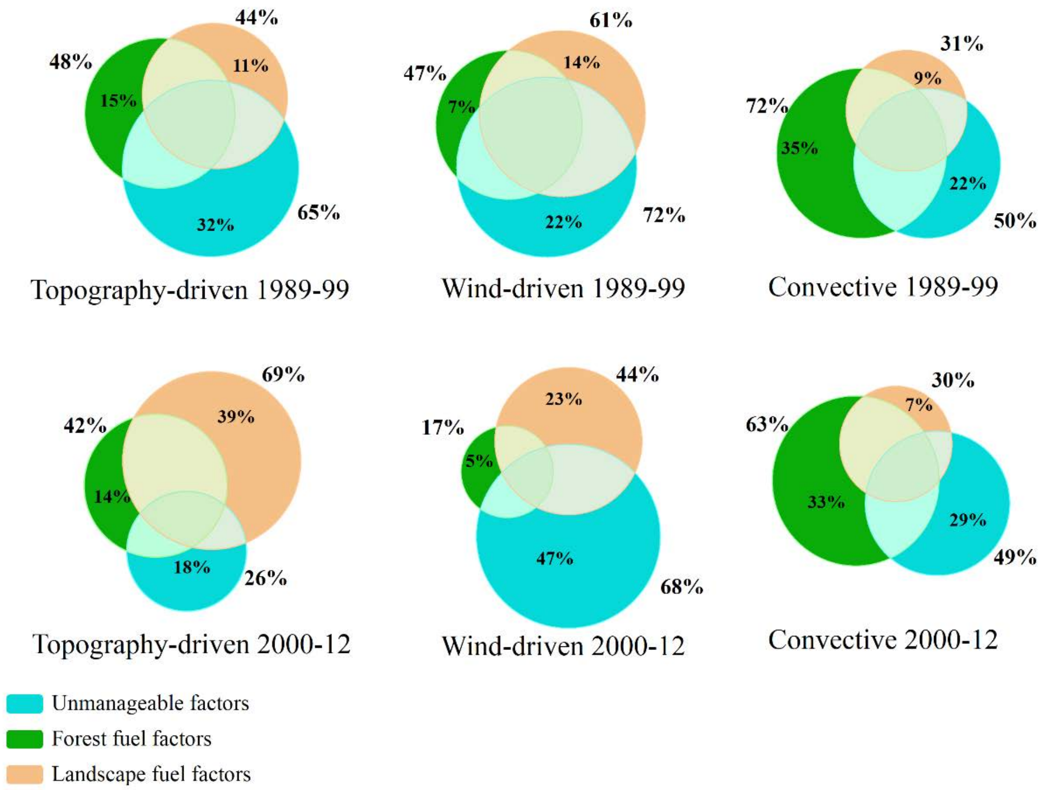


Figure 4. Partitioned contribution of each group of variables to the full model. The areas of the circles represent an approximation of the percentage of gain explained. The numbers represent the percentage of the gain of the final model explained by each group of variables. Inside the circle, the numbers show the contribution from that group exclusively. The numbers outside the circles express the contribution of that group of variables even with the information that cannot be separated from the other groups.

Convective fires showed a higher portion of gain in the model explained by forest variables alone (~35%). Unmanageable factors explained a larger fraction (22%) of the gain than landscape fuel factors (9%). Fuel-related factors together (landscape and forest) accounted for ~70–80% of the total model gain, whereas unmanageable factors explained ~20–30% of this gain.

Temporal model validation

We could not separate goodness-of-fit in any of the original models with their projection (CI95%; Fig. 3), showing that the models had similar goodness-of-fit values in the temporal validation. Results from the assessment of the relative contribution of each group of variables from the two decades (CI95%; Fig. 5) showed that in convective fires, the relative contributions of the three groups of environmental variables did not differ between decades. However, in topography-driven fires and wind-driven fires, landscape fuel factors and unmanageable factors showed different contributions in both decades whereas forest fuel factors had similar contributions. Higher consistency in model composition was therefore achieved when modelling convective fires than topography-driven or wind-driven fires.

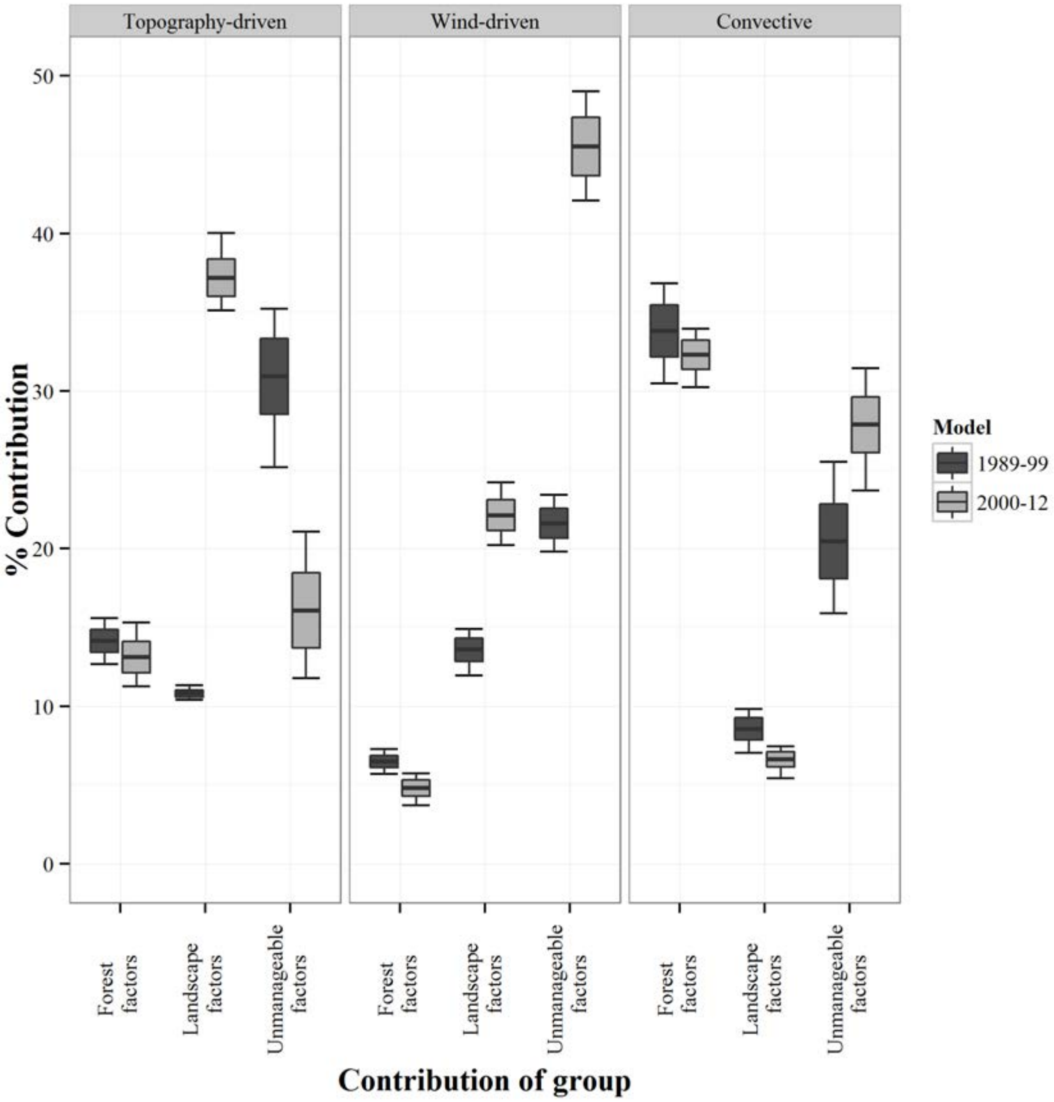


Figure 5. Mean, standard error and 95% CI for the partitioning contribution values. The statistics were calculated for each k-partitioning model in the two decades. Confidence intervals were calculated using non-parametric methods.

DISCUSSION

We have shown by applying a spatial distribution modelling approach that a combination of variables including climate, topography and vegetation can lead to an accurate prediction of the occurrence of the different fire spread patterns in Catalonia. Further, we have assessed the relative contribution of the different factors to the occurrence of each of these fire spread patterns. These assessments could eventually lead to the creation of modelling platforms allowing the prediction of future fire regime scenarios accounting for spatial heterogeneity in fire spread pattern incidence. Some studies have used fire typologies under different criteria from ours, usually using size as classification factor (Ganteaume and Jappiot 2013; Terrier et al. 2013). However, we consider that fire spread pattern classification based on the fire behaviour triangle better matches the concept of fire typologies in a fire regime context, because the classification of fire spread patterns has been shown to be related to other aspects of fire regimes such as fire severity (Lecina-Diaz et al. 2014).

Predictive modelling of fire spread patterns

Not all the models achieved a high predictive value (Fig. 2). Arguably, some key variables may be missing from our assessment (e.g. information associated with site-specific weather conditions of each fire). Nonetheless, some insights can be extracted from the results. For example, topography-driven fires were especially difficult to predict (AUC1989–99 ¼ 0.729 and AUC2000–12 ¼ 0.645), which suggests that the combination of variables used was unable to explain their occurrence as accurately as with the other two fire typologies. This is unsurprising, as topography-driven fires probably occur under a wider range of situations than the other two kinds of fire spread pattern in which general winds do not prevail or fuel availability is not high enough to allow convection cells. In ecological terms, topography-driven fires could be described as 'generalists' because they occupy a wider range of environmental conditions and are more difficult to predict than the other two more 'specialised' fire typologies (Brotons et al. 2004).

Wind-driven fires were, as expected, strongly associated with mean annual wind speed. However, it is noteworthy that the variable 'mean annual wind speed' does not represent the real weather conditions of the fires when they occurred, so ways of dealing with this fact should be improved in future research. The model for the 1989–99 data underpredicted actual fire occurrence in 2000–12, whereas the model developed using 2000–12 data was able to explain the occurrence of wind-driven fires during the 1990s. This decrease in the predictive power was mainly due to the occurrence of wind-driven fires for the first time high up in the mountain ranges (i.e. the Pyrenees) where they had not occurred in the 1989–99 decade. Indeed, the AUC value for 2000–12 data without counting Pyrenean mountain fires was similar to the original model (AUCwithout mountain fires ¼ 0.818). Novel combinations of environmental factors may have appeared in the mountain areas during the 2000–12 period that were not reported in the decade before, such as pastureland abandonment and more droughts, and thus lower moisture conditions that yielded more vegetation available to burn (Améztegui et al. 2010) and bigger fires (Dal Zennaro et al. 2005). This interpretation does not completely support our hypothesis that wind-driven fires show low dependence on vegetation variables.

Convective fires achieved high predictive scores. The landscape features most suited to producing convective fires were coniferous forests with a well-developed understorey (90–100% understorey cover and 1.5-m maximum understorey height) and 60% canopy cover. These are quite common characteristics of multilayered forest structures, where mature tree canopy cover is often not high enough to control understorey development. The variable pooling temperature and solar radiation also had weight in the model. Fuel is the most important variable determining these kinds of fires, but once a site has high vegetation loads, potential dryness can explain forest features (composition, structure, fuel availability, etc.) provoking convective fires. In addition, wind had negative effects on the occurrence of convective fires. The relationship between fire and vegetation (Bond and Keeley 2005; Pausas and Keeley 2009) explains that vegetation recovery is more difficult in high- fire-recurrence areas, with the result that vegetation resilience decreases (Díaz-Delgado et al. 2002; Pausas and Keeley 2009). Consequently, steppes and shrublands tend to be the main vegetation cover in these areas (Bond and Keeley 2005). The high-fire-recurrence areas in Catalonia (~15–30 years; (Pique et al. 2011)) correspond to the areas with higher wind rates. Consequently, the higher the wind rates, the lower the overall system capacity for fuel accumulation, which potentially reduces the likelihood of convective fires.

The increase detected in the predicted values in the projection of the models (Fig. 2) can be caused because: (1) a higher presence of a very important variable in the original model captures more variability in the projected model (convective fires 1989–99 projected to 2000–12: understorey growth in the 2000–12 decade captures fire occurrences in this decade); (2) the original model considers a wider range of processes, which include the data from the projected model (wind-driven 2000–12 with 1989–99 data); or (3) the original model presents a low predictive ability, which produces an increase of the projection prediction by chance (topography-driven fires).

Relative contributions of environmental factors to the final models

Variation partitioning analysis showed that fuel generally emerges as the main factor behind fire occurrence. Although the forest fuel factors seemed more important in convective fires, landscape fuel factors appear to dominate in wind- and topography-driven fires. As convective fires need large amounts of heat to induce convection conditions, it seems logical that forest structures affect these fires to a larger degree. The weight of the forest fuel factor decreased sharply in wind-driven fires, for two potential reasons: (1) in Catalonia, in areas highly exposed to wind-driven fires, fire recurrence is higher and thus vegetation recovery capacity decreases, resulting in a dominance of shrublands (commented on previously); and (2) the spatial variability of forest features does not affect wind-driven fires because these fires may not depend on forest structures to burn. Despite there being studies that show how forest structure can affect burn severity in wind-driven fires (Alvarez et al. 2013), other studies suggest that other aspects of fire regimes, such as fire size or fire occurrence, could perhaps be unrelated to forest structure (Wright and Agee 2004). This is consistent with the results obtained by other authors such as Moritz (2003), who reported that fire spread in extreme wind conditions is independent of shrubland vegetation age, which can be a proxy of vegetation structure and forest biomass accumulation. Odion et al. (2014) also stated the capacity of wind over 35 km h-1 to lead to crown fires, regardless of fuel structure and density, thus disassociating fire spread with vegetation structure. Further- more, even unmanageable factors showed high variability among the different kinds of fire spreads; in general, their contribution was higher in wind-driven fires than in convective fires, whereas in topography-driven fires, their role was more uncertain. Although this fact was already known and used in operational firefighting systems, this is the first time that is being quantified and differentiated within fire spread patterns.

According to the interdecade group contribution analysis (Fig. 5), the consistency shown by convective fires supports the good performance of the models in this kind of spread pattern. This is significant and at the same time predictable, as convective fires are the ones that rely most on specific kinds of fuel structure and thus are easier to model at a landscape level.

Model limitations and uncertainties

Good model performance using both calibrated and independent projection data does not prove that the models represent reality, only that they are not far wrong (Araújo et al. 2005). It is therefore vital to apply the models critically and not to overestimate their predictive ability, specially taking into account the dependent-variable sample size. The importance of meteorology, for instance, is not directly reflected in the present work. Although meteorological conditions can be directly related to vegetation availability to burn (moisture content), which most determines the occurrence and intensity of fires (Castro et al. 2003; Dennison and Moritz 2009; Flannigan et al. 2009; Parisien et al. 2011), we needed widespread information to produce both spatial and temporal projections, so we used climate spatial variability considering weather conditions, helping to under- stand fire occurrences in over long-term periods. Despite this, some structural factors did take on importance independently of meteorological variability, showing the important influence of other components of the fire behaviour triangle in the occurrence of large wildfires. In addition, climate factors have been included in the model as an unmanageable factor, but in contrast with topographic factors, they can change over time. Future studies need to differentiate climate factors from topographic factors.

Fire regimes and global change

In the Mediterranean region, convective fires have become the major challenge facing firefighters owing to their wandering behaviour, spotting ability and high intensity stemming from their spread characteristics. Convective fires are the largest and most destructive fires, and they could also be the newest ones because there is no evidence of their existence in the area before the 1990s (Castellnou et al. 2009), a product of high fuel load accumulation in the landscape in the wake of land abandonment and poor forest management. Moreover, in the current context of global change, convective fires could increase in incidence owing to land abandonment increasing and a worsening of extreme weather conditions. Wind-driven fires also pose particular difficulties for firefighters, not owing to their uncertain spread direction but owing to the speed and intensity they can achieve (Alvarez et al. 2013). Topography-driven fires are the least dangerous for firefighters, people and ecosystem resilience in this area. Their spread direction is predictable, as is their maximum intensity, normally at the top of the slopes. Arguably, this more predictable behaviour makes them easy for firefighters to stop, and they are usually not very large (Table 2).

As convective fires are associated with manageable factors, such as a highly developed understorey, convective fire occurrence can be altered through forest management. Wind-driven fires are more difficult to fight through proactive forest management as they are strongly associated with unmanageable factors. Forest planning and management should lend even more importance to fire spread patterns and, depending on their probability of occurrence, plan the most suitable actions for large-wildfire prevention. Moreover, differentiating fire spread patterns and considering the different severity and size that each kind of spread pattern can provoke open up the possibility of developing an integrated landscape management system.

The results presented here offer insights about potential approaches allowing the assessment of environmental change impacts on different types of fire spread patterns. Changes in land-use vegetation cover or changes in forest structure are just an example of the type of events that can differentially deter- mine the occurrence of different kinds of spread patterns. This emphasises the need for relative contribution assessment according to different fire spread patterns when evaluating global change effects in fire regimes, although its applicability might be limited owing to the lack of fire spread pattern information at a global scale.

ACKNOWLEDGEMENTS

This work received financial support from the BIONOVEL CGL2011– 29539 project sponsored by the Spanish Ministry of Education and Science, and from the FIREfficient project, funded by the European Commission, Directorate-general of Humanitarian Aid and Civil Protection. The authors thank the Servei de Prevenció d'Incendis de la Generalitat de Catalunya for providing data on fire perimeters and ignitions, the Catalan Firefighters' body for providing data on fire spread patterns and for their valuable comments on the manuscript, to Asier Larrañaga for the useful help provided and Assu Gil-Tena for her comments on the manuscript.

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SUPPLEMENTARY MATERIAL CHAPTER 1

APPENDIX 1: Predictors' description

This appendix details the variables introduced in the model. It includes their description, the main data sources used and the computational building process when necessary. Their hypothetical effect on the different fire spread patterns is also displayed. A resume of this appendix is presented in Table 3 from the manuscript.

The main factors identified to explain fire spread pattern occurrences were chosen according to the factors describing the fire behavior triangle (Parisien and Moritz 2009): topography, climate (as a proxy of weather) and vegetation. Factors were introduced into the model in raster format at 250 m resolution. The size was chosen due to be consistent with source data resolution, because this resolution includes enough information to understand landscape features at the scale of large fires and covers all the area under study with a small computational load.

Topographic factors:

These factors explain topographic landscape arrangements relevant to fire spread in some specific situations. Data sources are the Digital Elevation Model (DEM) of Catalonia (ICC 2011) at 30 m and 1:50 000 topographic maps.

i. Slope:
   - Description: Mean slope (in degrees) 1 km around each pixel.
   - Hypothesis: Slope can be relevant in topography-driven fires because the angle of flame with respect the terrain in the surroundings can influence fire spread (fire spreads faster uphill (Rothermel 1972)). In wind-driven

fires, the interaction of wind with terrain can influence fire spread if there is an alignment between wind direction and uphill slope (Campbell 1995).

ii. Slope Standard Deviation:

- Description: Standard deviation of slope-values within a 1 km radius around each pixel. It informs about terrain heterogeneity. The larger the standard deviation, the higher the slope divergences around each pixel.
- Building: From slope data (50 meters resolution), standard deviation is calculated within the pixels inside a 1 km radius around each pixel.
- Hypothesis: Terrain heterogeneity may influence the spread of topography-driven and wind-driven fires, since flame spread may be favored by a higher amount of uphill runs (Rothermel 1972).

iii. Ravine junction:

- Description: Number of ravine junctions around each pixel. A ravine junction is defined as the place where two or more ravines/gorges/rivers joint.
- Building: The river crossing-segment nodes were selected from the topographic map. Then, for each pixel, the sum of the number of ravine junctions within its surroundings (1 km) was conducted.
- Hypothesis: The presence of a ravine junction in the evolution of a topography-driven fire may have effects on fire spread, since it defines the possibility of fire development in new watersheds.

iv. Ridge main direction:

- Description: Percentage of area around each pixel (1 km) covered by areas lying North-South (N-S) or East-West (E-W) (producing two different variables).
- Building: This variable has been calculated as a function of the rate of N+S aspect pixels respect to E+W pixels. Higher ratio values indicate that east-west ridges dominate in the region, and lower ratio values indicate that north-south dominate in the region. An aspect map was built from DEM at 50 m (N, S, E and W aspects plus flat areas with <2º slope). After calculating the ratio N+S/E+W, east-west ridge direction were chosen if the ratio was >2 and north-south ridge direction were chosen if the ratio was <0.5. However, this ratio also includes troughs. In order to exclude them, a mask selecting only pixels at least 20 m above their surroundings

was applied. One layer per main direction was obtained (N-S or E-W), indicating whether a pixel is a ridge of that direction or not. From these layers, the percentage area covered by ridges of a specific direction around each pixel was calculated.

- Hypothesis: Wind interaction with main terrain alignment may be relevant in the evolution of a wind-driven fire. While perpendicular ridges create specific streams on the upwind face, parallel ridges can increase wind effects.

v. Elevation dominance:

- Description: This variable informs about the relative height of each pixel with respect to its surroundings.
- Building: Average height of the surroundings (1 km) of each pixel was first considered. Then this value was subtracted from height value of each pixel. Positive values indicate that the pixel is above its surroundings, and vice-versa.
- Hypothesis: This elevation position can determine topography-driven or wind-driven fire spread, since uphill runs (which theoretically are more fire prone) are more prevalent at certain relative elevation positions (when height dominance is negative).

Climate factors:

Some climatic conditions vary over the landscape and can determine certain landscape arrangements linked to moisture vegetation or wind predisposition. Source layers are Digital Climatic Atlas of Catalonia (Ninyerola *et al.* 2000) and the regional Wind Map (Gencat 2004).

i. Solar radiation and temperature:

- Description: Solar radiation and air temperature (Ninyerola *et al.* 2000) are good factors to explain vegetation dryness. These two variables were calculated together in order to have one single variable explaining dryness of each site.
- Building: These two variables were evaluated together by annual mean standardization ($z=x-\mu/\sigma$; z= standardized value, x=original value, μ=mean of the original values, σ=standard deviation of the original

values), in order to bring all of the variables into proportion with one another and thus avoid the absolute values of the original variables giving wrong weightings in the gathering process (i.e areas with high solar irradiation with high temperatures have larger values than those with low temperatures).

- Hypothesis: Fire burns faster the driest part of vegetation and, therefore, all fires can be influenced by this factor. However, convective and topography-driven fires may be more influenced by this dryness index than wind-driven fires, since the latter may be able to burn regardless of the vegetation conditions.

ii. Mean annual wind speed:

- Description: Average of the mean annual wind speed 1 km radius around each pixel.
- Building: Average of the mean annual wind obtained from the Wind Map (Gencat 2004) 1 km around each pixel. This was calculated as the mean annual wind speed 60 meters over the surface through deterministic models.
- Hypothesis: Wind-driven fires may be the most affected by this factor.

Vegetation factors:

Landscape fuel factors:

Landscape fuel factors are the variables that detail non-forest vegetation covers. Data sources were based on different land cover map versions of the region under study (Land Cover Maps of Catalonia (LCMC) (Ibañez *et al.* 2002) and the Spanish Forest Map at 1:50 000 (Vallejo Bombin 2005)).

i. Shrublands:

- Description: Percentage of shrublands area around each pixel (1 km). Two sorts of shrublands were differentiated according to their origin, since this can influence shrubland shape and composition. Shrublands in Catalonia come from regeneration of bare soil originated basically from crop abandonment or wildfires (Calvo *et al.* 2002).

- Building: Shrubland covers were intersected with fire perimeters. If shrublands were inside these perimeters, they were considered burnt shrubs, while if not, they were considered shrubs regenerated from crop abandonment.
- Hypothesis: Shrublands are a very flammable and thin fuel. Under drought conditions, their branches become extremely fire prone. Their role on different fires is uncertain, but they may affect all fires.

ii. <u>Herbaceous crops</u>:

- Description: Percentage of area around each pixel covered by herbaceous crops.
- Hypothesis: A large area of Catalonia is covered by cultivated land (31% according to the third version of the LCMC). Fire can also burn these lands, burning in a different way depending on plants' moisture, which in Catalonia is a function of irrigation. Herbaceous crops may influence wind-driven fires, and in a lesser extent topography-driven fires (usually these crops are situated on flat areas) or convective fires (not enough vegetation accumulation).

iii. <u>Irrigated crops</u>:

- Description: Percentage of area around each pixel covered by irrigated crops.
- Hypothesis: irrigated crops may not have much effect on fires due to their high moisture content, except for wind-driven fires, which may be able to burn in several vegetation conditions.

iv. <u>Grasses</u>:

- Description: Percentage of area around each pixel covered by grasses. Natural grasses (in these latitudes, they usually are alpine grasses) and pasturelands were not differentiated due to their similar characteristics in terms of fire spread.
- Hypothesis: Grasses may have influence on topography-driven and wind-driven fires, but not in convective ones, due to their low fuel load.

Forest fuel factors:

Forest structure variables were included to explain fire spread in detail. Source data were forest and cover maps built according to forest inventory timings. Based on Brotons *et al.*

(2013), different LCMC (Ibañez *et al.* 2002) were used, as well as the 2000 Spanish Forest Map (Vallejo Bombin 2005) and the National Forest Inventory (NFI2 and NFI3; Villaescusa and Díaz 1998; Villanueva 2005) with data available for Catalonia, and continuous layers of forest structure information were generated by applying kriging interpolation techniques {Formatting Citation}.

i. Forests:
   - Description: Percentage of area around each pixel covered by forests.
   - Hypothesis: The presence of forest cover around an ignition pixel may determine fire spread in all types of fires.

ii. Forest structure:
   - Description: Forest structure was identified through factors such as basal area or number of trees per hectare.
   - Building: Mean basal area and trees per hectare in forest areas around each pixel (1 km) were calculated from forests maps. To calculate these, only tally trees (with a diameter at the breast height $\geq$ 7.5 cm) were taken into account.
   - Hypothesis: The role of the variables 'mean basal area' and 'trees per hectare' on fire spread is uncertain, since it is not exactly known how these structures can affect to different kinds of fires spread patterns. For instance, while small basal areas and high rates of trees per hectare could indicate a young forest that can result in more flammable situations (thin and low branches), an old and well develop forest (high basal areas) could create high levels of heat and induce more convection.

iii. Forest composition:
   - Description: forest structure was separately assessed as conifers and broadleaf according to main species.
   - Building: Forest structure was splitted between conifers or broadleaves, in relation with the main species inside each pixel (selected in terms of basal area) according to the forest map.
   - Hypothesis: The main hypothesis is that conifer species would be more prone to fire than broadleaves (Valette 1990) in all types of fires. Nevertheless, conifer incidence may be higher in convective fires, since they need specific fuel amount available which is easier to find in conifer

forests, whereas topography-driven or wind-driven fires do not exclusively depend on forest composition.

iv. Forest vertical structure:

- Description: Forest vertical structure was described by understory features such as recovery and height.
- Building: Mean understory recovery and height (mean and maximum) in forested areas around each pixel (1 km) was calculated from forest maps.
- Hypothesis: The greater the recovery and the height, a greater probability of convective fire occurrence. Their role on topography-driven or wind-driven fires is not clear.

v. Forest canopy cover:

- Description: Horizontal coverage of forest tree canopies of forest pixels 1 km around each pixel
- Hypothesis: Canopy continuity may influence fire spread in all kinds of fires.

References – Appendix 1

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APPENDIX 2: Models' results

The present appendix shows the summary of MaxEnt's gain values from the different models used in the variation partitioning analyses. The different group of variables introduced to the model is shown in the first column. Detailed information about the variables included within each group is found in Table 3 in the manuscript.

The gain shown corresponds to the "Regularized training gain" units in the MaxEnt's output results. Here we present the average of the gain values from the cross-validation analyses (each replicate-fold represented 15% of the sample data and was used as the validation set, hence 9 repetitions per each different spread pattern from each decade were run).

Table A.1. Summary of MaxEnt's gain values from the different models used in the variation partitioning analyses

Group of variables introduced to the model	Gain					
	Decade 1989-1999			Decade 2000-2012		
	Topography-driven	Wind-driven	Convective	Topography-driven	Wind-driven	Convective
Forest fuel factors	1,023	1,102	1,023	0,479	0,228	1,039
Landscape fuel factors	0,436	1,447	0,436	0,789	0,597	0,493
Unmanageable factors	0,714	1,703	0,714	0,292	0,923	0,805
Forest and landscape fuel factors	1,109	1,844	1,109	0,919	0,715	1,163
Forest fuel and unmanageable factors	1,298	2,035	1,298	0,668	1,045	1,527
Landscape fuel and unmanageable factors	0,911	2,201	0,911	0,974	1,287	1,096
Complete model (all factors)	1,429	2,354	1,429	1,138	1,356	1,640

CHAPTER 2

Integrating fire spread patterns in fire modelling at landscape scale

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This chapter has been published in Environmental Modelling and Software (doi: 10.1016/j.envsoft.2016.10.001)

ABSTRACT

Fire spread modelling in landscape fire succession models needs to improve to handle uncertainty under global change processes and the resulting impact on forest systems. Linking fire spread patterns to synoptic-scale weather situations are a promising approach to simulating fire spread without fine-grained weather data. Here we present MedSpread—a model that evaluates the weights of five landscape factors in fire spread performance. We readjusted the factor weights for convective, topography-driven and wind-driven fires (n=123) and re-assessed each fire spread group's performance against seven other control simulations. Results show that for each of the three fire spread patterns, some landscape factors exert a higher influence on fire spread simulation than others. We also found strong evidence that separating fires by fire spread pattern improves model performances. This study shows a promising link between relevant fire weather information, fire spread and fire regime simulation under global change processes.

Keywords

Wind-driven fires; topography-driven fires; convective fires; landscape fire succession models; Mediterranean; synoptic weather situations

Highlights

- We used fire spread patterns to simulate fire spread in landscape succession models
- Modelling fire spread patterns improved simulations of fire propagation
- Factors governing fire spread differed among topographic, convective and wind fires
- Synoptic weather situations can populate fire spread modelling at large spatial scales

INTRODUCTION

Fire models are designed to reproduce essential fire regime descriptors (Sturtevant et al., 2009; Sullivan, 2009). The last ten years have seen a surge in the development of fire models (Miller and Ager, 2013) as part of a wider effort to capture the essential processes driving fire dynamics in real landscapes. Fire models reproduce specific fire regime attributes that serve to assess fire impacts on different scales of applicability. While some models focus on fuel-heat transfers at small scale, other models are able to simulate fire dynamics and patterns at regional and long-term scales. Models that spatially reproduce fire spread can be collapsed into two groups according to the scale considered and processes modeled: the fire level and the landscape level.

The first group of models working at the fire scale (Keane et al., 2004), known as Fire Growth Models (FGMs), simulate fire spread growth of single events and mainly aim to support operational decision making and assess the effectiveness of different fuel treatments on fire behavior and spread (Duff and Tolhurst, 2015; Stratton, 2004). FGMs use detailed spatial and temporal information on weather, fuel and topography affecting fire behavior and spread to reproduce the potential growth of fires (Albini, 1976; Anderson, 1983; Rothermel, 1983). *Farsite* (Finney, 2004) and *Prometheus* (Tymstra et al., 2010), for example, have been used for contrasting purposes in different countries (Salis et al., 2013; Suffling et al., 2008). However, the complexity characterizing fire as a process makes each event highly specific and context-dependent, thus introducing significant constraints on the extrapolation of model results to other contexts or fire events (Andrews and Queen, 2001; Zhou et al., 2005).

The second group of models simulate multiple fire events at the landscape scale and reproduce long-term fire regimes shaped by dynamic interactions between wildfires, vegetation and climate on wide temporal and spatial scales (e.g. Boychuk et al., 1997; Brotons et al., 2013; de Groot et al., 2003; He and Mladenoff, 1999; Keane et al., 2002; Loepfe et al., 2011; Millington et al., 2009). Known as Landscape Fire Succession Models (LFSMs), they simulate specific fire regime properties operating at landscape scale, such as fire occurrence or frequency in large areas. These models are often capable of handling a range of factors influencing forest landscape dynamics and fire regimes, such as climate or land-use management (Keane et al., 2004). However, as LFSMs answer questions that tend to target coarser spatio-temporal scales, fire spread modelling usually passes unnoticed and the underlying physics is largely simplified. Fire spread simulation within LFSMs ranges from predetermined fire shapes (Green et al., 1983) to dynamic lattice or vector spread strategies determined by probabilistic functions or empirically-based equations (Adou et al., 2010; Keane et al., 2004; Sullivan, 2009).

There is a challenge to bridge the current gap between FGMs and LFSMs (Sturtevant et al., 2009). Although the two kinds of models have been designed to achieve different goals, large-scale long-term LFSMs performance could be improved by including key processes that reproduce fire spread in a more reliable way. Improved performance over a wider range of temporal and spatial scales of final fire shapes may eventually lead to a better assessment of several aspects tied to operational suppression needs, effectiveness of vegetation treatments, effects of treatments designed to preclude runoff or post-fire regeneration patterns at these scales (Gil-Tena et al., 2016). The resulting fuel heterogeneity from a simulated fire, in turn, may influence the spatial pattern of subsequent fires (Turner and Romme, 1994; Yang et al., 2008).

Fire spread is determined by weather, topography and fuel (Keane et al., 2004; Parisien and Moritz, 2009). The specific contribution of these factors to fire propagation is still unknown, and several studies have shown that relative influence of weather, topography and fuel can vary (Gardner et al., 1999; Green et al., 1983; Mouillot et al., 2001; Turner et al., 1989). Of these factors, weather conditions present the most variability within and between fires (Rothermel 1983). The complexity of weather conditions is not easily translated into fire modelling frameworks capable of extrapolating calibration results at local scales from one fire to another (Andrews and Queen, 2001). Furthermore, model requirements to adequately and accurately reproduce fire spread are usually highly complex and reliant on data at fine temporal and spatial resolutions on weather changes during a given fire event (Hargrove et al., 2000). However, fire spread patterns do tend to be repeatable and often predictable in time and space (Duane et al., 2015). In Mediterranean ecosystems, these patterns have been described as convective fires, wind-driven fires and topography-driven fires (Castellnou et al., 2009; Duane et al., 2015). These spread patterns can be related to specific synoptic weather situations, which in turn dictate general weather conditions at a regional-landscape scale. A synoptic weather situation describes general atmospheric characteristics prevailing in a region over a temporal span of hours to days, and defines the relation between general atmospheric circulations and surface conditions (Crimmins, 2006). Synoptic weather situations may therefore be the appropriate factor-weather scale influencing coarse spatial fire patterns (Turner et al., 2001). Fire spread patterns could then be used as a better approach to reliably simulate fire spread without needing detailed weather data, which is difficult to gather over long-term periods in future climate projections without high levels of associated uncertainty.

Once under the influence of a synoptic weather situation, the specific contribution of the multiple drivers governing fire spread (slope, wind, etc.) can be different for each spread type. A fire could therefore become more affected by wind than fuel structure in a windy situation (Jin et al., 2014; Moritz, 2003), whereas vegetation flammability and structure may have a higher influence in other situations (Artès et al., 2015). Thus, under each synoptic weather situation, fire spread drivers could have different roles in determining final fire perimeters, thus offering a promising link between local fire spread patterns and fire regimes at the landscape scale.

The aim of this study was to assess the potential advantages and limitations of incorporating fire spread patterns defined by synoptic weather situations into a fire spread algorithm in a LFSM context. Here we present MedSpread, a landscape fire spread model that reproduces fire spread from the ignition point of a fire of predefined size. By fitting actual fire scars occurred in a Mediterranean area from 1989 to 2012, we attempted to assess the performance of MedSpread when including the main fire spread patterns (i.e. wind-driven, topography-driven and convective fires). First, we assessed the contribution of each driver potentially affecting fire spread for each of the different fire spread patterns and discussed their role through a sensitivity analysis. Second, we calibrated the relative contribution of each of these factors on fire spread for each of the three main fire spread patterns documented in the study area. Third, we attempted to determine the potential improvement of fire spread performance for fires only influenced by one factor alone. Finally, we discuss the incorporation of fire spread patterns into a LFSM as a way to bridge the gap between fire spread and landscape fire models by boosting fire spread model performance.

MATERIALS AND METHODS

2.1.MedSpread Model

The purpose of the MedSpread model is to examine the spatial interactions between vegetation (i.e. fuel load and forest composition), topography, and wind forces when determining fire spread. Given a set of ignition points, the model spatially simulates fire spreading from each ignition point and burns the predefined target area associated to each ignition. It can be applied to mimic the spread and burning of an observed real-life fire perimeter from its known ignition point, but it can be also used to simulate fire scars from estimated ignition points. Hence, the model simulates fire spreading from an ignition until the target area is reached (i.e. when the fire has completely burnt the total area to be burnt), and an early fire extinction only happens if all active fronts arrive at non-burnable areas (e.g. water, urban settlements or rocks/bare soil).

MedSpread is a spatially explicit raster-based model implemented on the SELES platform (Fall and Fall, 2001) and it fits within the empirical models (Sullivan, 2009). It requires two types of input data: (1) a set of ignitions characterized by spatial location with the associated required metadata; and (2) a set of raster layers representing the potential landscape drivers of fire spread. In its current version, spatial resolution is 1 ha.

MedSpread simulates fire spread based on a polynomial algorithm formulation. It relies on a single fire spread formulation including the main factors affecting spread, with a weight-parameter associated to each of these factors in order to find optimal combinations of factors that minimize the differences between simulated and observed fires by varying these weights. We chose a linear formulation in the spread algorithm in an effort to clearly understand each factor's role in determining fire spread.

In detail, the fire spread and burn procedure in MedSpread work as follows. Ignitions to be modeled are randomly selected, and they burn successively, one at a time, in sequential order. If ignition year (or time step) is indicated, it respects the temporal hierarchy when selecting ignition order. Each ignition has associated information on target burnt area, fire spread pattern and wind direction. When an ignition is activated, spread rate (*SR*) is calculated for its 8 neighbors (queen's case) following a polynomial model where explanatory factors are species flammability (*SppFlam*), fuel load (*Fuel*), aspect (*Aspect*), slope in relation to fire front (*Slope*), and wind effect in relation to dominant wind direction (*Wind*). These explanatory variables are multiplied by weight-parameters representing the relative influence of each factor on fire front progression (Eq.1).

(Eq.1) $$SR = wW \cdot Wind + wS \cdot Slope + wA \cdot Aspect + wF \cdot Fuel + wSpp \cdot SppFlam$$

where *wW*, *wS*, *wA*, *wF*, and *wSpp* are the weight-parameters of the corresponding five explanatory variables set out above.

The order in which these evaluated cells will spread and burn depends on the speed at which the fire is spread from the source cell to them. *SpeedTime* is the fire speed variable and is a function of the *SR* of the evaluated cells. First, the *SR* value is multiplied by an acceleration value *Acc* which, similarly to FARSITE (Finney, 2004), determines the strength of the driving factors in accelerating fronts (Eq.2). *SpeedTime* for each neighboring cell is then calculated as a negative exponential of the accelerated *SR* (Eq.3, Figure A.2-A). The SELES platform gives priority to negative values of time, where the values closest to 0 are the first to be evaluated. In addition, *SpeedTime* is multiplied by a random value that will eventually provide some stochasticity to the fire spread process (Eq.3). The model allows assigning flexible stochasticity power via the *StochasticSpread* parameter: when *StochasticSpread* =1, the spread process is deterministic. The evaluated cells are thus entered into a priority queue according to their *SpeedTime* value in ascending order in absolute terms (i.e. cells with lower values are placed at the front of the queue). The first cell in the queue is activated and then its neighbors are evaluated by calculating *SR* and *SpeedTime* for all its burnable neighbors. These neighbors are added to the queue according to their *SpeedTime* value calculated from the activated cell, but updated with a *t* value (*SpeedTime* + *t*). The *t* value accounts for the current effective computing time, namely the time at which each source cell is being processed (i.e. *SpeedTime* value of the processed cell). As a new activated cell likely shares unburnt neighbors with its predecessor cell, fire may spread to cells already evaluated from another cell. All the evaluated cells will either way be added to the priority queue according to their currently calculated *SpeedTime* and respecting the time-ascending order of the queue. However, a cell will only be activated from the fire front that has reached that cell fastest, discarding other burning attempts.

(Eq.2) $$SRA = SR \cdot Acc$$

(Eq.3) $$SpeedTime = -e^{-SRA} * U(StochasticSpread, 1)$$

After selecting the activated cell, it is time to decide if it has to burn. The probability of burning (*pBurn*) is a function of the *SR* (Eq.4) and dictates whether a cell burns or not, proxying fire intensity. Cells will effectively burn if *pBurn* is greater than a selected value from a uniform random distribution (Eq.5). The *rPb* parameter allows to modulate fire intensity, namely the relation between fire spread and probability of burning (Figure A.2-B). If the activated cell in the queue does not burn, it mimics an unburnt patch inside the perimeter, and the total burnt area is not increased. Put simply, even if a cell does not burn, fire is allowed to spread to neighboring cells. The model design was conceived to always burn the ignition cell. Once the burning process is completed, the cell is removed from the head of the queue and the next cell in the queue gets activated, so fire spread is attempted from that new source cell to its neighbors. See *Supplementary Material A* for a detailed schematic sequence of fire spreading as implemented in the MedSpread model.

(Eq.4) $$pBurn = \left(1 - e^{-(SR)}\right)^{rPb}$$

(Eq.5) $$Burn : \begin{cases} if\ \left(pBurn \geq U(0,1)\right) \rightarrow YES \\ if\ \left(pBurn < U(0,1)\right) \rightarrow NO \end{cases}$$

2.1.1. Use of the model

MedSpread is a widely applicable model and it can be used to simulate any kind of fire spread pattern. The user is able to decide the types of fire to be simulated, if there are any. As MedSpread is designed to examine the role of spreading factors in determining fire spread of different fire spread patterns, the latter have to be defined before the simulation.

The input variables the user must provide to the model are the following:

- An ignition database including: ignition identification, target burnt area, fire spread pattern, wind direction and year if applicable
- An ignitions' layer containing fire initiation pixels with the ignition identification code
- A Forest Map layer containing main land uses and forest tree species
- A Digital Elevation Model
- An Aspect layer
- A Fuel Map layer indicating the amount of fuel in each burnable pixel
- The burnt area of actual fires' layers of each year if applied.

In order to initialize the spatial factors describing landscape characteristics in Eq.1, analysts should consult literature for the region where it is applied (see *2.3. Model initialization* for an example in a Mediterranean region). Any values assigned to the factors have to be constrained between 0 and 1.

Since MedSpread is an empirical model based on the relative effect of factors on the fire spread of actual fires, weights of the factors in the polynomial formulation are to be calibrated (*wW*, *wS*, *wA*, *wF*, and *wSpp*). Each weight-parameter can range from 0 to 1, and all the weights must sum to 1 to explain 100% of relative factors effects.

The model, based on the SELES platform, employs three kinds of files: the model (.sel), the events description (.lse), and the scenario parameters (.scn). The user must specify in the scenario parameters the list of changing parameters to be tested. Each scenario-launch examines one set of parameters and it can simulate several runs. As a function of the level of stochasticity, the user wants to provide to the spread function, several repetitions of the parameters set should be run (see Figure B.6). The outputs can be analyzed out of the system to calibrate the parameters according to the performance of the model.

2.2. Study area and fire spread pattern classification

We used MedSpread to reproduce actual fires recorded in a real Mediterranean landscape. The study is focused on fires that occurred in Catalonia, a 32,107 km² region in the NE of the Iberian Peninsula. Climate is mainly Mediterranean, with hot dry summers, rainy springs and autumns, and cold and dry winters. Relief in Catalonia is highly heterogeneous: altitude ranges from 0 to 3143 m a.m.s.l. with an average of 637 m a.m.s.l.; slope ranges from 0 to 72º in a 50 m map resolution with a mean slope of 12º. According to the 2005 Land Cover Map of Catalonia (Ibañez et al., 2002), 60% of the area is covered by shrubland and forests, 36.7% of which is forest, mainly evergreen (60% coniferous; Gracia et al., 2000). Dominant tree species are pines (*Pinus halepensis*, *Pinus nigra*, *Pinus sylvestris, Pinus uncinata* and *Pinus pinea*) and oaks (*Quercus ilex* and *Quercus suber*). Forest understory is highly heterogeneous and usually rich in helio-xerophytic species, similar to Mediterranean shrublands. Mean annual burnt area over the period 1942–2002 was 8000 ha/year, corresponding to 0.75% of the Catalan wildland area (González-Olabarria and Pukkala, 2007). Since the 1980s, most of the burned area

(68%) was caused by fires larger than 500 ha (2% of fires), and most of the fires (67%) occurred in the summer season (June–September (Piñol et al., 1998)).

From the analysis of the main weather synoptic situations affecting large wildfire occurrence in Catalonia (Montserrat-Aguadé, 1998) and their interaction with landscape features, three synoptic weather situations have been distinguished (*North*, *Regular*, and *South*) leading to three main fire spread patterns (wind-driven, topography-driven and convective fires (Castellnou et al., 2009; Duane et al., 2015; Rothermel, 1991)) (Figure 1). The association of fire spread patterns to these synoptic weather situations is based on the main weather attributes at ground-level that arise from each synoptic weather situation and the fire behavior actually recorded. In wind-driven fires, spread is dominated by strong atmospheric wind. Strong atmospheric wind situations occur in Catalonia in different synoptic situations, but often when there is a high-pressure area situated over the Iberian Peninsula and a low pressure area situated in the Mediterranean, provoking forceful northern winds; this is the *North* synoptic situation (Montserrat-Aguadé, 1998). Topography-driven fires are less dependent on strong atmospheric attributes and instead related to unspecific hazardous synoptic weather situations (Castellnou et al., 2009; Duane et al., 2015). These situations are resumed in a *Regular* high-pressure synoptic weather situation in a summer day in the Mediterranean ("barometric swamp"; Clavero and Raso, 1980). Convective fires are fires that are spread by massive spotting and dominated by airstreams created through convection caused by the fire, as a consequence of high vegetation loads (Rothermel, 1991). Vegetation availability is the result of high temperatures and low moisture conditions. In this region, these conditions are usually associated with Saharan air mass intrusions, defining *South* synoptic situations.

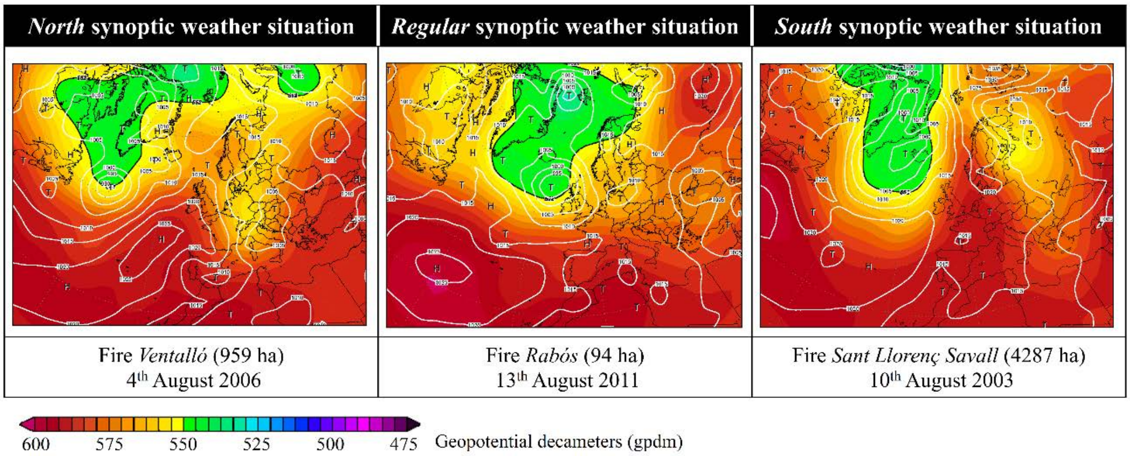

Figure 1. Synoptic weather maps for the three main fire situations in Catalonia. Representation of the three main fire weather situations identified in Catalonia (NE of Iberian Peninsula) in a map of a reference fire day. The map shows the geopotential height of 500hPa and the ground pressure. The figure charting the synoptic weather situation was extracted from *www.wetterzentrale.de*.

2.3 Model initialization

The MedSpread model was run for a period of 24 years simulating several fire events. We gathered all fires greater than 50 ha recorded during this period and which were previously classified according to each spread pattern (Table 1; see *Supplementary Material B* for further details). A total of 41 fires per fire spread type were simulated, which is the minimum number of fires in the spread groups. To include possible bias on fire simulation related to total burnt area, we randomly selected the 41-fire sample by fire size classes inside each fire spread pattern, setting a proportional number of fires per 5 size-classes.

Table 1. Number of fires >50 ha per spread pattern used in the analysis

Synoptic Weather Situation	Fire spread pattern	Number of fires classified and >50 ha occurred in the period 1989-2012	Final number of fires per fire size class used for the simulations (41 per group)	
			Size class (ha)	Nº Fires
North	Wind-driven fires	71	0-150	13
			150-300	9
			300-500	7
			500-1000	4
			>1000	8
Regular	Topography-driven fires	41	0-150	16
			150-300	15
			300-500	7
			500-1000	3
			>1000	0
South	Convective fires	51	0-150	12
			150-300	8
			300-500	7
			500-1000	4
			>1000	10

We assigned the values ranging from 0 to 1 to the five landscape factors in the *SR* parametric formula (Eq.1) on the basis of bibliographic research or model pre-calibration. Details on the data sources used can be found in *Supplementary Material B*.

1. The effect of wind direction on fire spread was calculated by the difference angle between wind direction and front direction, with front direction calculated as the angle between the evaluated cell and the source cell. Angles between wind and fire front are linearly scaled to [0,1], with 180º being the maximum difference.
2. Steeper and upload slopes are known to have a driving effect on fire spread (Butler et al., 2007; Campbell, 1995). The slope between the active cell and its neighboring cells was calculated as a % and values were truncated between -50% and +50% (Butler et al., 2007). Values out of this range were saturated to the corresponding extreme (minimum or maximum). The [-50%, 50%] rank was linearly transformed to [0,1].
3. Values for aspect variable were assigned based on Campbell, (1995), as follows:
   - 0.1 when the spreading cell is facing North
   - 0.9 when it is facing South

- 0.3 when it is facing East
- 0.4 when is facing West

4. Fuel load source variable was depicted by wood volume in m^3/ha for all forest and shrubland pixels. The normalization of volume values to [0,1] was parameterized through a quadratic relationship considering that medium-volume forests allow light to pass through the canopies, leading to multilayer forest structures and thus producing the highest fire intensity and spread rates (Kitzberger et al., 2012; Taylor et al., 2014).
5. Species flammability factor values describe the relative flammability and combustibility of tree species and burnable land covers (including shrublands, grasslands and agricultural land). To assign species flammability values, we conducted several simulations and selected the values that reproduced the best percentage match between observed and simulated fires for each fire group (See *2.3.2. Experimental design* for further details on model evaluation).

The parameters in Eq.2, Eq.3 and Eq.4 were also adjusted:

- The acceleration value (*Acc* in Eq.2) was set to 10 after testing a wide range of values. Fire shape results above this value were too variable, whereas fire shape results below this value showed no meaningful change.
- After simulating a single fire with several *StochasticSpread* values in the whole range [0,1], the parameter was adjusted to 0.75, which bore low variability in the outputs (Figure B.6). We did not provided large power to stochasticity to avoid that the variability in the outputs deny adequate estimation of model parameters.
- The *rPb* parameter modulating fire intensity (Eq.4) was calibrated by choosing the value that led to a percentage of unburnt islands inside the fire perimeter of about 9% of final fire size, as found to be the case in Catalonia by Díaz-Delgado et al., (2004). This value corresponded to 0.05.

2.4. Analyses

The experimental design was conceived to find an optimal weight-parameters combination in the spread formulation (Eq.1) for each of the three fire spread patterns present in Catalonia by reducing differences among simulated and observed fires, and to help discuss potential improvements with respect to other control simulations. We evaluated model performance by analyzing final fire shape, which is an appropriate method for capturing fire spread processes behind burnt areas (Green et al., 1983). We compared the fire scar characteristics of simulated and observed fires by the shifting of weight-parameters in Eq. 1.

2.4.1. Model evaluation

One possible way to evaluate the performance of the spatially-explicit fire spread model is to assess areal match-up between simulated and observed fires (Kelso et al., 2015). However, we wanted to include other attributes capturing processes that may not be directly reflected in the percentage of match area (Hargrove et al., 2000). We included two other attributes: *Distance to ignition* as the distance between ignition point and furthest perimeter point, and *Direction to ignition* as the angle direction formed by this point and the ignition. We aimed to capture the deviation between simulated and observed scars, and express it as a percentage of deviation. For the descriptive attribute *Distance to ignition*, we applied the methodology described by Adou et al., 2010, based on percent relative difference (RD%) between predicted and observed values. This measure is calculated as the ratio of the absolute difference between observed (O) and simulated (S) values divided by the half sum of these values, times 100: $RD\%=200\times|O-S|/(O+S)$. *Direction to ignition* expressed the difference angle formed by the main direction vectors of the simulated and the observed fires. This attribute already indicates a percentage of deviation, as it is 0º for same-direction vectors and 180º for opposite-direction vectors. The difference angles were normalized to 180: $RD\%=100\times|\alpha S-\alpha O|/180$. As percentage match-up area represents agreement (unlike the other two attributes), we used the attribute *Unmatched area* = 100 - percentage of match area as percentage of deviation when assessing spatial disagreement.

2.4.2. Sensitivity analysis

To assess the effect of each spread factor in Eq.1 on final fire perimeter attributes and quantify the model's sensitivity to weight-parameter variability, we ran different weight-parameter combinations by progressively increasing the weight of one factor from 0 to 1. The other four factors held the remaining weight until 1 distributed equally. In our experiments, the resolution of changing parameters went up to decimals of the main increasing factor. Since the other parameters held the remaining weight until 1, the maximum ratio between parameters was of 36 (0.9 main factor and 0.025 the rest). This was considered to be enough to understand the roles of the different factors in our experiments, although other users could decide to increase this ratio up to the value desired. Three replicas per weight-parameter combination were run, and results were averaged per fire to assimilate stochasticity. Given the low variability in the stochastic assessment (Figure B.6), three replicas were enough to achieve comparable results.

2.4.3. Calibration and validation of weight-parameters for fire spread patterns

Model calibration according to its performance is not solved by a direct method; each model has its procedure according to its purpose, structure, available data and use (Bennett et al., 2013). In the present work, a mix of the three evaluated attributes could generate confusing results as the attributes do not work to the same units and they could weight differently in the final overall assessment. Hence, the best factor weight-parameter combination was chosen on the basis of the *Unmatched area* attribute, which informs about the model error. We selected the model that minimize model errors as a whole, by assessing the mean error per group of fires (Bennett et al., 2013). The calibration cannot be directly done by adjusting regression techniques since the attribute evaluated for model performance is not observed, but is the result of the spatial combination of observed and simulated fires.

The best weight-parameter combination for each fire spread pattern was defined as the combination that most minimized the error of the model. A k-fold cross-validation procedure was performed beforehand to generate model predictions with available data. From the 41 fires of each fire spread pattern, we used 85% to calibrate the models and the remaining 15% to validate results. The cross-validation singled out the best weight-parameter combination for each fire spread pattern and highlighted the performance of each training-model applied in the validation sample. Like for the sensitivity analysis, three runs per weight-parameter combination were performed and averaged to assimilate stochasticity.

2.4.4. Comparison with control experiments

The results of the weight-parameter calibration process were compared to control experiments in which only one of the five landscape factors was considered (with its weight in Eq.1 equal to 1) plus an experiment simulating round fires, which consisted in a null hypothesis of fire spread without factors inducing heterogeneity in fire speed. Comparison was done while assessing the overlapping of confidence intervals (95%) for the mean. Although optimized weight-parameter combination for each kind of fire spread pattern was chosen according to the *Unmatched area* attribute, we also evaluated the other two attributes *Distance to ignition* and *Direction to ignition* in order to better compare simulated and observed fires in terms of overall model outcomes.

2.4.5. Comparison with an all-fires-together calibration

We also assessed potential improvement on overall fire spread simulation in an experiment where fire spread pattern was omitted and all fires were calibrated together. The all-fires-together optimal weight-parameter combination was first adjusted using the same methodology as described above but with the total pool of fires (n=123, i.e. 41 for each of the three fire spread types). We applied the same cross-validation sample as in the separate group-by-group assessment. Significant differences between assessments of separated groups and the all-fires-together simulation were examined through confidence intervals (CI 95%) that were calculated with the average of the k-fold calibration sample results.

RESULTS

3.1.Sensitivity analysis

Differences between simulated and observed fires took distinct patterns on the three attributes analyzed. *Direction to ignition* and *Distance to ignition* involved around 20–40% of differences whereas *Unmatched area* involved around 50–75%. Although conceptually similar, these values did not represent the same divergences, which means fire spread performances can only be compared within the same attributes.

Wind-driven fires were mostly affected by the wind factor (Figure 2, first row). Wind affected *Unmatched area* and *Distance to ignition* but a large wind-weight lent too much length to final fire perimeter shape, and optimum performance was reached at intermediate values (i.e. around 0.5). In the *Direction to ignition* assessment, wind effect was the factor that most minimized differences between observed and simulated fires, but increasing wind weight did not bring an improvement on fire direction. This was logical, since wind weight affected fire spread in its elongation but it did not change fire spread direction.

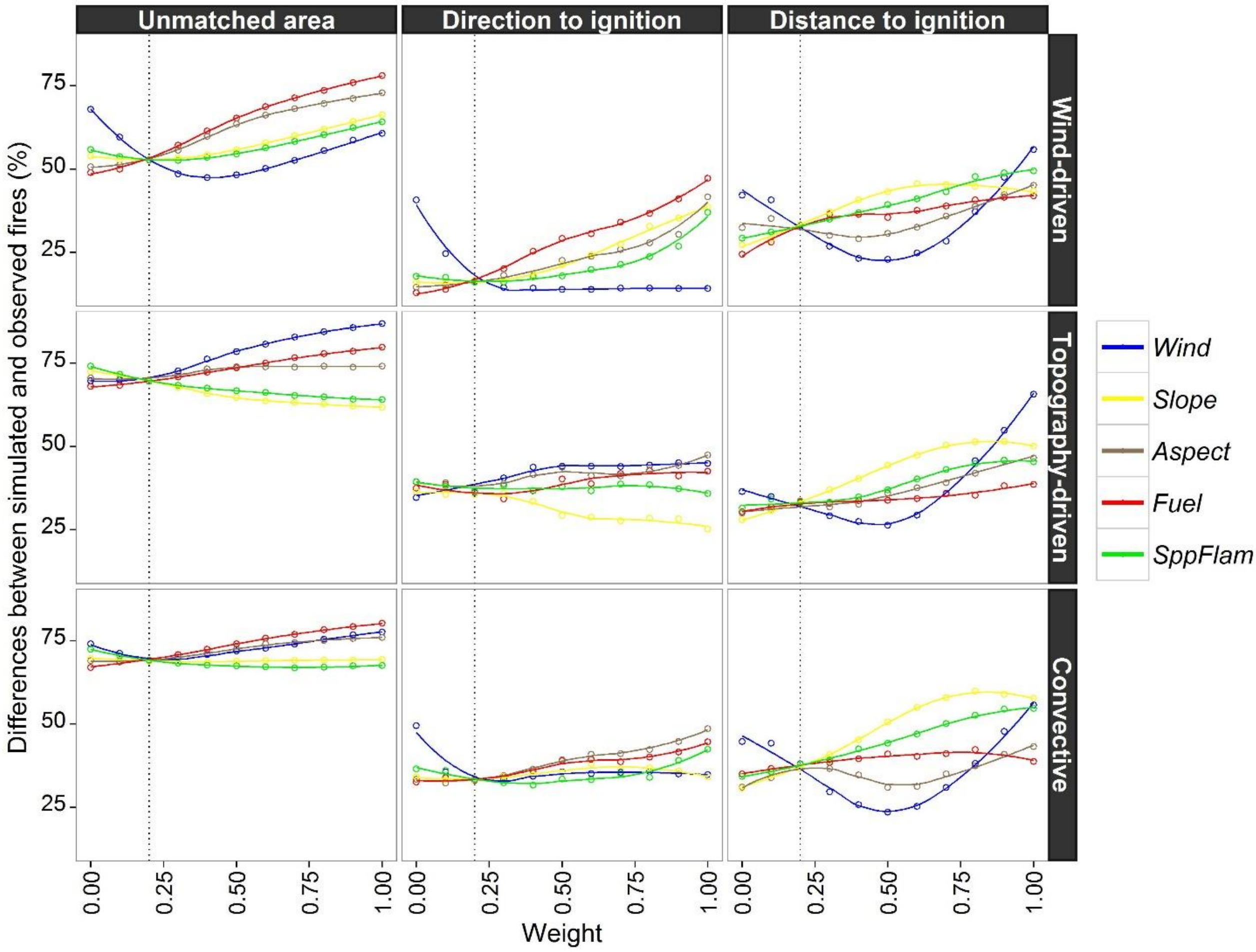

Figure 2. Sensitivity analysis results. Changes in the differences between simulated and observed fires in each of the evaluated perimeter attributes (columns) in each fire spread pattern (rows) along a range of weight values for each factor [0,1]. Color lines show the changes when only the weight of such driver increased, and the rest of the factors held the remaining weight (until 1) distributed equally. The dotted vertical line shows an equal weight combination among all factors (0.2).

For topography-driven fires, increasing slope weight steadily decreased the differences between simulated and observed fires in the *Unmatched area* assessment (Figure 2, second row). Increasing species flammability weight also reduced these differences. Increasing slope weight also tended to decrease simulated-vs-observed differences in the *Direction to ignition* attribute, whereas the other factors did not show divergent effects. Unexpectedly, increasing slope weight had a negative influence on ability to capture

Distance to ignition trends. Mean weight of the wind factor was the combination that gave the lowest differences with observed fires in this attribute.

Unmatched area in convective fires performed best in experiments increasing species flammability weight and to a lesser extent in experiments increasing slope weight (Figure 2, third row). *Direction to ignition* proved tough to simulate as none of the factors managed to reduce the differences among observed and simulated fires. Like the other fire spread patterns, *Distance to ignition* was mostly affected by wind, which is the factor that adds the most length to fire perimeter shape.

3.2. Optimal final weight-parameter combination

The optimal weight-parameter combination minimizing differences between simulated and observed fires included wind, slope and species flammability as the main drivers (Figure 3). Fuel load did not show incidence in any kind of fire, and aspect only affected wind-driven fires. Specifically, wind-driven fires were affected by *Wind* (0.425), *Slope* (0.325), *SppFlam* (0.212), and *Aspect* (0.038). Topography-driven fires optimization included *Slope* (0.525), *SppFlam* (0.387) and *Wind* (0.088) and convective fires held *SppFlam* (0.475), *Slope* (0.375), and *Wind* (0.15). Results on the coincident area showed that the calibration with specific combinations for each fire spread pattern turned out to around 50-60% of non-matching area (Table 2). Validation results attained slightly larger mean percentages of unmatched area than in the calibration, and the standard errors were also larger.

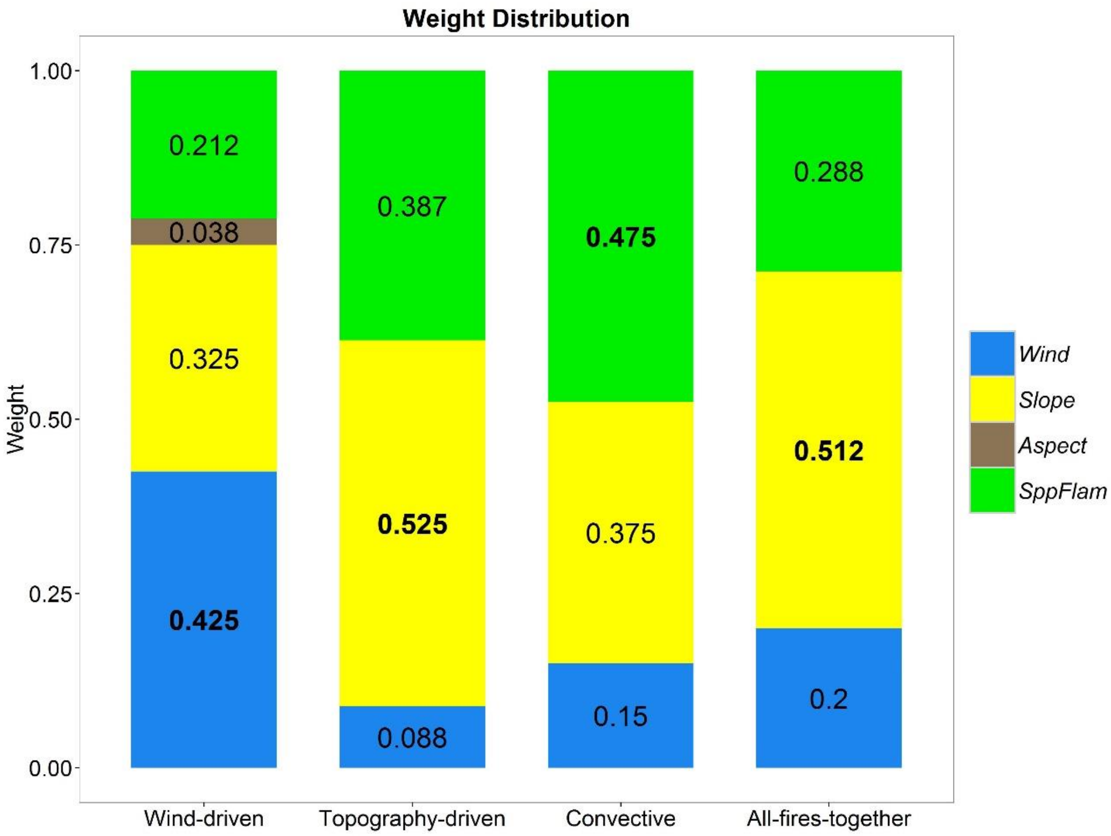

Figure 3. Optimized weight-parameters distribution. Weight-parameters of the factors in the calibration process for each fire spread pattern and for the all-fires-together optimization. The factor with the highest weight for each fire spread pattern is marked in bold.

Table 2. Results on the *Unmatched area* and the standard error for the test sample and the validation sample, in the separated calibration and in the all-fires-together calibration.

		Unmatched area (%)	
		Test (mean ± SE)	Validation (mean ± SE)
Separated-calibration	Wind-driven	45.51 ± 2.73	49.53 ± 8.01
	Topography-driven	59.77 ± 3.21	61.03 ± 7.86
	Convective	63.75 ± 2.86	65.72 ± 8.13
	Together (mean of the three groups)	56.34 ± 1.86	58.76 ± 4.791
All-fires-together calibration	Wind-driven – from all-fires-together	49.94 ± 3.17	49.86 ± 7.93
	Topography-driven – from all-fires-together	62.63 ± 3.48	63.07 ± 8.78
	Convective – from all-fires-together	64.35 ± 2.74	64.26 ± 7.52
	Together	58.97 ± 1.90	59.06 ± 5.06

3.3. Comparison with control experiments and with all-fires-together calibration

We compared the results from weight-parameter optimization with experiments where only one of the drivers was considered, with control round fires and with an experiment where all fires were calibrated together (Figure 4), in the latter case the optimized combination of weight-parameters was applied (*Slope* (0.513), *SppFlam* (0.288) and Wind (0.2); Figure 3). Details on simulations timings can be found in *Supplementary Material A*.

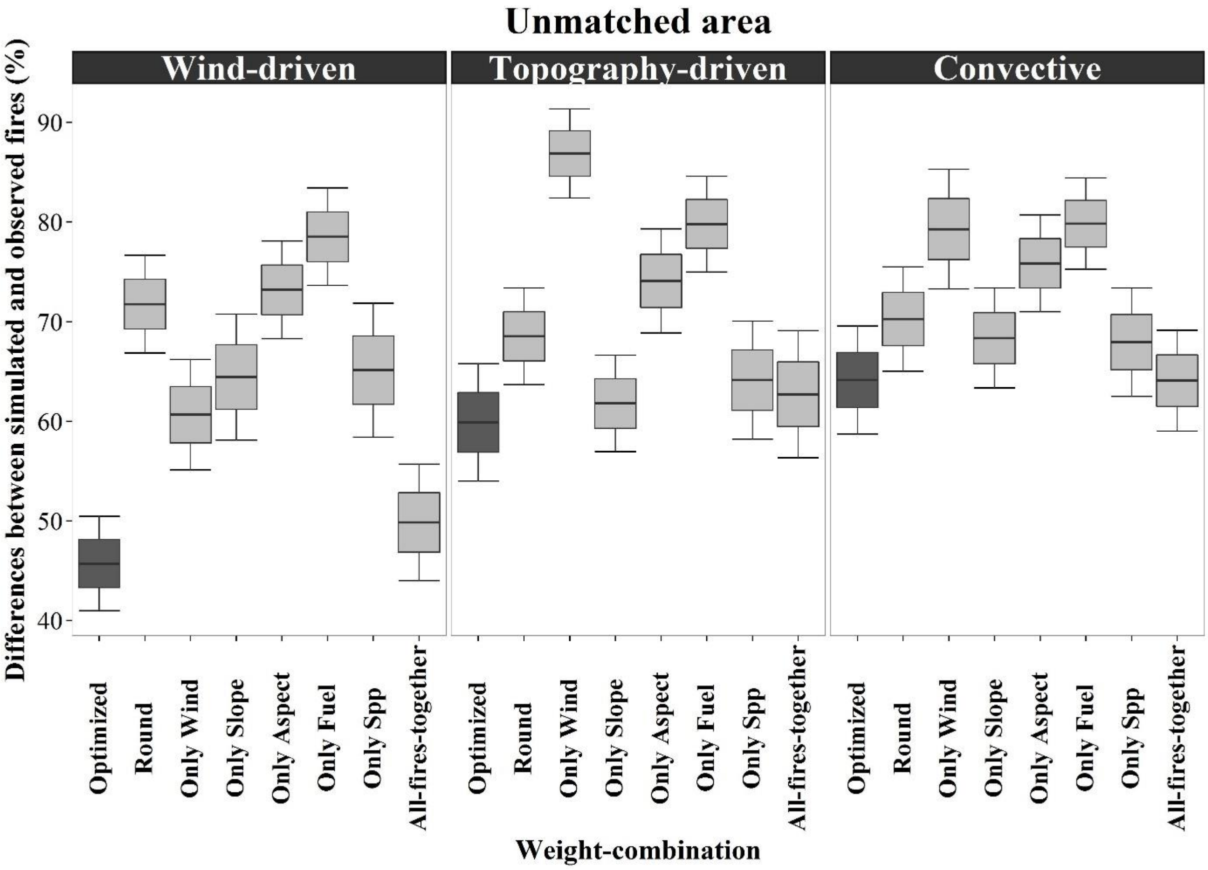

Figure 4. Differences between simulated and observed fires for the 8 experiments. Results per fire spread pattern on the *Unmatched area* attribute for the optimized combination of weight-parameters (in dark gray) and the comparison with the 7 control experiments (light gray). The central black line represents the mean of the values, lower and upper hinges indicate the standard error of the mean and the lower and upper whiskers indicate the limits on the confidence intervals (95%) of the mean (n=41).

From the evaluation of CI overlap, it follows that optimum combination for wind-driven fires was significantly different to round fires and fires propagated by only one driver in the *Unmatched area* assessment (Figures 4 and 5). However, assessment of *Direction to igniti*on indicated that the optimum combination shared the same performance as the experiment propagated only by wind (Figure C.1). *Distance to ignition* showed a meaningful improvement of optimized combination compared with round fires (see Figure C.2) and fires propagated only by wind, aspect or species flammability. Fires propagated only by wind performed substantially worse than the optimized combination, since they overestimated fire perimeter length (Figure 5), whereas fires propagated only by slope or aspect did not show significant differences to optimized fires.

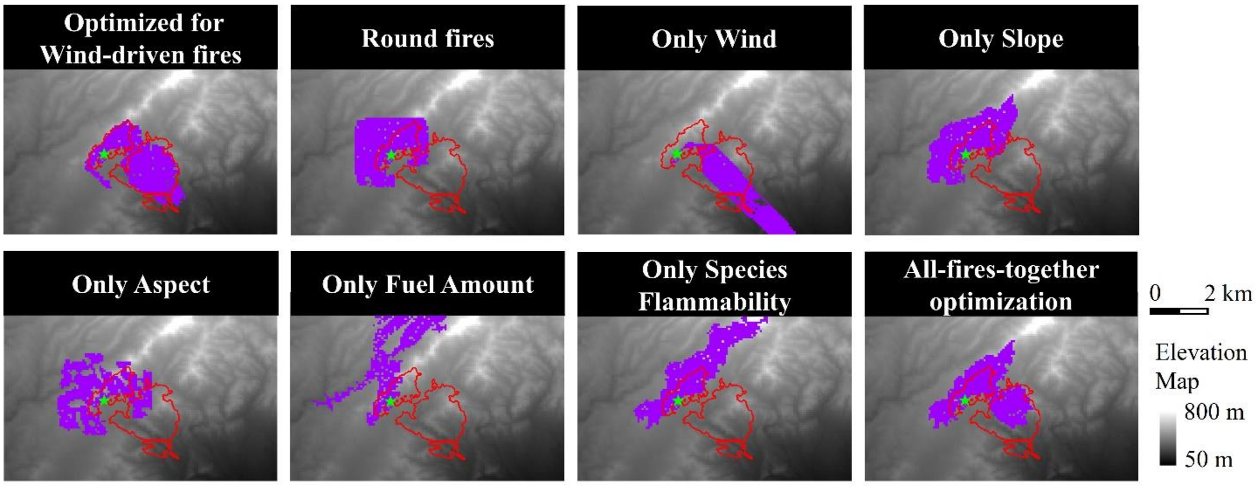

Figure 5. Wind-driven fire example. Simulation of a wind-driven fire example: *El Montmell* Fire, which burnt 834 ha on 04/17/1992 (see detailed information in Figure C.3). The figure shows the simulation results of the optimized weight-parameters combination for wind-driven fires, and of the other 7 control experiments. Ignition point is marked as a green star, the observed fire scar is within the red perimeter and the simulated fire is in violet.

While the optimized combination for topography-driven fires showed broad differences with fires propagated only by wind, it gave substantially similar results to fires propagated only by slope or by species flammability, which were consequently prominent factors in topographic-fire propagation (Figures 4 and 6). Topography-driven fires were not significantly different to round fires in the match-up area assessment. The *Direction to ignition* attribute presented significantly better results in the optimized combination than in round fires and fires propagated only by wind or by aspect (Figure C.1). In this attribute, fires propagated only by slope had even better performances than the optimized combination. Optimal combination for topography-driven fires performed significantly better in the *Distance to ignition* assessment than round fires and fires propagated by wind, but not in other control simulations (Figure C.2).

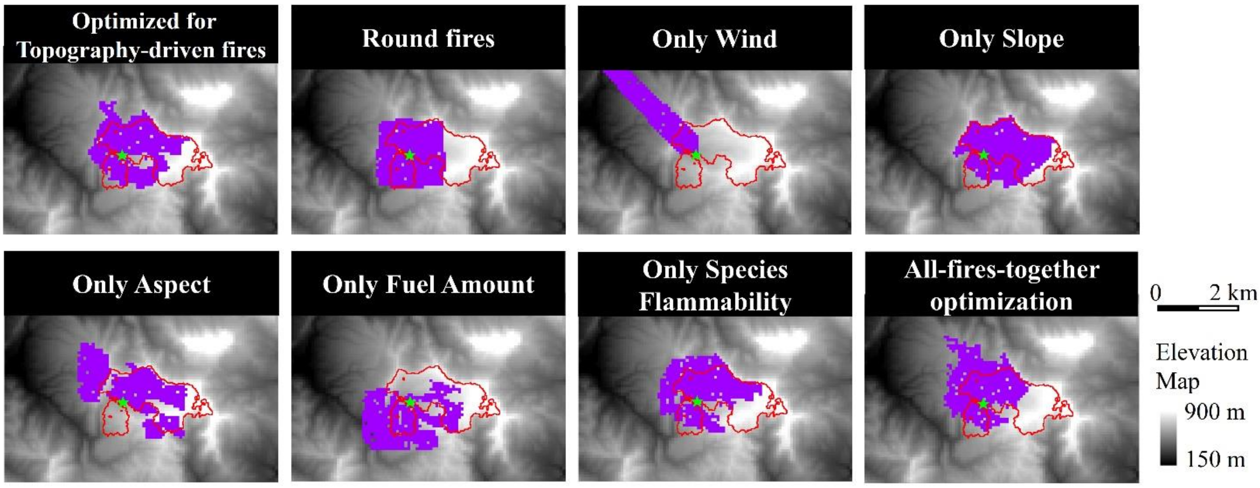

Figure 6. Topography-driven fire example. Simulation of a topography-driven fire example: *Tivissa* Fire, which burnt 549 ha on 07/23/1991 (more information in Figure C.4). The figure shows the simulation results of the optimized weight-parameters combination for topography-driven fires, and of the other 7 control experiments. Ignition point is marked as a green star, the observed fire scar is within the red perimeter and the simulated fire is in violet.

Optimized convective fires showed the smallest differences with round fires compared to wind-driven or topography-driven fires (Figures 4 and 7). The larger differences of the optimized combination in terms of *Unmatched area* were with fires only affected by wind, aspect or fuel loads. This result for fuel load was unexpected, since convective fires are usually associated with high fuel vegetation loads. Convective fires were similar to fires propagated only by slope or species flammability. In the *Direction to ignition* assessment, the optimized combination was not significantly different to any other control experiment, making it difficult to adjust direction of convective fires (Figure C.1). Nevertheless, in the *Distance to ignition* assessment, optimal combination for convective fire showed differences with round fires and fires propagated only by wind, slope or species flammability (Figure C.2).

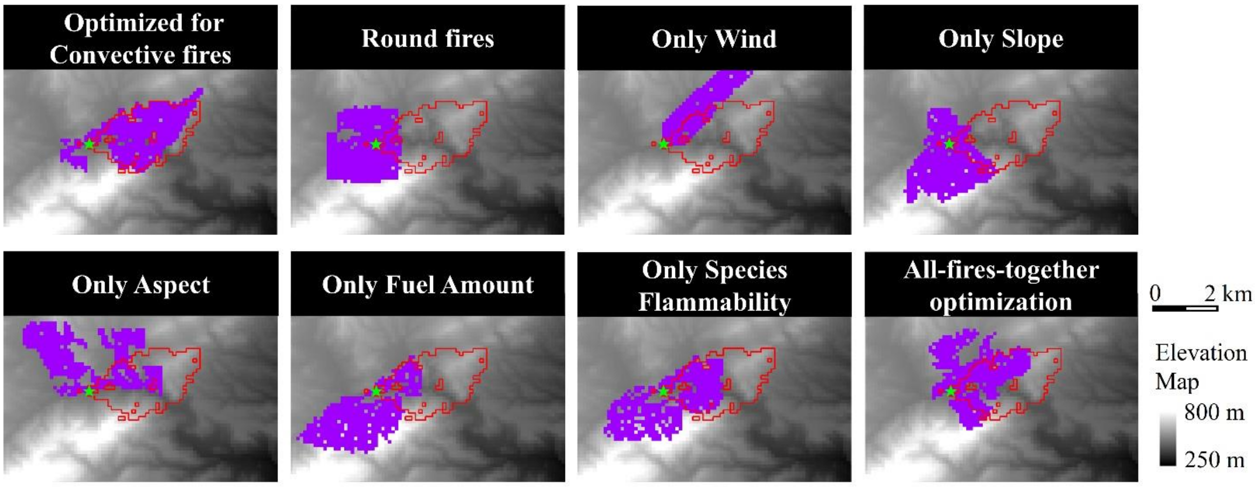

Figure 7. Convective fire example. Simulation of a convective fire example: *Mediona* Fire, which burnt 234 ha on 08/10/1994 (more information in Figure C.5). The figure shows the simulation results of the optimized weight-parameters combination for convective fires, and of the other 7 control experiments. Ignition point is marked as a green star, the observed fire scar is within the red perimeter and the simulated fire is in violet.

We compared *Unmatched area* between the separated evaluation and the all-fires-together results. Mean simulation performance was increased, but the improvement was not significant due to the high variability in the simulation results (Separated= 56.58 (95%CI: 53.01, 60.15), All-fires-together= 58.88 (95%CI: 55.18, 62.58)). In order to test potential increase of this performance, we selected a group of fires that effectively indicated an increase of model performance in comparison to the all-fires-together combination. A set of 24 fires per fire group presented significant results in the comparison test (Separated= 54.70 (95%CI: 50.65 - 58.75), All-fires-together= 63.00 (95%CI: 59.12, 66.89); the *t value* for 23 degrees of freedom was used to calculate confidence intervals in this set of fires). The general patterns of fires discarded were further evaluated and discussed to better understand the simulation results.

DISCUSSION

4.1. Predicting fire spread patterns

Our results show that distinct combinations of the factors driving fire spread differentially influenced propagation in wind-driven, topography-driven and convective fires in Catalonia. Fire spread patterns showed differences in model outcomes compared with control experiments, indicating that the separation of fires according to synoptic weather situations can improve fire modelling in LFSM.

The results of the optimized weight-parameter combinations highlight the need to account for the aggregate sum of multi-driver influences when modelling fire spread. In wind-driven fires, wind direction and topography can interact to determine fire spread and final perimeters in wind-driven fires (Figure 3). Although the wind factor has a higher weight, slope is also influential. When wind pushes fire in one direction, the interaction with local topography can determine spread at the landscape scale. Other variables related to orographic disposition, such as the relative position of ridges with wind direction (parallel or perpendicular ridges), may also influence fire propagation (Sharples et al., 2010) and should be considered in future analysis. The fact that slope is the factor that most affected fire direction in topography-driven fires may appear intuitive but is also a notable result, because topography-driven fires are the fire pattern most difficult to model at landscape scale. This is due to the lack of strong weather drivers in their occurrence data (Duane et al., 2015). Slope can affect fire spread rate by increasing fire speed through convection and thermal radiation (Butler et al., 2007), especially as local winds moving uphill as a result of diurnal hillside heating-cooling directly affect the propagation of these fires. Convective fires showed a higher dependency on the wind factor than was expected from the fire literature. Convective fires spread by high-vegetation loads and tend to modify the surrounding air conditions, advancing by massive spotting independently of topography or prevailing wind (Rothermel, 1991). From our results, we can infer that wind may be contributing by pushing the convective plume and thus determining fire spread. Fuel load had little influence in convective fire spread, whereas species flammability had the strongest influence. The species flammability factor may include other proxies of vegetation conditions. Moisture changes in fine-scale vegetation characteristics may affect vegetation landscape factors, which cannot be captured in this model due to data limitations at these scales. Lack of data on moisture conditions may be one of the main reasons for misleading direction model outcomes in convective fires. However, the convective fire process is particularly complex as it creates a positive feedback from fire-created weather in which the heat of the fire modifies local winds and humidity, enabling the fire process to change vegetation conditions during the same fire event, exponentially generating more heat and explosively spreading fire activity (Allen, 2007). The complexity associated with convective fires remains difficult to predict.

Comparison of optimal weight combinations with fires propagated only by one driver yielded meaningful insights. Each optimized fire spread pattern showed resemblances with different drivers alone in the three attributes analyzed, indicating the prevalence of these drivers in determining fire spread characteristics. Round fires mimicked fires propagated without a detailed spread algorithm. Wind-driven fires showed more difference with round fires than topography-driven and convective fires (Figure 4). This could signal both worst adjustment of these fires and/or higher similarity with round fires. Therefore, the need for very detailed fire propagation algorithms is different among the three spread patterns, with wind-driven fires needing more accurate fire shape simulations. Analyses including topographic fires and convective fires together given the similarity on the sensitivity analyses in the *Unmatched area* attribute and *Distance to ignition* performances (Figure 2) were discarded (results not shown). This did not improve the final performance and represented a precision lost when exploring the factors affecting fire spread in the different fires. Moreover, we did not find a priori significant differences between the outputs of fire spread patterns optimization with an all-fires-together calibration. It proved difficult to meet the modelling challenge without any more detailed information other than landscape factors rescaled at 1 ha spatial resolution. We expected to get significantly better performances when fitting each fire spread pattern rather than all-fires-together, but performances only tended to improve (non-significantly). Nevertheless, after discarding a set of 17 fires per spread pattern, differences between the optimization per fire spread pattern and the all-fires together calibration became significant. Qualitative analysis of the rejected fires revealed that discarded wind-driven fires were mostly present in highly complex reliefs where wind interacted strongly with local terrain (Sharples et al., 2010). It is likely that this poses problems for fire spread modelling. In fact, Forthofer et al., 2014 obtained errors up to 150% in wind speed and direction in lee slopes, unlike up slopes, where the errors were within the 30%. Even they used a detailed wind simulation procedure in time, space and attributes, they determined that simulations in steeper, more rugged terrain would be expected to give less accurate results. The discarded topography-driven fires roughly equated to those happening under the worst weather situations, i.e. dry fuel moisture conditions, and where burnt species were less flammable than usual. The discarded convective fires were predominantly very large fires (e.g. thousands of hectares) and fires burning agroforestry mosaics. The optimized convective combination here burns few crops, whereas the actual fires managed to burn a lot of crops as they were able to jump and burnt adjacent forest patches integrating crops inside the burnt perimeter (Allen, 2007). These results indicate that spotting should also be incorporated in the spread algorithm (Adou et al., 2010). It is worthy to note that although 1 ha spatial resolution may seem a coarse scale for the performance of fire spread simulation, we considered a correct resolution in terms of the main factors introduced into the model (species, slope, aspect, etc.). An increase of the spatial resolution could be related to an increase of detailed information of input factors, which is not the case in this work.

The spread model presented here uses some of the most common factors used to simulate fire spread in LFSMs (He and Mladenoff, 1999; Millington et al., 2009). However, the lack of weight of the fuel factor in all groups, and of the aspect factor in all groups but wind-driven fires, underscores the need to think through their parameterization. As stated earlier, the species flammability factor may also capture aspect-induced conditions and/or fuel characteristics of the type of forests (fuel biomass, structure, etc.). Nevertheless, spread at the landscape scale can be determined by the interaction of topography and wind, and less so by fuel load (Keeley and Fotheringham, 2001). Further research is needed to identify the influence of fire synoptic present and past conditions on different fuel structures leading to fuel availability (Sturtevant et al., 2009). In the current version of the model, vegetation factors are not affected by weather conditions, which may partly explain the unexpected small influence of fuel in spread propagation. Furthermore, a number assumptions had to be made to gather continuous fuel load data for all the study area. Even measured data comes with some degree of uncertainty, and spatial generalizations add more uncertainty. For example, shrubland fuel load at these scales cannot be characterized with few starting data, and this means that making assumptions is necessary. In Mediterranean fire ecosystems, a deep characterization of shrubland load is indispensable, and supplementary information (e.g. LIDAR data, remote sensing etc.) is useful in order to reliably assess fire behavior at large scale. The results of the present study also serve to point out main data limitations related to fire simulation. There is still a high degree of uncertainty inherent to the input data, which can affect fire simulation performance even in the more detailed fire growth models (Cencerrado et al., 2014).

4.2. Bridging the gap between local and landscape fire models

There is a debate over the usefulness of very detailed fire perimeter shapes when assessing future fire regimes (Keane et al., 2002), but for different questions on fire dynamics, a suitable fire perimeter simulation at long-term scales has the scope to answer many other questions. There is increasing focus on separating the factors affecting different kinds of fire as a way to better understand the processes behind fire. A recent study by Jin et al. (2014) highlighted the need for a separated assessment when evaluating the factors affecting fire occurrence and size in a comparison of two types of fires in California: fires occurring in the fall season and mostly affected by *Santa Ana* winds, and summer fires occurring under more steady weather situations. They showed how distinct factors differentially affected the occurrence and size of these two kinds of fires. Other studies such as Hély et al., (2001) also demonstrated how vegetation and weather have different roles in fire behavior in a boreal forest depending on season in which fires occurred. Similarly, Eastaugh and Hasenauer, 2014 assessed the seasonal variation in forest fire risk in Alpine areas. They proved that while an index based on the volume and ignitability of highly flammable surface litter is a more precise indicator of overall fire risk in winter, soil moisture index is a superior indicator of extreme summer fire risk conditions, suggesting that long-term drought conditions become the key driver of the risk in these days. Separating out the different kinds of fires may be the most useful approach to help understand the processes behind fire dynamics, and could be a potent tool for predicting future fire regimes, which is the big challenge for research and management as it moves towards evidence-based decision-making processes (Sturtevant et al., 2009). In this sense, the linkage between synoptic weather situations and observed fire spread patterns may help understand the weather drivers provoking fire spread over the landscape. Many studies already show non-linear relations between climate and fire (Cardil et al., 2015; Loepfe et al., 2012; Pausas and Fernández-Muñoz, 2011), and some of them point to relations with these synoptic weather situations as key to interpreting and predicting fire events (Crimmins, 2006; Montserrat-Aguadé, 1998). In extreme fire weather episodes, fires usually follow extreme patterns not well reflected in commonly-used fire spread algorithms. In extreme heat waves, convective fires spread through fire storms that create their own (Allen, 2007; Duane et al., 2015; Peters et al., 2004; Sturtevant et al., 2009) and are usually difficult to model with standard fire spread algorithms (Viegas, 2006). The classification presented in the present paper goes a step further by integrating the spread of convective fires, which is notoriously difficult to simulate at landscape scale (Sturtevant et al., 2009; Viegas, 2006), and developing a simple way to simulate extreme convective fire behavior. The modelling exercise presented in this paper does not necessarily simulate the spread of fire accurately, but it provides insights into the landscape factors governing fire spread in an extreme fire weather situation. Although the model is not underpinned by mechanistic processes, based on physical relations of spotting capacity or parameters of a changing environment, our approach does make it possible to capture, at a broad scale, the main drivers affecting this extreme behavior and incorporate them into future predictive landscape projections.

4.3. Insights for future research

Fire suppression can prove decisive in affecting final perimeter shape in highly anthropogenic landscapes (Duff and Tolhurst, 2015; Loepfe et al., 2011) but was not assessed here. Although we recognize the importance of fire suppression (Brotons et al. 2013), in this study we considered fire suppression as negligible for several reasons. First, the fires we chose to model are large fires (>50 ha) which are less influenced by fire suppression than small fires because they escape initial attack control and are able to overpower suppression capacity (Cui and Perera, 2008). Second, the modelling of a large number of fires (more than 40 per fire spread pattern) for a long time period with different policies behind fire suppression (Brotons et al., 2013) poses added difficulties to calibrate the exact role of suppression effort on fire spread. Third, the presence of wildland–urban interfaces near the fire can modify firefighters' suppression strategies, since they have to prioritize the protection of people and assets and may let fire burn under a more uncertain scenario (Loepfe et al., 2011). Finally, all these reasons mixed with the lack of consistent data needed yielded to avoid using firefighting as an input in the model. Future approaches should thus consider more detailed data on this field to better understand more fine spatial fire arrangements.

The differences in total burnt area among simulated fires might also influence the results of match-up area between simulated and observed fires. Size diversity can influence simulation performance, as small fires may outperform large fires as smaller fires have a higher probability of having occurred in more constant, predictable conditions. In very large wildfires (> 10,000 ha), there may be more than one synoptic weather situation affecting the fire, which would mean overlapping fire spread patterns during the fire event. In Catalonia, fires do not often burn for longer than two days, in contrast with other Mediterranean-climate regions such as Australia or California. The applicability of similar approaches as the one presented here in other areas should therefore acknowledge regional synoptic conditions and their relation with fire regimes.

CONCLUSIONS

Disaggregating fire spread algorithms into different fire spread patterns can help reproduce fire spread at landscape scales. This can be done by using synoptic weather situations to factor the incidence of weightings on fire propagation. Our results demonstrate that distinct combinations of the factors behind spread differentially influenced propagation in wind-driven, topography-driven and convective fires in the northeastern Iberian Peninsula. The classification of fire spread patterns according to synoptic weather situations has benefits for future modelling of fire regimes and the subsequent post-fire process understanding. We introduce the potential of incorporating weather forecasts into climate change scenarios in a landscape fire succession model, not only by accounting for changes in average precipitation or temperature, but also by incorporating the frequency of adverse fire weather synoptic conditions, which may be more influential determinants of fire spread and size (Crimmins, 2006) at these scales. The next step will be to adjust these synoptic weather situations to fire frequency, severity and size.

ACKNOWLEDGEMENTS

This study was funded by the Spanish Government through the FORESTCAST (CGL2014-59742-C2-2-R), NEWFORESTS (EU’s 7th programme, PIRSES-GA-2013-612645) and the ERA-NET FORESTERRA project INFORMED (29183). Andrea Duane was funded by the *Ministerio de Educación, Cultura y Deporte* (Spain) (FPU13/00108), Núria Aquilué by Natural Sciences and Engineering Research Council of Canada (Forest Complexity Modelling Fellow), and Assu Gil-Tena by the *Ministerio de Economía y Competitividad* (Spain) (Juan de la Cierva Fellow, JCI-2012-12089). We thank the Firefighting Services of Catalonia for data supply and the long discussions about fire spread, and to the *Servei de Prevenció d'Incendis de la Generalitat de Catalunya* for providing fire ignitions data. The EGIF fire database was provided by the *Área de Defensa contra Incendios Forestales* (MAGRAMA; Spain). Meteorological data was gathered from *Agencia Estatal de Meteorología* (AEMET, Spain). We thank Miquel De Cáceres for its unconditional support and for guiding us in some hard points of the process.

Author contributions:

A.D., N.A and L.B conceived the research; A.D. and N.A. coded the model; A.D, N.A. and A.GT prepared model initialization; A.D. analyzed data; A.D. led the writing of the paper, and N.A, L.B. and A.GT contributed to this part.

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SUPPLEMENTARY MATERIAL CHAPTER 2

SUPPLEMENTARY MATERIAL A: Details on the MedSpread Model

1. Details on the spread algorithm.

The fire spread algorithm in MedSpread is based on queues of evaluated cells which burn sequentially according to their landscape characteristics in relation to fire front. Further than explained in the manuscript, here we detail a sequential example of the algorithm. First, the main parameters are described:

- Spread rate (*SR*) is calculated for the 8 neighbors of all activated cells following a polynomial model where explanatory factors are: species flammability (SppFlam), fuel load (Fuel), aspect (Aspect), slope in relation to fire front (Slope), and wind effect in relation to dominant wind direction (Wind). The explanatory variables are multiplied by weight-parameters representing the relative influence of each factor on fire front progression.
- The order in which these evaluated cells will burn and spread depends on the speed at which the fire is spread from source cell to them. *SpeedTime* is the fire

speed variable and is a function of the *SR* of the evaluated cells. *SpeedTime* for each neighboring cell is calculated as a negative exponential of the accelerated *SR* (*SR*Acc* factor).

- The probability of burning (*pBurn*) is a function of the *SR* and dictates whether or not a cell burns, as a proxy for fire intensity. Cells will effectively burn if *pBurn* is greater than a random selected value from a uniform distribution variable.

Below is a sequential step list given as an example of the first three fire spread cells in the fictitious grid represented in Figure 1:

1. Ignition cell [3,2] is activated and becomes the head of the cell queue (t0 = 0).

2. All 8 of its neighbors are evaluated: assessment of Spread Rate *(SR)*, *SpeedTime* and probability of burning *(pBurn)*. Cells are added to the queue, sorted by their *Speed Time* in ascending order.

3. Ignition cell [3,2] burns (by definition of fire ignition), after which it gets removed from the head of the queue (it has been processed).

4. The next cell in the head of the queue is activated, i.e. the cell with the lowest *Speed Time*: [3,3]. Effective computing time (t) increases the *Speed Time* of the cell [3,3] (t1 = t0 + 0,0064).

5. The 7 neighbors of [3,3] are evaluated. A cell that has already been processed is not a potential neighbor for spread, so the cell [3,2] does not have to be evaluated. These cells are added to the queue according to their *Speed Time* value, but updated with the effective computing time: *Speed Time* + t1.

6. Cell [3,3] burns or not depending on *pBurn* (it will effectively burn if *pBurn* is greater than a random selected value from a uniform distribution [0,1]), after which it gets removed from the head of the queue.

7. The next cell at the head of the queue is activated, i.e. the cell with the lowest updated *Speed Time*: [3,4]. The effective computing time (t) increases the *Speed Time* of the cell [3,4] (t2 = t1 + 0,0043). Its source cell was [3,3].

8. The 7 neighbors of [3,4] are evaluated. Cell [3,3] does not have to be evaluated. These cells are added to the queue according to their *Speed Time* value, but updated with the effective computing time: *Speed Time* + t2.

9. Cell [3,4] burns or not depending on *pBurn* (it will effectively burn if *pBurn* is greater than a random selected value from a uniform distribution [0,1]), after which it gets removed from the head of the queue.

10. Not marked in the graph, the next cell at the head of the queue would be [2,3] with *Speed Time* calculated from [3,2].

11. Re-iterate…

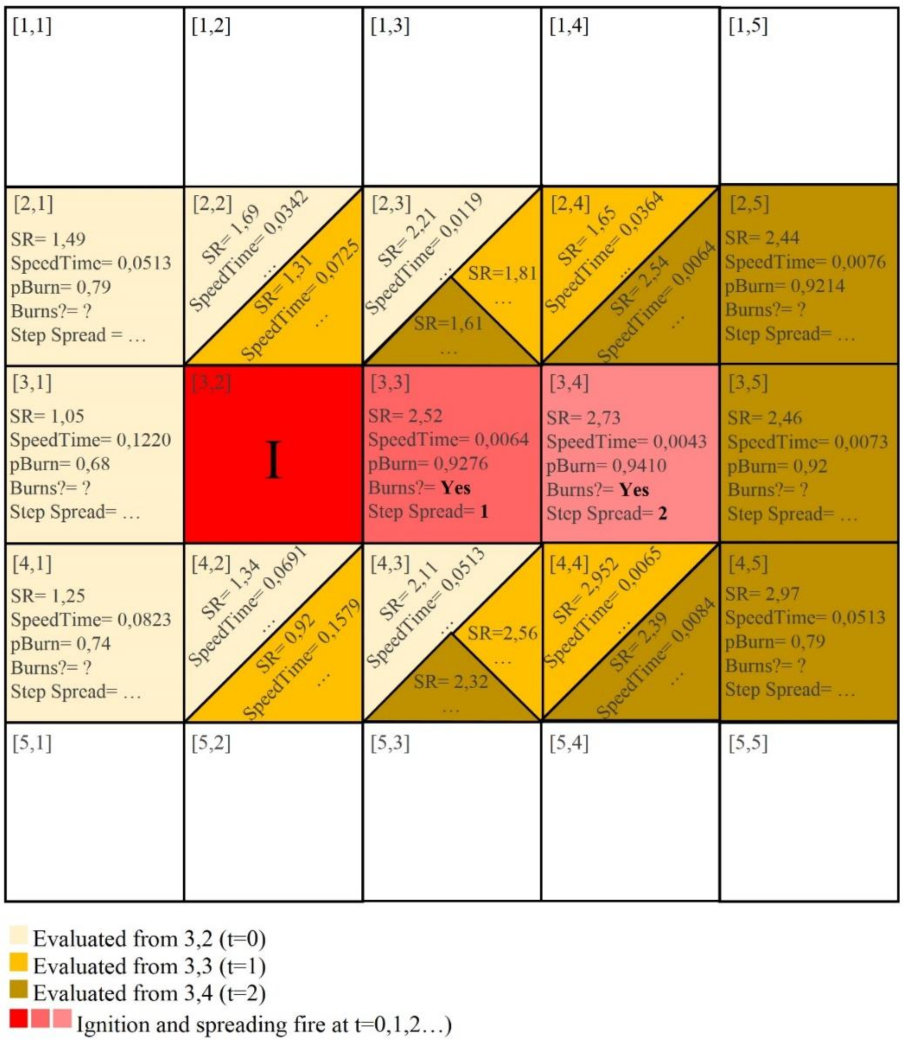

Figure A.1. Spread algorithm sequence example. Representation of MedSpread spread algorithm steps from an ignition point in a fictitious grid.

2. Details on shape of the spread functions.

SpeedTime in the spread algorithm is calculated as a negative exponential of the accelerated spread rate (SR) (Figure 2A). The probability of burning (pBurn) is a function of the SR and dictates whether or not a cell burns. Cells will effectively burn if pBurn is greater than a selected value from a uniform random variable. The parameter rPb serves to modulate the relation between spread rate and the pBurn (Figure 2B).

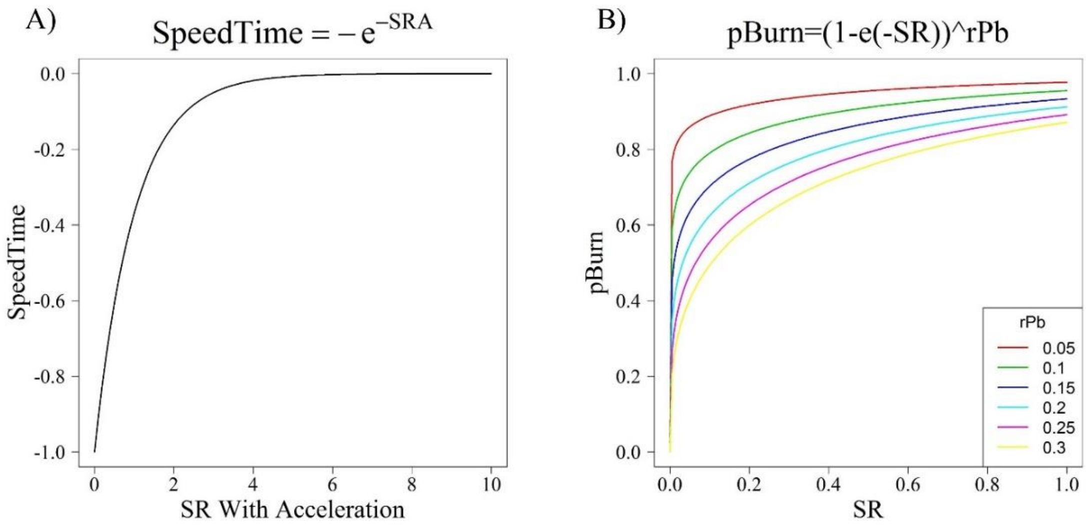

Figure A.2. MedSpread Functions. A) Relation between spread rate with acceleration (*SRA*) and *SpeedTime (*for an acceleration (*Acc*) value of 10*)*. *SpeedTime* dictates the order in which the evaluated cells burn, giving priority to negative values (smaller in absolute terms). B) Effect of *rPb* variation on the probability of burning (*pBurn*) in the range of spread rate (*SR*) values.

3. Computational load

The MedSpread model was based on the SELES environment (Fall and Fall, 2001). Time demand to run one simulation of all 123 fires of the study without generating spatial data was about 3 minutes. Runs lasted about 15 minutes per experiment when generating annual spatial data (up to 9 thematic layers (*BurntPatch*, *MatchArea*, *SpreadRate*, *ProbBurn*, *WindRate*, *SlopeRate*, *SppRate*, *AspectRate* and *FuelRate*) per 24 years, since each year all fires supposed to happen that year were simulated, and up to 3 runs for each experiment, i.e. 648 layers). These timings are based on a Windows 8 system with an Intel Xeon X5450 3 GHz CPU and 4 GB of RAM.

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SUPPLEMENTARY MATERIAL B: Details on model initialization

1. Fire data sources for model initialization

Fire ignition locations for the period 1989–2012 were obtained from the Catalan Fire Prevention Service. Ignitions located in non-burnable cells due to pixel size or generalization processes were manually relocated to the closest burnable pixel. If more than one ignition provoked the same final perimeter, we assigned the whole perimeter to the first ignition, assuming the possible under-fitting with the actual final fire perimeter shapes.

Wildfire perimeters for the same period were compiled from the Catalan Fire Prevention Service and the Cartographic Institute of Catalonia (ICC) who obtained fire boundaries from field analysis and from Landsat image analysis in large fires (ICC, 2014). We rasterized the polygon-shape perimeters to adapt the area to current simulation characteristics (100 m-size pixel in MedSpread). Finally, we cut the areas burnt outside Catalan administrative limits (3 fires: Nonasp 1994, La Jonquera 2012, Serós 2003) and reduced the final burnt area.

Fires that occurred from 1989 to 2008 had already been assessed and classified by Castellnou et al., 2009 in relation to fire perimeter shape and synoptic weather conditions. Fires that occurred after 2008 have been classified via the same methodology and published in Duane et al., 2015.

2. Factor data sources and parameterization in the MedSpread model.

WIND:

Wind direction data were required for each fire. We used data from the national database of forest fires (*Base de Datos Nacional de Incendios Forestales, EGIF*) gathered from the *Área de Defensa contra Incendios Forestales (MAGRAMA*) which spans a period from 1968 to 2011. In most of the fires, the database included data on weather conditions at outbreak of the fire, based on weather stations located *in situ* or near the fire. For fires not present in the database or missing detailed weather information, we used data from the closest weather station in the AEMET database provided by the AEMET, the Spanish Weather Agency (AEMET, 2012). The database contains hourly information since 1920 for the main meteorological stations in each Spanish province. Wind direction data for wildfires were selected at 4 p.m. (the maximum fire hazard hour in the Mediterranean (Carrega, 1991)). As wind-driven fires occurring in very complex orographies can be affected by a different wind direction to that given by mean weather station data, for these fires, wind direction affecting fire spread was taken from the Catalan Firefighter's database where Wildfire Reports give qualitative wind direction.

The effect of wind direction on fire front was calculated by the difference angle between wind direction and front direction, with front direction calculated as the angle between the evaluated cell and the source cell. Angles between wind and fire front were linearly scaled to [0,1], with 180º the maximum difference (Figure 1).

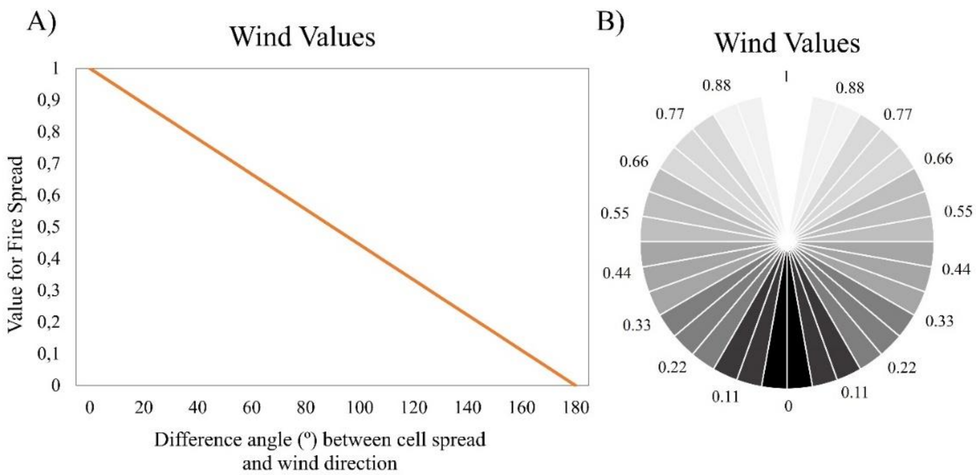

Figure B.1. Wind function parameterization. Function shape of the parameterization of wind angle differences values into MedSpread values [0,1]. A) Shows the linear relation between angle differences and MedSpread values. B) Represents the MedSpread values in some angle differences in a circle plot when supposing South wind.

SLOPE:

Slope is calculated dynamically in the MedSpread model when spread is calculated from a spreader cell to its neighbors. The elevation data necessary to calculate slope were obtained from the Digital Elevation Model of Catalonia (DEM; Catalan Cartographic Institute) at 30 m resolution, and resized to MedSpread resolution (100 m pixel size).

Steeper and upload slopes are thought to have a driving effect on fire spread (Butler et al., 2007; Campbell, 1995). The slope between the active cell and its neighboring cells was calculated as a percentage, and values were truncated between -50% and +50% (Butler et al., 2007). Values out of this range were saturated to the corresponding extreme (minimum or maximum). The [-50%, 50%] rank was linearly transformed to [0,1] (Figure 2).

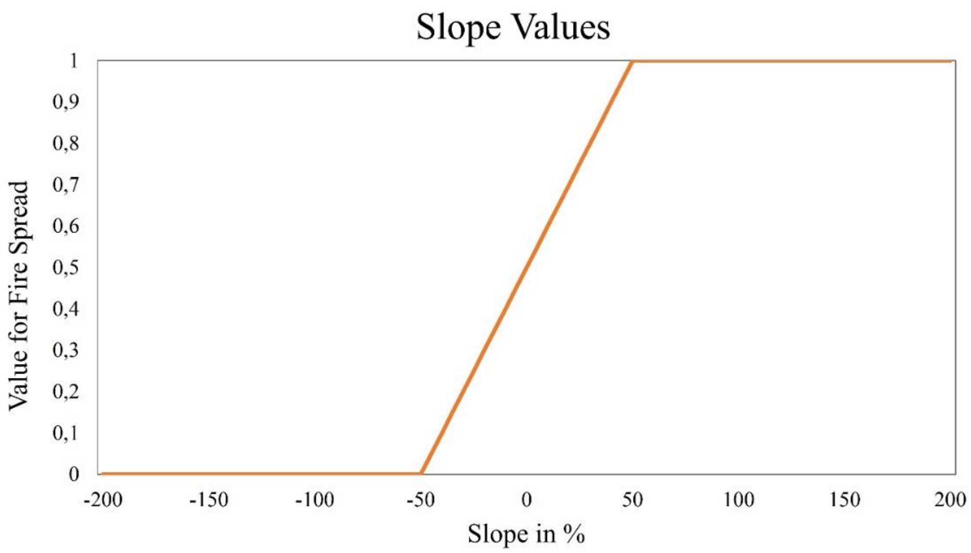

Figure B.2. Slope function parameterization. Function shape of the parameterization of slope values into MedSpread values [0,1].

ASPECT:

Aspect information is introduced into MedSpread from the spatial analysis of the same DEM used to compute the slope. Aspect factor values were based on Campbell, 1995 (Figure 3).

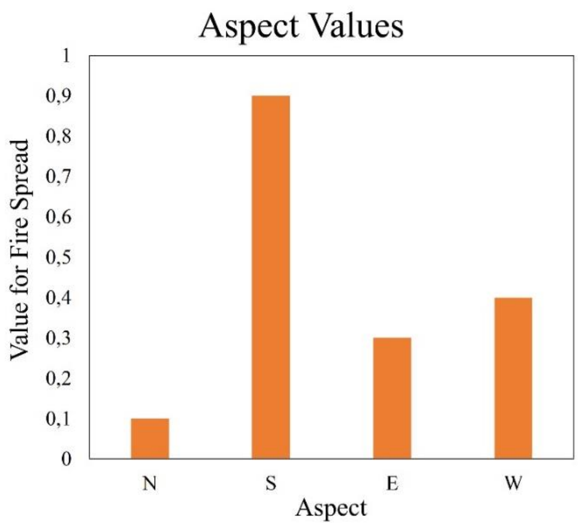

Figure B.3. Aspect parameterization. Values adopted by each aspect category in the MedSpread model.

SPECIES FLAMMABILITY:

The Land Cover Forest Type (LCFT) map in MedSpread is derived from subtracting information on orthophoto-based land cover maps (Land Cover Maps of Catalonia (Ibañez et al., 2002)), the Forest Map of Spain (dated to around 2000 (Vallejo Bombin, 2005)) and the second and third Spanish National Forest Inventories (NFI; Villaescusa and Díaz, 1998; Villanueva, 2005); see Brotons et al., 2013 and Gil-Tena et al., 2016 for further details). In the current exercise, the factors regarding *Species Flammability* and *Fuel Load* (see next section) were initialized at two different times of the 1989–2012 period: first at the beginning of the period, so with data corresponding to 1989 (second NFI), and then reinitialized with the actual values corresponding to the year 2000 (third NFI). Two-step initialization of the LCFT map was applied in an effort to better reproduce real fires using the most up-to-date forest landscape condition data.

Species flammability factor values describe the relative flammability and combustibility of tree species and burnable land covers (including agricultural lands). To assign species flammability values, we conducted several simulations and selected the values that reproduce the best percentage match area between observed and simulated fires for each group of fires, based on previous data from Brotons et al., 2013. These values are represented in Figure 4 at fire spread pattern level.

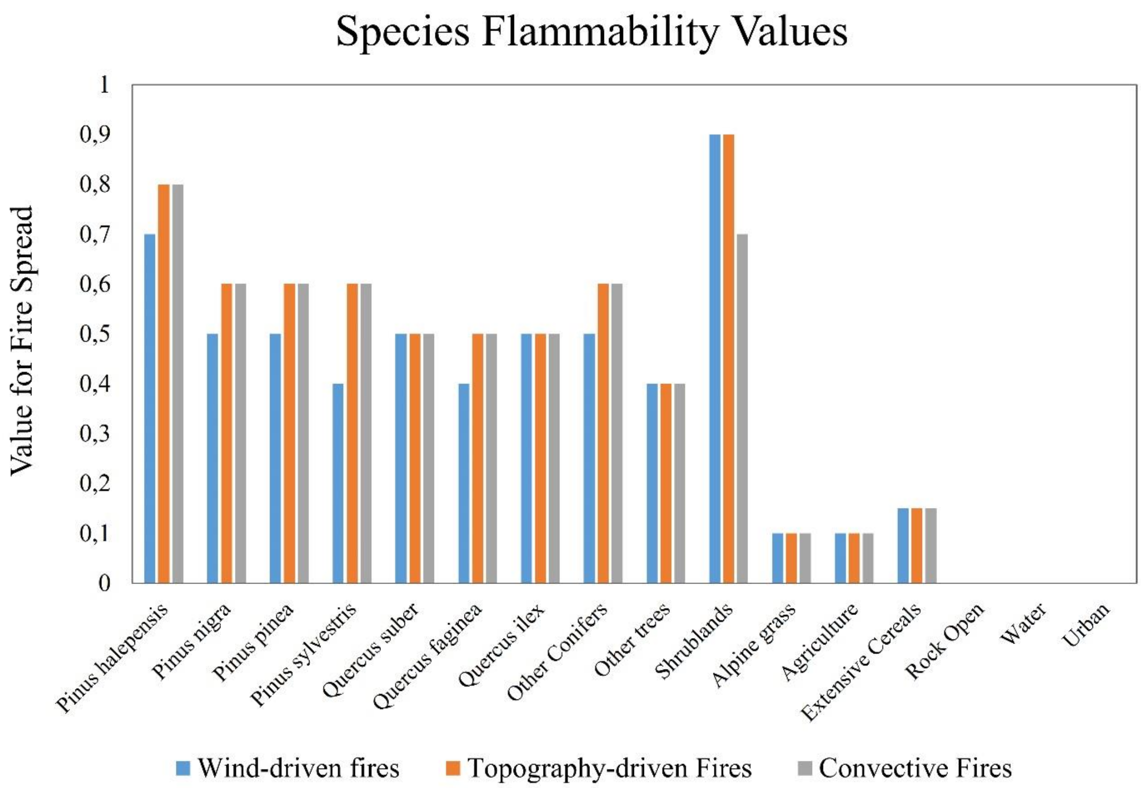

Figure B.4. Species flammability parameterization. Values adopted by each species and land cover type in the MedSpread model.

FUEL:

Two volume maps were computed for each NFI timing (1989–1991 and 2000–2001) and according to the LCFT map in 1989 and 2000 (see *Species Flammability Section* for details on how they were built). NFI plot volume data were obtained from a database manager created for the Catalan NFI project (MIRABOSC, http://www.creaf.uab.cat/sibosc/programari.htm). Volume with bark (VwB in m³/ha) was computed for each plot considering all the stems in the plot with a diameter at breast height (dbh) greater than 7.5 cm (Eq.1).

(Eq.1).

$$VwB = \pi * \left(\frac{\mathrm{dbh}}{2}\right)^2 * H * Cs,$$

where *H* is height and *Cs* is the coefficient of shape of the stem.

Ordinary kriging interpolations at MedSpread resolution were computed for each species using the plots that were unaffected by fires or management before the inventories (kriging interpolation requires steady processes; Gunnarsson et al., 2012). The kriging for each species was clipped by the species distributions according to the LCFT map in MedSpread. In the areas affected by fires before each NFI, we assigned the volume for each species by computing Thiessen polygons with the plots within each fire. For this process, at least 4 NFI plots per species were needed, so when there were 3 plots or less, we computed the average if possible or assigned the volume plot datum to the fire. If no NFI plot was located inside a fire, then a value of 0 was assigned. Finally, we combined the volume information on unburnt forest and burnt forest.

A fuel load value was also required for shrubland areas. Volume data for shrublands was not assessed in the NFI as it only reported information on woodland areas. The variable requested is *Volume with Bark* and not the more typical *Apparent Volume* for shrubs data as it has to be equivalent to forest. This variable is not usually measured for shrublands, but we approached it by multiplying shrubland height (according to time since last fire, with 2.2 meters as maximum height at 20 years (Fernandes et al., 2012; Keeley, 1986; Navarro and Cabezudo, 1998)) by a volume index calculated from *VwB* data (NFI) for trees species with a shrubby conformation, especially those reported in Navarro and Cabezudo 1998 as, typical to Mediterranean shrubland (*Arbutus unedo, Juniperus communis, Junniperus oxycedrus, Quercus cocciefera, Buxus sempervirens, Ilex aquifolium, Rhamnus alaternus, Pistacia terebinthus, Crataegus monogyna*).

Although on average Mediterranean forests grow to approximately 200 years (Sánchez-González et al., 2007; Trasobares et al., 2004), the stand structure that has a higher effect on fire probability is not the maximum mature age or maximum volume but an intermediate age around early stages. Volume values normalized to [0,1] were parameterized through a quadratic relationship (Eq.2 and Figure 5) considering that medium-volume forests allow light pass through the canopies, leading to multilayer forest structures that thus produce the highest fire intensity and spread rates (Kitzberger et al., 2012; Taylor et al., 2014).

(Eq.2)

Fuel: $\begin{cases} if\ (Volume < 225)\ \rightarrow\ Fuel = -0.000061 * Volume^2\ +\ 0.0154 * Volume\ +\ 0.0258 \\ if\ (Volume \geq 225)\ \rightarrow\ Fuel = 0.65 \end{cases}$

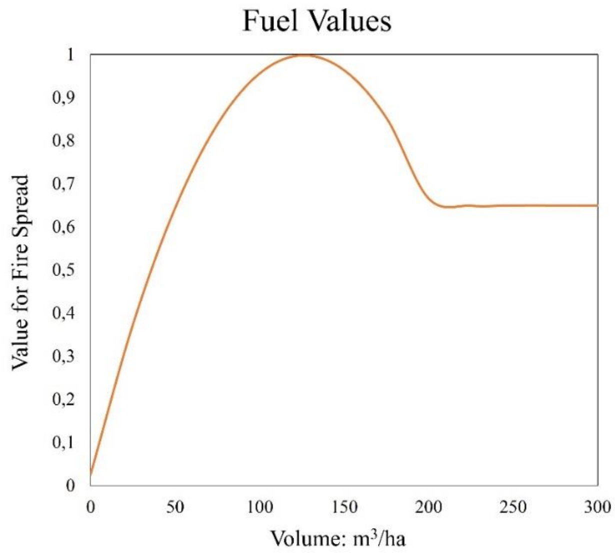

Figure B.5. Fuel load function parameterization. Function shape of the parameterization of fuel values in Catalonia into MedSpread values [0,1].

StochasticSpread parameter:

We performed 50 runs of a fire simulation (Margalef fire, 1816 ha, 17/07/1994, Convective fire) with equal weights for the five parameters on fire spread formulation. Each simulation changed the *StochasticSpread* parameter from 0 to 1, each 0.05. We assessed the variability of outputs of the three main attributes evaluated, and chose the value that provided little stochasticity to parameterize correctly the factor weights.

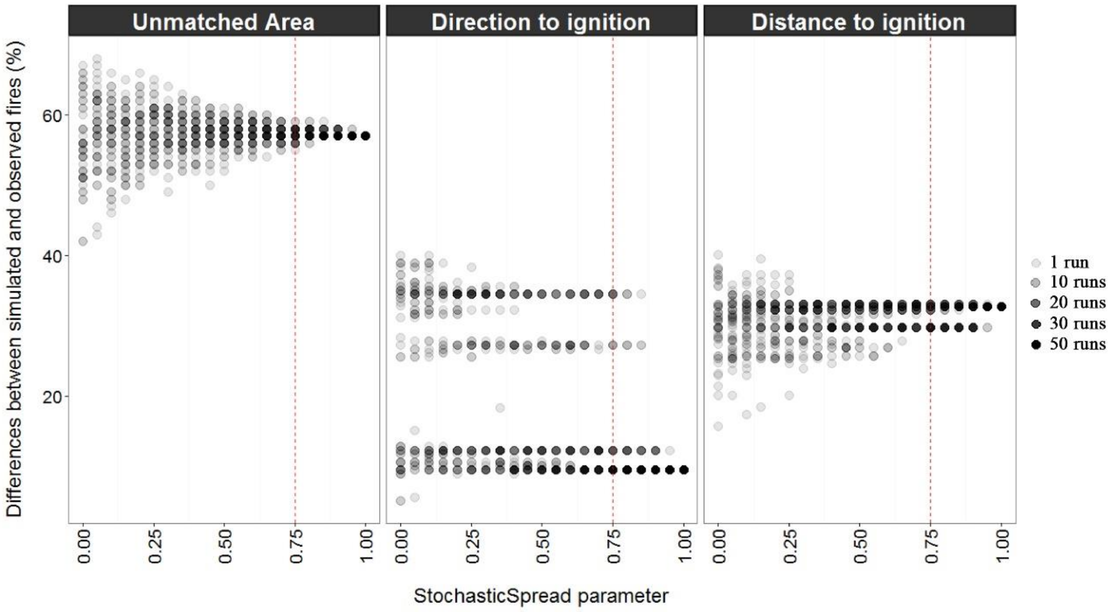

Figure B.6. *StochasticSpread* value parameterization. Outputs for the three attributes evaluated within the range of *StochasticSpread* values evaluated. The red line marks the final parameter chosen.

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SUPPLEMENTARY MATERIAL C: Complementary results and supporting information

1. Comparison with control experiments

Once weight-parameters were calibrated for each fire spread pattern according to the *Unmatched area* attribute, the optimal combination has been compared with seven other control experiments in the other two attributes. *Distance to ignition* and *Direction to ignition* attribute results are shown in Figure 1 and 2, respectively.

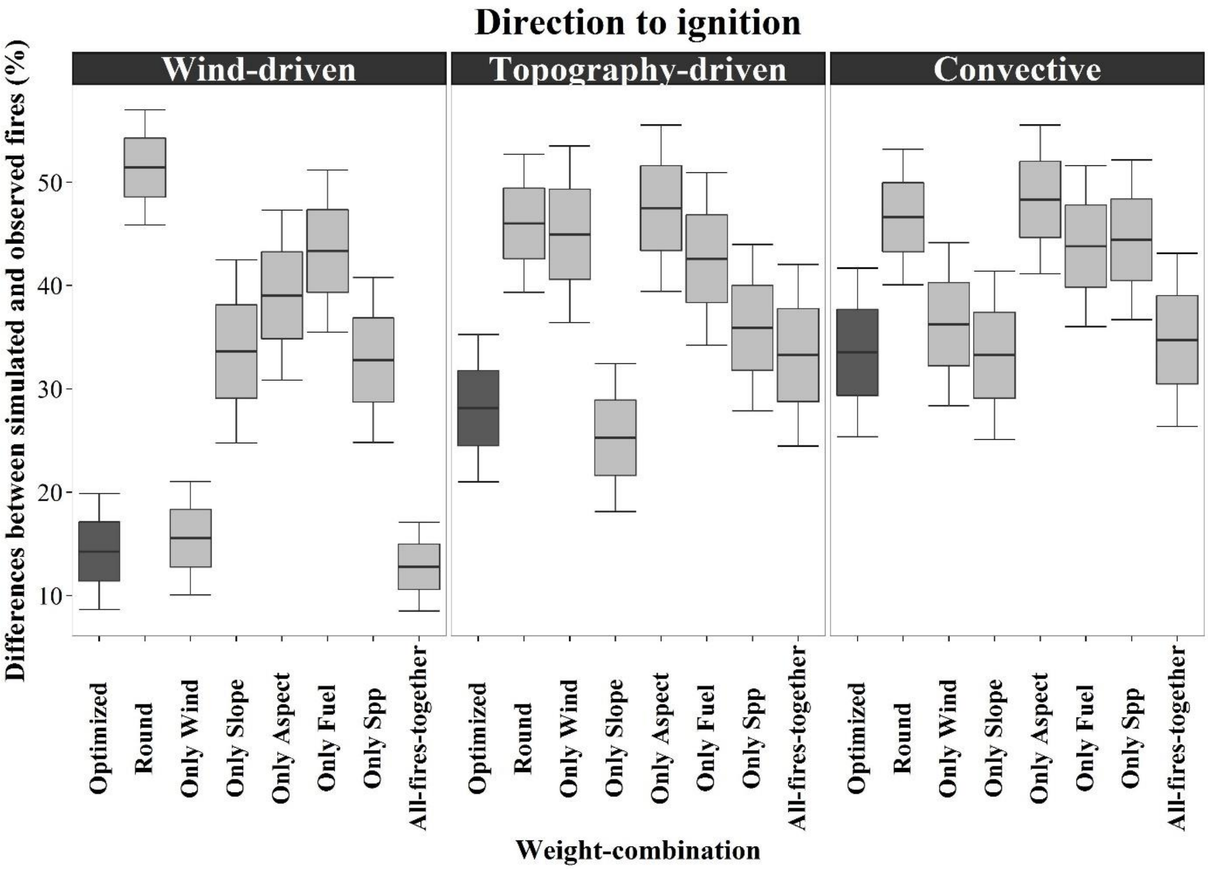


Figure C.1. Differences between simulated and observed fires for the 8 experiments regarding the *Direction to ignition* attribute.

Results per fire spread pattern on the *Direction to ignition* attribute for the optimized combination of weights (in dark gray) and the comparison with the 7 control experiments (light gray). The central black line represents the mean of the values, lower and upper hinges indicate the standard error of the mean and the lower and upper whiskers indicate the limits on the confidence intervals (95%) of the mean (n=41).

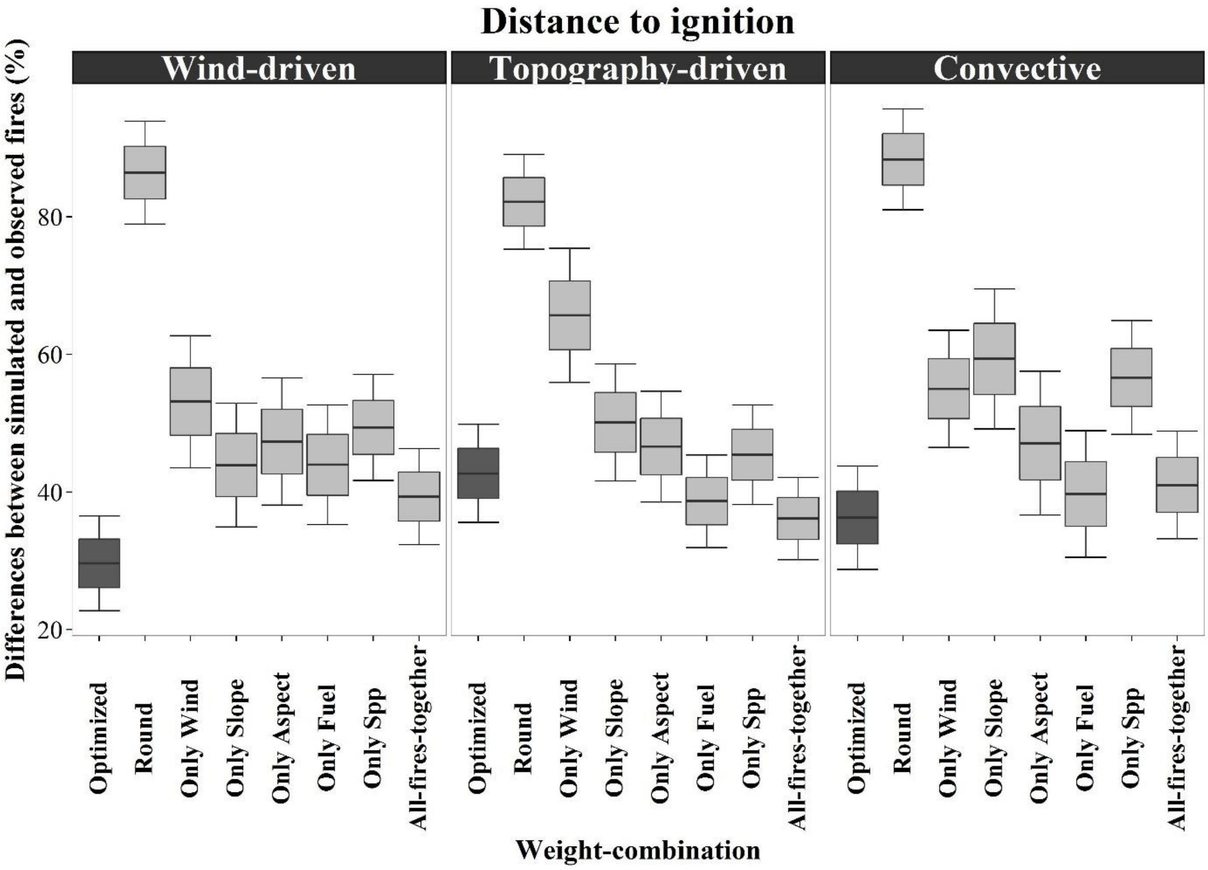


Figure C.2. Differences between simulated and observed fires for the 8 experiments regarding the *Distance to ignition* attribute.

Results per fire spread pattern on the *Distance to ignition* attribute for the optimized combination of weights (in dark gray) and the comparison with the 7 control experiments (light gray). The central black line represents the mean of the values, lower and upper hinges indicate the standard error of the mean and the lower and upper whiskers indicate the limits on the confidence intervals (95%) of the mean (*n*=41).

2. Complementary information on fire examples shown in Results

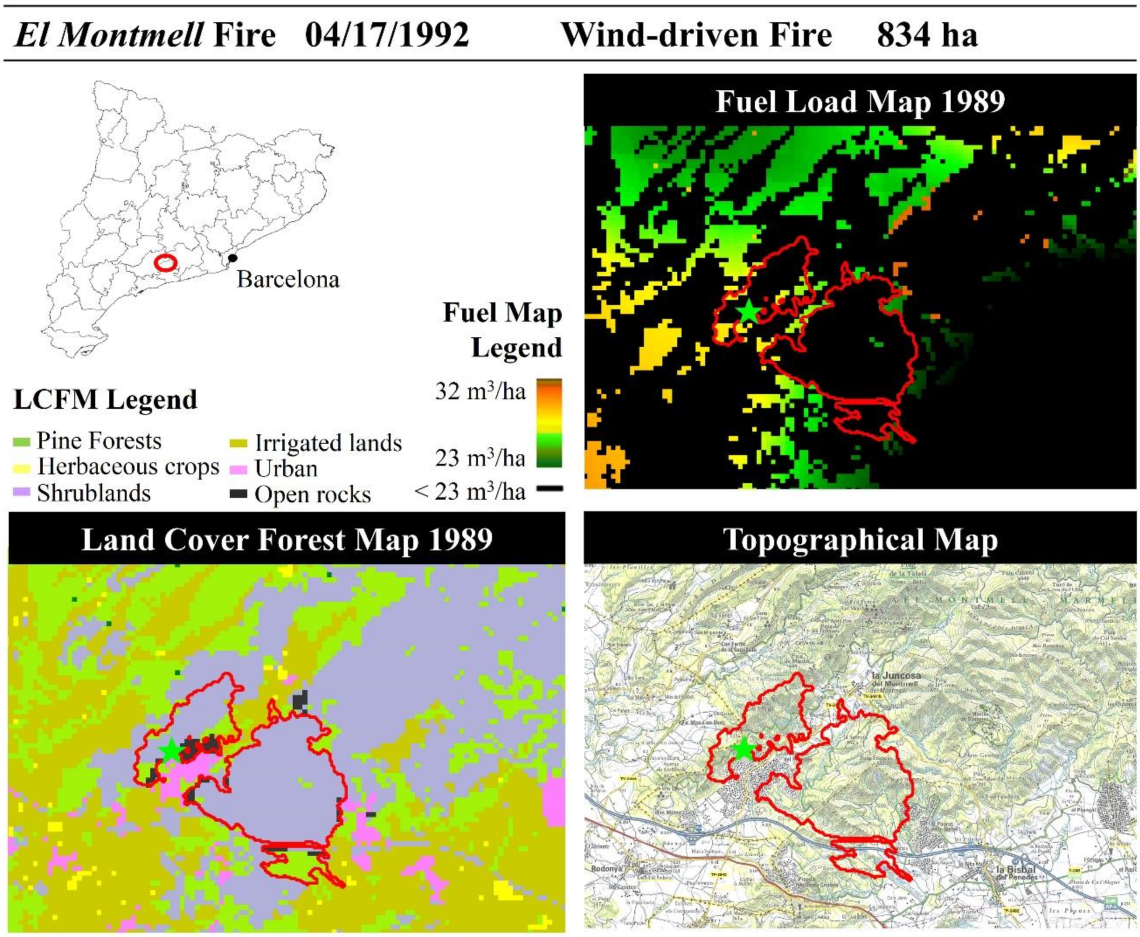


Figure C.3. *El Montmell* Fire. Location of the fire in Catalonia, Fuel Load Map in 1989, Land Cover Forest Map in 1989 and Topographical Map 1:50000 for the *El Montmell* fire area. Red line represents fire perimeter and green star the ignition point.

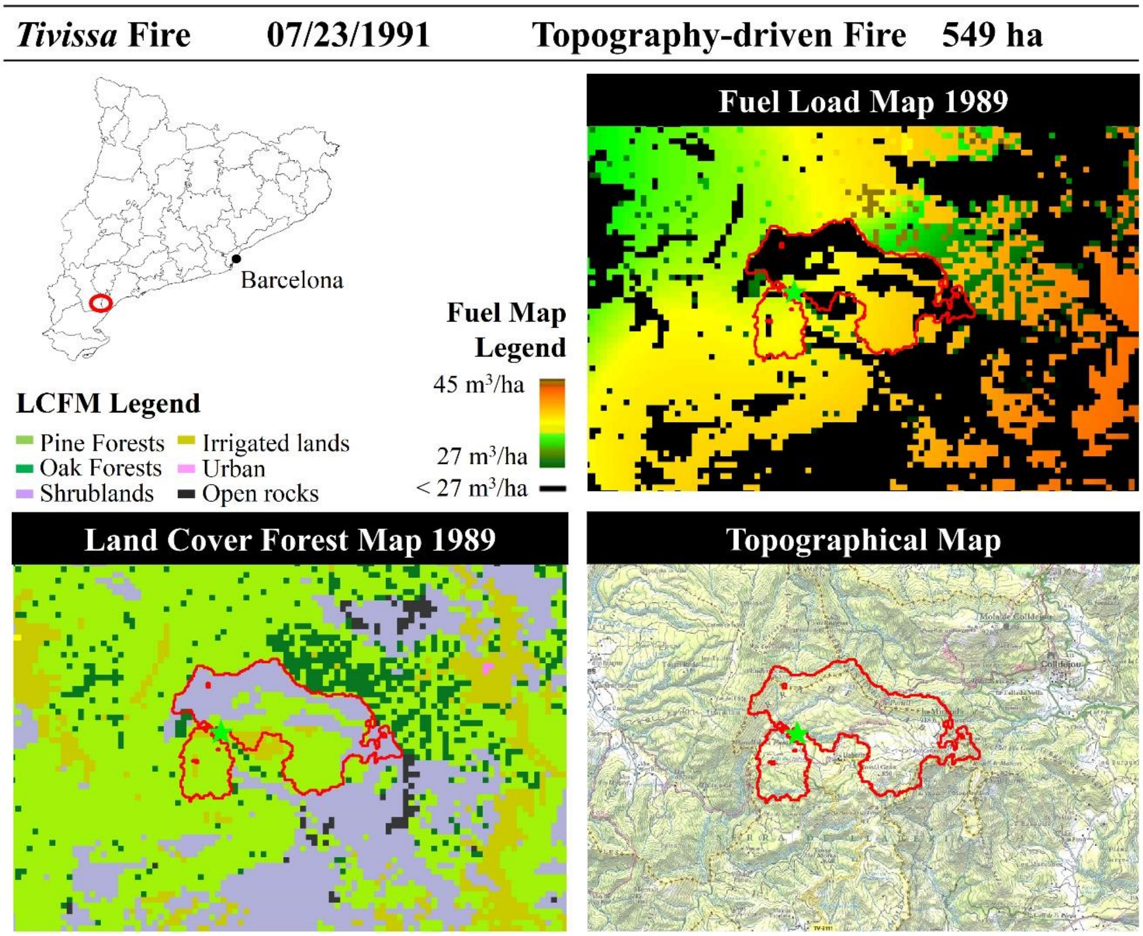


Figure C.4. *Tivissa* Fire. Location of the fire in Catalonia, Fuel Load Map in 1989, Land Cover Forest Map in 1989 and Topographical Map 1:50000 for the *Tivissa* fire area. Red line represents fire perimeter and green star the ignition point.

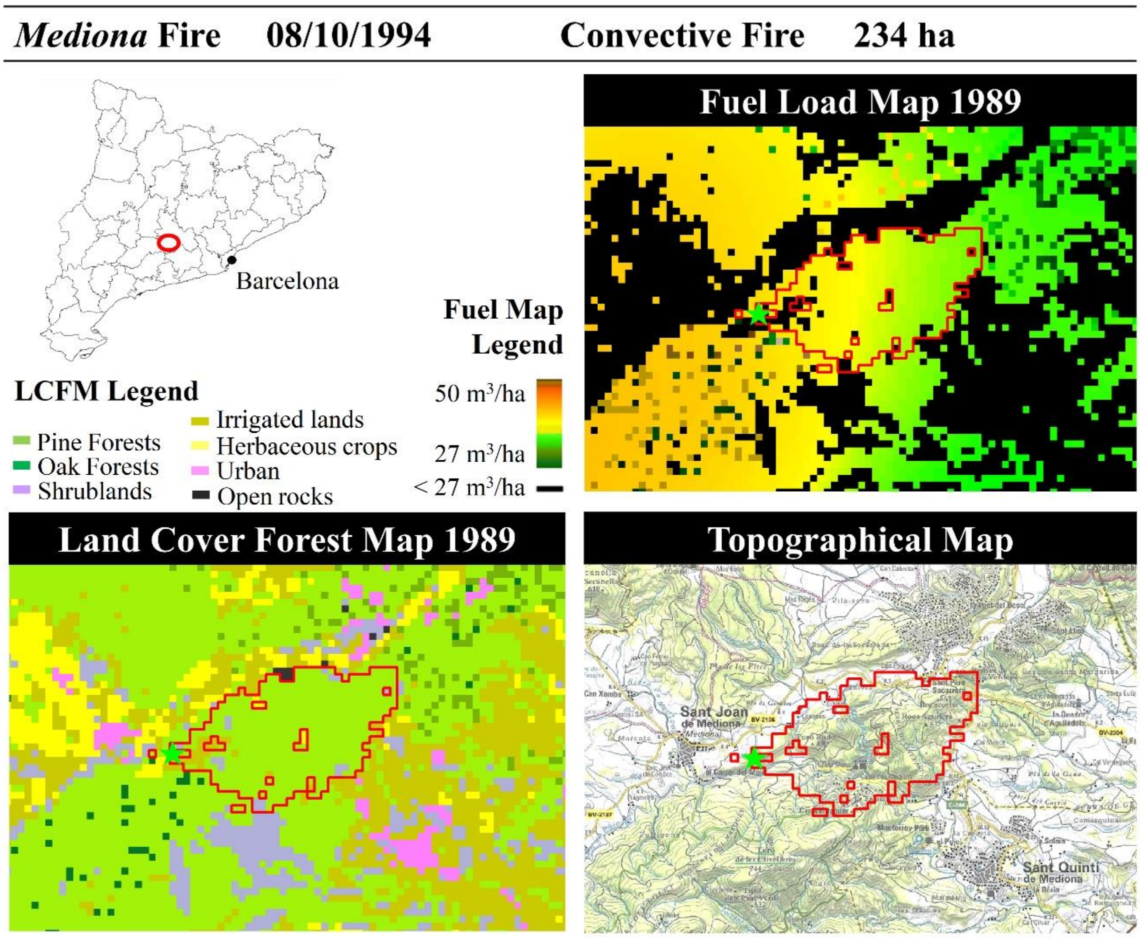


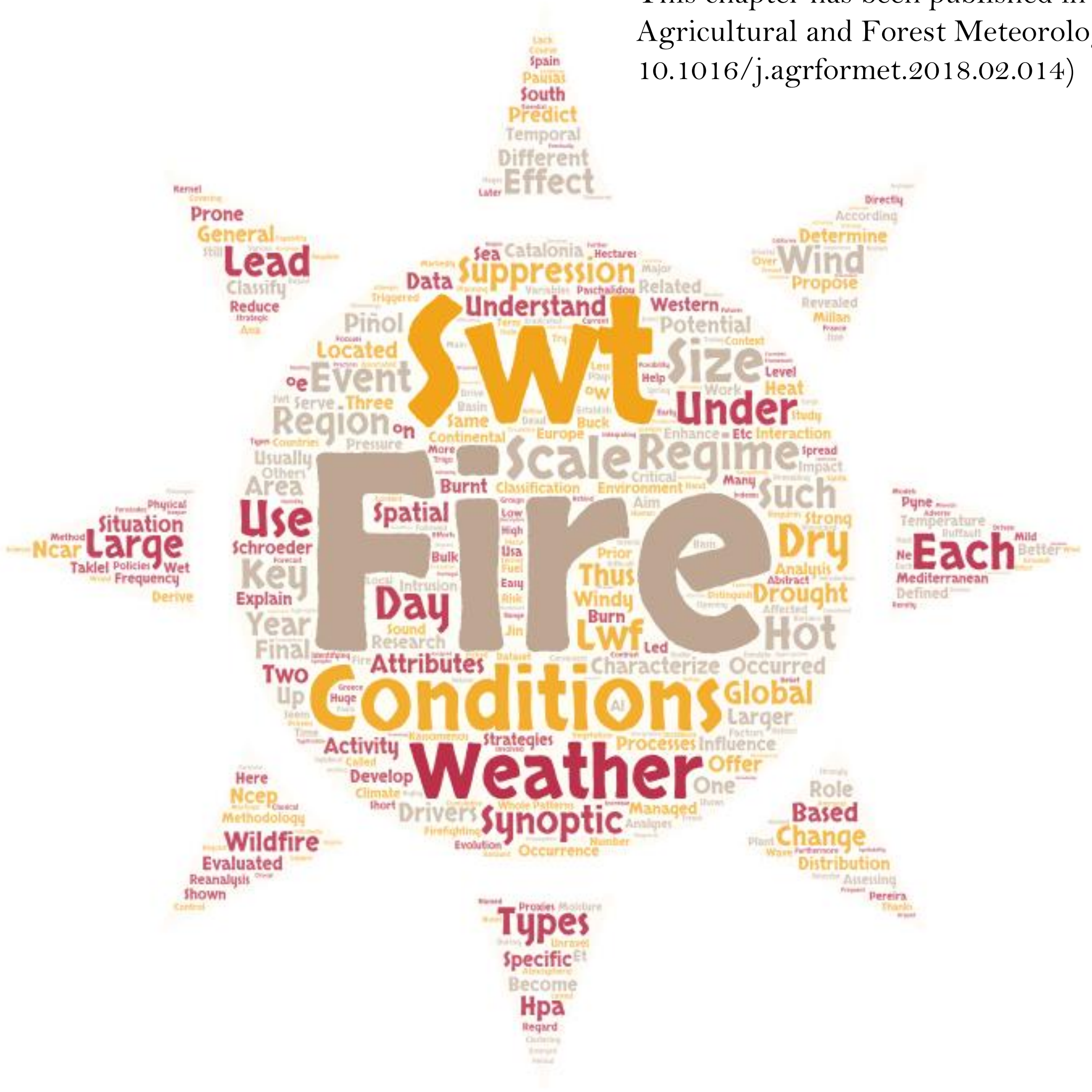
Figure C.5. *Mediona* Fire. Location of the fire in Catalonia, Fuel Load Map in 1989, Land Cover Forest Map in 1989 and Topographical Map 1:50000 for the *Mediona* fire area. Red line represents fire perimeter and green star the ignition point.

CHAPTER 3

Synoptic weather conditions and changing fire regimes in a Mediterranean environment

Andrea Duane and Lluís Brotons

This chapter has been published in Agricultural and Forest Meteorology (doi: 10.1016/j.agrformet.2018.02.014)



ABSTRACT

Analysis of global change effects on fire regimes requires evaluations of key processes explaining fire activity at the appropriate spatial and temporal scales. Classifications of the weather conditions prevailing at large continental scales (called “Synoptic Weather Types”, SWT) offer convenient potential proxies for integrating weather-related factors into our understanding of fire regime attributes at regional scales. Here we establish a methodology for identifying the major SWT that lead to wildfires and assessing their influence on fire regime in interaction with other global drivers such as drought events or fire suppression policies. Based on days with fires larger than 50 hectares that occurred in Catalonia, a region located in the western Mediterranean Basin, we propose a clustering methodology using data of temperature at 850 hPa, sea level pressure and winds at 925 hPa from the NCEP/NCAR reanalysis dataset covering the whole of western Europe (25-70ºN and 20ºW-40ºE). Our classification method proposes 6 SWT: three that were characterized by synoptic conditions leading to strong winds in the region, two that led to ‘hot and dry’ environments, and one that was not characterized by any strong weather determinants. Fires under ‘hot and dry’ conditions, such as the South intrusion SWT, triggered the bulk of fires and burnt area in the region. Spatial analyses of fire distribution under each SWT revealed markedly different fire-prone locations, opening the possibility for strategic planning of fire management based on local fire regimes. Fires occurring during mild years (wet spring conditions) and under ‘hot-and-dry’ SWTs have been eradicated from the region thanks to enhanced firefighting capability, and fire sizes in dry years have strongly reduced. In contrast, fires occurring under windy situations have not followed the same course of change and have not diminished in incidence over time, and seem to be more difficult to control using current fire suppression strategies. The role of SWT on determining fire regimes and its interaction with fire suppression strategies has a huge potential to help researchers and managers develop better fire analyses based on sound physical grounds and serve to understand and eventually regulate the adverse impacts of fire regime changes in a global change context.

Keywords

Wind-driven fire, Heat-wave, Catalonia, Fire size distribution, Kernel density, Drought event, Firefighting

Highlights

- We distinguished 6 synoptic weather types leading to large wildfires in Catalonia
- Three types were defined by wind, and two types involved hot and dry environments
- *South intrusion* triggered the larger number of fires and burned area in the region
- Different spatial distributions emerged from the influence of each situation
- Fire suppression managed to reduce fires in heat situations, but not in windy ones

INTRODUCTION

Weather plays a critical role in large wildfire (LWF) event occurrence (Flannigan et al., 2000; Pausas, 2004; Piñol et al., 1998; Pyne et al., 1996). Vegetation susceptibility to fire is directly affected by the cumulative impact on plant moisture content of weather conditions prior to a fire event in relation to average climatic conditions (Barbero et al., 2015). Weather conditions on the same day of a fire determine dead-fuel moisture conditions and directly influence ignitability and fire propagation (Pyne et al., 1996). Short-term weather conditions linked to fire events are usually associated to high-temperature, low-humidity and windy days (Piñol et al., 1998; Schroeder and Buck, 1970).

There have been various attempts to characterize the weather conditions that lead to fire events (Amraoui et al., 2015; Paschalidou and Kassomenos, 2016; Ruffault et al., 2016a; Schroeder and Buck, 1970). Synoptic climatology focuses on large-scale weather patterns defining general atmospheric conditions at a continental scale. Depictions of large-scale weather conditions aggregate a large amount of weather variables at a continental scale – temperature, precipitation, wind, atmospheric pressure – and usually better forecast and explain key environmental processes than any of these variables considered individually (Fernández-Martínez et al., 2016; Millan et al., 1998). The synoptic weather conditions affecting LWF occurrence can serve to characterize and classify these specific conditions into general groups, named Synoptic Weather Types (SWT). Research pioneered by Schroeder et al., 1964 and picked up later by others like Taklel et al., 1994 in the USA, Millan et al., 1998 in Spain, Pereira et al., 2005 in Portugal, Paschalidou & Kassomenos, 2016 in Greece and Ruffault et al., 2016b in France, among others, shows that SWT are regarded as a potential framework to derive, or describe, homogeneous fire-prone weather conditions. Furthermore, SWT offer a sound physical basis for the development of fire risk indexes, as they are easy to simulate by global and regional circulation models (Taklel et al., 1994; Trigo and Palutikof, 2001).

Each SWT might drive different fire-regime attributes (fire frequency, size, etc.). In this regard, Jin et al., 2014 revealed that fires occurring under Santa Ana winds in California were usually larger and less frequent than fires not occurring under these conditions. Synoptic weather typification was also shown to predict how a wildfire will spread in a specific relief (Duane et al., 2016), and has thus proven useful in operational fire-suppression strategies (Castellnou et al., 2009; Lázaro et al., 2016). SWT could thus become essential descriptors of fire activity and a key foundation for understanding fire regime attributes such as fire spread, size, location and frequency. In today's climate change context, SWT characterization can become a crucial piece of information for predicting fire regime evolution, beyond classical temperature-increase assessments (Batllori et al., 2013; Terrier et al., 2013).

Nevertheless, the effect of SWT on fire regimes can become modulated by other fire drivers such as drought conditions prior to the fire season or the efficiency of human fire suppression efforts. The dryness of a year has been shown as a determinant of final burnt area in many ecosystems, since it predisposes vegetation available to burn (Pausas and Paula, 2012). On the other hand, several studies (Brotons et al., 2013; Minnich, 1983; Piñol et al., 2007) have argued for effects of fire suppression practices on final size of fires. However, nothing is known about how a specific SWT influences fire activity under particular drought or suppression conditions.

SWT have been proposed in many countries worldwide, but there is still a lack of any deeper understanding of the specific differences in the effects of these SWT on a broad range of fire regime attributes such as frequency, location, size and temporal evolution. Furthermore, the science on the interaction of SWT with other fire regime drivers is only in its early stages (Fernandes et al., 2016; Pereira et al., 2005), and further research is needed to unravel the key processes at work behind fire activity.

This study aimed to classify LWF-days into SWT for fire occurrences in Catalonia (NE Spain), a Mediterranean environment, for the period 1980–2015 according to general weather conditions in Western Europe. In Mediterranean environments from European countries with highly anthropogenic landscapes, evaluating the use of synoptic classifications to derive knowledge on the fire regime attributes is critical to our understanding of the fire phenomenon and will significantly contribute to our capacity to enhance wildfire prediction accuracy. Our objective was thus to develop a novel methodology allowing to distinguish different weather situations leading to LWF and classify them into general synoptic patterns using data from the NCEP/NCAR reanalysis (Kalnay et al., 1996). Working up from this analysis, our main aim was to investigate fire regime attributes for each SWT and correlate them to other fire drivers to try to understand the past, present and potential futures of fire regimes according to these SWT. We evaluated temporal trends on the number of days of each resulting SWT, unraveled the spatial probability of fires occurring under each SWT, and finally analyzed fire size distributions within each SWT according to drought conditions and fire suppression effects.

Climate and fire regime in the study area

Mediterranean environments are marked by hot and dry summers and strong seasonality (Olson et al., 2001). Cool wet winters promote biomass growth and extended summer drought favors the regular occurrence of wildfire (Batllori et al., 2013). In the Mediterranean Basin, macroclimate mainly results from the seasonal alternation between frontal cyclones associated with polar air masses during winter, and sub-tropical high-pressure systems from subsiding maritime and continental tropical air masses during summer (Tatli and Türkeş, 2013). In fact, during summer, two large semi-permanent weather systems located at each end of the Mediterranean Basin dominate its meteorological processes. At the western edge is the Azores high, and over the eastern borders is the low-pressure monsoon system that extends from the Middle East to the whole of southwestern Asia (Millan et al., 1998). The Mediterranean Basin has a complex orography that includes extensive coastal areas mostly backed by relatively high mountain ranges (Lionello et al., 2006), and it also favors the formation of deep convective cells and thermal lows over the major peninsulas (Hoinka and Castro, 2003). Other thermally driven systems subordinated to larger weather structures thus develop during day and can strongly modify the regional flows (Millan et al., 1998).

Catalonia is located in the NE Iberian Peninsula and covers an area of approximately 32,000 km² (Serra et al., 1999). Climate is Mediterranean, with hot dry summers, rainy springs and falls, and cold winters (Albentosa, 1980). Continental and Pyrenean influences are found, with precipitation and temperature variations related to distance-to-sea and altitude (Lana et al., 2001). Traveling depressions and blocking anticyclones characterize precipitation, temperature, and moisture variability, and the relative location of highs and troughs determines atmospheric wind (Martín-Vide et al., 2008; Millan et al., 1998). In summer, the presence of thermal lows due to terrestrial warming distinguish a fair proportion of days (Lionello et al., 2006), along with the prevalence of local winds (i.e. sea breezes; Grimalt et al., 2013). Catalonia has a complex relief that greatly affects weather dynamics. Most of the mountain ranges are orientated east-west, while some mountain chains near the sea follow the coastal south-west to north-east direction. The Pyrenees, the major east-west-oriented mountain range in the North of the region, strongly affects climate variability (Soriano et al., 2006). There are also flat areas near big river basins located in the West and South. The coast with the Mediterranean Sea outlines the eastern part of the region, and this proximity to the sea generates milder conditions in summer and winter than in more continental areas.

In the period 1970–2010, more than 9,000 fire events greater than 0.5 ha occurred in Catalonia, and total burnt area was about 400,000 ha (Turco et al., 2013). Mean annual area burnt was 8,000 ha/year, corresponding to 0.75% of Catalan wildland area. Catalonia is characterized by a quite low fire return interval (between 60 and 400 years for homogeneous fire regions of about 45,000 ha; Pique et al., 2011) with very large and intense wildfires. Burnt annual area shows strong annual variation, with two peaks in 1986 and 1994 burning 65,000 and 75,000 ha, respectively. Most of the burnt area is caused by a few large fires (González-Olabarria and Pukkala, 2007), and most of the fires occur in the summer season (June–September; Piñol et al., 1998). Stand-replacing fires appear to be the most common in the area, with a large proportion of the burnt area being affected by crown fires (>85%; Rodrigo et al., 2004). The dominant fire management strategy in Catalonia is fire suppression, with investments increased six-fold since the early 1980s. There is a general downtrend in the number and size of fires since the big fires of 1986 and 1994, which is mainly explained by increased effort on fire prevention and suppression (Brotons et al., 2013; Turco et al., 2013). However, in Catalonia the specific role of fire suppression efforts in determining fire regimes is still under debate (Brotons et al., 2013; Otero and Nielsen, 2017; Piñol et al., 2007).

METHODS

The first goal of the present study was to build a methodology to distinguish the synoptic conditions of fire occurrence days by clustering weather data at a continental scale. We then aimed to evaluate fire attributes within each of the resulting climatic groups and assess their temporal evolution and interaction with other critical drivers.

Dataset

Fires

We selected fires larger than 50 ha that occurred in Catalonia during the 1980–2015 period. We chose fires occurring between May and September to get summer conditions. We only selected the first day of fire occurrence, although a few fires lasted more than one day. The result was a list of 230 dates when a minimum of one fire larger than 50 ha was recorded.

Climate Data

The values for atmospheric characterization were sourced from the NCEP-NCAR reanalysis dataset (Kalnay et al., 1996), which provides atmospheric weather variables at different atmospheric levels with a 2.5°×2.5° latitude and longitude resolution, and downloaded using the 'RNCEP' package (Kemp et al., 2012) implemented in R-software. One value per day was averaged from the four 6–hour periods per day provided. To simply but consistently characterize atmospheric circulation, synoptic conditions were described with the following variables in each point of the grid:

- Air Temperature at 850 hPa: This variable informs about air temperature at an altitude in the atmosphere where pressure is 850 hPa (around 1500 m.a.s.l. in the atmosphere). Several authors have stressed the importance of this variable in wildfire development (Cardil et al., 2014; Ruffault et al., 2016b), and it is generally used to analyze past fire weather and fire weather forecasts (García-Ortega et al., 2011; Millan et al., 1998). It is close enough to the surface to be representative of the low troposphere state, but it avoids some of the problems that affect near-surface reanalysis variables, such as local contamination effects (Pereira et al., 2005; Trigo et al., 2005).
- Sea Level Pressure (SLP): This factor represents barometric pressure at the surface. SLP describes the position of low and high pressures. It is fairly informative on many atmospheric dynamics: it can determine wind speed and direction on high barometric gradients, and it informs on atmospheric stability. The degree of stability or instability of the atmosphere will impact fire spread, fire intensity, and the movement of smoke (Haines, 1988; Potter, 1996; Potter and Anaya, 2015; Tatli and Türkeş, 2013; The Scottish Goverment., 2013).

- U and V wind at 925 hPa: We picked the two components of the wind vector (direction and strength) at 925 hPa. Wind is a key atmospheric driver for wildfire development, as it brings the flame closer to fresh fuel, thus accelerating spread in wind direction (Rothermel, 1983). The 925 hPa level was chosen as representative of the low troposphere state without suffering some of the problems that affect near-surface reanalysis variables (Ruffault et al., 2016b).

We selected the area included between parallels 25°N and 70°N, and between the meridians 20°W and 40°E (Figure 1). Number of grid points considered totaled 475. Similar articles (Cardil et al., 2015) opted for smaller windows focusing on the Iberian Peninsula, but we increased the scope here, since recent papers showed that most patterns associated with large wildfires in Southern Europe appear to be linked to synoptic configurations with the centers of action located in relatively distant sectors: the Atlantic ridge location, the Central Europe anticyclone oscillation, and the Saharan anticyclone influence (Paschalidou and Kassomenos, 2016; Ruffault et al., 2016b).

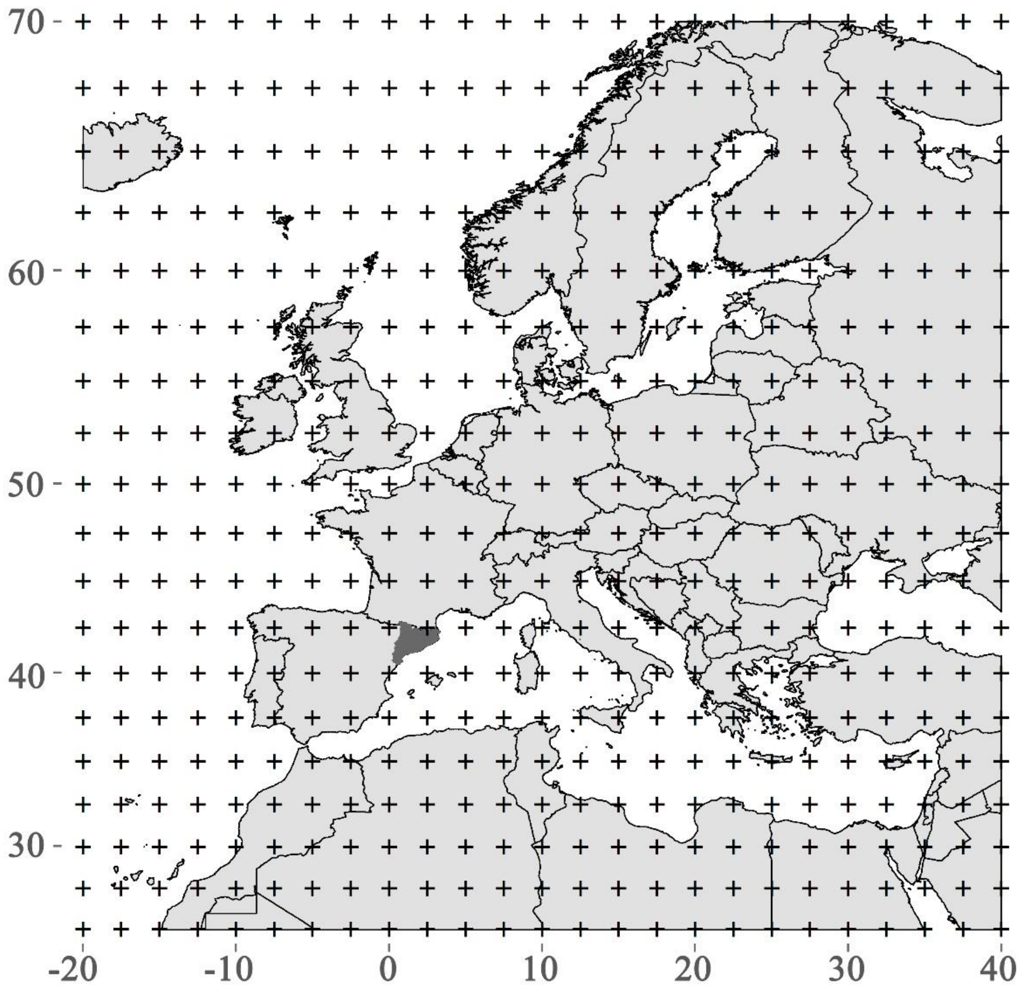


Figure 1. Grid points (crosses) of weather data for the analyses in the selected domain, and locational situation of the study area (dark grey).

Statistical analyses

Clustering

We computed noise fuzzy c-means clustering (NFCM) to classify all fire days into synoptic weather groups (Bezdek, 1981; Dunn, 1973). Fuzzy clustering methods allow the objects to belong to several clusters simultaneously, with different degrees of membership between 0 and 1. By iteratively updating cluster centers and the membership grades for each data point, NFCM iteratively moves the cluster centers to the 'right' location within a dataset. We used fuzzy c-means clustering because it gives comparatively better results than the k-means algorithm for overlapped datasets. The method requires specifying the value of the parameter *m*, which determines the level of cluster fuzziness and significantly influences the fuzziness of the resulting partition. Here, the fuzziness coefficient was set to a very low value, i.e. m = 1.05, similar to other natural processes (Olano et al., 1998). The noise clustering method (Dave, 1991) tries to make classifications more robust to the effect of outliers. The algorithm considers an additional cluster called Noise to the objects considered outliers, i.e. that have low membership values to all clusters. Users can specify the distance from which an object is considered an outlier. Here, after testing different values, we set this distance (in n-dimensional units) at 50. Before conducting the clustering, the data was standardized by subtracting the mean and dividing it by its standard deviation with data for the 1980–2015 period at each grid point.

The number of clusters is the most important parameter in this kind of analysis, while the other parameters commonly have less influence on the resulting partition. We selected 6 groups as optimal number of clusters according to the 'elbow criteria' (Figure A.1) as well as through the interpretation of cluster results. This number of groups is similar to other studies in southern Europe (Paschalidou and Kassomenos, 2016; Ruffault et al., 2016b). The algorithm minimizes intra-cluster variance, and as the minimum is a local minimum, the results depend on the initial choice of centroids. For this reason, we started the algorithm with 10 different random sets of initial seeds, and the initialization with least distance to centroid was the one selected. We used the 'vegclust' function in the R-package 'vegclust' (de Cáceres et al., 2010). The final function included the following parameters: *mobileCenters* (number of clusters) = 6; *m* (fuzziness exponent) = 1.05; *dnoise* (noise distance parameter) = 50 and *nstart* (number of random initialization sets) =10. Centroid maps of the 6 SWT clusters were then plotted (after un-standardizing results) in an attempt to analyze the synoptic wildfire climatology of each SWT. To understand the role of SWT on fire regime, we described general features of fires occurring under each SWT, including total number of fires, mean fire size, total burnt area and percentage of burnt area of each SWT over total burnt area.

Spatial distribution of SWT fire occurrence

Synoptic weather situations may lead to spatial variability in fire risk. To evaluate this hypothesis, we performed kernel analyses (Silverman, 1986) of fires classified under each SWT. The kernel algorithm calculates a point density by adding the values of all the kernel surfaces where they overlay the raster cell center. The kernel surface is a smoothly curved surface fitted over each point, and diminishes with increasing distance from the point, reaching zero at the radius distance from the point. Here, we calculated kernel density at 1000 m pixel resolution with a 50 km radius influence. We then tested Pearson correlations values between density maps.

Classification of non-fire days

We applied the classification obtained from fire-days clustering to all other non-fire summer days (from 1st May to 30st September). All summer days were assigned to one of the 7 possible groups done in the previous classification, i.e. the 6 SWT plus the 'noise' group which summarizes situations that could not be clearly attributed to the other groups. We thus obtained a total number of days of each SWT each year, including both fire-days and non-fire days. The function used was 'vegclass' in the R-package 'vegclust' (de Cáceres et al., 2010).

Temporal trends

The temporal trends of number of SWT days both for the days with fires and for all summer days were assessed. We investigated whether there was a significant linear trend (Mann-Kendall test) in the number of days of each group from 1980 to 2015, and the magnitude of such trend (Sen's slope). We also computed the same tests for the ratio of fire days to all summer days to assess whether there was a detectable increase or decrease in the proportion of fire days of each SWT. In addition, we performed a partial correlation trend test (Pearson's rho test) implemented in the 'trend' package in the R software (Pohlert, 2016) in which we assessed the evolution of one factor (fire days) once separated from a covariate (all summer days). We thus obtained the significance of the test and the magnitude of the trend.

Fire size distribution in the SWT

In an effort to understand the role of SWT on fire regime, we fitted power-law distributions (Cui and Perera, 2008) to each SWT. Note that we worked to the prior hypothesis that fire regime drivers such as cumulative drought conditions or fire suppression strategies might have different roles on fire size distribution between the different SWT. Thus, fires were split within each SWT into fires occurring in climatically adverse years according to high vegetation dryness (dry years) and low vegetation dryness (mild years), and into years with low firefighting capability and high firefighting capability. The dryness of a year plays a critical role in Mediterranean fire burnt area, since it predisposes vegetation available to burn (Pausas and Paula, 2012). Here, dryness was estimated from the Standardized Precipitation-Evapotranspiration Index (SPEI; Russo et al., 2017; Vicente-Serrano et al., 2010), which indicates the deviations of the current (e.g. period of reference) water balance (precipitation minus potential evapotranspiration) with respect to the long-term water balance, with time-scales between 1 and 48 months and at a 0.5º × 0.5º spatial resolution. In our case, we selected the SPEI index for July of each year (the month with highest number of fires and burned area), and taking drought conditions of three months before the date, as done previously (Pereira et al., 2005; Russo et al., 2017; Trigo et al., 2013; Van Wagner, 1987). We used the 11 grid points overlapping Mediterranean Catalonia and computed the average annual SPEI for the entire study area. The series data were combined with fire data (burnt area in fires larger than 50 ha) and analyzed with the Pettitt's test (Pettitt, 1979) implemented in the R-package "trend" (Pohlert, 2016) to find a breakpoint in SPEI values. Temporal trend analyses on the relation between SPEI drought index and annual burnt area revealed a breakpoint at SPEI = -0.21 allowing to separate mild years from dry years (Figure A.2). Firefighting capability was divided into two different periods, as it has been proved that in recent years increased resource investment and efficiency in firefighting in Catalonia has led to a decrease in final fire size (Brotons et al., 2013). While firefighting efforts in Catalonia before the year 2000 were focused on vigilance and early detection of ignitions, key enhancements of firefighting capacity involved the introduction, after 2000, of logical analyses of fire behavior (Brotons et al., 2013; Otero and Nielsen, 2017). This knowledge has allowed technical fire brigades to anticipate changes in fire propagation (Costa et al., 2011) and reduce final total burnt area. We therefore identified two periods according to overall fire-suppressing effectiveness in the study region with the pre-2000 period described as low firefighting capability and the post-2000 period described as high firefighting capability. We then fitted fire size distributions for the four groups (mild years and low firefighting capability, dry years and low firefighting capability, mild years and high firefighting capability, dry years and high firefighting capability) and tested differences between the four distributions within each SWT using ANOVA tests. Within-group differences found on ANOVA were also tested for significance using Tukey's test.

RESULTS

Description of SWT

We ultimately identified 6 distinct SWT resulting from the clustering process, and we named them to maintain coherence according to earlier works on the subject (Grams et al., 2017; Montserrat-Aguadé, 1998) as *Scandinavian trough*, *Atlantic ridge*, *Atlantic trough*, *Zonal regime*, *European blocking* and *South intrusion* (Figure 2).

The *Scandinavian trough* SWT was identified by a deep low-pressure area situated over the Scandinavian islands and the Azores high located in western Portugal, provoking North-West high-speed winds over Catalonia. These 'Mistral' winds (as they are called in the area) were cold winds generated in northern latitudes, when in Catalonia temperature at 850 hPa remained around 15ºC. A total of 34 fire days were identified as *Scandinavian trough* SWT. Median fire size was big (281.53 ha), but total burnt area was relatively small (23,586.54 ha; 8% of total burnt area; Table 1).

The *Atlantic ridge* SWT entailed similar effects on Catalonia to the *Scandinavian trough* SWT, but the general European situation was different, with the Azores high invading a larger part of Western Europe and low-pressure areas situated in the Western-Central Mediterranean Sea. Under this situation, high-speed North wind spells (called 'Tramontane' in the area) prevailed in Catalonia. Similar to the *Scandinavian trough* SWT, temperature at 850 hPa was not especially high for a summer situation (13-14ºC), reined in by the northern stream that dragged cold air from Northern Europe. Thirty-four fire-days were classified as *Atlantic ridge* SWT, with a total of 43 LWF burning an area of 55,260.77 ha, making it the second-ranked group in terms of total burnt area (20%; Table 1).

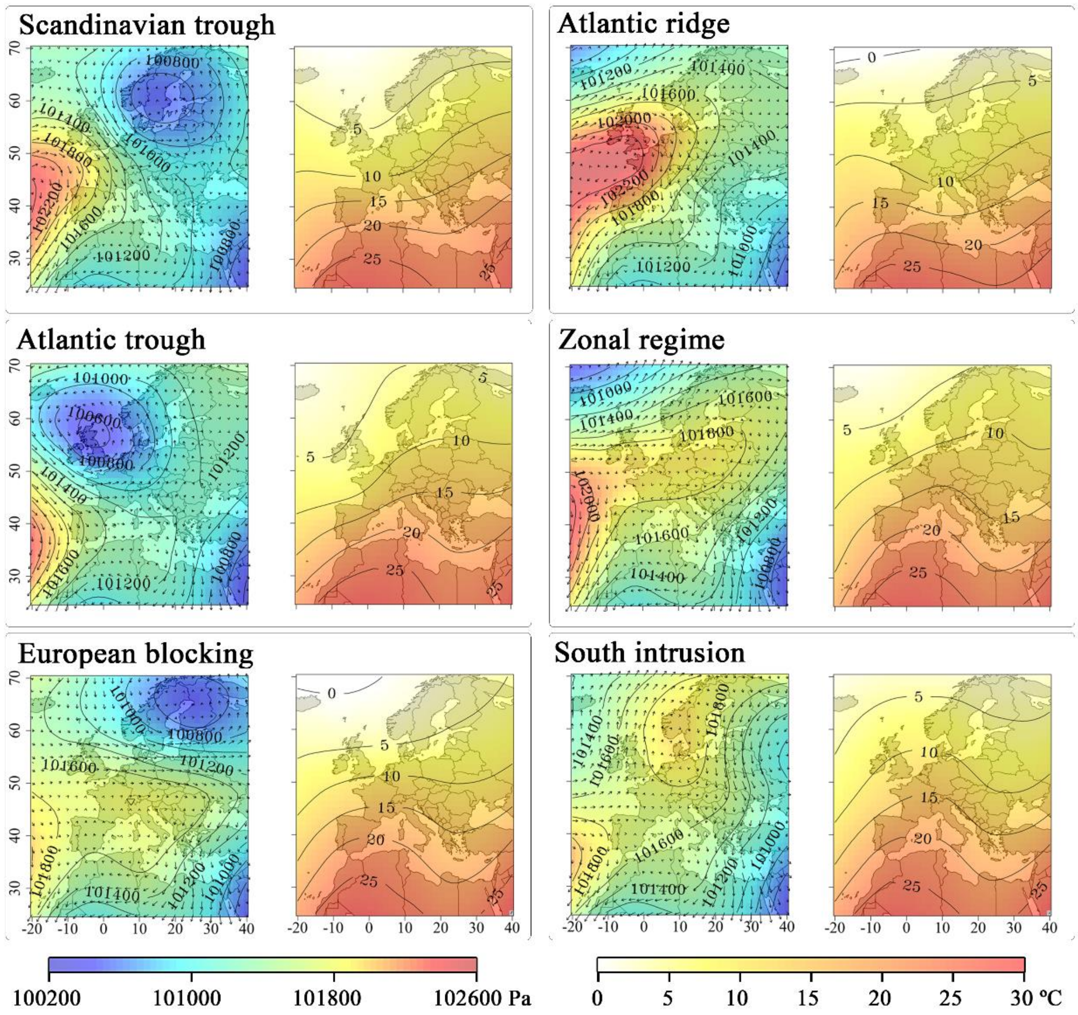


Figure 2. Synoptic Weather Type centroids of cluster results. For each SWT, left panel shows isobars (lines) and interpolated sea-level-pressure (colors), with arrows in each grid point indicating direction and strength of wind. Right panel shows isotherms (lines) and interpolated temperature (colors).

Table 1. Descriptive statistics for each SWT resulting from the cluster analysis

Group	Number of days	Number of fires	Mean fires per day	Median fire size (ha)	Maximum fire size (ha)	Total burnt area (ha)	Percentage of total burnt area
Scandinavian trough	34	41	1.21	281.53	4818.61	23586.54	8.42%
Atlantic ridge	34	43	1.27	154.35	15336.72	55260.77	19.72%
Atlantic trough	29	41	1.41	211.68	8111.63	44562.51	15.90%
Zonal regime	32	38	1.19	146.93	1880.00	13819.28	4.93%
European blocking	37	50	1.35	199.44	15273.01	45295.36	16.16%
South intrusion	54	81	1.50	221.07	25776.00	97742.56	34.87%

The *Atlantic trough* SWT also induced windy conditions in Catalonia with prevailing westerly winds. It presented similarities to the *Scandinavian trough* SWT, but with the center of the low-pressure area situated north of the British Isles. Temperature at 850 hPa was around 15ºC with a North-West to South-East increasing gradient. Twenty-nine fire days were classified as *Atlantic trough* SWT, and it was the second-ranked group in terms of fires per day (1.414).

The *Zonal regime* SWT corresponded to a situation defining a relatively calm and normal summer day in Catalonia (also called 'barometric-swamp'). The Azores high embraced central Europe, generating dry and warm air in summer, but with no anomalies in wind or temperature in Catalonia. Temperature at 850hPa remained around 18ºC. The *Zonal regime* SWT ranked lowest in terms of number of fires per day, median fire size, maximum fire size, and total burnt area (5%).

The *European blocking* SWT was dominated by the influence of the central European anticyclone. Temperature at 850 hPa remained high across the whole Iberian Peninsula, and around 18ºC in Catalonia. The stationary 'blocking' nature of the European high redirected crossing troughs, and the low-pressure area was situated over the Scandinavian isles, but this did not have direct effect on the weather in Catalonia. *European blocking* SWT counted a total of 34 days and 50 LWF, with a total of 45,295.36 ha burned (16% of total).

Finally, the *South intrusion* SWT was the group causing the highest temperatures in Europe. Although in the centroid plot the temperature over Catalonia was similar to in the *Zonal regime* or *European blocking* SWT (18–19ºC), a ridge of high temperatures crossed Central Europe, bringing the hot environment of this SWT. It was characterized by the appearance of a ridge from northern Africa (Saharan high) that moved northwards to Europe (García-Herrera et al., 2005; García-Ortega et al., 2011). The Saharan high is a very dry continental air mass, which generates 'heat waves'. Wind was low but with a southerly component. The *South intrusion* SWT entailed the largest number of fires (81), number of fire days (54), number of fires per day (1.50), maximum fire size (25,776.00 ha), total burnt area (97,742.56 ha) and percentage of total burnt area (35%).

Windy situations (*Atlantic ridge*, *Scandinavian trough* and *Atlantic trough*) accounted for 44% of total burnt area, while the 'hot and dry' situations (*European blocking* and *South intrusion*) accounted for 51% of total burnt area. The remaining 5% occurred under the *Zonal regime* SWT (Table 1).

Spatial distribution of SWT

Analysis of the spatial distribution of fires under each SWT showed markedly different distributions in their location and size (Figure 3). Kernel maps integrated the occurrence data into fire density per square kilometer (Figure 4). The *Scandinavian trough* SWT mostly generated fires in the South-West, whereas the *Atlantic ridge* SWT mostly affected the North-East, although they showed a correlation of 0.721 (Table A.1). The *Atlantic ridge* SWT showed little correlation with the rest of the groups. The *Atlantic trough* and *Zonal regime* SWT showed high correlation on fire location (rho=0.887), mostly affecting Western and Central Catalonia. The *European blocking* and *South intrusion* SWT also showed high correlation on fire location (rho=0.887), with high fire densities in Central Catalonia. The *European blocking* SWT affected a larger area embracing all Catalonia, whereas the *South intrusion* SWT deeply influenced Central Catalonia and a small area in the southwest. Fire density distributions showed significant differences among SWTs in the correlation analysis at $p<0.001$.

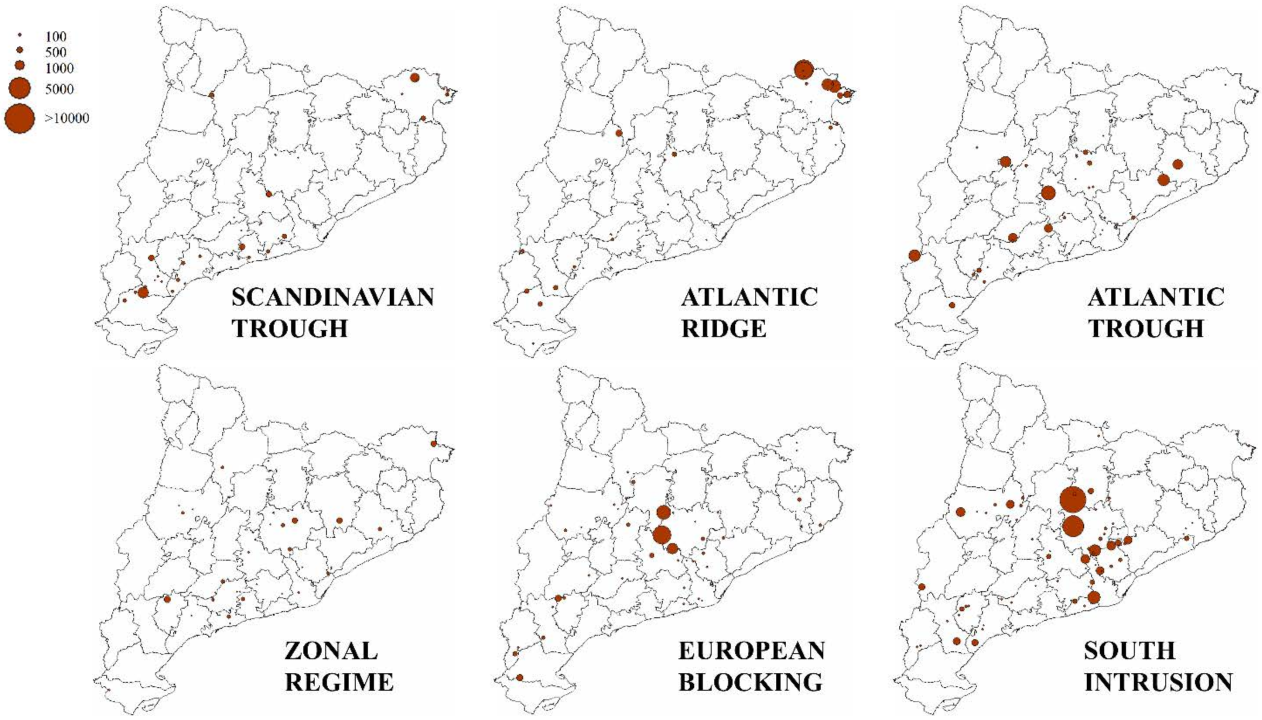


Figure 3. Spatial fire distribution in Catalonia for each SWT. Circle radius represents fire size.

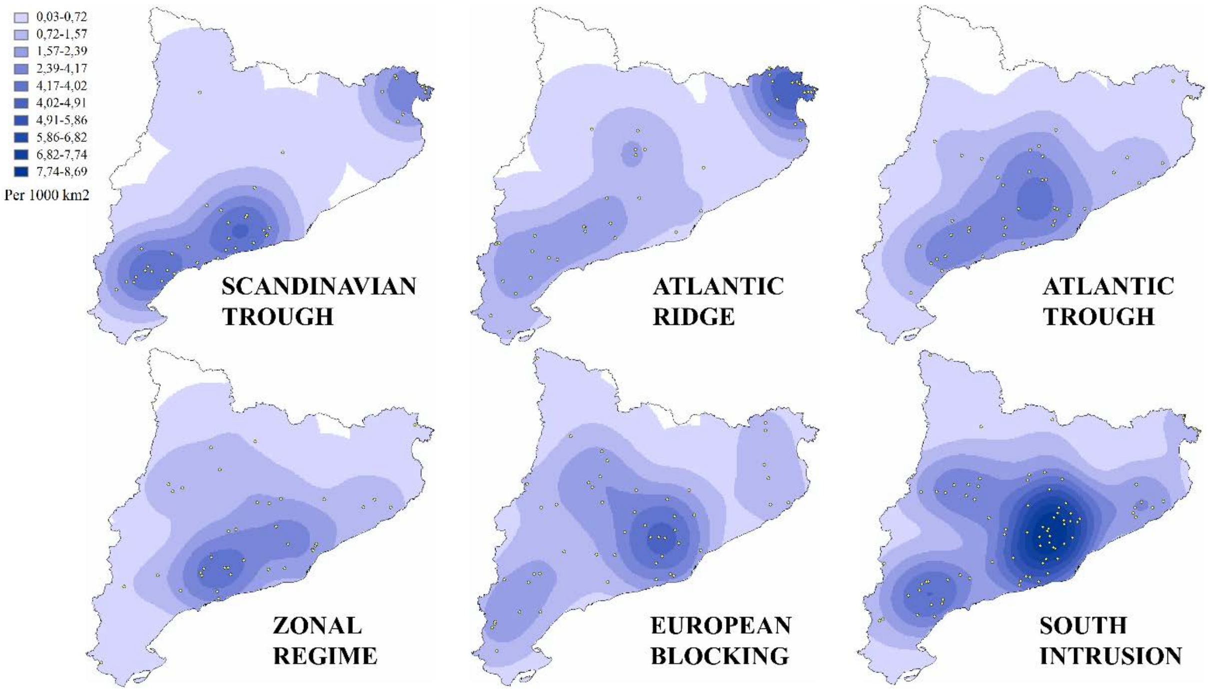


Figure 4. Kernel density maps of fire distribution for each SWT. Yellow points represent fire ignition location regardless of size. Spatial resolution is 1 km, and kernel radius influence is 50 km.

Classification of non-fire days and temporal trends

We obtained a general overview of fire-prone summer conditions each year from the classification of non-fire days. The situation bringing the most fire days per year was the *European blocking* SWT, with a mean of 23.7 days per year, whilst the less frequent was the *Atlantic ridge* SWT with 14.03 days per year. The Mann-Kendall test (Hirsch et al., 1982) confirmed that the only SWT with a significant trend was the *Atlantic trough* SWT, which has increased in frequency since the beginning of the 1980s (Sen's Slope: 0.3125 year^{-1}; Figure 5 and Table A.2).

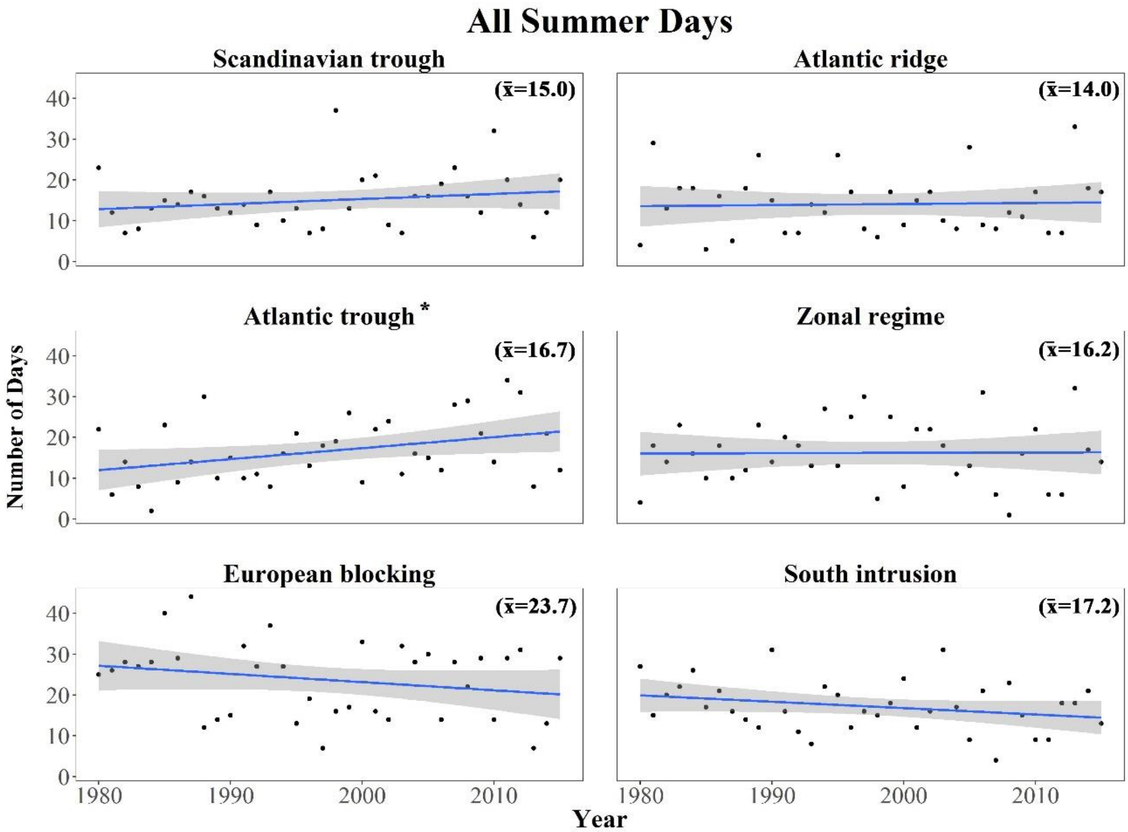


Figure 5. Temporal evolution of SWT number of days for both fire and non-fire days together. The line plots the linear trend with a 95%CI. The average number of SWT days per year is indicated in the top right area of each panel. An asterisk next to the SWT name indicates where the trend is significant at $p<0.05$.

On the other hand, the number of days with LWF has significantly decreased for some SWT, particularly the *Zonal regime* SWT and the 'hot-and-dry' situations (*European blocking* and *South intrusion* SWT; Figure 6 and Table A.2). For instance, only 3 days have led to LWF under the *Zonal regime* SWT since 1998. The trend in number of fire days has not changed during the period for the three wind-dominated groups (*Scandinavian trough*, *Atlantic ridge* and *Atlantic trough* SWT).

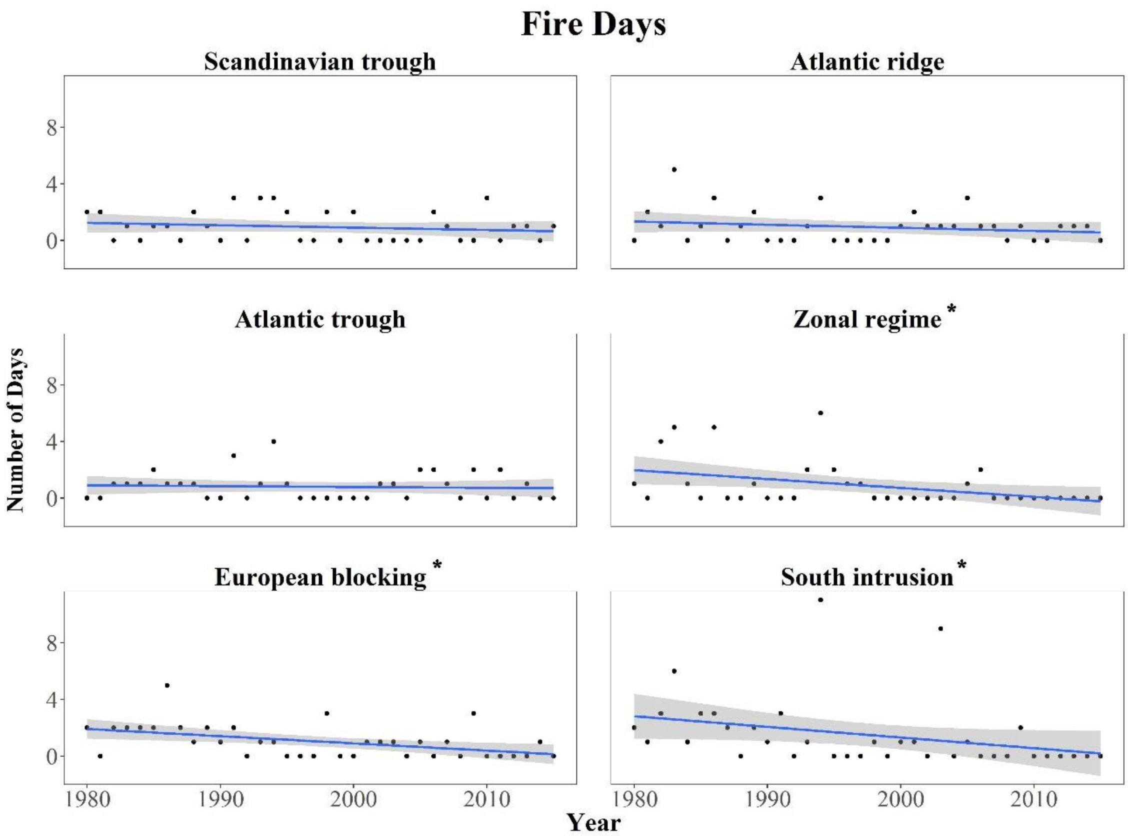


Figure 6. Temporal evolution of SWT number of days for fire days. The line plots the linear trend with a 95%CI. An asterisk next to the SWT name indicates where the trend is significant at $p<0.05$.

Finally, to interpret the trends of fire days regardless of the evolution of all summer days, we assessed temporal changes in the proportion of fire-days during the summer season. This proportion showed a similar pattern to fire days, since it decreased for *Zonal regime*, *European blocking* and *South intrusion* SWT but remained stable for the three windy groups (Figure 7).

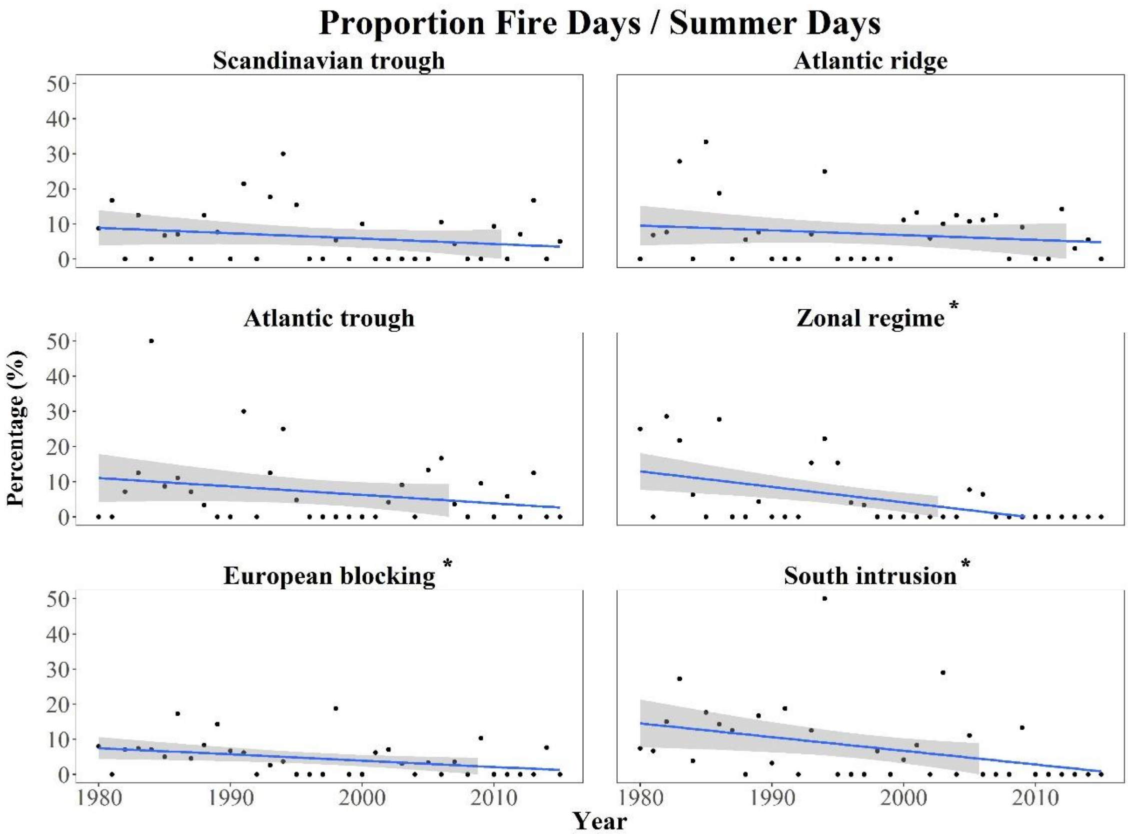


Figure 7. Temporal evolution of the relation between fire days and all summer days for each SWT. The line plots the linear trend with a 95%CI. An asterisk next to the SWT name indicates where the trend is significant at $p<0.05$.

Fire size distribution for SWT

Fire sizes within each SWT followed a power-law distribution (Cui and Perera, 2008). The power-law distribution follow a negative linear relation between log(N>S) and log(S), where N>S is the number of fires with size greater than a given size S. We fitted the power-law distribution for the four different groups within each SWT (mild years and low firefighting capability, dry years and low firefighting capability, mild years and high firefighting capability, dry years and high firefighting capability).

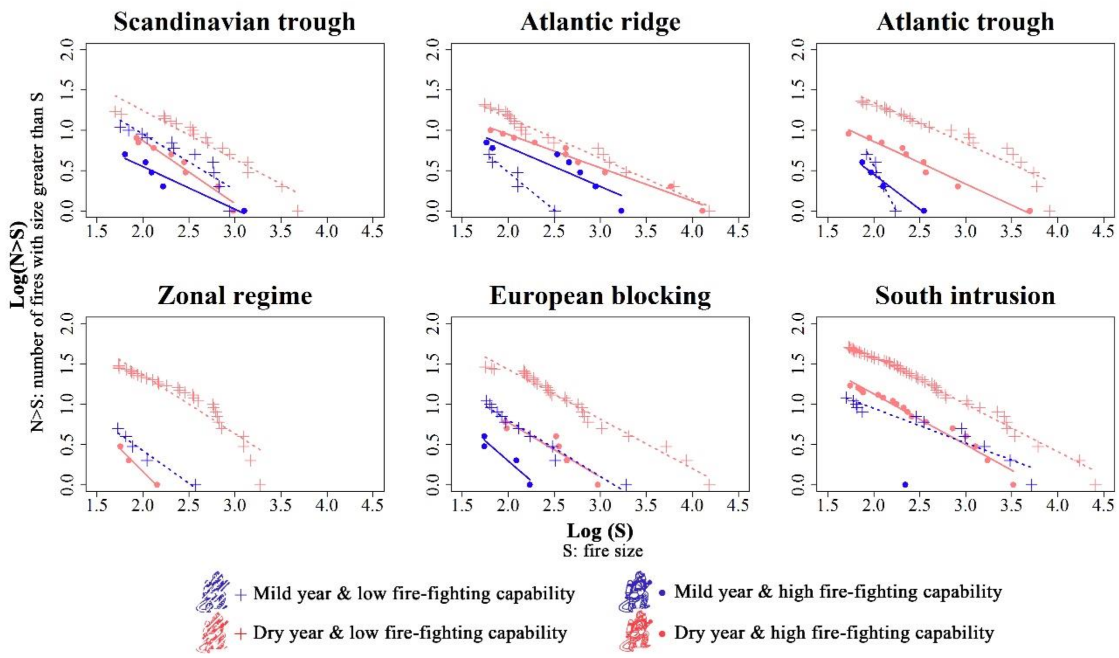


Figure 8. Power-law distributions for each SWT, separated between dry years (red) and mild years (blue). Points show actual values and lines correspond to the fitted linear model for each distribution.

As expected, fire size distributions with more and larger fires corresponded to dry years with low firefighting capability in all SWT (Figure 8). Fire sizes showed significant differences ($p<0.1$) in the distributions between the four combinations of drought and firefighting capability in all SWT (Table A.3), and highly significant differences within the *South intrusion* SWT ($p<0.005$). Fire regime within the *Scandinavian trough* SWT was more affected by firefighting capability than drought conditions: fires were larger in mild years with low firefighting capability than in dry years with high firefighting capability (Figure 8). In contrast, fires occurring during the *Atlantic ridge* and *Atlantic trough* SWT were larger in dry years with high firefighting capacity than in mild years with low firefighting capacity. Within the *Atlantic trough* SWT, fewer and smaller fires occurred under mild conditions. Note that under the *Zonal regime* and *South intrusion* SWT, fires occurring under mild conditions with high firefighting capability practically disappeared (only one case recorded in *South intrusion* SWT conditions). Fires occurring under *European blocking* and *South intrusion* SWT in dry years with high firefighting capability showed a very similar fire size distribution to fires occurring in mild years with low firefighting capability. Overall, firefighting capability had a lower incidence on fire size decrease during wind-dominated SWT (*Scandinavian trough*, *Atlantic ridge* and *Atlantic trough*) than under other SWT.

DISCUSSION

The goal of this study was to analyze climatic patterns in the initiation and spread of LWF and assess key fire regime attributes arising from the categorization of prevailing weather conditions. To this end, we focused on Catalonia, an area located in the western Mediterranean Basin. The study found strong differences in fire regime descriptors under different SWT, supporting the idea that SWT classification offers a useful and valuable way to classify wildfire in order to enhance our ability to understand changes in fire regimes and guide operational fire risk prevention. Note that although this study is not the first to classify fires into synoptic groups, we go a step further to provide spatially explicit information on the influence of each synoptic situation, analyze temporal trends for each fire of the SWT groups separately, and assess how the interplay of SWT, drought conditions and suppression efforts determines fire regimes.

Weather conditions related to large wildfires

The resulting SWT showed a range of similarities with other studies (Lázaro et al., 2016; Ruffault et al., 2016b) but specificities within our study area. The *Scandinavian trough* SWT was characterized by the occurrence of strong northwestern wind spells in the British Isles–Gulf of Lion corridor, where the relative position of the Azores high with the low-pressure area over the Baltic Sea accelerated wind from the North-Atlantic Ocean. Instead, the *Atlantic ridge* SWT induced fast northerly wind spells in North-Eastern Catalonia for the barometric gradient created in the eastern Azores high. The North and North-West wind is usually very dry (Montserrat-Aguadé, 1998) and favors wind-driven fires (Duane et al., 2015). Low temperature in these situations might hamper fuel ignitability, but once the flame has started, intense winds pose big difficulties for fire suppression efforts (Costa et al., 2011; Jin et al., 2014). The fewer fires in central Catalonia in both the *Scandinavian trough* and *Atlantic ridge* SWT may be explained by orographic wind shadowing from the Pyrenees. The highest density of fires occurring in the *Atlantic ridge* SWT were located in the eastern extreme of the Pyrenees. Given a North wind situation, the mountain range acts as a barrier, and accelerates wind in the flanks of the range (Peña et al 2011), which provokes fast winds in northeastern Catalonia where the Pyrenees reach the sea. In return, Southern Catalonia became the most affected area in the *Scandinavian trough* SWT. The northwesterly flow can also penetrate through the westernmost end of the Pyrenees (the Cantabrian end). The entrance of the flow is channeled through the Ebro river valley and accelerates even more until the river mouth, in southern Catalonia, where the strongest winds can gust at 150 km/h. Since these strong winds repeatedly affect the area, they result in the highest fire recurrence in Catalonia (Díaz-delgado et al., 2004; Loepfe et al., 2011).

The *Atlantic trough* SWT entailed westerly winds with traveling low-pressure systems in Catalonia. It included both unstable rainy situations and strong westerly winds (which locals call 'Ponentades'). In the international literature, cyclonic conditions have also been significantly linked with fire development (Levin and Saaroni, 1999; Paschalidou and Kassomenos, 2016). Cyclonic situations are prone to convection, which will be promoted by atmospheric instability if there is a large temperature differential between the two air masses involved and extreme turbulence due to lee-side troughs and breezes. This situation is a major factor in the development and spread of convective fires, where fire creates its own environment and spreads by massive spotting (Duane et al., 2015; Pyne et al., 1996; Rothermel, 1983), all further promoted by atmospheric instability (Quílez, 2009). Westerly winds often arrive in Catalonia under the Foehn effect after crossing the whole Iberian Peninsula (800 km), resulting in strong gusty, warm and very dry 'Ponentades' (Millan et al., 1998). Moreover, they tend to block humid sea breezes from entering inland, thus reinforcing the dry atmosphere which directly increases fire-prone environments. Westerly winds do not find any perpendicular orographic barrier when reaching Catalonia, meaning that Central Catalonia and the coastal area become the most affected fire zones.

The *Zonal regime* SWT atmosphere was characterized by anticyclonic circulations with a lack of weather fronts (Clavero and Raso, 1980; Montserrat-Aguadé, 1998). The absence of wind at high levels over Catalonia translated into loose winds of variable direction at the surface. Thus, orographic relief together with the relative position of landscape with regard to the sea coast influence local winds (katabatic and anabatic winds). Without strong weather determinants, fires occurring under this situation were not very large, and occurred at locations scattered across the entire region.

The synoptic types distinguished by the hottest and driest conditions were the *European blocking* and the *South intrusion* SWT. The *European blocking* SWT was characterized by high pressures in Southern and Central Europe leading to hot days in the Iberian Peninsula. High pressures can lead to the development of large fires (Crimmins, 2006; Paschalidou and Kassomenos, 2016; Pereira et al., 2005), as in summer they involve hot dry air desiccating the land. In Catalonia, terrestrial warms coming from surface air heat-up create low pressures that may generate instability and convection (Millan et al., 1998), and promote the convective fires discussed above. Furthermore, daily variations in land air temperature coming from this surface-air heat-up induce sea breezes and thermal winds, which play a fairly relevant role in wildfire development (Costa et al., 2011; Duane et al., 2015). Due to the blocking nature of this SWT, *European blocking* SWT episodes usually lasts for several days, thus exacerbating low fuel moisture conditions and increasing fire risk at the end of the episode (Russo et al., 2017). The *South intrusion* SWT also includes what other works have termed ‘heat waves’ (Cardil et al., 2015; García-Herrera et al., 2005). Advection from the Saharan air mass provokes an increment of air temperature at 850 hPa equal to or higher than 20°C, which involves high temperature and low moisture at surface (Cardil et al., 2015; Montserrat-Aguadé, 1998). Under very hot dry days, wildfires are easy to initiate and propagate, since fuel gets desiccated and becomes more available to burn. High fuel availability also helps create convective fires, which become very large fires that are difficult for fire suppression brigades to control (Costa et al., 2011). LWF during heat-wave events have burned thousands of hectares across multiple ecosystems in the Mediterranean region (e.g. 1994 in Spain, 2003 in Portugal, 2007 in Greece; Cardil et al., 2014). Both the *European blocking* and *South intrusion* SWT produce higher fire occurrence in Central and Southern Catalonia, where broad amounts of fuel have accumulated over the past decades in the wake of land abandonment processes (Duane et al., 2015; Pausas and Fernández-Muñoz, 2011; Poyatos et al., 2003). The Aleppo pine (*Pinus halepensis)* forests present in the area might facilitate ignitability and spread under these hot situations (Gil-Tena et al., 2016; Keeley et al., 2012).

SWT and fire regimes

LWF frequency has decreased in Catalonia in the past few years (Brotons et al., 2013; Turco et al., 2013). Weather conditions promoting wildfires have not decreased over the years, but the increasing effectiveness of prevention and suppression have reduced the amount of large fires in many regions of Southern Europe (Turco et al., 2017). However, our analysis of the specific evolution of wildfire days for each SWT shows that not all fires showed the same trend. The number of LWF under *Zonal regime*, *European blocking* and *South intrusion* SWT (i.e. those characterized by hot and dry conditions) have decreased significantly regardless of the change in non-fire days. In mild conditions with high firefighting capability, LWF have virtually disappeared during *Zonal regime* and *South intrusion* SWT and only 4 LWF were reported during *European blocking* SWT. Mild weather conditions during these SWT made it easier for firefighters to bring fires under control. As already mentioned, key enhancements of firefighting capacity have allowed technical fire brigades to anticipate changes in fire propagation (Brotons et al., 2013; Costa et al., 2011) and reduce final total burnt area since 2000. The changes in fire control are especially noticeable in these types of SWT under mild conditions. Nonetheless, during dry years, firefighters still struggle to control fires, even though they have managed to significantly reduce fire sizes with respect to pre-2000. The current fire regime in dry years is very similar to the pre-2000 fire regime in mild years under the *European blocking* and *South intrusion* SWT.

Fires occurring under the *Atlantic ridge*, *Scandinavian trough* and *Atlantic trough* SWT (i.e. the wind-dominated SWT) did not show a different trend to that presented by the non-fire days. The lack of independent correlation suggested that these fires are still influenced by the frequency of these weather situations. Fire suppression effectiveness depends on weather, accessibility and terrain, and the current limit of fire suppression brigades in Catalonia is of 3-meter-high flames or a rate of spread of 2 km/h (Costa et al., 2011). Fast fires driven by wind can spread at more than 6 km/h and quickly overwhelm suppression capacity, which is why there has been no reduction in large wind-driven fires in recent years, in contrast with fires occurring during hot-and-dry days. Convective fires also pose difficulties for firefighters, but since convective fires need a certain release of energy before reaching their 'fire weather' environment (Rothermel, 1991), they need time to develop the convective behavior. The improved fire detection and fast suppression during recent years (San-Miguel-Ayanz et al., 2013) has meant that potential convective fires have been swiftly controlled, and ultimately prevented from actually occurring. In contrast, wind-driven fires become uncontrollable right from the early stages of propagation, keeping them beyond firefighting capacities.

The fire regime on windy days is still highly dependent on weather determinants and are difficult to suppress, especially under the *Atlantic ridge* and *Atlantic trough* SWT where fires are large and frequent in dry years. Firefighting capabilities may be high, but humans play a weaker role in controlling fires in areas affected by these kind of SWT in dry years than in other areas and situations (Duane et al., 2015). Similarly, the dominant effect of meteorology on regions dominated by wind-driven fires raises questions over efforts to reduce fires by fuel management (Duane et al., 2015; Jin et al., 2014; Keeley et al., 1999). Firefighters have made more progress decreasing dry-year fire sizes during *Scandinavian trough* SWT episodes than the other two wind-dominated SWT. This may be because the incidence of *Scandinavian trough* SWT is mainly located in Southern Catalonia, an area marked by heterogeneous relief. Given an enhanced firefighting capability to use landscape opportunities (i.e. areas of local low fire spread) to stop fires, firefighters have been able to reduce final fire sizes in this region in lee slopes, ravine junctions, etc., unlike in areas to the North where softer reliefs have hampered firefighters' efforts to control fires sooner. This points to a complex interaction between climate, weather, fire suppression and topography in determining final fire sizes.

Although other studies have demonstrated an increase of summer heat waves in various Mediterranean regions (Cardil et al., 2014; Giorgi and Lionello, 2008; Moriondo et al., 2006), our data does not support the same trend. This may be because temperature was not the only descriptor used here to characterize our situations. Another factor behind these differences might be that our clusters summarized the centroid of the fires occurring in similar situations, and might have softened extreme heat waves (temperature at 850 hPa of 25°C or more). When projecting temporal trends, extreme days (>25°C) might be hidden in the noise group, and not reflected in the *South intrusion* SWT trends. However, climate-change projections for the Mediterranean Basin show an increase in extreme weather events, with longer, more frequent, and even more intense heat waves (Giorgi and Lionello, 2008; IPCC, 2014; Moriondo et al., 2006), along with an increase in frequency of long droughts in Southern Europe (Giorgi and Lionello, 2008). Some studies have proved that the occurrence of droughts in southern Europe during the preceding spring can enhance the amplitude of heat waves in the following summer (Fischer et al., 2007), implying that droughts and heat waves are closely related (Trigo et al., 2013). On the other hand, the results of this study would suggest that the percentage of total burnt area under the different SWT might change from past trends, and fires occurring under windy situations could account for the majority of burnt area in the next few years due to weakened control by fire suppression systems. Even so, the current Achilles heel of fire suppression units is collapse under simultaneous fires in extreme weather conditions (Marc Castellnou, head of the firefighters service in Catalonia; personal communication). In the global change context, situations like this cannot be ruled out. Efficient fire management aiming to avoid catastrophic events should consider the type of fires potentially affecting each local subregion. For example, in Central Catalonia, an area mostly affected by hot and dry SWT, fire management should increase efforts to reduce fuel amount in order to avoid convective fires. One possibility here is to recuperate fires burning under mild weather conditions which have been eliminated, and thus potentiate a landscape mosaic with old fire patches that firefighters can use as suppression opportunities (Regos et al., 2014). Ultimately, fire-smart management (Fernandes, 2013) should be promoted in Mediterranean regions according to the relative incidence and projections of the different SWT, which have been shown to follow different patterns of change in response to different drivers of global change.

CONCLUSIONS

Here we presented a characterization of SWT according to large-scale atmospheric conditions that allowed to identify weather patterns leading to wildfires. Fires occurring under the different SWT exhibited distinct spatial patterns and evolution, raising prospects for further targeting management strategy based on local fire regime. It is crucial to not consider all fires equally, since not all fire types evolve in the same way. Enhanced firefighting capability has eliminated fire occurrences during mild years under 'hot-and-dry' SWT and reduced fire sizes in dry years. In contrast, fires occurring under wind-dominated situations are still the most difficult to control and have not diminished in incidence over time.

It was possibly to depict weather conditions via the use of few variables that represented large-scale conditions. Aggregating a number of weather variables at continental scale often better predicts certain ecological processes than any of the component variables considered individually or combined. To operationalize the SWT framework, sub-classifications could be implemented to improve predictability of fires under specific local conditions. Moreover, other studies should explore the role of cumulative effects of SWT occurring more than one day in a row.

The methodology presented here is not intended to replace other fire weather prediction tools, but rather to complement them and, mostly, to better understand how SWT determine fire history. We believe that this characterization of SWT is necessary in the current fire regime change context occurring in the Mediterranean Basin. These SWT patterns can serve researchers and managers to help develop better fire spread analyses based on sound physical grounds and, combined with fire management, help explain current fire dynamics in the area. Our synoptic-scale atmospheric variables are well reproduced by circulation models and can serve to understand fire regime changes in the wider context of climate change. Future fire projections should integrate the role of SWT as a determinant of wildfire activity.

ACKNOWLEDGMENTS

This study was funded by the Spanish Government through the FORESTCAST (CGL2014-59742-C2-2-R), and the ERA-NET FORESTERRA project INFORMED (29183). The research leading to these results has also received funding from “la Caixa” Banking Foundation and from the CERCA Programme from Generalitat de Catalunya. Andrea Duane was funded by the Ministerio de Educación, Cultura y Deporte (Spain) (FPU13/00108). We thank the Servei de Prevenció d’Incendis de la Generalitat de Catalunya for providing fire ignitions data, and the Firefighting Services of Catalonia for their constant support. We also thank Aitor Ameztegui and Jordi Pagès for their kind help on reviewing the manuscript.

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SUPPLEMENTARY MATERIAL CHAPTER 3

Supplementary material A. Complementary methods and results

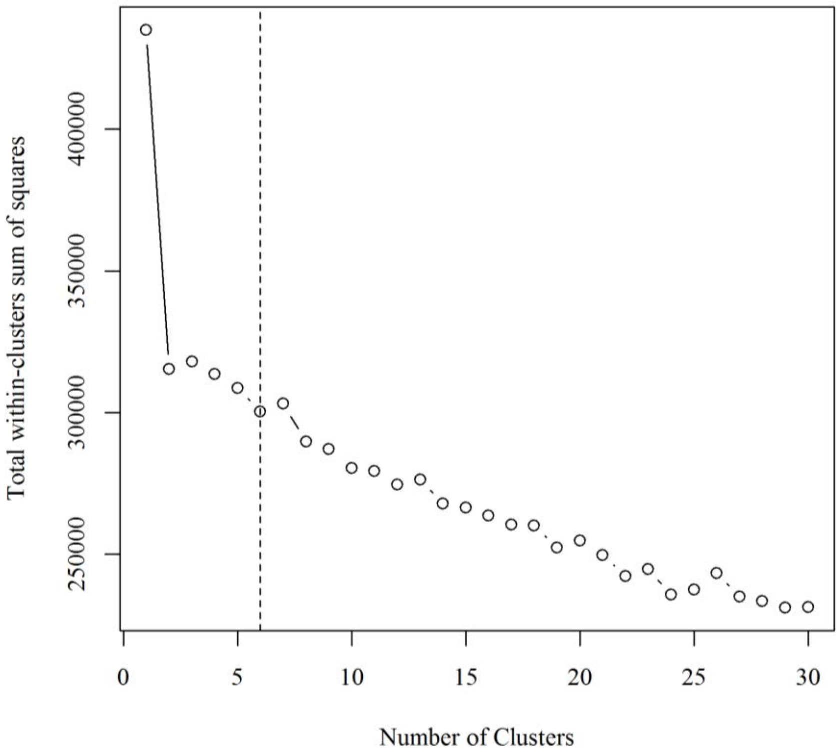

Figure A.1. Assessment of the optimal number of clusters with the Elbow method. The vertical line represents the chosen number of groups in the present study (6).

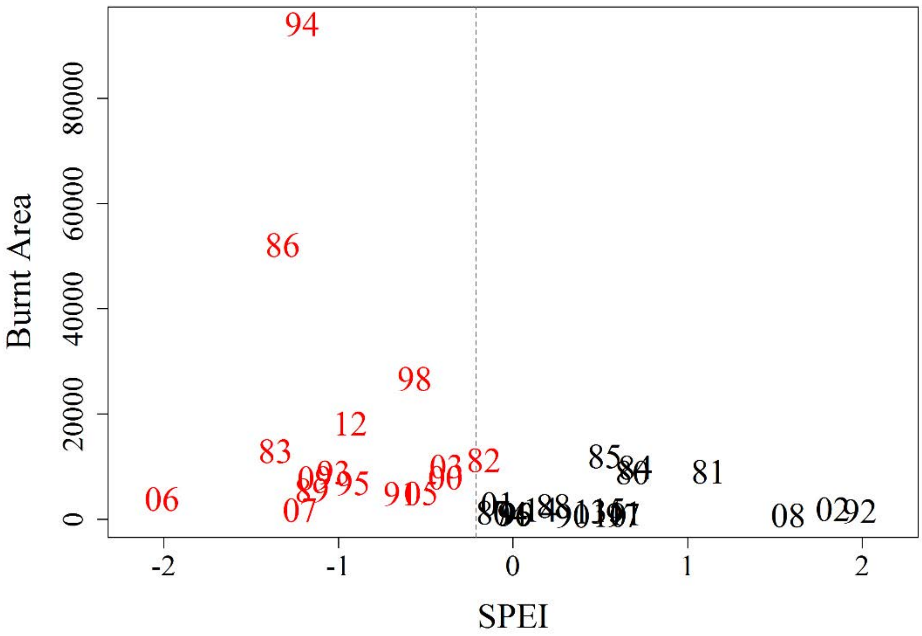

Figure A.2. Separation of years according to the Pettitt's test combining SPEI values and burnt area for each year. The vertical line shows the breakpoint at SPEI=-0.21. Red numbers represent dry years, and black numbers represent mild years.

Table A.1. Pearson's rho correlation values between kernel density maps in Figure 4. Orange indicates correlation values greater than 0.8, yellow between 0.7 and 0.8, and light yellow between 0.6 and 0.7. No color means correlation value under 0.6.

	Scandin-avian trough	*Atlantic ridge*	*Atlantic trough*	*Zonal regime*	*European blocking*	*South intrusion*
Scandinavian trough	-					
Atlantic ridge	0,721	-				
Atlantic trough	0,604	0,383	-			
Zonal regime	0,451	0,220	0,887	-		
European blocking	0,358	0,274	0,771	0,679	-	
South intrusion	0,322	0,158	0,857	0,750	0,887	-

Table A.2. Coefficients of the linear trends and tests results for temporal analyses on figures 5, 6 and 7. Bold numbers indicate significant trend at p<0.05

Group	Trends for…	Mann-Kendall Test	Sen's Slope	Sen's Intercept	Partial Correlation Trend Test	Partial correlation coefficient r(tx:z)
Scandina-vian trough	All Summer Days	0.2987	0.1144	12.5278		
	Fire Days	0.3496	0.0000	1.0000	0.1272	-0.2590
	Proportion Fire Days/Summer Days	0.2601	0.0000	4.6750		
Atlantic ridge	All Summer Days	0.9129	0.0000	13.5000		
	Fire Days	0.6281	0.0000	1.0000	0.5404	-0.1055
	Proportion Fire Days/Summer Days	0.9322	0.0000	5.7200		
Atlantic trough	All Summer Days	**0.0262***	**0.3125**	10.6875		
	Fire Days	0.6680	0.0000	1.0000	0.6677	-0.0741
	Proportion Fire Days/Summer Days	0.3191	0.0000	3.4500		
Zonal regime	All Summer Days	1.0000	0.0000	16.0000		
	Fire Days	**0.0093****	**0.0000**	0.0000	0.0052 **	-0.4563
	Proportion Fire Days/Summer Days	**0.0024****	**0.0000**	0.0000		
European blocking	All Summer Days	0.5477	-0.0917	27.7792		
	Fire Days	**0.0020****	**-0.0435**	1.6304	0.0021 **	-0.4966
	Proportion Fire Days/Summer Days	**0.0071****	**-0.1662**	6.0947		
South intrusion	All Summer Days	0.1719	-0.1429	19.2857		
	Fire Days	**0.0005*****	**-0.0500**	1.7000	0.0004 ***	-0.5627
	Proportion Fire Days/Summer Days	**0.0019****	**-0.2201**	7.5574		

Table A.3. Linear coefficients of Power-Law distributions from Figure 8. Distributions with the same letter within the SWT indicate lack of significant differences between them.

SWT	Climatic	Fire-fighting	Slope	Intercept	R-squared		P-value
Scandinavian trough	Dry	Low [a]	-0.6084	2.4623	0.9024	a	0.0109*
		High [b]	-0.7789	2.4284	0.9418	b	
	Mild	Low [b]	-0.6946	2.3423	0.8102	b	
		High [c]	-0.5294	1.6073	0.8857	c	
Atlantic ridge	Dry	Low	-0.5049	2.1663	0.9749	a	0.0057**
		High	-0.4129	1.7725	0.9698	a	
	Mild	Low	-0.9388	2.3554	0.9230	b	
		High	-0.4858	1.7604	0.7726	c	
Atlantic trough	Dry	Low	-0.5086	2.3604	0.9049	a	0.0154*
		High	-0.5264	1.9138	0.9615	b	
	Mild	Low	-2.3169	5.1918	0.9556	c	
		High	-0.8685	2.1896	0.9540	c	
Zonal regime	Dry	Low	-0.7318	2.8303	0.8815	a	0.0957·
		High	-1.1397	2.4460	0.9551	b	
	Mild	Low	-0.8052	2.0341	0.9384	b	
		High	-	-	-	-	
European blocking	Dry	Low	-0.6144	2.6592	0.9664	a	0.0527·
		High	-0.6769	2.1272	0.8161	b	
	Mild	Low	-0.6977	2.1985	0.9536	b	
		High	-0.9837	2.2639	0.8461	c	
South intrusion	Dry	Low	-0.5867	2.7588	0.9862	a	0.0000***
		High	-0.6312	2.3905	0.9601	b	
	Mild	Low	-0.4288	1.8072	0.8998	b	
		High	-	-	-	-	

CHAPTER 4

Climate-fuel feedbacks drive fire activity in dynamic Mediterranean landscapes

Andrea Duane, Luke Kelly, Kate Giljohann, Enric Batllori, Mick McCarthy and Lluís Brotons

This chapter is under review in Ecosystems

ABSTRACT

There is a need to understand the interplay between climate, fire and fuels. Here, we aim to investigate whether past fires limit fire activity by reducing fuel availability ('fire leverage') in Catalonia (NE Spain; 32,107 km^2), a Mediterranean region encompassing diverse landscapes of agricultural plains, and pine-oak mosaics. We built a hierarchical model to assess variations in annual burnt area in relation to weather, past fires and fire management for a 35-years period. The model also quantified how average wind speed and fuel structure modulated leverage. We found that the cumulated burnt area in the last 5-7 years preceding a year reduced the re-occurrence of fires. Annual burnt area increased with both dry weather conditions and the number of hot days (≥30º C) and declined with increasing fire suppression effort. Model outputs also suggested that landscapes with higher mean annual wind had lower leverage, and that landscapes with more fuel cover in continuous areas had higher leverage. Our results indicate that climate-fire relationships in Mediterranean landscapes are dynamic: past fires create fuel-limited periods in fire regimes usually limited by weather. In Catalonia, interactions between climate and fuels are shaped by anthropogenic influences, which have pushed the system towards a weather-dominated fire regime. Results also reveal that areas with intermediate levels of ecosystem productivity, such as Mediterranean biomes, are those most likely to display high fire leverage. Our work highlights the multiple factors regulating leverage and helps to understand the interplay between climate, vegetation, and recurrent fires in shaping fire regimes.

Keywords

Burnt area, Climate change, Dynamic landscapes, Fire management, Fire weather, Fire leverage, Forest connectivity, Hierarchical model, Mediterranean-type ecosystem, Wind-driven fires

Highlights

- Past fires create fuel-limited periods in fire regimes usually limited by weather
- Biomes with middle levels of ecosystem productivity are likely to display leverage
- Anthropogenic influences pushes the system towards weather-dominated fire regimes

INTRODUCTION

Global change is shifting fire regimes with consequences for people, biodiversity and ecosystems (Pausas and Fernández-Muñoz 2011; Brotons and others 2013; Moritz and others 2014; Kelly and Brotons 2017). In response, there is a need for research on the drivers of changing fire regimes such as climate, fire-weather and land use - and how they interact (Thompson and Calkin 2011; Fernandes 2013). Quantifying the drivers of fire regimes in areas around the globe will help to reduce uncertainty in a more fire-prone future (Parisien and Moritz 2009; Batllori and others 2013; Price and others 2015a).

The role of climate on fire activity has been suggested to change along a productivity/aridity gradient in which fuel availability and moisture shape fire-climate relationships at regional scales (Archibald and others 2009; Bradstock 2010; Krawchuk and Moritz 2011; Pausas and Paula 2012; Pausas and Ribeiro 2013). In the extremes of this gradient, fire regimes can be described as fuel-limited and moisture-limited fire regimes. In fuel-limited fire regimes, despite a high frequency of flammable conditions, low and fragmented fuels limit the development of large fires. In moisture-limited fire regimes where fuels are generally abundant and continuous, fire activity is limited by the sporadic occurrence of conditions conducive to fire (e.g., drought).

In moisture-limited fire regimes where fuels are generally abundant, fires may introduce a negative feedback process as previous fire events can create a time window during which subsequent fires are more governed by fuel limitations than by the occurrence of flammable conditions. As time since fire increases, and vegetation recovers after fire, fuel stops constraining fire spread and fire activity is once again controlled by climatic conditions. The concept of 'fire leverage' has been introduced to describe and quantify the inhibitory effects of past fires on future fires (Loehle 2004; Price and others 2015b).

Leverage is defined as the unit reduction in fire area resulting from one unit of previous fire as measured at a regional scale over a long period (Loehle 2004). Leverage integrates the chance that a given fire encounters a previous fire and reduces fire spread, and is influenced by the amount and arrangement of burnt areas and the rate of post-fire vegetation recovery (Price and others 2015b). The occurrence and strength of fire leverage may also depend on land use and environmental gradients – but these associations have been little studied. We predict that fire leverage will be higher in landscapes with high and continuous forest cover than in landscapes with scattered vegetation, where vegetation is already dispersed enough to prevent wildfires to occur. We also predict that areas subject to higher average wind speeds will have lower fire leverage because in fires driven by wind the role of fuel for fire spread is reduced (Keeley and others 1999; Moritz and others 2004; Duane and others 2015).

The interaction between fire dynamics and human drivers can also influence the strength of leverage and the ability to detect it. Specifically, in regions with strong fire suppression policies, the capacity of past fires to remain a barrier to fire spread is reduced by an overall reduction in burnt area. Indeed, the 'fire paradox' (Minnich 1983) claims that increased fire suppression leading to smaller fires, actually promotes large wildfire events under severe weather conditions due to the increased continuity of burnable patches. Therefore, the combined effect of fire management and land use changes may inflate the effect of climatic drivers (e.g., extreme weather events) over fuel-limitation processes (e.g., leverage) in many places.

How the interplay of landscape properties and fire management govern current and future fire regimes is still uncertain. Reducing this uncertainty is a prerequisite to forecast ecosystem dynamics and to develop effective fuel-control strategies under changing climates. In this study, we tested whether past fires limit fire activity across a broad Mediterranean region comprising a mosaic of agricultural plains, pine-oak forests and mountainous shrublands. We also explored if fire leverage is influenced by a fuel-continuity gradient and to average wind conditions. We tested these ideas using 35-years of data from Catalonia (NE Spain), a densely populated Mediterranean region with 60% of forest cover, where land-use changes, rural abandonment and high investment on fire suppression promoted a switch from a fuel-limited fire regime in the beginning of the 20th century to a currently moisture-limited (drought-driven) fire regime (Pausas and Fernández-Muñoz 2011; Brotons and others 2013; Otero and Nielsen 2017).

METHODS

Study area

Catalonia is located in the NE Iberian Peninsula and covers an area of approximately 32,000 km² (Fig. 1a). The climate of the region is Mediterranean, with hot dry summers, rainy springs and falls, and cold winters. The topography of Catalonia influences climate, weather and vegetation patterns. Average wind speed in the northern and southern Catalonia is higher than in the center (Gencat 2004). The strongest winds can gust at 200 km/h (Liberato and others 2011). Sixty percent of the study area is covered by forest and shrublands (Fig. 1b). Dominant tree species are pines (*Pinus halepensis*, *Pinus nigra*, *Pinus sylvestris, Pinus uncinata* and *Pinus pinea*) and Holm oaks (*Quercus ilex* and *Quercus suber*). Forest cover in Catalonia has increased considerably since the middle of last century, mostly due to farmland abandonment and subsequent afforestation (Puerta-Piñero and others 2012).

Fire return intervals in Catalonia currently range from 60 to 400 years for homogeneous fire regions of about 45,000 ha (Pique and others 2011). Annual burnt area is highly variable, with the largest areas burnt in 1986 (65,000 ha) and 1994 (82,000 ha). Most of the burnt area is caused by a few large fires and most fires occur in summer (June-September). Stand-replacing fires are the most widespread type of fire in Catalonia, with >85% of the burnt area being affected by crown fires. The prevalent fire management strategy in Catalonia is fire suppression, and firefighting investment has increased six-fold since the early 1980s (Otero and Nielsen 2017). A decreasing trend in the number and size of fires has been observed after the big fires that occurred in 1986 and 1994, mainly explained by increased fire prevention and suppression (Brotons and others 2013; Turco and others 2013; Duane and Brotons 2018).

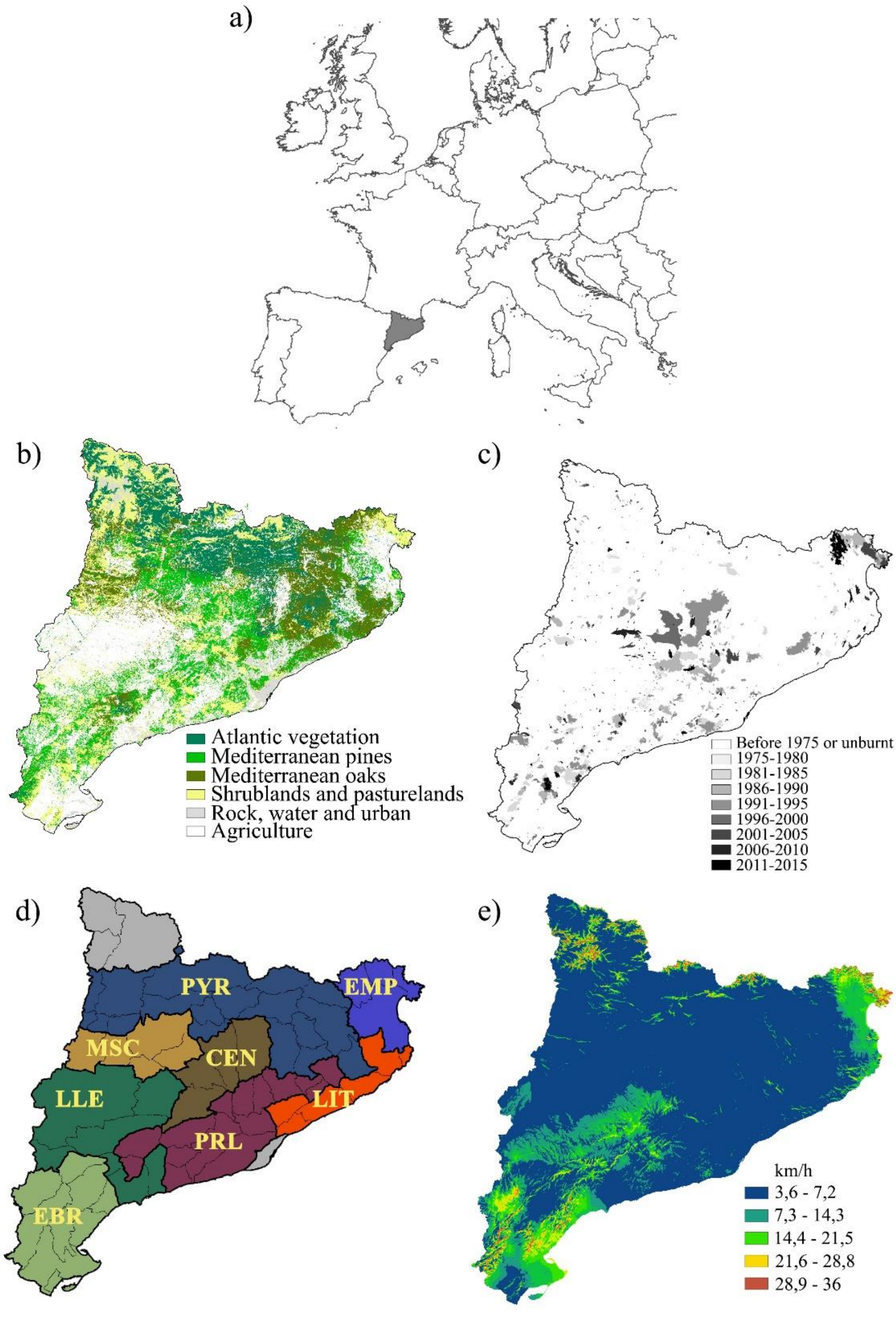

Figure 1. a) Location of Catalonia (dark grey) in Europe; b) Land Cover Forest Map from year 2000); c) Fire history, d) Fire Regime Zones (FRZ) and e) Mean annual wind map. In d), thin lines in within each FRZ are the original homogeneous areas that FRZ are clumped from. Regions without name are excluded from the analyses. PYR: Pyrenees, EMP: Empordà, MSC: Montsec, CEN: Central, LIT: Litoral, LLE: Lleida, PRL: Prelitoral, EBR: Ebre.

Fire history data

We collected fire data from two sources. For the period 1986-2015, official fire history mapping was sourced from the Catalan Government agency responsible for wildfire prevention (*Servei de Prevenció d'Incendis de la Generalitat de Catalunya*). For the period 1975-1985, data were sourced from Díaz-Delgado and others (2004), who mapped fire scars using Landsat imagery. Minimum fire size detected before 1992 was 10 ha, while after 1992 it was 1 ha (Díaz-Delgado and others 2004; Turco and others 2013). The combined fire data set (1975-2015) comprises 865 fires that burnt a total of 409,939 hectares (Fig. 1c).

Based on previous work in Catalonia (Pique and others 2011), we used spatial clustering to group the study area into ten Fire Regime Zones (FRZs) with similar vegetation types, wind speed and direction, orography and burnt area rates (Fig. 1d). We excluded two FRZs from our analysis: 1) Barcelona, an urban area that has experienced few fires, and 2) High-Pyrenees, an area with unique vegetation types. The eight FRZs included in the analysis ranged from 171,477 to 766,843 ha (av. 369,088 ha).

We modelled annual burnt area in each FRZ as a function of environmental and land use variables. The annual area of burnt forests (hereafter 'forest' includes woodlands and shrublands) was calculated each year from 1980 to 2015 in each FRZ by overlaying annual fire perimeters with forest cover maps.

Predictors of Annual Burnt Area

We categorized predictors of annual burnt area into dynamic variables that changed each year and across FRZ regions ('*Dynamic-variables'*) and static variables that were constant over time but varied among regions ('*Landscape-attributes*').

We used four '*Dynamic-variables'*:

- *BurntPreviously* represented the percentage of forest burnt in previous years. The effect of *BurntPreviously* on annual burnt area is thus a measure of fire leverage. We calculated *BurntPreviously* for cumulative time periods from 1 to 20 years before each year.
- *Wetness* represented water balance conditions defined by the Standardized Precipitation-Evapotranspiration Index (SPEI; Vicente-Serrano and others 2010;

Russo and others 2017). The index measures how water balance (precipitation minus potential evapotranspiration) at a point in time deviates with respect to the long-term water balance, with high and low SPEI values indicating wet and dry conditions, respectively. For each year, we used the SPEI values for the period of peak fire activity in the study region (July) and calculated the cumulative water balance three months before the date (Pereira and others 2005; Russo and others 2017). SPEI was gathered at a 0.5º x 0.5º spatial resolution.

- *HotDays* represented fire-weather conditions. We calculated the number of hot days (≥30º C) in July and August in each region and each year. Temperature data were obtained at 1 km^2 spatial resolution (De Caceres, M., Unpublished Data).
- *Year* represented the long-term trends in annual burnt area (Bradstock and others 2014). In Catalonia, increased resource investment and efficiency in firefighting has decreased final fire sizes over time (Brotons and others 2013; Turco and others 2013).

Landscape-attributes

We modelled how two *Landscape-attributes* modulated the effect of the *Dynamic-variables* on burnt area.

- *MeanWind* represented average wind conditions in each region. We used the Wind Map of Catalonia (Gencat 2004) calculated at 200 m resolution and averaged this value within each region (Fig. 1.e).
- *MedVegAggregation* represented the amount and connectivity of Mediterranean-type vegetation within the agricultural matrix and includes woodlands dominated by six major species (*Pinus halepensis*, *Pinus nigra*, *Pinus pinea*, *Quercus suber*, *Quercus faginea* and *Quercus ilex*) and shrublands. In Catalonia, Mediterranean-type vegetation is the most flammable and frequently burnt vegetation type compared to grassland, agricultural land and alpine vegetation (Díaz-Delgado and others 2004). We calculated the aggregation of Mediterranean-type vegetation in FRAGSTATS (McGarigal and others 2012) as the ratio of the observed number of like adjacencies (i.e. contacts between pixels of Mediterranean-type vegetation) and the maximum possible number of like adjacencies given *Pi* (*Pi* being the proportion of the landscape representing Mediterranean-type vegetation; He and others 2000). This index ranges from 0, when there are no like adjacencies and

thus vegetation is maximally disaggregated, to 100, when Mediterranean-type vegetation is clumped into a single patch. To compute *MedVegAggregation* we used the most recent land-cover map of Catalonia (Gil-Tena and others 2016) to account for the recent increase in forest cover across the area (Martín-Martín and others 2013).

Regression modelling

We fitted a hierarchical regression model to estimate the effect of the *Dynamic-variables* and *Landscape-attributes* on annual burnt area. Hierarchical modelling helps explore how dynamic variables that vary each year are modulated by more static attributes of the landscape. The model is defined as:

Eq.1

$$\log(BurntArea_t) = \beta_0 + \beta_1 \log(BurntPreviously) + \beta_2\, Wetness + \beta_3\, HotDays + \beta_4\, Year + (1|FRZ)$$

Eq.2 $$\beta_{[1-3]} = \gamma_{0_{[1-3]}} + \gamma_{1_{[1-3]}}\, MeanWind + \gamma_{2_{[1-3]}}\, MedVegAggregation$$

Where Eq.1 incorporates the effects of the four *Dynamic-variables* and Eq.2 the modulating effects of the two *Landscape-attributes* on each of the regression coefficients β_1, β_2 and β_3.

FRZ was incorporated as a random effect, with the intercept allowed to vary per zone. All predictor variables were standardized by subtracting the mean and dividing by the standard deviation. '*BurntArea*' was log-transformed to meet the assumption of normality in model residuals. Analysis started at 1980 and included past fires from 1975 to 1979, so regression modelling used 288 data points corresponding to eight FRZ and 36 years (period 1980-2015). Because there were no fires at the resolution of our spatial data in 58 of 288 registers, we randomly assigned a value of annual burnt area between 1 and 9 hectares (smaller than the minimum recorded fire size) to each register without fire records. This enabled the data to be log-transformed and the inclusion of years of low fire activity in the analysis.

We ran 20 alternative versions of the model by varying the cumulative amount of years in the variable *BurntPreviously* (from 1 year up to 20 years). If *BurntPreviously* referred to cumulated time periods larger than 5 years, data points were subsequently reduced one year (from 1980 through to 1994). When comparing the 20 models, we standardized the variable *BurntPreviously* for all models using the mean and standard deviation calculated with all data points. Hierarchical models were fitted in the package 'lme4' ver.1.1-12 (Bates and others 2015) in statistical software 'R' ver-3.3.0 (R Core Team 2016). Model and plotting code followed Pollock and others (2012).

RESULTS

We found evidence of fire leverage: *BurntPreviously* was negatively and significantly associated with annual area burnt (Fig. 2). The reduction in annual burnt area attributable to *BurntPreviously* depended on the cumulative number of years considered (Fig. 2). *BurntPreviously* had the strongest effect on annual area burnt calculated using the preceding 7 years. When *BurntPreviously* was defined by smaller (<4 years) or longer (>8 years) periods its effect was weaker and more uncertain (Fig. 2). In all models, *Wetness* had a negative influence on burnt area indicating larger burnt areas in drier years, and *HotDays* had a positive influence (Table 1). Annual burnt area declined over time across Catalonia, having a higher uncertainty models built with *BurntPreviously* defined by >11 years window (Table 1). The exploration of the effects of static and dynamic variables on fire leverage described below derive from a model with *BurntPreviously* defined by a 7-year period, that presented a deviance explained by fixed effects and random effects of 23% and 49%, respectively (model assumptions were meet (Fig. S1.1), with an overdisperson value of 3.43 and variance-inflation factor of 1.29).

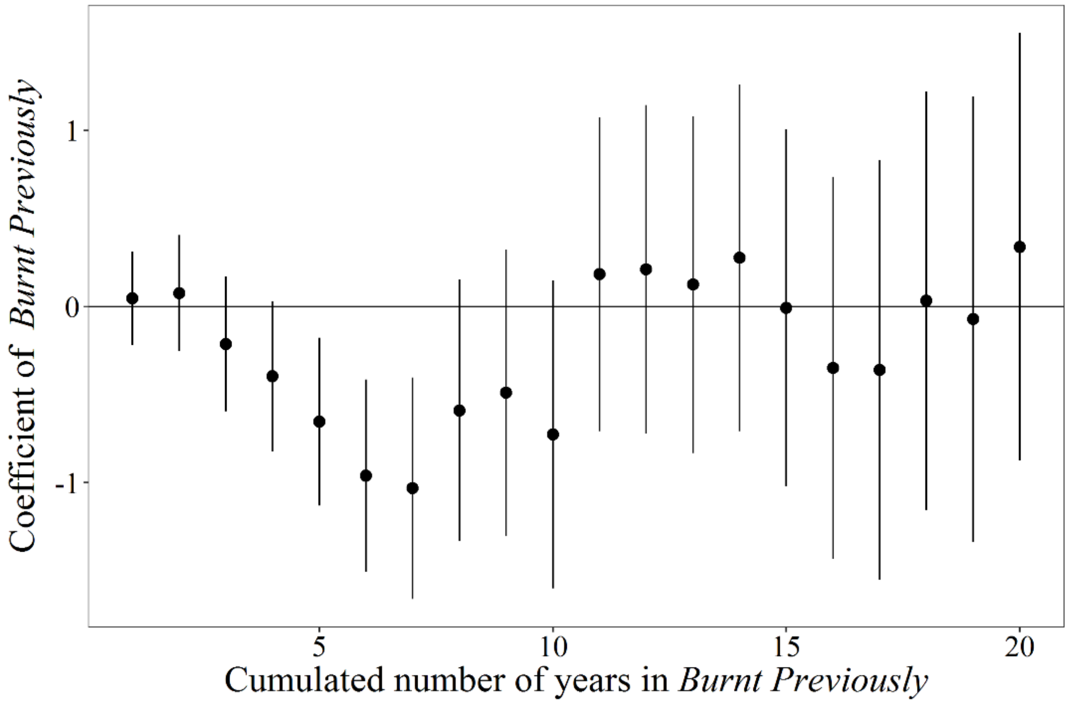

Figure 2. Fire leverage (i.e. effect of *BurntPreviously* on annual burnt area) for the different time periods that the variable *BurntPreviously* accounted for. Dots indicate the coefficient and error bars show 95% confidence intervals. Data were standardized for all models using the empirical distribution from model 1-year.

Table 1. Coefficients of the 20 models

Cumulative period for *BurntPreviously*	***BurntPreviously***			***Wetness***			***HotDays***			***Year***		
	Coefficient	Low CI95	High CI95	Coefficient	Low CI95	High CI95	Coefficient	Low CI95	High CI95	Coefficient	Low CI95	High CI95
1 year	0.05	-0.22	0.31	**-0.75**	**-0.99**	**-0.51**	**0.41**	**0.08**	**0.74**	**-0.69**	**-0.94**	**-0.45**
2 years	0.08	-0.26	0.41	**-0.76**	**-0.99**	**-0.52**	**0.39**	**0.06**	**0.72**	**-0.68**	**-0.93**	**-0.43**
3 years	-0.21	-0.59	0.17	**-0.77**	**-1.00**	**-0.53**	**0.36**	**0.04**	**0.69**	**-0.73**	**-0.98**	**-0.48**
4 years	-0.40	-0.82	0.03	**-0.76**	**-1.00**	**-0.53**	**0.36**	**0.03**	**0.69**	**-0.77**	**-1.02**	**-0.52**
5 years	**-0.65**	**-1.13**	**-0.18**	**-0.77**	**-1.00**	**-0.54**	**0.39**	**0.07**	**0.72**	**-0.84**	**-1.09**	**-0.58**
6 years	**-0.96**	**-1.51**	**-0.41**	**-0.75**	**-0.98**	**-0.52**	**0.37**	**0.05**	**0.69**	**-0.88**	**-1.15**	**-0.62**
7 years	**-1.03**	**-1.66**	**-0.40**	**-0.76**	**-0.99**	**-0.52**	**0.40**	**0.07**	**0.72**	**-0.86**	**-1.14**	**-0.58**
8 years	-0.59	-1.33	0.15	**-0.77**	**-1.01**	**-0.52**	**0.46**	**0.13**	**0.79**	**-0.73**	**-1.04**	**-0.41**
9 years	-0.49	-1.30	0.32	**-0.76**	**-1.00**	**-0.51**	**0.52**	**0.18**	**0.85**	**-0.64**	**-0.97**	**-0.31**
10 years	-0.73	-1.60	0.15	**-0.78**	**-1.02**	**-0.53**	**0.55**	**0.22**	**0.89**	**-0.59**	**-0.94**	**-0.25**
11 years	0.18	-0.71	1.08	**-0.83**	**-1.08**	**-0.58**	**0.52**	**0.18**	**0.86**	-0.28	-0.65	0.08
12 years	0.21	-0.72	1.14	**-0.74**	**-1.00**	**-0.49**	**0.54**	**0.21**	**0.88**	-0.16	-0.53	0.21
13 years	0.12	-0.83	1.08	**-0.75**	**-1.01**	**-0.50**	**0.55**	**0.21**	**0.90**	-0.17	-0.56	0.21
14 years	0.28	-0.71	1.26	**-0.79**	**-1.05**	**-0.53**	**0.56**	**0.22**	**0.90**	-0.07	-0.47	0.34
15 years	-0.01	-1.02	1.01	**-0.83**	**-1.10**	**-0.57**	**0.59**	**0.25**	**0.93**	-0.18	-0.60	0.24
16 years	-0.35	-1.43	0.74	**-0.78**	**-1.05**	**-0.52**	**0.69**	**0.34**	**1.03**	**-0.45**	**-0.88**	**-0.02**
17 years	-0.36	-1.55	0.83	**-0.78**	**-1.05**	**-0.51**	**0.69**	**0.31**	**1.06**	-0.44	-0.91	0.03
18 years	0.03	-1.16	1.22	**-0.69**	**-1.00**	**-0.37**	**0.73**	**0.35**	**1.12**	-0.50	-1.02	0.02
19 years	-0.07	-1.34	1.19	**-0.69**	**-1.01**	**-0.36**	**0.72**	**0.33**	**1.11**	-0.50	-1.06	0.06
20 years	0.34	-0.88	1.55	**-0.70**	**-1.02**	**-0.38**	0.38	-0.06	0.81	-0.02	-0.64	0.59

Table 1. Coefficients of the fixed effects for the 20 evaluated models, which only changed the cumulative time window that *BurntPreviously* accounted for (CI95=95% confidence intervals). Data were standardized for all models using the empirical distribution from model 1-year. Bold characters indicate confidence intervals not overlapping 0.

The relative contribution of *BurntPreviously*, *Wetness*, *HotDays* and *Year* was assessed by calculating the percentage of variance explained from the fixed effects, attributable to the sum of variance explained by the factor itself and when interacting with *Landscape-attributes*. The variable with the strongest influence on annual burnt area was *Wetness* (38%), followed by *Year* (32%), *BurntPreviously* (19%) and *HotDays* (10%). In summary, dynamic variables associated with previous fires and fire management policies (*BurntPreviously*, *Year*) explained 52% of variance in the model, and dynamic variables associated with weather (*Wetness*, *HotDays*) explained 48% of fixed effects variance. The random effects of the variable 'region' were also significant (Fig. S1.2).

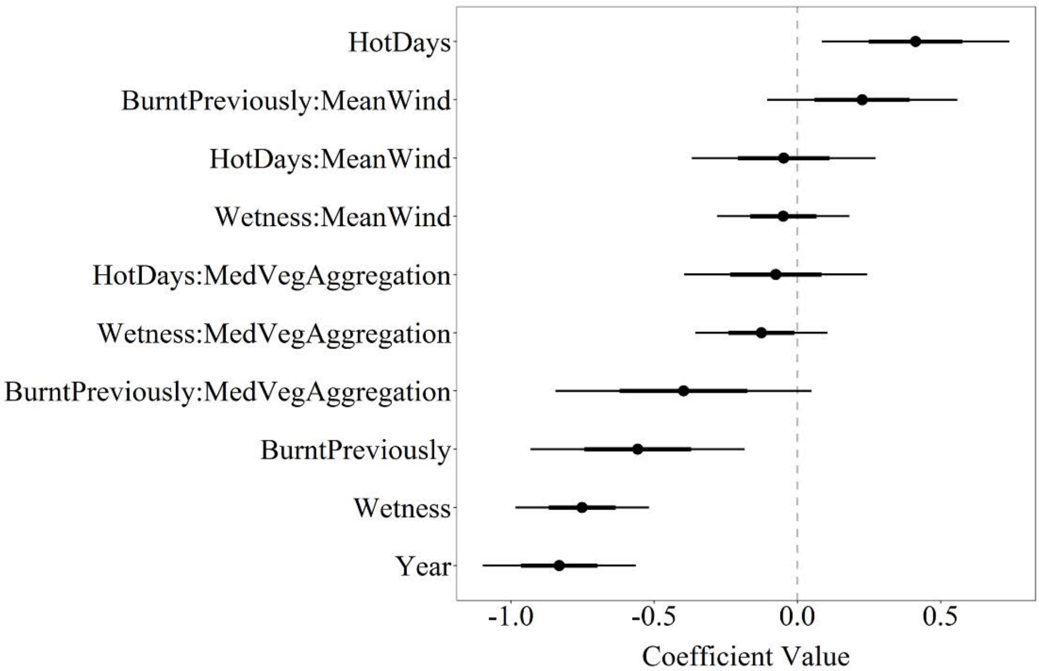

Figure 3. Coefficients of fixed effects for the model with 7-years cumulative burnt area. Thick lines represent standard error around parameters estimates. Thin lines represent 95% confidence interval.

The modulating effect of the static landscape attributes *MeanWind* and *MedVegAggregation* on annual burnt area was small (Fig. 3). In all cases, the 95% confidence intervals of each interaction between dynamic and static variables overlapped zero (Fig. 3). Nevertheless, two relationships that approached statistical significance are worth highlighting. First, *MedVegAggregation* reduced the effect of *BurntPreviously*, revealing stronger fire leverage in areas with aggregated Mediterranean-type vegetation than in regions where forests were more fragmented (Figs. 3 and 4a). Second, results suggested a positive influence of *MeanWind* on the effect of *BurntPreviously*, indicating that regions with stronger winds experienced smaller leverage effects. The two regions with strongest winds had the lowest leverage values (Ebre and Empordà regions, Figs. 3 and 4b).

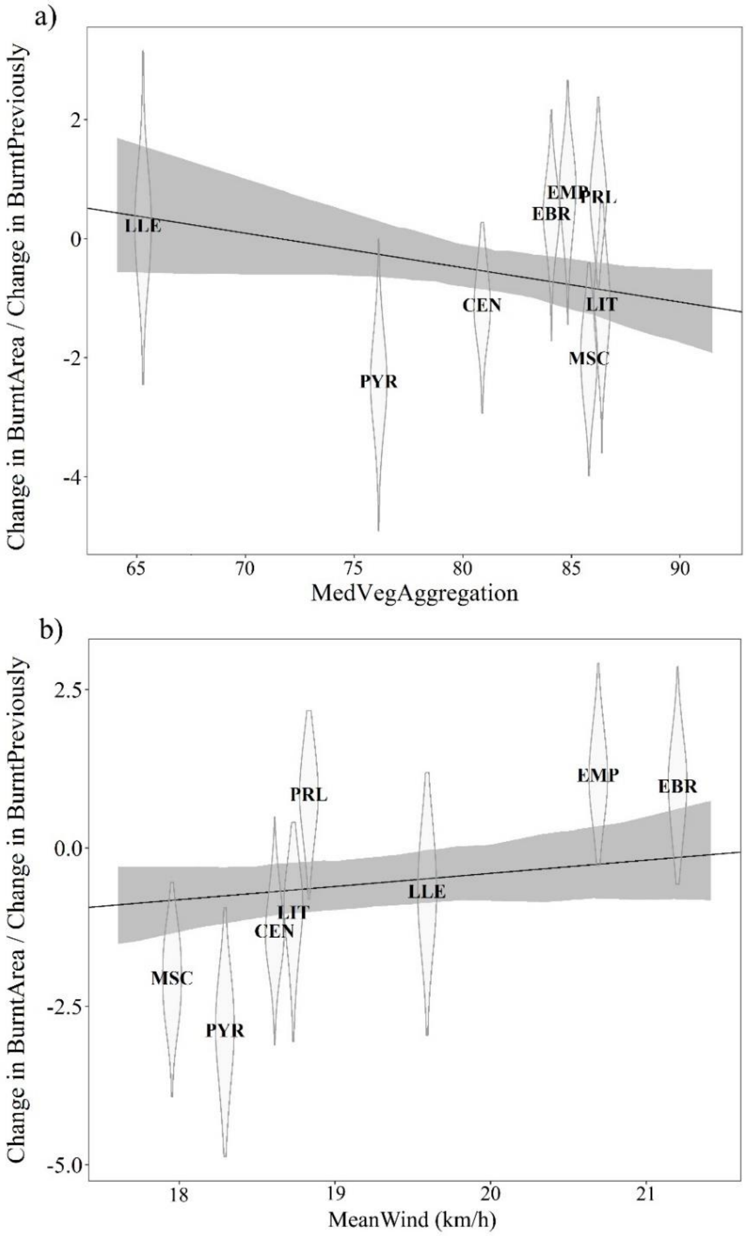

Figure 4. Effects of a) Mediterranean Vegetation Aggregation and b) Mean Wind on leverage for the model of 7-years cumulative burnt area. The y-axis corresponds to the effect of old fires on burnt area (leverage). The solid line shows the modulating effect of the *Landscape-attribute* on leverage, and the grey zone shows the 95% confidence interval. The eight violin plots represent the dispersion of values within each fire regime region, and each region is located in the x-axis according their *Landscape-attribute* value. Labels show region names as depicted in Fig. 1: PYR: Pyrenees, EMP: Empordà, MSC: Montsec, CEN: Central, LIT: Litoral, LLE: Lleida, PRL: Prelitoral, EBR: Ebre

The inter-annual variability of observed and modelled burnt area for each region was similar (Fig. 5). Importantly, periods of low fire activity after large burnt areas could be identified in all regions (CEN: 1987-1993; EMP: 1987-2000; EBR: 1996-1995; PRL: 1995-2001; LIT: 2004-2011; MSC: 1999-2008; LLE: 2004-2015; PYR: 1996-2002). The model successfully predicted most years with large or moderate burnt areas, however it under predicted extremely high burnt areas (e.g. 1986, 1994 or 2003; Fig. 5).

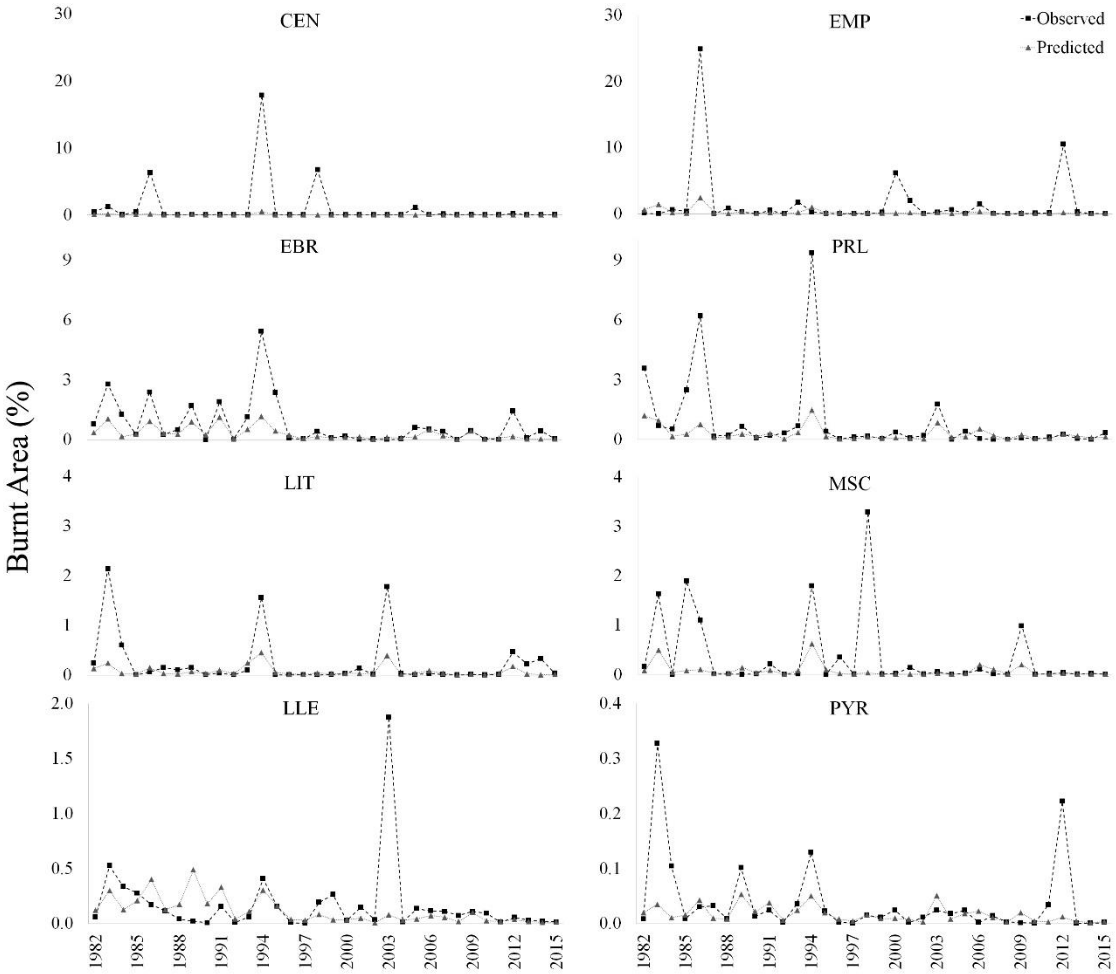

Figure 5. Observed (black dashed line and squares) and modelled (grey pointed line and triangles) burnt area in each fire region between 1982 and 2015 for the model with 7-years cumulative burnt area for *BurntPreviously* variable. Panel titles show region names as depicted in Fig. 1: PYR: Pyrenees, EMP: Empordà, MSC: Montsec, CEN: Central, LIT: Litoral, LLE: Lleida, PRL: Prelitoral, EBR: Ebre. Note the different scales of the y-axis

DISCUSSION

We have demonstrated fire leverage in a region encompassing a mosaic of agricultural plains, pine-oak forests and mountainous shrublands. Fire activity was strongly constrained by the cumulated burnt area over a period of up to 7 years. There was some evidence that this effect was stronger in landscapes with higher and more continuous forest cover, supporting the hypothesis that the inhibitory effects of past fires are more important in ecosystems where the amount and connectivity of fuel is high. Climate was also a strong influence: the annual burnt area increased with both dry weather conditions and the number of hot days, and mean annual wind speed had a negative effect on fire leverage.

Burnt area dynamics in moisture-limited fire conditions

Our analyses indicate that the annual burnt area in Catalonia is attributable to weather factors (~50% of model explanatory power), a temporal trend attributable to fire suppression efforts (30%) and past fire activity (20%). Domination of weather variables is in agreement with previous studies describing the region as moisture-limited system where adverse fire weather conditions drive large fires (Pausas and Fernández-Muñoz 2011). The present study highlights that previous fires and fire suppression policies are also significant drivers of overall fire activity. Past fires can limit fire activity in subsequent years for a period of about 7 years, during which fire activity is more limited by fuel than hot, dry weather. Importantly, ecosystems can switch from moisture-limited to fuel-limited over relatively short periods. Eight years after fire, vegetation recovery may have accumulated enough fuel to not represent a barrier for fire spread. In Catalonia, the widespread tree species *Pinus halepensis* recruits massively one year after fire, and can reach heights of >165 cm ten years after fire (Eugenio and others 2006). Similarly, shrublands are highly flammable and they are mostly dominated by fire-adapted species that have high capacity to either resprout or recover from seed after disturbance (Vilà-Cabrera and others 2008). Such vegetation recovery patterns suggest that vegetation in the area generates enough fuels to carry fire in a relatively short period. Additionally, an increasing ratio of dead-to-live biomass and relatively low decomposition rates, characteristic traits of Mediterranean plants (Christensen 1985), are also likely to increase fire activity and spread with time since fire.

Fire management also had a negative effect on burnt area. The relationship can be explained by two advances. First, an improved fire prevention system has increased social awareness about fire safety, reduced fire ignitions and increased the detectability of fires (Turco and others 2013; Otero and Nielsen 2017). Second, better fire suppression and improved firefighting techniques have limited the final size of fires once they start (Brotons and others 2013; Otero and Nielsen 2017; Duane and Brotons 2018). Nevertheless, the reduction of burnt area due to fire management has been counteracted by an increasing forest cover that positively influences the amount of fuel and likelihood of fire spread. Since the effects of past burnt area to subsequent fires can be depicted as 1) high-past-fire-activity reducing future burnt area or 2) low-past-fire-activity promoting future burnt area, our results provide the underlying mechanism for the two faces of a dynamic process: the “fire paradox” (increasing fire activity due past fire suppression) and the “fire leverage” (decreasing fire activity due past fire activity). The significant effects of past fires found in our analyses demonstrates that the ‘fire paradox’ represents a major driver of fire activity in this fire regime, and that under stronger investments in fire suppression, inhibitory effect of reduced burnt area will be counteracted by an increasing dependence on adverse weather conditions and extreme fire years.

Although fire in the study area is considered moisture-limited, our results suggest that the influence of past fires vary along a gradient in forest connectivity. Leverage was strongest in landscapes with more continuous forest cover (above an aggregation value of Mediterranean vegetation of 76%), whereas the weakest effects of past fires were observed in more fuel-limited regions. In fuel-limited fire regimes, fuel is already scattered enough to prevent fire activity, so past fires do not influence subsequent fire activity. However, when extrapolating these results to broader scales, not all moisture-limited fire regimes are equally influenced by past fires: this impact depends on the amount of annual burnt area. For instance, in fire regimes characterized by low fire return intervals, the probability that a new fire encounters a past fire with a low enough fuel load to prevent fire to spread can be scarce (Price and others 2015a). We propose that there is a spectrum within the aridity-productivity gradient (fuel- vs. moisture-limited fire regimes) in which fire constitutes a feedback itself, specifically in biomes located in intermediate productivity levels: temperate forests, savannas and Mediterranean ecosystems. The period in which fire inhibits future fires will differ between biomes depending on fuel recovery rates and fire spread patterns. Further research is needed to test our hypothesis at the biome scale.

Our results also suggested fire leverage changes with average wind conditions: past fire inhibitory effects were weaker in regions with strong winds. In wind-driven fires, the role of fuel for fire spread is reduced (Duane and others 2015, 2016), as wind spreads flames to unburnt fuels, pre-heating fuels, increasing oxygen input, and eventually increasing fire intensity and spotting (Rothermel 1991). Previous studies have identified no (or weak) fire leverage in Mediterranean shrublands subject to high winds such as in areas of California dominated by Santa Ana winds (Keeley and others 1999; Moritz and others 2004; Price and others 2012). In Mediterranean ecosystems, where vegetation has a suite of traits to recover after disturbance, shrub and grass fuels accumulate rapidly after fire enabling fires to reoccur after short periods (i.e. one year in chaparral ecosystems of Southern California; Keeley and others 1999; Price and others 2012). Fire spread pattern thus appears to be a key factor for understanding the role of fuels and climate in fire regimes. We note that modelled estimates for the influence of forest arrangement and average wind conditions had considerable uncertainty. The small number of regions included in our analyses limited our ability to reduce this uncertainty at the scale of our study. Future work could expand our analyses by adding additional data to allow a more specific assessment of these research questions.

Global change and fire management insights

The frequency of hot, dry weather conditions had the strongest influence on annual burnt area in Catalonia. As the climate warms and becomes more extreme (IPCC 2014) we expect increasing rates of burnt area. Our results also suggest that large fires will reduce the risk of subsequent fires (via the leverage effect). Such patterns reinforce the notion that one of the consequences of ongoing climate change in such systems could be an increase on fire activity variability, with larger extremes (Westerling and others 2011; Regos and others 2014). But how these relationships play out in a more extreme climate and at longer time scales (several decades) is difficult to predict. For instance, an increase in fire suppression effectiveness will promote the occurrence of very large fires ('mega-fires') under extreme fire-weather through a buildup of fuels. However, climate change may also impact vegetation dynamics and could alter relationships with fire in other ways (Batllori and others 2013). Firstly, if lower productivity results in reduced forest cover, the fire regime could become less weather-driven and more fuel-limited. In these cases, leverage could be diminished as the system becomes more fuel-limited. Secondly, reduced productivity and lower rates of post-fire vegetation recovery would increase the period in which the inhibitory effect of past fires prevails, amplifying fuel-limited periods. Better integration of vegetation-climate relationships in assessments of future fire regimes is key to forecast ecosystem change.

While our models have helped to disentangle the effect of past fires in burnt area, accurate modeling of burnt area remains a major challenge (Pereira and others 2005; Russo and others 2017). Fixed factors in our hierarchical model explained 23% of inter-annual variability in burnt area. This suggests that other, finer-scale processes are likely to be affecting fire activity in the region. We expect model accuracy would be improved by including information about fire ignitions, other fuel treatments (mechanical treatments, grazing) and the effectiveness of suppression techniques (back burning, aerial firefighting). The largest differences in our comparison of predicted versus observed values were detected in years with particularly high burnt area and when extreme heatwave events and severe droughts affected Catalonia (Cardil and others 2015). A few large fires associated with extreme fire behavior, usually identified as convective fires (Rothermel 1991), accounted for the bulk of burnt area in these years (Duane and others 2015). Our model predictions did not approximate extreme values of burnt area observed in those years. This suggests that climate and weather data that incorporates the effects of previous droughts on fuel moisture content (Keeley 2004) or extreme heatwaves events (Cardil and others 2015) usually associated with convective fires would also improve model fit. The complexity associated with convective fires remains difficult to predict (Allen 2007; Duane and others 2016).

Fire regimes are changing across the globe, and further modifications in the coming decades under changing climates will pose problems for people, biodiversity and the services that ecosystems provide (Moritz and others 2014). Fire suppression policies have been central to efforts of reducing fire risk in Europe and North America, but they have failed to reduce the impact of very large fires (Moritz and others 2014; Otero and Nielsen 2017; Schoennagel and others 2017). Additionally, such policies may diminish the self-regulatory effect of fires (fire leverage) reinforcing the role of weather conditions in driving fire regimes (fire paradox). In Catalonia, a combination of fire suppression, afforestation and human-caused climate-warming has pushed the system towards a more weather-dominated fire regime. Consideration of alternative fire management strategies will be critical. One way of managing fire in Mediterranean areas undergoing land abandonment and afforestation is to reduce the amount and continuity of fuel in the landscape (Fernandes 2013). This can be achieved in various ways such as active management of forests to create more widely spaced trees, land use conversion to sustainable agriculture and re-establishment of traditional practices such as grazing (Moreira and Pe'er 2018). Our work suggests that fuel management through planned burning has an important role to play in managing fire in Catalonia. Knowing the time window during which fire remains a barrier for fire spread means that more effective prescribed burning plans can be developed. In all cases, a better understanding of the role of fuel, climate and land use and their interactions will improve decision making and reduce uncertainty about future fires.

ACKNOWLEDGMENTS

This study was funded by the Ministerio de Economía y Competitividad from the Spanish Government through the INMODES project (CGL2017-89999-C2-2-R). The research leading to these results has also received funding from "la Caixa" Banking Foundation and from the CERCA Programme from Generalitat de Catalunya. Andrea Duane was funded by the Ministerio de Educación, Cultura y Deporte (Spain) (FPU13/00108) and (EST16/00984). Luke Kelly was supported by a Victorian Postdoctoral Research Fellowship funded by veski on behalf of the Victorian Government.

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SUPPLEMENTARY MATERIAL CHAPTER 4

APPENDIX S1. Additional results from modelling.

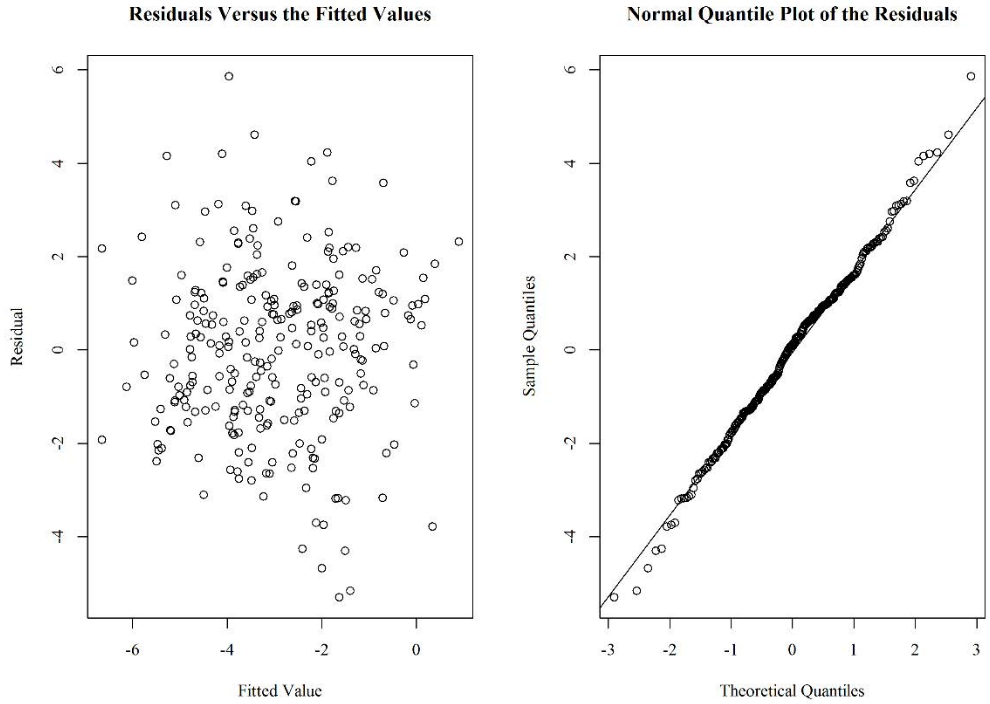

Figure S1.1. Residuals plots for the model of 7-years cumulative burnt area. Left plot shows the scatterplot of residuals versus the fitted value. The right plot shows the distribution of residuals versus the theoretical normal distribution.

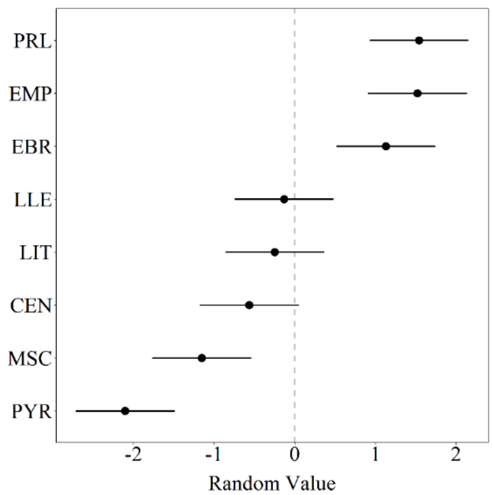

Figure S1.2. Random parameters for the 8 regions for the Intercept for the model with 7-years cumulative burnt area for *BurntPreviously* variable. PYR: Pyrenees, EMP: Empordà, MSC: Montsec, CEN: Central, LIT: Litoral, LLE: Lleida, PRL: Prelitoral, EBR: Ebre

CHAPTER 5

Adapting fire management to future climate change

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This chapter is prepared to submit in Science of the Total Environment

ABSTRACT

Fire regimes are shifting, or are expected to do so under global change. Current fire suppression is not able to control all fires, and its capability might be compromised under worsening climate conditions. Alternative fire management strategies may allow to counteract predicted fire trends, but we lack quantitative tools that demonstrate fire management effectiveness at the landscape scale. Here, we present the design, parameterization and application of a landscape fire succession model for Catalonia (a Mediterranean region ~32,000 km^2 in NE Spain) that simulates future fire regimes considering the influence of climate and fire management in determining fire intensity and final burnt areas. We sought to quantify changes in fire regimes induced after the implementation of different fire management scenarios aiming at counteracting predicted future increases of burnt areas. We first projected burnt area changes from 2011 to 2100 resulting from climate change under the RCP 8.5 scenario of HadGEM-CC model and under current fire suppression levels. We then evaluated the capacity of four different fire management strategies to counteract climate change potential effects: 'let it burn', fixed effort of prescribed burning with two different spatial allocations, and adaptive prescribed burning dynamically adjusting efforts according to the impact of recent past fires. Results showed the appearance of novel climates associated with similar barometric configurations to current conditions but with higher temperatures (i.e. hot wind-driven fires). These novel climates led to an increase in burnt area, which was partially counteracted at the end of the century by an increase in suppression opportunities due to past fires. Convective fires spatially shifted to forested areas weakly impacted by wildfires at present (i.e. Pre-Pyrenees). All prescribed burning scenarios decreased the amount of high-intensity fires and extreme fire events. The 'let it burn' strategy, although less costly, was not able to reduce high-intensity fires due to increasingly adverse weather conditions in the future. The adaptive prescribed burning scenario resulted in the most cost-efficient strategy. Our results provide quantitative evidence of fire management effectiveness, and bring to light key insights that could guide the design of fire policies fit for future novel climate conditions. We propose to recognize fire as an intrinsic element of Mediterranean ecosystem dynamics and propose adaptive landscape management focused on the reduction of fire negative impacts rather than on the elimination of this disturbance from the system.

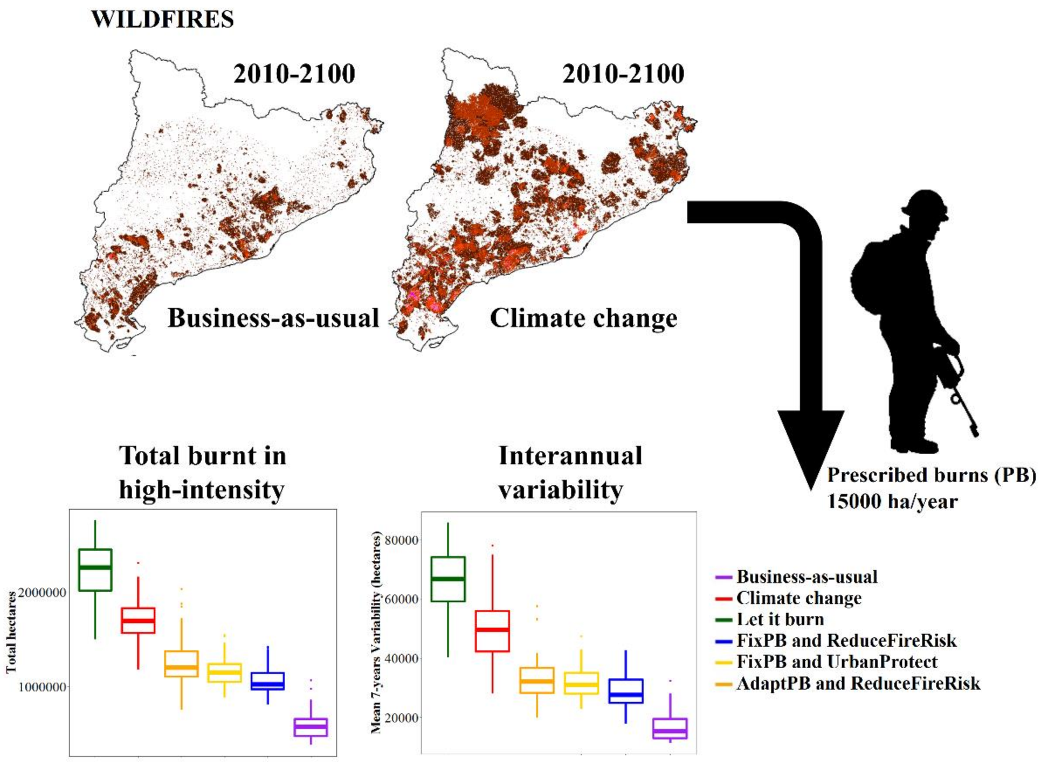
Keywords

Burnt area, climate change, convective fires, fire intensity, fire management, fire regime, fire suppression, landscape fire-succession model, novel climates, prescribed burning, wind-driven fires

Highlights

- We evaluated fire management practices effects on fire regime under climate change
- Projected higher burnt area is partially offset by new suppression opportunities
- Prescribed burning can reduce high-intensity fires associated with climate change
- Adaptive prescribed burning can gain in cost-efficiency compared to rigid strategies
- Relaxing fire suppression is a cheaper option but with higher undesired impacts

Graphical Abstract



INTRODUCTION

Fire regimes have been changing during the last decades around the world (Bowman et al., 2011; Fréjaville and Curt, 2015; San-Miguel-Ayanz et al., 2013; Schoennagel et al., 2017). In many regions, anthropic influences are behind such changes: a combination of land-use changes, human-caused climate warming and fire suppression has pushed fire regimes to be more dominated by uncontrollable weather events (Moreira et al., 2001; Pausas and Fernández-Muñoz, 2011; San-Miguel-Ayanz et al., 2013; Duane et al under review). Investment in fire suppression has been the main strategy followed by many governments to control wildfires, but they have systematically failed in regulating them (Fernandes, 2013; Moritz et al., 2014; Schoennagel et al., 2017; Tedim et al., 2016). In addition, fire regimes are expected to further shift with global change, with important consequences for humans, biodiversity, ecosystem resilience and associated ecosystem services (Amatulli et al., 2013; Pausas et al., 2008; Westerling et al., 2011). In Mediterranean ecosystems, several studies predict increases in fire activity to the end of the century (Amatulli et al., 2013; Batllori et al., 2013). There is a call pleading for the implementation of ecosystem and fire management actions to help overriding or mitigating current trends (Fernandes, 2013; Khabarov et al., 2014; Thompson and Calkin, 2011), and future expected negative fire regime impacts.

Climate change is one of the most important direct driver of ecosystem change forecast for the 21st century (Aponte et al., 2016; Millar et al., 2007; Moritz et al., 2012). Its effects are largely beyond the control of local management agencies and they can have strong impacts on fire regimes due to the projected increases in temperatures and precipitation variability (Batllori et al., 2013). Many studies have demonstrated that, beyond temperature and precipitation, atmospheric circulation types play an important role on fire activity (Duane and Brotons, 2018; Pereira et al., 2005; Ruffault et al., 2016). These circulation types inform about other relevant factors such as barometric gradients and atmospheric stability, with direct influence on wildfire development (Rothermel, 1991). Evaluating how these general conditions will evolve into the future can bring to light 'novel' climate situations that in turn may shift the potential fire activity from the historical range of variability to novel fire regimes (Schoennagel et al., 2017). Understanding and anticipating future climate is therefore critical to forecasting potential fire activity and eventually helping to guide the development of fire management strategies that reduce fire negative impacts.

Fire management is and will continue to be key to offset increasing burnt area trends associated with climate change (Khabarov et al., 2014; Moritz et al., 2014). During the last decades, increases in fire suppression efforts have been the backbone of fire management policies developed in many countries -- with counterintuitive effects: strong fire suppression has promoted extreme wildfire events under adverse weather conditions because of fuel build-up at the landscape scale (Minnich, 1983; Duane et al. under review). Alternative fire management strategies have been identified as crucial to control wildfire events under worsening climates (Calkin et al., 2015; Khabarov et al., 2014). The exploration of fire management options has also targeted fuel management as a major avenue to reverse negative climate impacts and restoring fire resilient ecosystems (Hessburg et al., 2016). Additionally, fire management cannot turn a blind eye to ongoing unplanned wildfires: it is pivotal that adaptive management strategies are developed accounting for ongoing processes to ensure effective decisions. Policies that promote adaptive resilience to wildfire by which people and ecosystems adjust and reorganize in response to changing fire regimes are strongly recommended (Schoennagel et al., 2017).

Fuel reduction created by prescribed burning (PB) has been advocated as a possible alternative to strong fire suppression policies. PB is the planned use of fire to achieve defined objectives (Fernandes et al., 2013). There is still a debate about the suitability, effectiveness and preparedness of its implementation (Fernandes et al., 2013; Price et al., 2015). Moreover, although much work testing burning effects at local scale has been carried out (Alcasena et al., 2017; Valor et al., 2015), few studies have quantified the effects of prescribed burns at the fire regime scale over the long-term, nor the amount needed to remain under sustainable thresholds required in different biomes and socio-ecological contexts (Price et al., 2015). Prescribed burning effectiveness is difficult to quantify, since it depends on: 1) how long a treated area will remain as a low-fuel area; 2) the probability of a fire to pass through within the time that the area remains as a low-fuel cell, and 3) the type of fire arriving at that area (i.e. wind-driven, convective, etc.). Furthermore, fire management targeted to reduce fuel could benefit from already ongoing wildfires and decrease management costs by letting these fires to burn under controlled conditions. Although similar to prescribed burning, consequences of this kind of management strategy are uncertain under warming climates. Applicability of different management scenarios requires from quantitative assessments that can reveal the real effectiveness on wildfire risk reduction under future climates.

Landscape dynamic models are pivotal tools that allow us to anticipate medium and long term effects of fire management strategies under climate change. But, the use of models requires the incorporation of key ecological, anthropogenic and climatic processes that interact across temporal and spatial scales. While we now have a good knowledge of the processes driving fire activity (fuel, climate, suppression), our ability to integrate this information into modelling tools that allow the projection of these systems under future global change scenarios is scarce (Gil-Tena et al., 2016; Titeux et al., 2016).

In this work, we aimed to anticipate the effects of different fire management strategies on future fire regimes under changing climatic situations. Our first goal was to project impacts of future ‘novel’ climates in the total burnt area, location, intensity and variability of fires during the 21st century and under current management. Then, using a landscape modelling approach the following hypothesis were tested: 1) burnt area will increase under climate change; 2) PB can modify fire regimes by decreasing high-intensity unplanned fires; 3) PB impact will be higher if targeted in high-risk areas rather than in other defensive locations; 4) PB plans can adapt to ongoing fire activity and increase its efficiency; and 5) A 'Let it burn' strategy can mimic the PB strategy with lower efforts. In the present work, and for testing these hypothesis, we developed a modified version of the spatially explicit fire-succession MEDFIRE model (Brotons et al., 2013) and applied it to Catalonia (NE Spain), a very densely populated Mediterranean region covered 60% by forest, which has experienced strong changes in fire regimes during the last decades due to changes on land-uses and settlement patterns, rural abandonment, and high investment in fire suppression and prevention. An intense debate on the applicability of fuel-control policies exists in the region, but there is a lack of knowledge on how this can be effective in face of uncertain changing climates.

METHODS

1. Study area

Catalonia is located in the NE Iberian Peninsula and covers an area of approximately 32,000 km^2. Climate is Mediterranean, with hot dry summers, rainy springs and falls, and mild winters. Catalonia has a complex relief that greatly affects weather dynamics, with precipitation and temperature variations related to distance-to-sea and altitude (Lana et al., 2001). The Pyrenees, a major mountain east-west oriented range in the North of the region, strongly affects climate variability (Soriano et al., 2006). Average wind speed in the northern and southern Catalonia is higher than in the center (Gencat, 2004). Sixty percent of the study area is covered by forests and shrublands. Dominant tree species are pines (*Pinus halepensis*, *Pinus nigra*, *Pinus sylvestris, Pinus uncinata* and *Pinus pinea*), Holm oak (*Quercus ilex*) and Cork oak (*Quercus suber*). Fire return intervals in Catalonia for the period 1980-2000 range from 60 to >400 years for homogeneous fire regions of around 45,000 ha (Pique et al., 2011). Annual burnt area is highly variable, with the largest areas burnt in 1986 (65,000 ha) and 1994 (82,000 ha). Most of the burnt area is caused by a few large fires and most fires occur in summer (June-September). Stand-replacing fires are the most widespread type of fire in Catalonia, with >85% of the burnt area being affected by crown fires (Rodrigo et al., 2004). The prevalent fire management strategy in Catalonia is fire suppression, and firefighting investment has increased six-fold since the early 1980s (Otero and Nielsen, 2017). A decreasing trend in the number and size of fires has been observed after the big fires that occurred in 1986 and 1994, mainly explained by increased fire prevention and suppression (Brotons et al., 2013; Duane and Brotons, 2018; Turco et al., 2013).

2. The MEDFIRE Model

The MEDFIRE is a landscape dynamic fire-succession model that allows to examine spatial interactions of multiple ecological and human induced processes influencing land-covers and vegetation dynamics. The model has been already applied to assess fire regime drivers (Brotons et al., 2013; Aquilué et al. under review) and to evaluate vegetation and fire regime dynamics towards the future (Gil-Tena et al., 2016; Regos et al., 2014). Here, we developed an updated version of the model aimed to explore fire regime dynamics under the interaction of multiple drivers: climate, fire management (i.e. unplanned fire suppression and planned prescribed burns) and fuel accumulation processes (i.e. afforestation and forest aging).

The MEDFIRE model works with two dynamic spatial state variables that are updated by the drivers of change: 1) Land-Cover Forest that describes the main land-covers and dominant species in forest areas; and 2) Forest Age that tracks the age of dominant forest species and shrublands. Spatial resolution is 1 hectare and temporal resolution is 1 year. A brief description of the two modules affecting landscape dynamics (fire dynamics and vegetation dynamics) are detailed below.

1. The fire dynamics module

Fire dynamics in the MEDFIRE model is implemented through two sub-modules: the wildfires sub-module and the prescribed burns sub-module. In the wildfires sub-module, fire regime is simulated as an emergent landscape-scale property. Annual burnt area, fire sizes, fire shapes and fire intensity are the emergent fire regime descriptors that arise from model interactions. In the prescribed burns sub-module, controlled fires are generated to eventually impact wildfire regime.

1.1 The wildfires sub-module

Wildfires are simulated under different 'Synoptic Weather Conditions' (hereafter SWC). These are categorisations of atmospheric weather variables depicting short-term weather conditions (hours to days) at large continental scales. SWC have been shown to drive several fire regime attributes such as fire size, location or fire spread (Duane and Brotons, 2018). Working with SWC allows one to reliably include relevant weather-factors influencing coarse spatial fire patterns while avoiding the need of detailed weather data. Fires occurring under the different SWC are simulated independently from each other and all take into account the following steps:

1.1.1. Potential climatic burnt area

The model starts by determining the climatic potential for fire activity for a given year. Potential climatic burnt area (in hectares) represents the sum of fire-weather windows in a summer that are conductive to fire. This potential depends on SWC and on medium-term weather conditions (~weeks or months) that influence potential burnt area by making fuels more available, thus increasing fire spread and eventually promoting larger fires. Medium-term weather conditions in the present model are classified into categories defining the climatic severity of the year. Annually, the model draws a potential climatic burnt area from a probability distribution that depends both on the SWC and the climatic severity of the year. Once a potential climatic burnt area is set, the model sequentially simulates as many fires as needed until that area is reached.

1.1.2. Fire ignition, spread and potential fire size

For each fire, the model first randomly chooses an ignition point according to a probability ignition map comprehensively masked by each SWC. Then, for each fire, the model selects a fire spread pattern that can depend only on SWC, or also on fuel landscape accumulation (Duane et al., 2015). In the latter case, a buffer around the ignition analyses landscape properties and their potential capacity to sustain very-intense fires (i.e. convective fires). Fires propagate according to the different fire spread patterns that modulate the relative role of factors influencing fire spread (wind, slope, aspect and species flammability; Duane et al., 2016). Fires propagate until reaching a potential fire size. Potential fire size of each fire is previously drawn from a fire size distribution that depends on the fire spread pattern and the climatic severity of year.

1.1.3. Fire suppression

Fire fronts can be suppressed. In these cases, the potential fire size is not finally burnt but it still adds to the potential climatic burnt area. Fire suppression depends on the fire spread pattern and it follows two different strategies: Active and Opportunistic. In active fire suppression, fire fronts are stopped when fire intensity is low enough to be controlled by firefighters. Since fire brigades are not able to immediately start suppression when fire intensity decreases, it is necessary to concatenate a number of consecutive pixels of low intensity fire to allow suppression. This fire management strategy mimics fire suppression operations in elevation changes or in low flammable land-uses as agricultural fields. In opportunistic fire suppression, fire fronts can also be stopped if they reach a low-fuel area. In the same way as active fire suppression, the opportunistic alternative starts after fire has burned a minimum number of consecutive low-fuel cells. This strategy mimics fire suppression operations occurring in past fire scars that provide low-fuel areas suitable to operate. All kinds of past fires (both wildfires and prescribed burns) can generate a fire suppression opportunity. The number of years that past fires act as suppression opportunities is a model parameter.

1.1.4. Fire effects

Fires stop spreading when all fire fronts have been suppressed or when they reach their potential fire size. Final burnt area and perimeter shape are emergent model outputs that arise from the interaction between fire spread across the landscape and fire suppression effectiveness within that fire. Cells effectively burnt can be classified according to fire intensity within the cell: low or high intensity. Fire intensity depends on both fire spread rate and climatic severity. The threshold dividing the two intensities is a model parameter. However, no matter the fire intensity, fires are always stand-replacing and vegetation age drops to 0. Fire intensity is thus a proxy of fire behaviour that helps to understand fire regime dynamics.

1.2. The prescribed burns sub-module

The model allows simulating prescribed burns aimed at reducing burnt area through the generation of fire suppression opportunities in preselected, planned sites. There are two possible implementations of prescribed burns: 1) a fixed prescribed burnt area per year or 2) and adaptive prescribed burnt area per year. In the former, the user sets a fixed amount of prescribed burns to be burnt every year. In the latter, prescribed burns are planned considering the areas burnt in most recent years. This seeks to maximize planned fires effectiveness by taking advantage of what has already been burnt to avoid useless or excessive planned fires. Through this strategy, the area burnt with prescribed burns per year is emergent and it is only applied if the burnt area in previous years does not reach a user-fixed threshold. This threshold refers to an established value aiming to attain a desired fire regime. If the burnt area of previous years exceeds such value, prescribed burns do not occur that year, otherwise the difference is prescribed to burn. The time window that past fires can be used as opportunities and the extent to be burnt are specific model parameters.

As for wildfires, the model simulates as many prescribed burns as necessary to reach the annual prescribed burnt area. The size of planned fires is drawn from a fire size distribution and are initiated according to a probability map. Prescribed burns allocation can follow any constriction the user decides (i.e. target species, protected areas, etc.). Prescribed burns spread according to the formulae proposed by Duane et al. (2016) and correspond to the less intense fire spread pattern. Planned fires always reach target fire size and always burn in low intensity.

2. The vegetation dynamics module

The vegetation dynamics module replicates post-fire regeneration and shrublands colonization by tree-forest species as presented by Brotons et al. (2013) and Gil-Tena et al. (2016). After a fire, a forest species can persist or be replaced according to its post-fire functional trait (resprouter, seeder, or serotinous; Rodrigo et al., 2004). Additionally, homogeneous forests burnt in the same fire event will partially regenerate by contagion. Afforestation is a probabilistic process depending on orographic variables and the proportion of mature forest around the shrubland to be colonized.

3. Model initialization and parameterization

State variables

State variables are initialized for the year 2010 and cover all the Catalonia region at 1 ha of spatial resolution. Both Land-Cover Forest and Forest Age variables were built by Gil-Tena et al. (2016). Briefly, the 2009 Land Cover Map of Catalonia (Ibàñez and Burriel, 2010) updated by 2010 wildfires serves as the baseline map. In forest areas, dominant species and age are assigned according to National Forest Inventories data and spatial interpolation techniques (i.e. kriging, Gunnarsson et al., 1998).

1. The fire dynamics module

1.1. Wildfire sub-module

1.1.1. Potential climatic burnt area

We estimated the climatic burnt area potential using existing records of annual burnt area in Catalonia before the establishment of the current strong fire suppression policy (year 2000), when fires were mostly stopped because of changing weather conditions (vegetation was plentily available and did not limit fire spread). Observed fires were classified according to the climatic severity of the year (medium-term weather conditions) and weather conditions of their occurrence day (short-term weather conditions, SWC). Short-term weather conditions determine moisture content of dead fuels, wind speed and direction and atmospheric stability, which eventually regulate fire spread (Rothermel, 1991). Duane and Brotons (2018) found six SWC leading to large wildfire generation in Catalonia. To simplify model building and analyses, we grouped the six SWC into three according to main weather factor that distinguishes them: Wind SWC, Heat SWC and Regular SWC. Medium-term weather conditions in Catalonia strongly impact fire activity (Castro et al., 2003), since they determine the growth of fine fuels and moisture content of soil and live-fuel (Castro et al., 2003; Keeley, 2004), that prompt fire initiation and spread. We used the Standardized Precipitation-Evapotranspiration Index (SPEI; Vicente-Serrano et al., 2010) to assess vegetation dryness conditions, and set the value found by Duane and Brotons (2018) to separate dry years from mild years (SPEI=-0.21; more details in Appendix S1). The model selects the climatic severity of the year from a uniform probability, being 45% of years dry for the calibration period. We then fitted log-normal probability distributions of burnt area potential for each combination of short-term (Wind SWC, Heat SWC and Regular SWC) and medium-term (mild and dry) weather conditions using 1980-2000 as observed data (Table S1.1). We checked distribution parameters by applying probability distributions within the same time period (Fig. S1.1).

1.1.2. Fire ignition, spread and potential fire size

In Catalonia, ignition pressure has been related to land-cover variables (higher ignitions in mosaic landscapes encompassing human and natural covers, and in areas close to roads), topography variables (increasing ignitions at slopes' bottoms) and vegetation flammability variables (increasing ignitions in low-moisture regions) (González-Olabarria et al., 2012). The probability of ignition has been adjusted with a logistic regression using landscape variables at 2 km resolution (Eq. S1.1). For each SWC, an ignition mask is used to exclude areas with low probability for that SWC. The delimitation of masked areas follows current knowledge on the areas of Catalonia prone to be affected by fires linked to a particular SWC (Duane and Brotons, 2018). From their work, we selected pixels with more fires than 0.1/1,000 km^2 to be suitable for the occurrence of each SWC.

For each ignition point the model assigns a fire spread pattern. For ignitions occurring under Wind or Regular SWC, fire spread pattern was directly assigned to wind-driven and topography-driven types, respectively. In contrast, fires occurring under Heat SWC could be either topography-driven or convective, depending on fuel load availability. Duane et al. (2015) found convective fires to be strongly related to forest amount and structure around fire ignitions. We simplified their finding and fitted the probability of becoming a convective fire (in contrast to remaining a topography-driven one) that increased as the proportion of old-grown Mediterranean pine species 1 km around the ignition did (more details in Appendix S1).

Fire spread follows the formulae and parameterization presented in Duane et al. (2016) (Eq. S1.3). Wind direction of simulated fires was assigned according to the type of fire spread pattern and ignition location (more details in Appendix S1). Potential fire size distributions were adjusted for the three fire spread patterns under the two different climatic severity types following Power-law distributions (Table S1.2 and Fig. S1.2).

1.1.3. Fire Suppression

Fire suppression initialization encompasses active fire suppression and opportunistic fire suppression. For the latter, Duane et al. under review found that in Catalonia past fires act as a barrier for fire spread during seven years, although this value is smaller in windy situations. Opportunistic fire suppression worked then until a time when fire interval reached seven years in convective and topography-driven fires, and five years in wind-driven fires. Active fire suppression was calibrated according to burnt area in Catalonia for the period 2000-2015 (Table S1.4). Opportunistic and active fire suppression started once fire spread across a number of low-fuel contiguous cells.

1.1.4. Fire effects

We calibrated the threshold that separates high from low intensity fires by selecting the value that pulled 15% of the cells as low-intensity fires (Rodrigo et al., 2004) in three Catalan fires that occurred in mild years (one per fire spread pattern).

1.2. Prescribed burning sub-module initialization

Prescribed burn size distribution was adjusted from the current prescribed burning database in Catalonia, previously filtered for the 25% larger prescribed burns (distribution parameters are given in Appendix S1). Fire spread followed the formulation for topography-driven fires, the more controllable type for firefighters in Catalonia. Prescribed burns could only be applied if cell age was older than 30 years, both 1) to ensure that individual had develop reproductive organs (Zagas et al., 2004), and 2) to apply burns in mature forest structures that allowed the control of fire intensity (Taylor et al., 2014).

2. The vegetation dynamics module initialization

Vegetation dynamics parameters are also obtained from Gil-Tena et al. (2016): the probability of post-fire regeneration matrix follows the results from Rodrigo et al. (2004), and the probability of afforestation follows a logistic regression calibrated for the study area according to vegetation, climate and topography variables.

4. Scenario definition

We explored the effects of different fire management practices on fire regime under changing climate conditions (Fig. 1 and Table 1). The axes of variability between scenarios were climate, fire management strategy and spatial allocation of management. Climate change can influence fire regime by increasing climatic potentials and decreasing low intensity fires, while any fire management scenario is supposed to play a role on fire regime by mainly influencing opportunistic fire suppression.

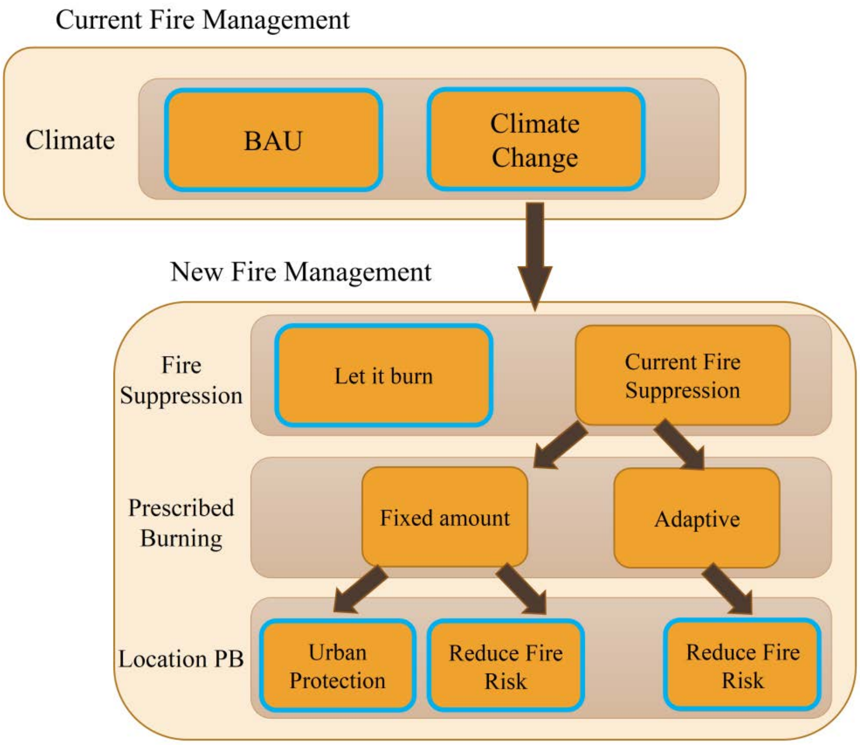


Figure 1. Nested scenario definition according to different scenario elements. Blue squares identify the combination of drivers used in the 6 proposed scenarios.

Table 1. Details of the climatic and fire management scenarios used in the present work

Scenario name	**Climate**	**Fire suppression**	**Planned fires**	**Rationale and scenario details**
Business-as-usual (BAU)	Current	Current	No	This scenario assumes that both current suppression efforts and current climate will persist in the future. We used this as the baseline scenario.
Climate change	RCP 8.5	Current	No	This scenario simulates fire dynamics assuming that current fire suppression efforts will not change over time and climate will change following a high-end emissions scenario.
Let it burn	RCP 8.5	Relaxed	No	In this scenario fire suppression efficiency is relaxed with the idea of increasing opportunities for fire suppression. Active fire suppression of topography-driven fires (the most controllable for firefighters) was fully removed. Active fire suppression for convective fires decreased to the same levels of wind-driven fires. Fire activity was simulated under a high-emission climate scenario.
FixPB and ReduceFireRisk	RCP 8.5	Current	15,000 ha/year	This scenario simulates a prescribed burning program seeking to reduce the extent of unplanned wildfires under a climate change context. The amount set (15,000 ha/year) was established after preliminary analyses and after discussion with local stakeholders, and aims at reproducing a realistic extent of planned fires in Catalonia (Alcasena et al., 2017; Salis et al., 2016). Prescribed burns were located in similar locations to ignition probability, aiming to increase opportunistic fire suppression in areas highly exposed to wildfires.
FixPB and UrbanProtect	RCP 8.5	Current	15,000 ha/year	This scenario simulates a prescribed burning program seeking to safeguard communities from fire under a high-emission climate scenario. The amount set (15,000 ha/year) was established after preliminary analyses and after discussion with local stakeholders, and aims at reproducing a realistic extent of planned fires in Catalonia (Alcasena et al., 2017; Salis et al., 2016). Prescribed burns were mainly located close to urban areas.
FixPB and ReduceFireRisk	RCP 8.5	Current	Adaptive	This scenario simulates a prescribed burning program seeking to reduce the extent of unplanned wildfires by efficiently optimizing prescribed burns. The amount of annual prescribed burn area derives from what was previously burnt. We targeted an “optimal” burnt amount per year: the same than in 2000-2015 decade (7,000 ha/year on average) plus 15,000 ha /year, that is: 22,000 ha/year. The model tracks the total burnt area in the previous 7 years (years that fires can suppose an opportunity for fire suppression), and applies PB until 22,000 ha/year x 7 years = 154,000 ha are reached. Prescribed burns were located according to wildfire ignition probability, aiming to increase opportunistic fire suppression in areas highly exposed to wildfires.

Climate change scenario and novel extreme fire prone conditions

The climate scenario was framed within the Representative Concentration Pathways (RCPs) built for the assessment report on climate change IPCC5 (Moss et al., 2010). We used RCP 8.5, the worst-case scenario forecast for the end of the 21st century. High-end climate scenarios like the RCP 8.5 are generally considered to be more realistic under current greenhouse emission rates (Beaumont et al., 2008; Raupach et al., 2007). This scenario is characterized by increasing greenhouse gas emissions over time, leading to high greenhouse gas concentration levels which reach an average increment of 3.7ºC by the end of the 21st century (Riahi et al., 2007). We used data from the model UKMO-HadGEM-CC including short- and medium-term variables needed to calculate medium-term and short-term weather indices from nowadays to 2100. We calculated medium-term weather conditions of the future by calculating for July each year the preceding 3-months SPEI index. We splitted all the temporal simulations (from 2011 to 2100) into three periods (2011-2015 (observed), 2016-2060 and 2061-2100), and calculated for each period the percentage of dry years (more details in Appendix S2).

Projected novel climate extreme fire prone conditions

Climate is expected to change in the future and bring novel conditions that might violate our current assumptions about relations between climate and fires (Amatulli et al., 2013; Khabarov et al., 2014; Schoennagel et al., 2017; Westerling et al., 2011). Projected novel climates were identified according to future climates (combinations of weather variables) not recorded in the past because of the higher temperatures projected for the future. We therefore classified future days according to barometric gradients only (sea level pressure and wind). Then, we examined the temperature of each of these classified days to check whether they belong to 'novel climates' (more details in Appendix 2). 'Novel climates' correspond thus to Hot-Wind SWC and Hot-Heat SWC, and were associated to new extreme weather conditions conductive to fire (Flannigan et al., 2009).

How explicitly novel climates will influence fire regimes is challenging because these conditions occur outside the range of historical records. Here we applied the following procedure to estimate the effects of novel climates on 1) potential climate burnt area and 2) fire suppression. Novel conditions are hotter and drier than past conditions, so larger potential burnt areas are expected to occur (references). We adjusted two more climate potential distributions for years belonging to this new class of 'extreme' conditions, one for Hot-Wind SWC and the other for Hot-Heat SWC according to literature (Table S2.2). These extreme conditions occurred if a year was classified as dry and if the proportion of Hot-Heat SWC or Hot-Wind SWC was high. We adjusted a logistic probability of becoming an extreme year that increased as the proportion of novel climates did (Appendix S2). Under novel climates leading to extreme years, suppression capacity for convective fires is predicted to collapse, since it may be compromised due to wild-land urban interface attendance, extreme fire spread and intensity or fires' simultaneity (references). We therefore adopted the current lower efficiency observed for wind-driven fires.

5. Model simulation and data analysis

We ran 100 replicates of the six scenarios from 2011 to 2100. From 2011 to 2015, the model burnt the actual burnt areas in Catalonia. Response variables were: 1) yearly and total burnt area per SWC and prescribed burns; 2) yearly and total burnt area - burnt in either high or low intensity fire; 3) temporal variability of unplanned fires, computed as the range between maximum and minimum burnt areas over a 7-years moving window; and 4) cell-level probability of being burnt in high or low intensity, and in convective fires and in wind-driven fires. Finally, we reported Fire Return Intervals per homogeneous fire zones (Pique et al., 2011). These zones have not been used for any modelling step, but they are useful to understand changes on fire regime. Fire regime attributes were plotted against time with smooth loess curves. Plots were built with the 'ggplot2' R-package (Wickham, 2009).

RESULTS

Future climate and novel fire conditions

The scenario RCP 8.5 predicted the appearance of novel climate conditions for Catalonia. Temperatures within days classified as 'novel climates' were significantly higher than in observed SWC (Fig. 2). Moreover, the frequency of these situations changed over time according to the SWC typology: whereas Hot-Heat SWC days steadily increased from 1-

2 to ~30 days per year at the end of the century, Hot-Wind SWC days doubled the number of Hot-Heat SWC from ~2060 to 2100 (Fig. 3).

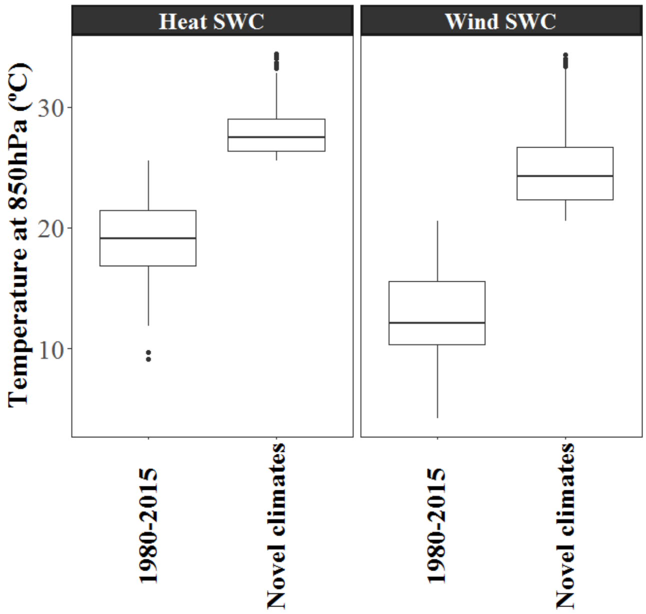


Figure 2. Distribution of temperatures in Catalonia at 850 hPa within SWC for the past (1980-2015) and for the 'novel climates', which have barometric gradients similar to past-SWC but with higher temperatures. Temperatures of novel climates refer to the period 2016-2100

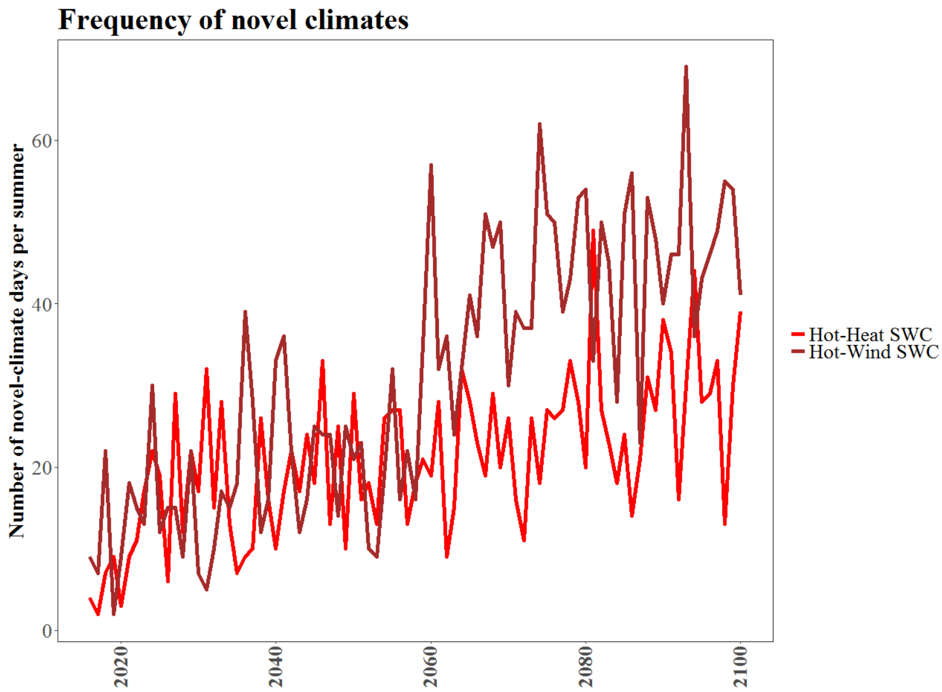


Figure 3. Evolution of the number of novel climates per year from 2016 to 2100 for Hot-Heat SWC and Hot-Wind SWC.

Effects of climate change on fire regime

Climate change impacted burnt area potential (Fig. 4). These effects differed among synoptic weather conditions. Climate burnt area potential of both Heat SWC and Regular SWC increased approximately 60% regarding the BAU scenario. Such increase was especially evident in the second half of the assessed period. The Climate change scenario also predicted a 280% increase of climate burnt area potential for Wind SWC.

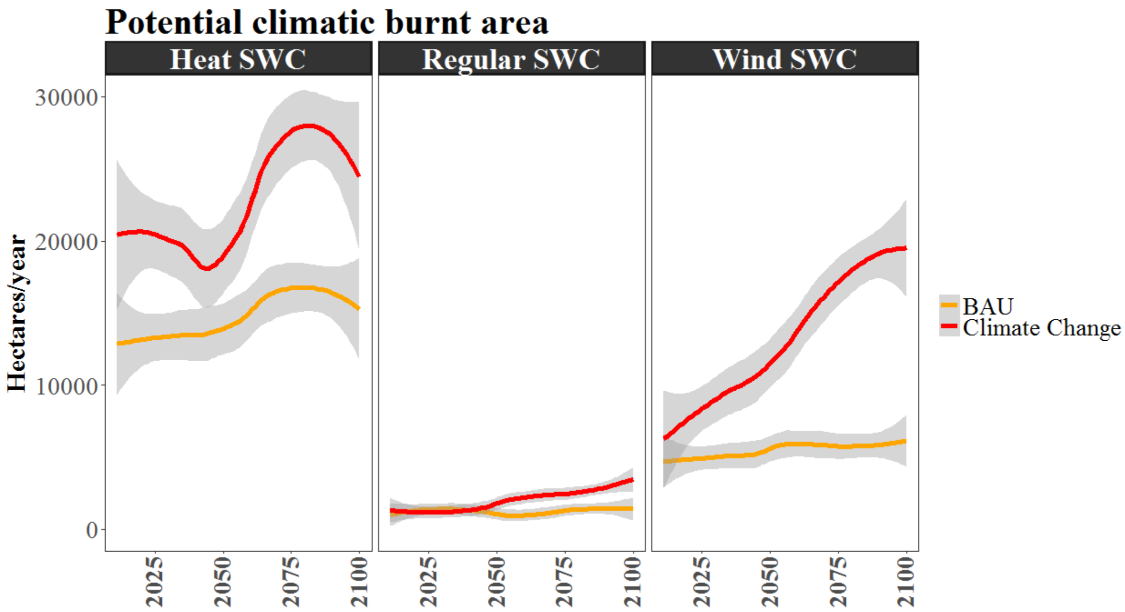


Figure 4. Evolution from 2016 to 2100 of the climatic target of each SWC in the baseline scenario (BAU) and the Climate change scenario. Lines correspond to the 'loess' fit. Shaded areas indicate the 95% confidence interval.

Actual burnt area differed substantially between Business-as-usual (BAU) and Climate change scenarios (Fig. 5). Since fire management was similar in both scenarios, differences in final burnt area were due to increases in climate burnt area potentials. However, under Heat SWC, predicted burnt area was much larger in the Climate change than in the BAU scenario because the model assumes that fire suppression capacity decreases in extreme years. It is worth to note that this increment of burnt area can lead to higher fire suppression opportunities, thus counteracting the increasing climate burnt area potential. This explains why the increase in predicted burnt area in Wind SWC levels-off at the end of the century in the Climate change scenario when compared to the climatic burnt area potential.

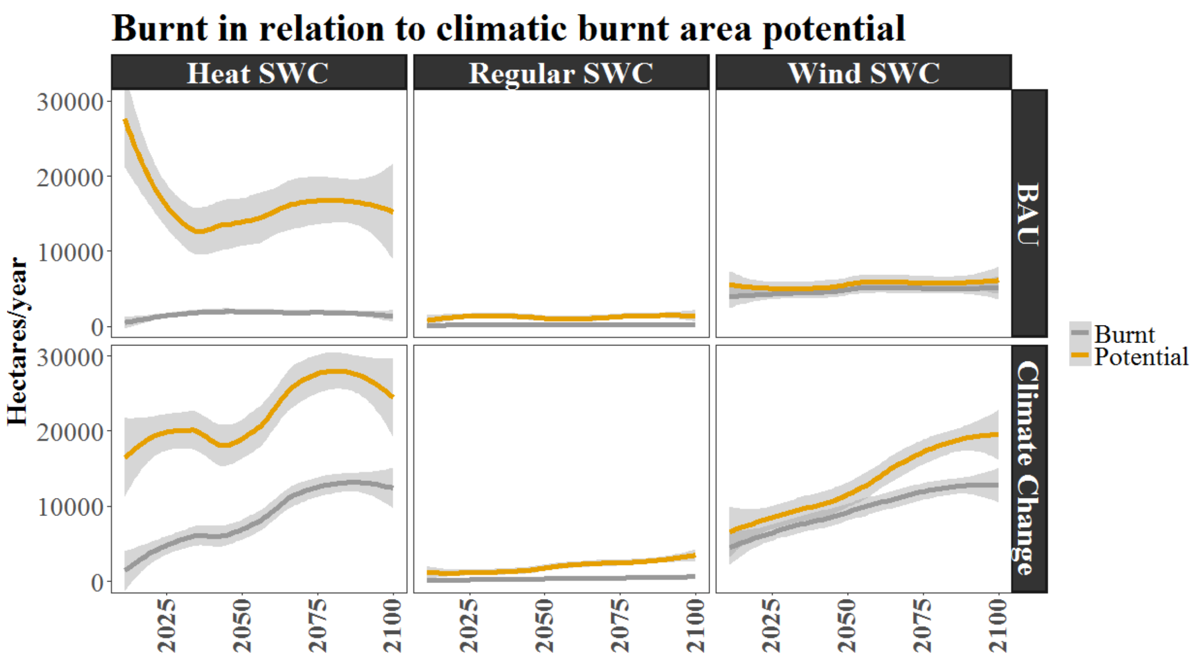


Figure 5. Evolution from 2016 to 2100 of the climatic burnt area potential and the actual burnt area under each SWC in the business-as-usual and the Climate change scenario. Solid lines correspond to the 'loess' fit. Shaded areas indicate the 95% confidence interval.

Fire management effects on fire regimes under climate change

Burnt area varied under the different management scenarios (Fig. 6). The scenario 'Let it burn' entailed the largest burnt area under the Heat SWC and Regular SWC. In contrast, in this scenario, predicted burnt area under Wind SWC was smaller than when assuming climate change with current management, because opportunistic fire suppression took advantage of larger burnt areas from the other fire typologies. Burnt area decreased in all scenarios with PB for the three SWC. Fixed PB aimed to reduce fire risk was the most effective, followed by Fixed PB aimed to protect urban houses, and finally Adaptive PB (Fig. 6). Nonetheless, the total amount of PB was much smaller in Adaptive PB (1100326 ha) than in the other two PB scenarios (1,350,000 ha; Fig. 7).

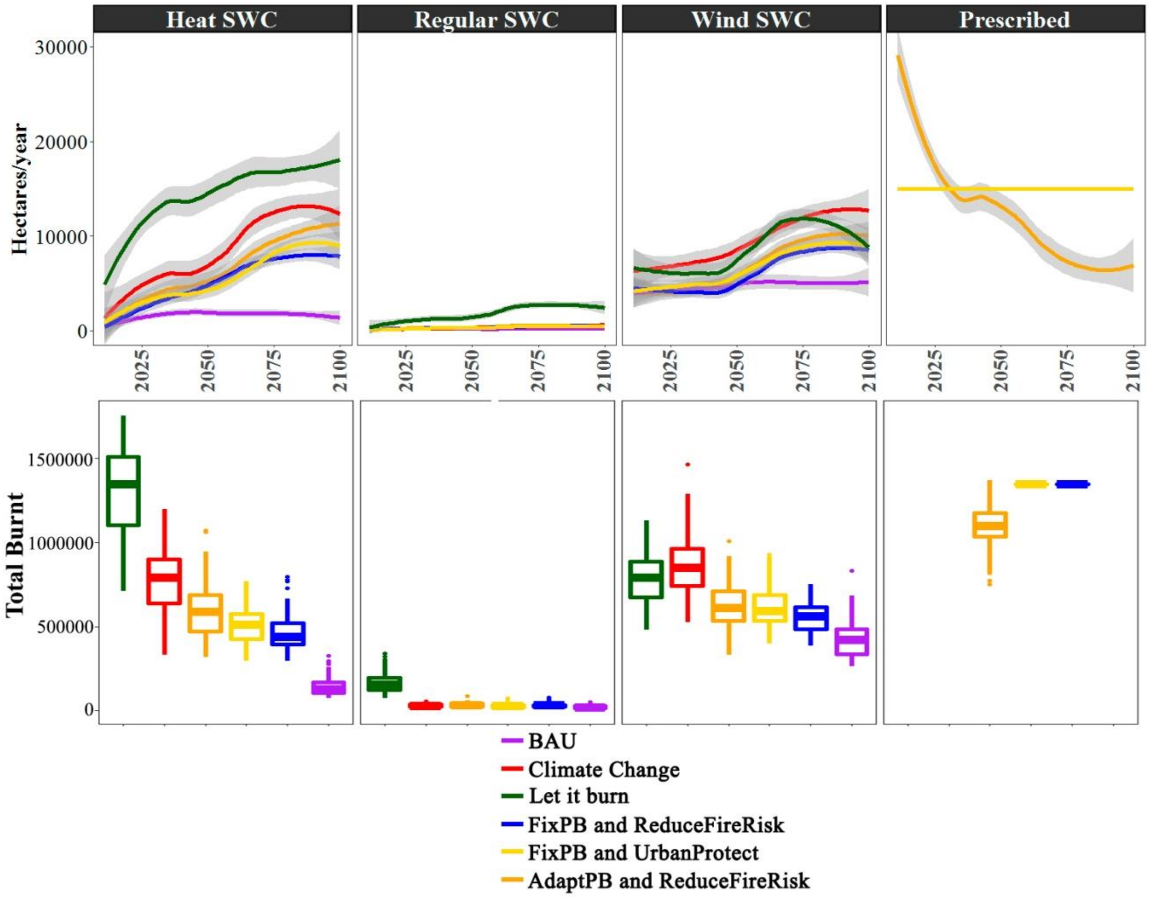


Figure 6. Evolution from 2011 to 2100 (upper panel) and totals (lower panel) of burnt area under each SWC and in prescribed burns for the six scenarios (Table 1). Prescribed burning results are only shown where applicable. Lines in the upper panel correspond to the 'loess' fit, and shaded areas indicate the 95% confidence interval. Boxplots in the lower panel show burnt area distributions.

In the three scenarios with PB, the total burnt area (by both unplanned and planned fires) was the largest (Fig. 7). Among these, the Fixed PB Urban protection scenario exhibited the largest burnt area: it was less effective in reducing high-intensity burnt areas than the two other PB scenarios. However, the 'let it burn' scenario led to the largest high-intensity burnt areas (Fig. 7). The Climate change scenario predicted the second largest amount of high-intensity burnt areas. Adaptive PB was next, because under this strategy unplanned fires are more common than in other Fixed PB strategies. Total low-intensity burnt areas mostly captured prescribed burns, since in the other scenarios low intensity burnt areas were rare.

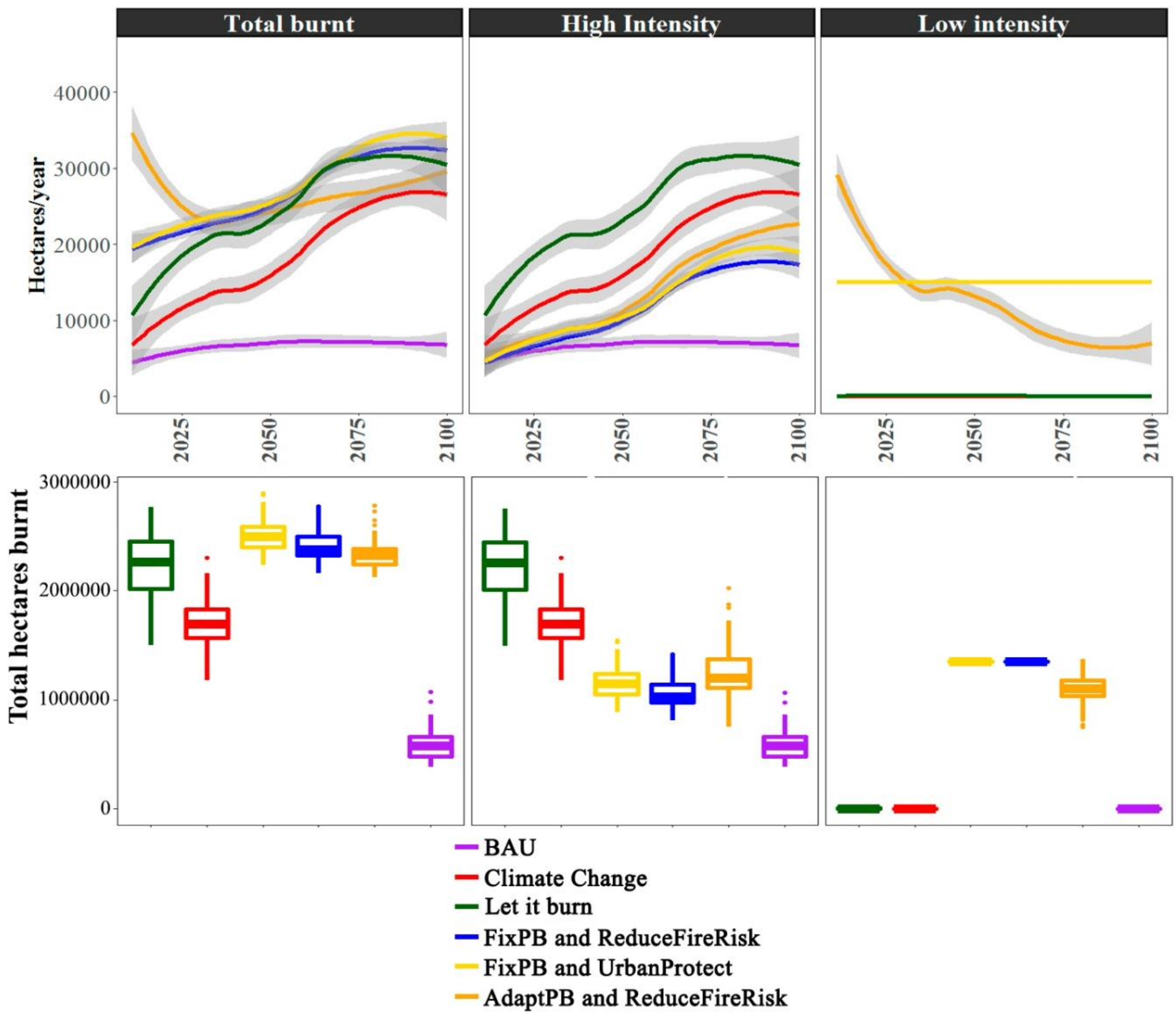


Figure 7. Evolution from 2016 to 2100 (upper panel) and totals (lower panel) of total, high-intensity and low-intensity burnt area, for the six scenarios (Table 1). Lines in the upper panel correspond to the 'loess' fit, and shaded areas indicate the 95% confidence interval. Boxplots in the lower panel show the distribution of values.

Fire management also influenced the interannual variability of unplanned fires. Variability here refers to the average (across the century) of the difference between maximum and minimum burnt areas by unplanned fires in 7-year time-windows (Fig. 8). Scenarios with PB reduced total variability in relation to the climate change scenario, specifically the one with Fixed PB aimed at reducing fire risk. The 'Let it burn' scenario had the largest variability. Interannual variability for an example simulation per scenario are shown in Figs. S3.1 and S3.2.

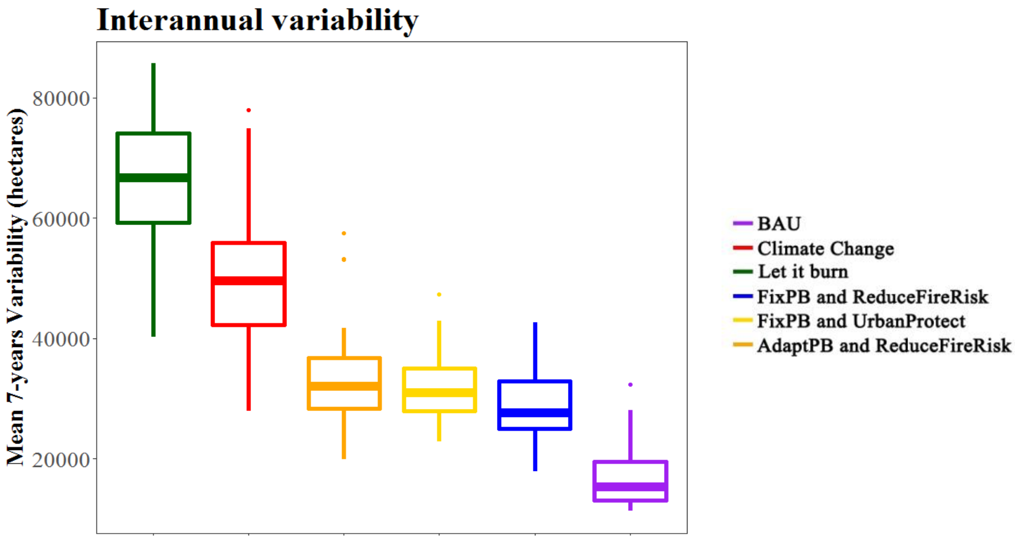


Figure 8. Total interannual variability of burnt area in high-intensity for the six scenarios (Table 1).

Climate change decreased the fire return interval (FRI) with respect to the BAU scenario (Fig. 9). In contrast, fire management scenarios considering PB increased the FRI in relation to the Climate change scenario. The 'Let it burn' scenario induced the smallest FRI. Predicted spatial patterns of FRI across the study area were similar among all scenarios, with smaller FRI consistently identified in southern, central and north-eastern Catalonia.

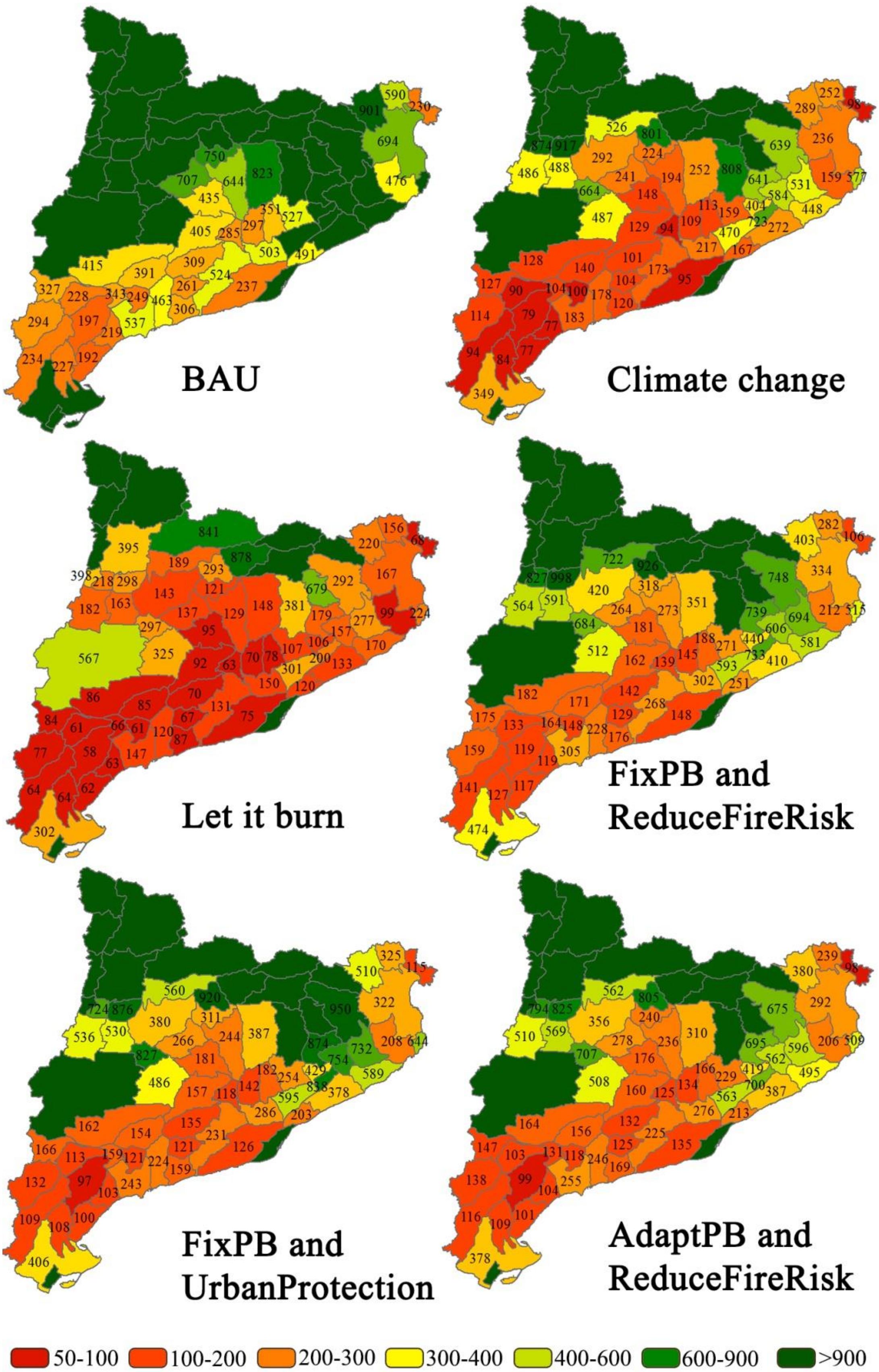


Figure 9. Fire Return Interval (in years) per Homogenous Fire Zone for the six scenarios (Table 1).

Cell probability of being burnt high- and low-intensity fires was assessed per scenario (Fig. 10 and 11). Values for high-intensity burnt areas reached up to 550% for the 'let it burn' scenario, meaning that a pixel has a probability of being burnt 5.5 times in the whole period. The BAU scenario predicted more low-intensity burnt areas than the Climate change scenario, because low-intensity burnt areas only happen in mild years, which are rare under climate change. For the low-intensity burnt areas, the probability only reached 250% because prescribed burns were only targeted to forests older than 30 years, so in the whole period the same forest could not burnt more than three times.

The probability of burn in a convective fire (Fig. S3.4) under the climate change and the 'let it burn' scenario marked some displacement to areas usually not affected before (i.e. Northwest). High-recurrence in more typical convective fire areas inhibited the accumulation of enough fuel to allow convective fires to return and thus move to other locations (illustrative example of a single simulation in Fig. S3.3). The probability of burn in a wind-driven fire (Fig S3.5) displayed strong incidence in southern and northern Catalonia.

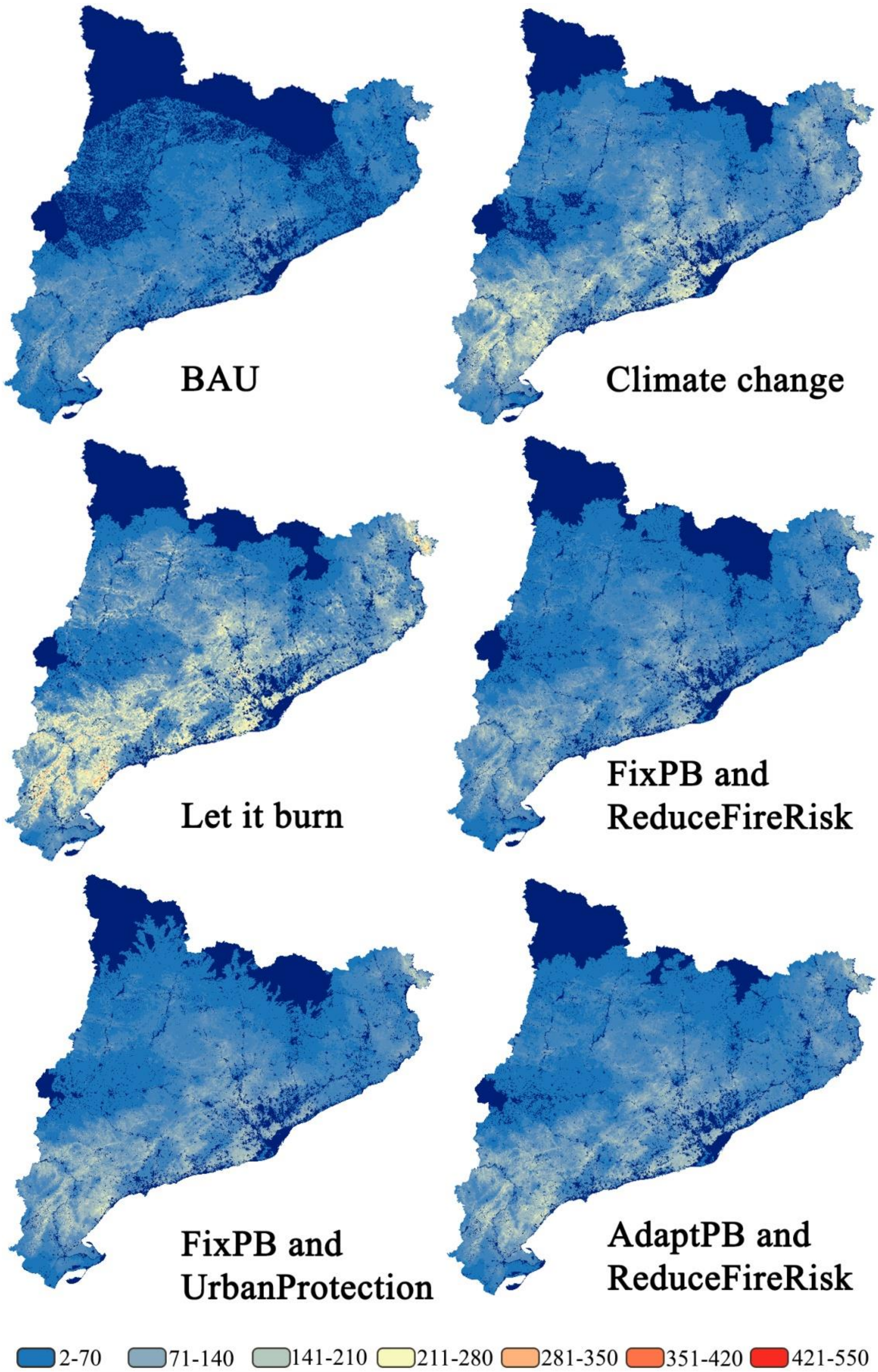


Figure 10. Probability of high-intensity burn (%) during the period 2016-2100 for the six scenarios (Table 1). A value of 100% means that the cell will burn at least one time in the whole period. Dark blue in northern areas correspond to low fire-risk areas in the high Pyrenees, usually not affected by summer fires.

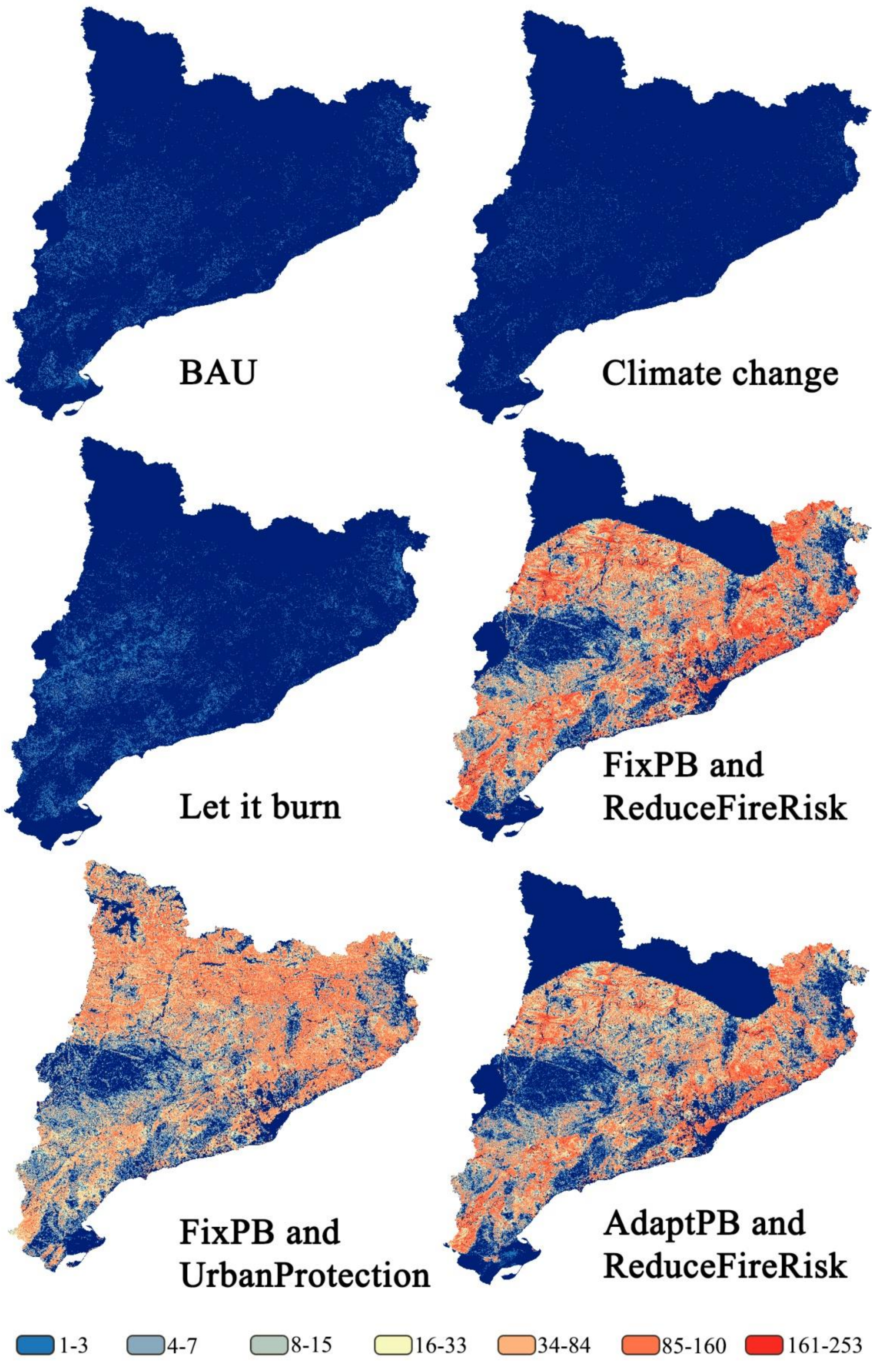


Figure 11. Probability of low-intensity burn (%) during the period 2016-2100 for the six scenarios (Table 1). A value of 100% means that the cell will burn at least one time in the whole period. Dark blue in northern areas correspond to low fire-risk areas in the high Pyrenees, usually not targeted to reduce summer fires.

DISCUSSION

Here we provided quantitative evidence of the capability of prescribed burnings to modulate fire regimes under changing climatic conditions. Climate change leads to an increase of fire-weather conditions provoking larger burnt areas and higher intensities than those predicted by the business-as-usual scenario. Fire management has the opportunity to override the expected growing negative fire impacts by increasing the amount of controlled low-intensity fires. By fostering low-fuel landscapes, fire regimes can become less dependent on extreme weather conditions and minimize public losses or non-return ecological states. Moreover, we also demonstrated that certain management strategies are more cost-efficient when these are adapted to dynamic changes of the system. We propose to recognize fire as an intrinsic element of Mediterranean ecosystem dynamics and develop adaptive fire management focused on the reduction of negative fire impacts rather than on the total removal of this disturbance from the system. All these results provide useful information for governments interested in exploring the implementation of new fire policies under future climates.

Novel climate conditions – feedbacks between climate, landscape and fire

We have evaluated future climate conditions and characterized the presence of ‘novel climates’ not seen before. Predicting future fires with data outside the historical records surpasses established fire-climate relations. This study aligns with recent findings (Amatulli et al., 2013) pointing to an increase of weather conditions conducing to fire in many Mediterranean regions: climate will be hotter and drier (IPCC, 2014). Our results provide significant advances in the understanding on how the increase in climate burnt area potential may eventually impact fire regimes: the interaction with landscape characteristics and fire suppression reveal a leveling-off of burnt area at the end of the century. Larger burnt areas associated with greater climate burnt area potentials will limit subsequent fire activity because of the leverage effect (Duane et al. under review). Self-regulating fire processes will be crucial to explain fire activity in a climate change context with increased climate burnt area potential.

Importantly, the impact of climate change will differ according to the different types of fires. While under the business-as-usual scenario most of burnt area corresponds to fires occurring under windy conditions, burnt area under Climate change scenario is equally distributed among fires occurring under Heat and Wind SWC, plus a small part burnt under Regular SWC. Although up to 50% of burnt area potential in Heat SWC is suppressed by firefighters, there are still a large number of convective fires that will escape from firefighters' capacity under extreme climates, which does not occur under the BAU scenario. Simultaneity of convective fires will be one of the big challenges that societies will face under climate change, when extreme fire behavior and unpredictability of wildfire development will compromise people safety (Adams, 2013; San-Miguel-Ayanz et al., 2013; Tedim et al., 2013).

The increased high-intensity burnt area resulting from climate change may decrease fire return intervals and increase fire recurrence in all Catalonia. Importantly, climate change and fire recurrence increment will displace convective fires to areas not affected by these fires before (Fig S3.3). Convective fire occurrences depend on high-fuel landscape accumulation (Duane et al., 2015), which can be compromised in central and southern Catalonia if fire recurrence increases. This is because both the increasing climate burnt area potential and sufficient fuel accumulation will promote the occurrence of large fires in the Pre-Pyrenees, a mountainous area that has not experienced these fires in the past.

The model presented here is aimed at understanding climate change impacts on fire regimes during the 21st century. However, we have not included some indirect influences of climate change on fire activity during this period. Climate change will impact ecosystems' productivity and, in return, fire activity potential. Actually, certain combinations of fire and drought events could lead to irreversible changes on ecosystem properties (i.e. tipping points sensu; Batllori et al., 2017). We have not captured specifically this relationship in this work and further works must aim at disentangling the specific contribution of climate to fire regimes by means of impacts on changing vegetation due to more aridity conditions (Batllori et al., 2013).

Fire management impacts on fire regime

In this study, we quantified the effects of different management strategies on fire regimes. Prescribed burning led to the largest reduction of high-intensity burnt areas, especially when the preferential allocation targeted to reduce wildfires (instead of other parallel objectives such as protecting urban areas). In contrast, areas burning in low-intensity conditions largely increased. The overall fire extent can remain similar or even increase.

The application of prescribed burns helped to decrease unplanned fire extent as well as areas burning in high intensity. High-intensity fires have shown to have strong impacts on biodiversity, soils, water, carbon stocks and eventually human lives (Fernandes et al., 2016; San-Miguel-Ayanz et al., 2013; Tedim et al., 2013). Instead, low-intensity fires have neutral or positive effects on soils and biodiversity, and carbon emissions are much lower (Fernandes et al., 2013). Additionally, PB decreased extreme fire peak activity (Fig. 8). Extreme large wildfire events can become a social emergency threatening human lives and properties. Under a climate change context, fire management targeted to increase the proportion of low-intensity fires can help to solve large wildfire event phenomena and lower their impacts on ecosystems and people.

Prescribed burning management targeted to reduce wildfires has only slightly positive impacts compared to prescribed burning targeted to protect urban areas (Fig. 7). Urban settlements are both a vulnerable asset to protect and also a wildfire ignition source (Syphard et al., 2013). When protecting urban areas, management also prevents wildfires to initiate, and so fires burning in high-intensity are also constrained. Since fires occurring in the wild-land urban interface change suppression tactics and can represent as much as 95% of suppression costs (Quadrennial Fire Review, 2015), reducing wildfires on the wildland-urban interface can further improve overall fire management. All this point to wildland urban interfaces as key coupled-systems to target management efforts (Moritz et al., 2014).

Moreover, the effectiveness at the long term of the different management strategies should be considered. Cost-effective analysis is a reliable tool to make comprehensive decisions (Catry et al., 2010; Clayton et al., 2014). In our study, adaptive prescribed burning reduced its extent by taking advantage of large areas burnt in previous years. High-intensity fire risk reduction was lesser under this strategy, but more effective in terms of efforts. Policy makers can use this information to reach a consensus of appropriate management strategies that help to achieve desired fire regimes under sustainable investments.

Relaxing fire suppression had a large impact on fire regimes. A number of works have presented this strategy as a way to increase landscape fuel-reduction at a low-cost, taking advantage of already running fires instead of starting ‘new’ fires with PB (Houtman et al., 2013; Regos et al., 2014; Reinhardt et al., 2008). Although it can initially seem to be a cheaper option than prescribed burning (it takes advantage of the ongoing suppression operative), the implementation of this strategy can have several drawbacks. For instance, our model results suggest that total high-intensity burnt areas may not really diminish. Our model lets fires to burn under low-intensity in mild conditions within unplanned perimeters, but given the decreasing amount of mild-weather years, most fire-cells are burnt in high-intensity. This can entail different consequences for soil, carbon emissions and biodiversity than when applying PB. In addition, areas burnt under the 'let it burn' strategy lack the decision on where to burn, whereas PB strategies let the manager decide where.

In fact, the effectiveness of prescribed burning could be increased by prioritizing management locations that provide highly-efficient suppression opportunities. These are mainly locations related to specific topographic features (mountain passes, ravine junctions, etc.; Duane et al., 2015) that can become gateways to the development of new fire fronts. These locations can differ according to the type of fire spread pattern that affects that area (Duane et al., 2015). Thus, adapting PB allocation according to the most common fire spread pattern that might affect each location can entail higher benefits. Moreover, prescribed burning plans should also be specific for the different species fire-response functional traits. Biodiversity conservation could be enforced by implementing fire management recipes that emulate fire regimes to which particular species are adapted (for instance, frequent and low-intensity fires for low intensity fire-adapted non-serotinous conifer species such as *Pinus nigra* stands in Catalonia).

Fire policy insights under changing climates

We have shown that adaptive prescribed burning can have positive impacts in reducing extreme events and high intensity fires. Our model has allowed us to test the effectiveness of PB by incorporating the two main elements modulating PB effectiveness: post-fire regeneration establishment and aging, and fire regime characteristics (frequency, type of fire spread pattern, etc.). The amount burnt in PB in the present work has been discussed as reasonable and feasible (15,000 ha/year; Marc Castellnou, head of firefighters in Catalonia, personal communication), which overall points to a clearly suitable implementation of this fire management strategy in Catalonia. But PB it is not a panacea. Prescribed burning has other limitations beyond those of quantifying its proven effectiveness. Around the world and particularly in southern European countries there is a social resistance to accept fire as a management tool (Fernandes et al., 2013), particularly to the use of fire as seen from an urban point of view (Otero and Nielsen, 2017). Moreover, managers also find impediments associated to its costs, to finding specialists that can carry out the burn, to the risk of it escaping out of control, etc. (Altangerel and Kull, 2012). Prescribed burning will be more efficient and accepted if it can be presented as a multi-objective management tool (i.e. besides decreasing fire extent and intensity, prescribed burns can also be used to restore habitats, maintain open forests, improve pastures in mountain areas, facilitate natural regeneration, control spreading of pests and diseases, etc. (Fernandes et al., 2013).

Fire management can be conceived as a way to achieve a certain fire regime that benefits both ecosystems and humans without entailing unnecessary risks. Many studies have demonstrated both that 1) fires are a natural process of many ecosystems that benefit some flora and fauna, and 2) totally excluding fire from the system is impossible. Fire-related management goals have started to shift from 'total fire removal' to a 'coexistence with fire' (Moritz et al., 2014). To work towards fire regime control, the best pathway to take is to promote fuel reduction at the landscape scale so preventing fire regime to be mostly controlled by climate (Pausas and Fernández-Muñoz, 2011; Duane et al. under review). Consequently, under projected extreme adverse climate conditions, we can still have the capacity to control final burnt area through fuel-reduction (Fernandes et al., 2016; Khabarov et al., 2014). Fuel reduction at the landscape scale can be achieved in several ways: by land-use conversion, fuel mechanical treatments, grazing, or controlled fires (by prescribed burns or letting-burn strategies). From all this, while prescribed burning does not suppose a reduction of total fire extent, a realistic implementation of PB across the study area (15,000 ha per year) can reduce high-intensity burnt areas and limit mega-fires. This option is potentially applicable at the Catalan scale after consultation with local stakeholders. Furthermore, fuel reduction over large areas by prescribed burning is the most efficient method of the current available measures to mitigate wildfire risk (Altangerel and Kull, 2012). Fuel-mechanical treatment on a large scale is struggling for reducing fire risk at the landscape scale if applied under the current subsidies-investment schemes. A profound change in our economic systems has to occur to conceive wood and timber as a beneficial market product and to make fuel-mechanical treatments economically sustainable to be applied at the landscape scale (for instance, promotion of bioeconomy policies could help achieving this; Fight et al., 2004). Grazing as a wildfire control tool is finding more supporters, since it diminishes carbon emissions and, at the same time, it allows recovering some food alternative products that override increasing water-demand systems dependent on intensive-production. However, other impacts associated to over-grazing pressure (soil compaction, herbaceous species selectivity, etc.), are associated with these practices. Most probably, a combination of different fuel management practices could lead to an optimal reduction of extreme wildfire events, increase ecosystem resilience, benefit local economies and preserve biodiversity under the threat that climate change supposes. Integrative strategies that take into account the various social, economic and ecological dimensions of fire regimes offer appropriate solutions for highly populated landscapes in a changing future.

ACKNOWLEDGMENTS

This study was funded by the Spanish Government through the INMODES (CGL2014-59742-C2-2-R). The research leading to these results has also received funding from "la Caixa" Banking Foundation and from the CERCA Programme from the Generalitat de Catalunya. Andrea Duane was funded by the Ministerio de Educación, Cultura y Deporte (Spain) (FPU13/00108). We thank the Servei de Prevenció d'Incendis de la Generalitat de Catalunya for providing fire ignition data, and the Firefighting Services of Catalonia for their constant support.

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SUPPLEMENTARY MATERIAL CHAPTER 5

APPENDIX S1. Model initialization

This appendix details the parameters used in the fire module of the MEDFIRE model used for Catalonia.

1. Climate potential distributions

Each year the model choses a climatic burnt area potential from a distribution. There are six distributions that depend both on the synoptic weather conditions (SWC) and in the medium-term weather conditions. Climate potential distributions are calibrated with burnt areas in Catalonia between 1980 and 1999. After 2000, burnt areas are strongly influenced by suppression, when an enhanced fire suppression system started in Catalonia modifying fire regime in the area (Brotons et al., 2013; Otero and Nielsen, 2017).

Medium-term weather conditions were represented by the SPEI index. This index indicates the deviations of the current water-balance (precipitation minus potential evapotranspiration) with respect to the long-term water balance. We selected the SPEI index for the period of peak fire activity in the study region (July) and calculated the cumulative water balance three months before the date (Pereira et al., 2005; Russo et al., 2017). Duane and Brotons (2018) found a value of -0.21 SPEI separating mild years from dry years according to fire activity in Catalonia.

Burnt areas were the sum of all fires occurring under each SWC occurring between May and September every year. Fires were gathered from official registers from the Fire

Prevention Agency of the Government of Catalonia. All probabilities followed a lognormal distribution with the parameters indicated in Table S1.1. In the model, the annual climatic burnt area potential is upper truncated at 200,000 ha per SWC, and lower truncated at 10 ha.

Table S1.1. Parameters of log-normal distributions for the six climatic combinations.

SWC	Medium-term conditions	Mean	Sd
Heat	Mild	5.29	2.45
Heat	Dry	8.28	2.19
Regular	Mild	3.28	1.43
Regular	Dry	6.17	1.88
Wind	Mild	4.81	2.11
Wind	Dry	8.17	1.50

2. Validation of climatic potentials for the same period

We validated climatic potentials from the same calibration period (1980-1999) to the actual burnt area in this period to check for calibration inconsistences. We run 1,000 simulations applying climatic potentials using observed proportion of mild and dry years in this period. In all three SWC, climatic targets were within the interquartile range (Fig. S1.1).

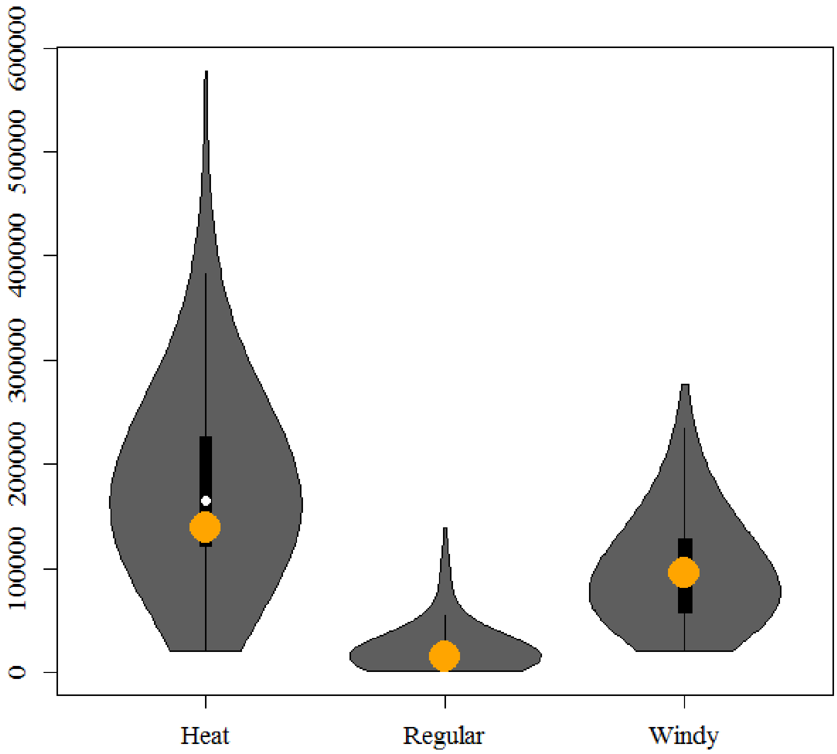

Figure S1.1. Violin plots of the climatic target distributions and observed burnt areas (orange points) for each SWC. All observed data fall within the interquartile range.

3. Probability of ignition

We modelled fire ignitions of fires greater than 50 hectares according to explanatory variables using a multivariate logistic regression model. Fire ignitions database was gathered from the Forest Fire Prevention Service of the Government of Catalonia and totaled 252 observations occurred in Catalonia from 1987 to 2012. We defined the dependent variable of the logistic model as a binary variable of fire ignition occurrence in a 2x2 km grid: 1 if at least there is an ignition within the cell and 0 otherwise. The subset of 4 km^2 cells containing at least one ignition (250 cells) was completed with 5 time more cells of non-ignitions randomly distributed over the space (Syphard et al., 2008). Values from 60% of the cells were randomly chosen for model fitting, while the remaining 40% was reserved for independently testing the predictive capacity of the model (Cardille et al., 2001; Martínez et al., 2009).

Predictor variables included elevation, slope, precipitation and four variables related to land-uses: road density within the cell, and dominance of natural covers (forest and shrubs), wildland urban interface (natural and urban) and agro-forest interface (natural and agriculture) within the cell. The probability of ignition followed the equation Eq. S1.1.

[Equation S1.1] $logit(P_{ignition|non-ignition})$= *-2.159* - *0.001*·Elevation + *0.124*·Slope *-0.001*·Precip + *0.165*·RoadDens + *1.619*·Nat + *1.502*·UrbNat + *1.541*·CrpNat

where *Nat*, *UrbNat* and *CrpNat* represent the dominant presence of natural lands, wildland-urban interface, and agro-forest interface within the cell, respectively.

4. Probability of becoming a convective fire

The probability of becoming a convective fire instead of remaining a topography-driven fire only occurs under the Heat SWC, since convective fires, associated to extreme behaviors, need very high temperatures to occur (Rothermel, 1991). Local probability of convective fire strongly depends on fuel landscape variables (Duane et al., 2015). We simplified the logistic model presented by Duane et al. (2015) to similar variables included in the MEDFIRE model. This probability depends on the proportion of old (age between 30 and 150 both inclusive) forest of Mediterranean pines (*Pinus halepensis*, *Pinus nigra* and *Pinus pinea*) in a square neighborhood of 1900 meters of size around the ignition point (in %100; Eq. S1.2).

The probability was calibrated using actual topographic and convective fires occurred in Catalonia from 1980 to 1999 (classified in Duane et al. (2015), previously classifying fires according to the climatic severity of the year (Table S1.2, Fig. S1.2).

[Equation S1.2] $logit(P_{convective|topography})_{[mild-dry]}$ = *Intercept* + *Slope* * *PropOldPines*

Table S1.2. Parameters of logistic model of becoming convective fires according to the climatic severity of the year.

Medium-term weather conditions	Intercept	Slope
Mild	-0.76	0.022
Dry	-0.50	0.038

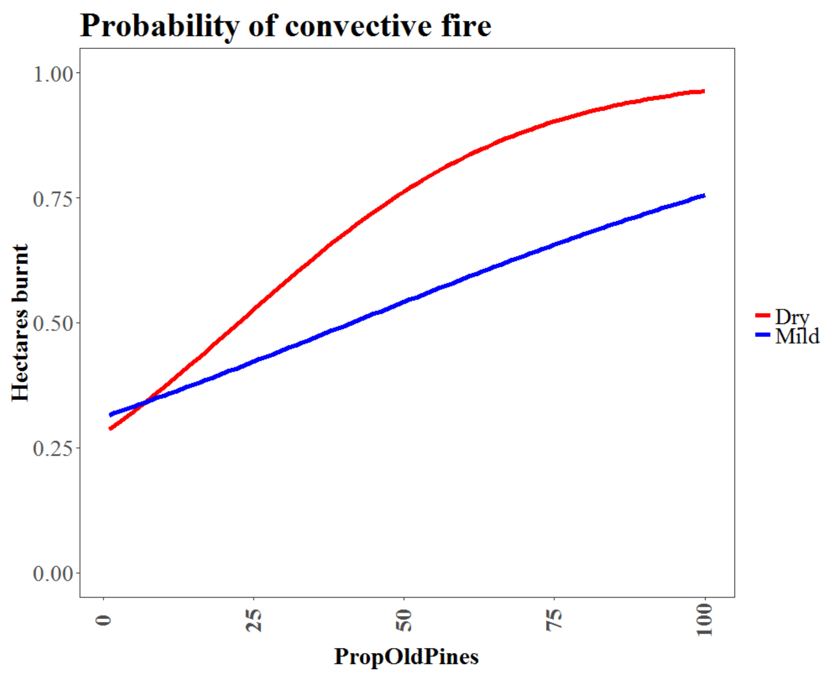

Figure S1.2. Probability of becoming a convective fire according to the proportion of old Mediterranean pines around an ignition (1900 x 1900 m) and the type of year. Function parameters are those displayed in Table S1.2.

5. Fire spread and potential fire size

Fire spread followed the formulation defined by Duane et al. (2016) (Eq. S1.3) calibrated for the different fire spread patterns.

[Equation S1.3] $$SR = wW * Wind + wS * Slope + wA * Aspect + wSpp * SppFlam$$

where wW, wS, wA and wSpp are weights for the 4 factors.

A wind direction had to be assigned for each ignition, since wind-direction factors influences all kinds of spread patterns. Wind direction of convective fires was 80% southern, 10% south-western and 10% south-eastern (Duane and Brotons, 2018). Wind direction of topography-driven fires was randomly chosen among the eight cardinal directions (Duane and Brotons, 2018). Wind direction of wind-driven fires was selected according the location of ignition point: we built three probability maps (the combination of all them summed 1) for each of the three main wind directions related to each SWC (North, North-West and West) built from wildfire density maps of each SWC (Duane and Brotons, 2018).

Potential fire size distributions depended on the fire spread pattern and the climatic severity of the year, and follow power-law distributions (Table S1.3 and Fig. S1.3). Power-law distributions describe negative linear relation between log(N>S) and log(S), where N>S is the number of fires with size greater than a given size S.

Table S1.3. Parameters of power-law distributions for fire spread pattern and medium-term weather conditions.

FSP	Medium-term weather conditions	Intercept	Slope	R^2
Wind-driven	Mild	2.88	-0.71	0.90
Wind-driven	Dry	2.70	-0.55	0.96
Topography-driven	Mild	3.06	-0.89	0.97
Topography-driven	Dry	3.39	-0.96	0.91
Convective	Mild	2.49	-0.59	0.96
Convective	Dry	2.60	-0.50	0.96

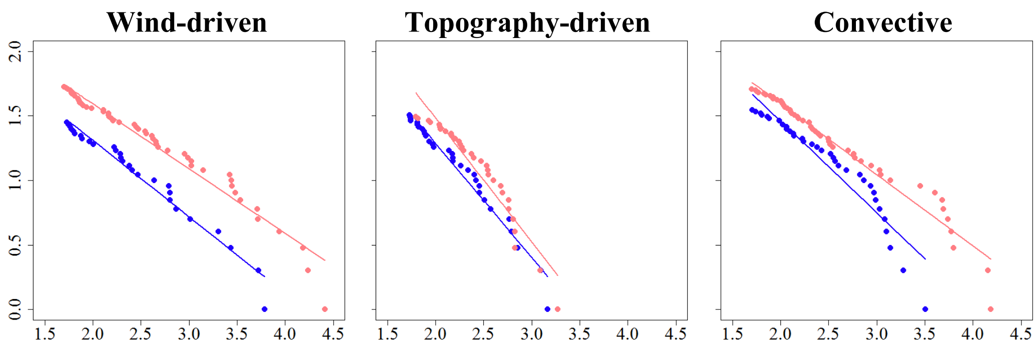

Figure S1.3. Power-law distributions of fire sizes for the different FSP and medium-term weather conditions. Blue dots and lines correspond to mild years, and red ones correspond to dry years. Points show actual values and lines correspond to the fitted linear model for each distribution.

6. Fire suppression

Fire suppression in Catalonia became strongly effective since 2000 year after improving fire suppression techniques allowing technical fire brigades to anticipate changes in fire propagation (Costa et al., 2011) and reduce final total burnt area. We applied the climate potential calibrated for period 1980-2000 to period 2000-2015 according to observed climate data, and assigned an active fire suppression value that reproduced observed burnt area. This active fire suppression value was different according to the different fire spread patterns, since Duane and Brotons (2018) found that firefighters in Catalonia have become extremely effective in controlling convective and topography-driven fires, but not wind-driven fires. Under an improvement of fire detection and fast suppression during last years (San-Miguel-Ayanz et al., 2013), potential convective fires are swiftly controlled, which prevented them to actually occur. In contrast, in wind-driven fires, wind makes the fire uncontrollable from the early stages of fire propagation making them stay beyond firefighting capacities.

We simulated fire regime for the period 2000-2015 using observed proportion of mild and dry years in this period. We simulated several values of fire suppression and compared simulated burnt area with observed burnt area. Fire suppression value that minimized differences between observed and simulated fires for each fire spread pattern was selected as the current fire suppression (Table S1.4).

Table S1.4. Active fire suppression values per fire spread pattern. Values indicate the threshold of Spread Rate under which fires are suppressed.

FSP	Active Fire Suppression
Wind-driven	30
Topography-driven	80
Convective	70

7. Prescribed burning parameters

Prescribed burn sizes followed a distribution based on the Catalan PB database (available in http://interior.gencat.cat/ca/serveis/informacio-geografica/bases-cartografiques/cremes-prescrites-dels-bombers/). We selected the 25% of larger fires to better fit our model parameters. Final distribution followed a log-normal with mean log = 1.974 and sd log = 0.683.

References – Appendix S1

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APPENDIX S2. Future climatic conditions

This appendix describes the procedures followed to get future climate data

1. Medium-term weather conditions

We calculated medium-term weather conditions from 2016 to 2100. We calculated the 3-months SPEI index for each July. The SPEI was calculated for each of the five locations overlapping Catalonia from data of the HadGEM-CC model. The HadGEM-CC is a coupled atmosphere-ocean and Earth-System model with a horizontal resolution of 1.25 degrees of latitude by 1.875 degrees of longitude (Collins et al., 2011; Martin et al., 2011). Data of the climate model and projections were obtained from the CMIP5 multi-model database (https://esgf-node.llnl.gov/). We firstly computed water balance (precipitation minus evapotranspiration). Evapotranspiration was calculated with the FAO-56 Penman–Monteith equation (Allen et al., 1998) as proposed by the R-package SPEI (Beguería et al., 2014; Vicente-Serrano et al., 2010). We used monthly minimum temperature, maximum temperature, mean wind speed and mean cloud cover as input. Since the SPEI informs about water-balance deviations from a reference period, future SPEI required from the water balance of historical series. We used HadGEM-CC data model projections to the past (1901-2005) as the reference period. SPEI was calculated for the future (2016-2100) and values from the five locations were averaged to obtain a single value per year for all Catalonia.

We divided all future time series into three periods (2011-2015, 2016-2060 and 2061-2100) and calculated the percentage of dry years in each period (Moritz et al., 2012). Duane and Brotons (2018) found a threshold of SPEI= - 0.21 splitting years in mild and dry years according to fire activity. We fitted a linear regression between mean SPEI per period and the percentage of dry years per period, assuming that 99% of years in the 2061-2100 were dry (Table S2.1, Fig. S2.1).

Table S2.1. Percentage of dry years per period.

Period	Mean SPEI	% of dry years
1980-2015	-0.19	45
2016-2060	-1.07	61
2061-2100	-2.83	99

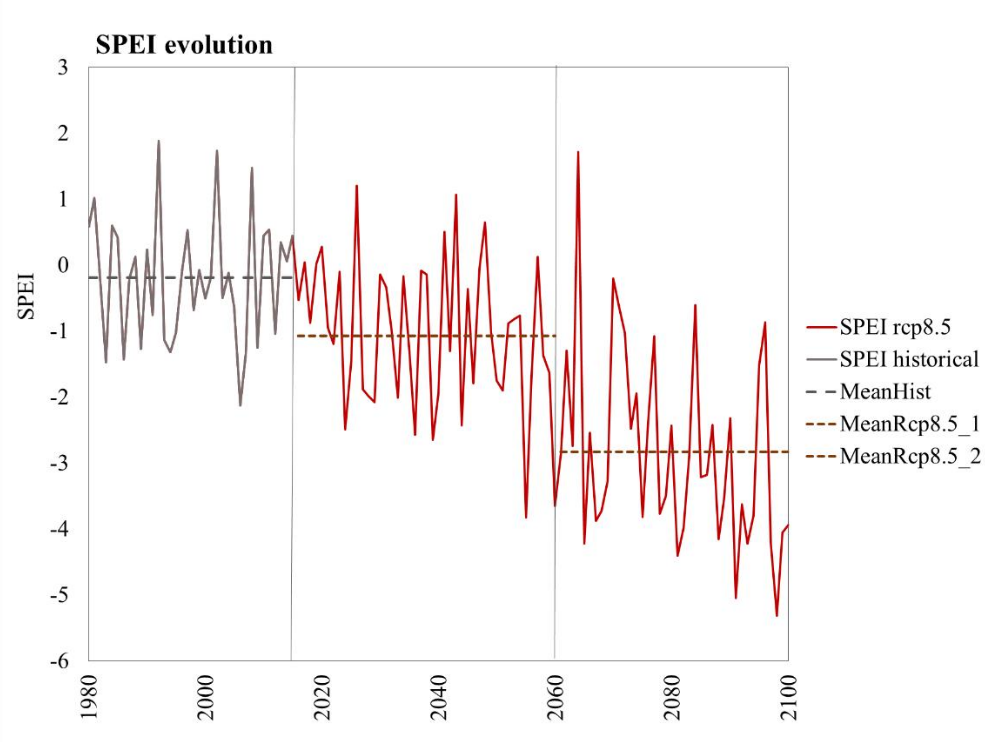

Figure S2.1. SPEI values from 1980 to 2100. Values from 1980 to 2015 correspond to historical values, and from 2016 to 2100 the projected ones under the RCP 8.5 scenario. The two vertical lines indicate the periods considered, and horizontal dashed lines display mean SPEI value for each period.

2. Probability of becoming an extreme year

Extreme years refer to summers with a high frequency of projected novel climates. We modelled the probability of becoming an extreme year with a logistic function that increased such probability as a function of the proportion of novel climates during summer.

1) Firstly, we calculated 'Novel climates' characteristics and frequency.

We followed the same procedure as in Duane and Brotons (2018), who classified all summer days into 6 weather groups according to 3 variables measured at the continental scale: temperature at 850hPa, wind at 925 hPa and sea level pressure. For the classification of future summer days we initially proceeded in the same way. We downloaded the data from HadGEM-CC model from the portal https://esgf-node.llnl.gov/projects/esgf-llnl/, including wind data from layer 850hPa, since the 925hPa (used to classify past-fire days) was not available. Spatial region covered the region 25–70°N and 20°W–40°E, and summer days included 1-May to 30-September. We resampled data to meet the spatial resolution of original classification, which was a bit grosser than future projections models.

Summer days from 2016 to 2100 were classified according to fire days from the past, with function vegclass from package Vegclust (De Caceres et al., 2010). But since temperature varies so much along the century, a lot of days (up to 90% in the late century under the RCP 8.5 scenario) were classified as Noise (their attributes were too different to any fire-day centroid).

Hence, we classified days according only to sea level pressure and wind variables, which alone explain important patterns on general atmospheric meteorology. We needed to re-classify past fires using only these two variables, trying to get the most similar groups to previous classification. A new *dnoise* distance had to be calibrated, since dimensional units of PCA changed. We selected the *dnoise* value that minimized distances between original and new clusters. Classification was very similar to previous one, and resulting groups were named equally, with only few fires changing their group membership.

We classified again all summer days from 2016 to 2100 according to new clusters, and the new classification reached similar percentages of Noise as in the past (around 30%). Once all summer days were classified according to the six groups from the past, we merged the different groups according to the main weather driver characterizing them over Catalonia: Wind days (*Scandinavian trough*, *Atlantic ridge*, and *Atlantic trough*), Heat days (*European blocking* and *South Intrusion*) and Regular days (*Zonal Regime* and Noise).

We examined future temperature on top Catalonia for each classified day within the three SWT. We classified days within each SWT as a function of temperature larger than observed in the past > 25.55ºC (Heat SWC) and >20.38ºC (Wind SWC). We finally calculated the summer frequency of Hot-days within each SWT.

2) We calculated the probability of becoming an extreme year

The probability for each SWC followed a logistic regression that increased as a function of the number of Hot-days for each SWC. Nowadays, we have not experienced an extreme year in the past, whereas in the future some summers at the end of the century reach percentages of 50% of Hot-Days. Years with more than 30% of Hot-Days were considered extreme. We then fitted a logistic regression with an increasing trend from 0.8 to 0.3 (Eq. S2.1).

[Equation S2.1] $$logit(P_{extreme|non-extreme})_{[HeatSWC-WindSWC]} = -3.064 + 27.73 * PropHot$$

3. Potential climate burnt area distributions for extreme years

We adjusted new parameters for climate potential distributions during extreme years for both Heat SWC and Wind SWC (Table S2.2). Amatulli et al., (2013) found a peak on fire activity forecasted to the future around 80% larger than seen in the past for EU-Mediterranean countries based on temperature variables. In our model, we adjusted a new distribution for Heat SWC based on climate potentials observed in the past under severe years, plus an extreme value of +80% of the largest value observed. For Wind SWC, bases for their climate potential calibration was a bit different, because no works on projected changes on fire-wind situations have been done to the future yet. Indeed, hot windy days are not frequent in Catalonia, in contrast with other regions (Jin et al., 2014; Ruffault et al., 2016). Currently in Catalonia, windy days are associated to cold winds coming from Northern latitudes. Projected novel climates point to similar wind patterns with hot temperatures. So we adjusted climate potential according to regions that differentiate fires occurring under hot windy situations than not. Jin et al. (2014) found that fires occurring under Santa Ana winds in California were ~230% larger than fires occurring under Non-Santa Ana winds. In our model, we adjusted a new distribution for Wind SWC based on climate potentials observed in the past under severe years, plus an extreme annual burnt area of +230% of the largest value observed.

Table S2.2. Parameters of log-normal distributions for the climatic potentials in extreme years.

SWC	Mean	Sd
Heat	8.61	2.30
Wind	8.52	1.76

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APPENDIX S3. Supplementary results

This appendix displays complementary figures from results.

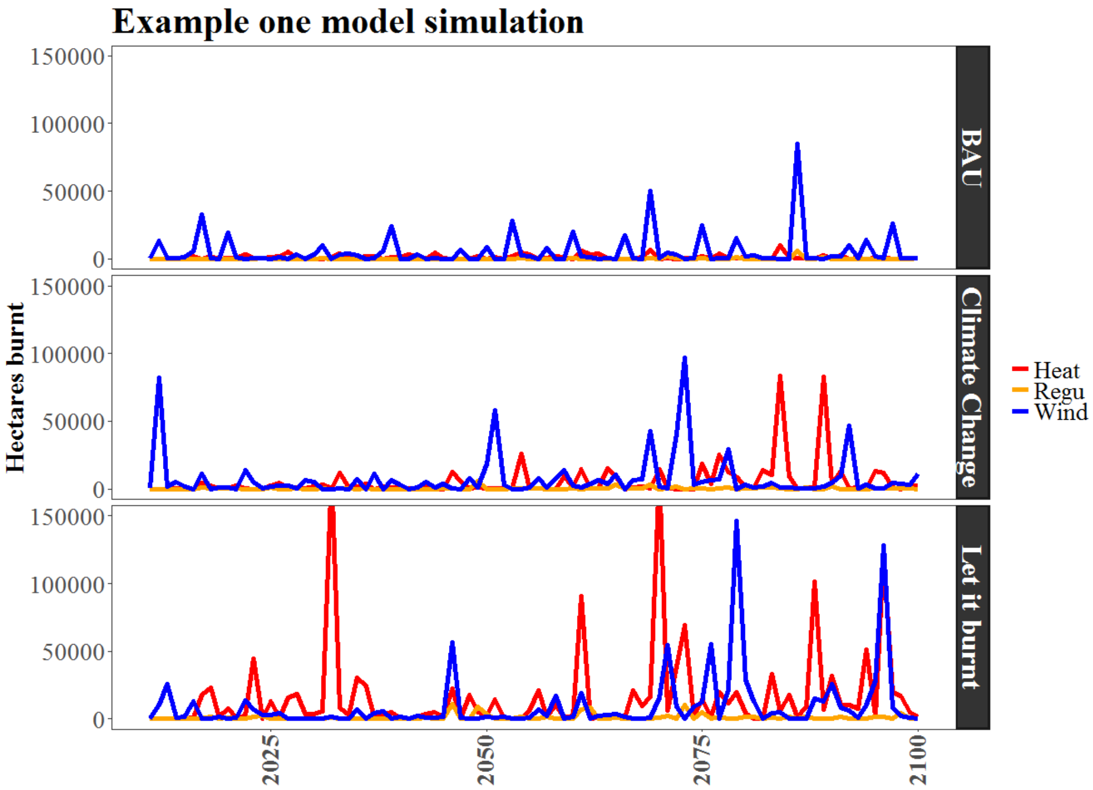

Figure S3.1. Burnt area under the different SWC for three scenarios (without PB) for one example simulation.

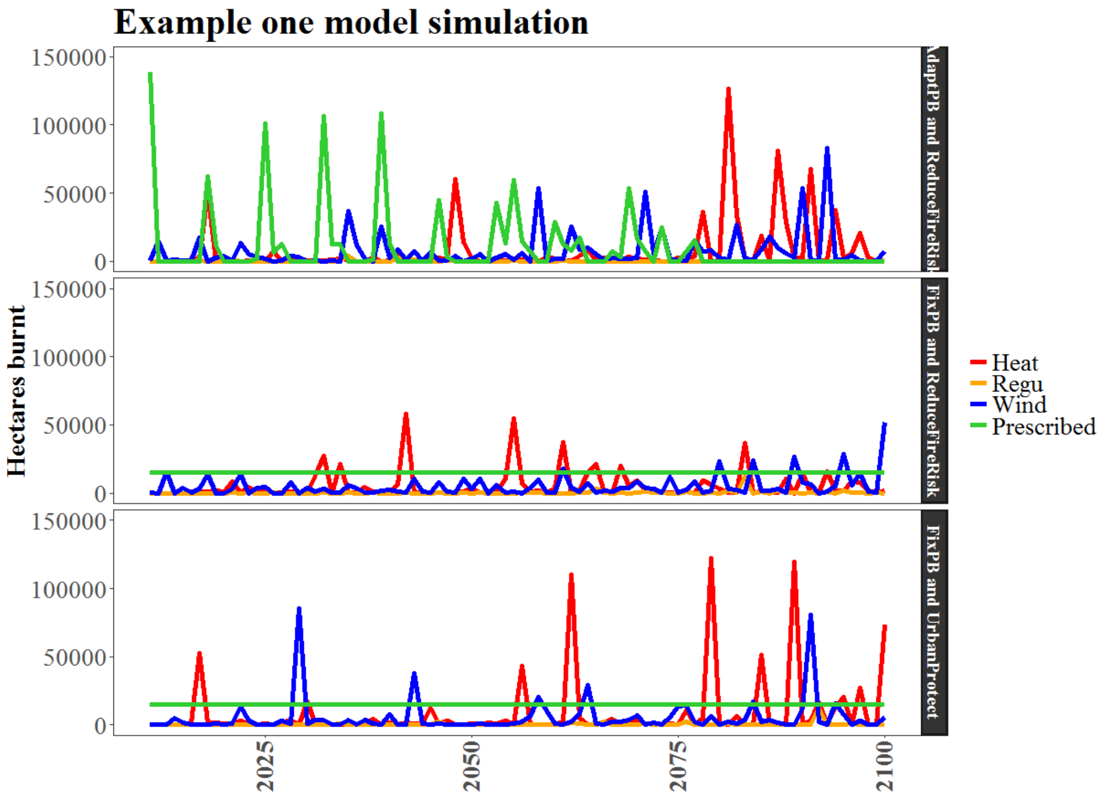

Figure S3.2. Burnt area under the different SWC for three scenarios (with PB) for one example simulation.

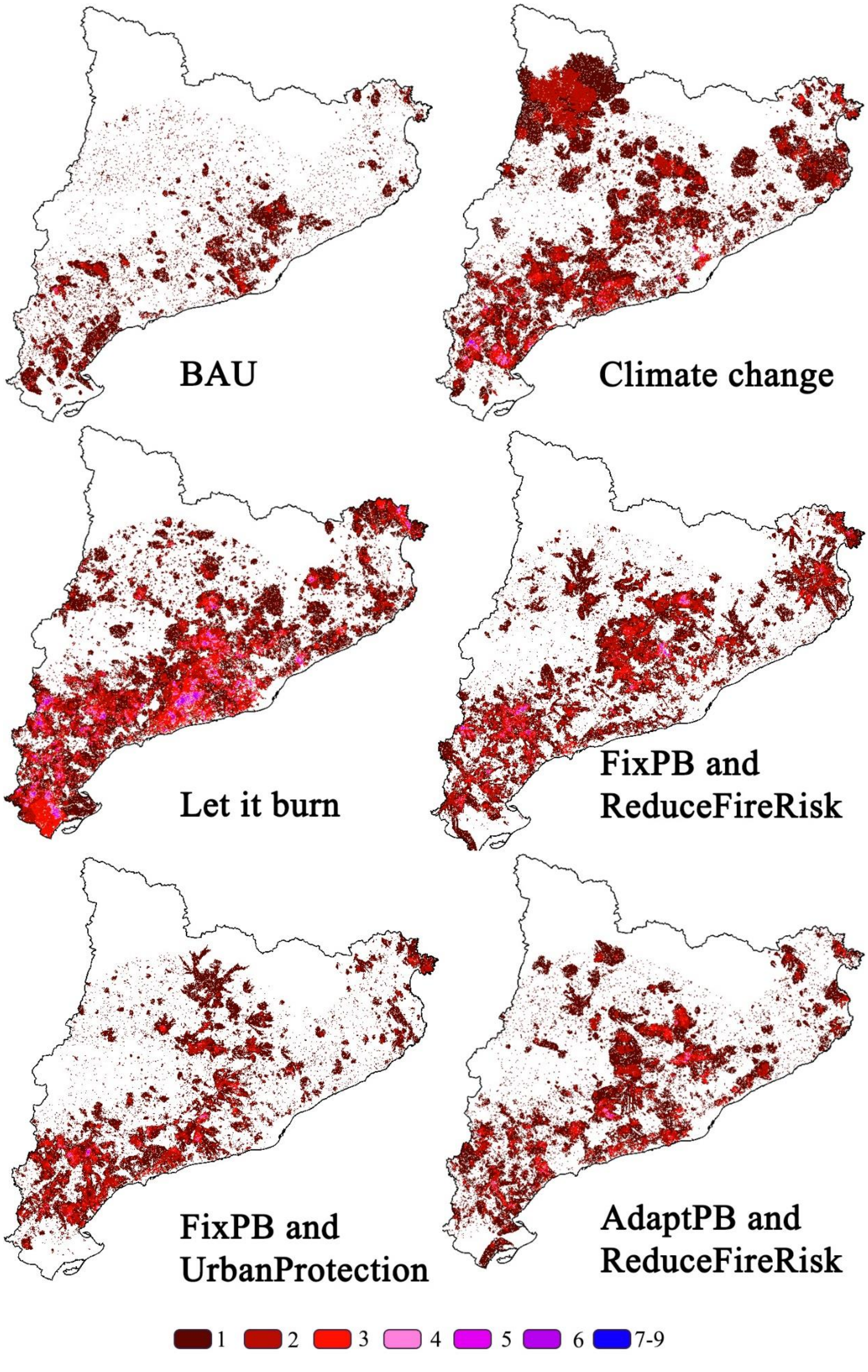

Figure S3.3. Times burnt in high-intensity in the 2010-2100 period for the six scenarios (Table 1) for one example simulation.

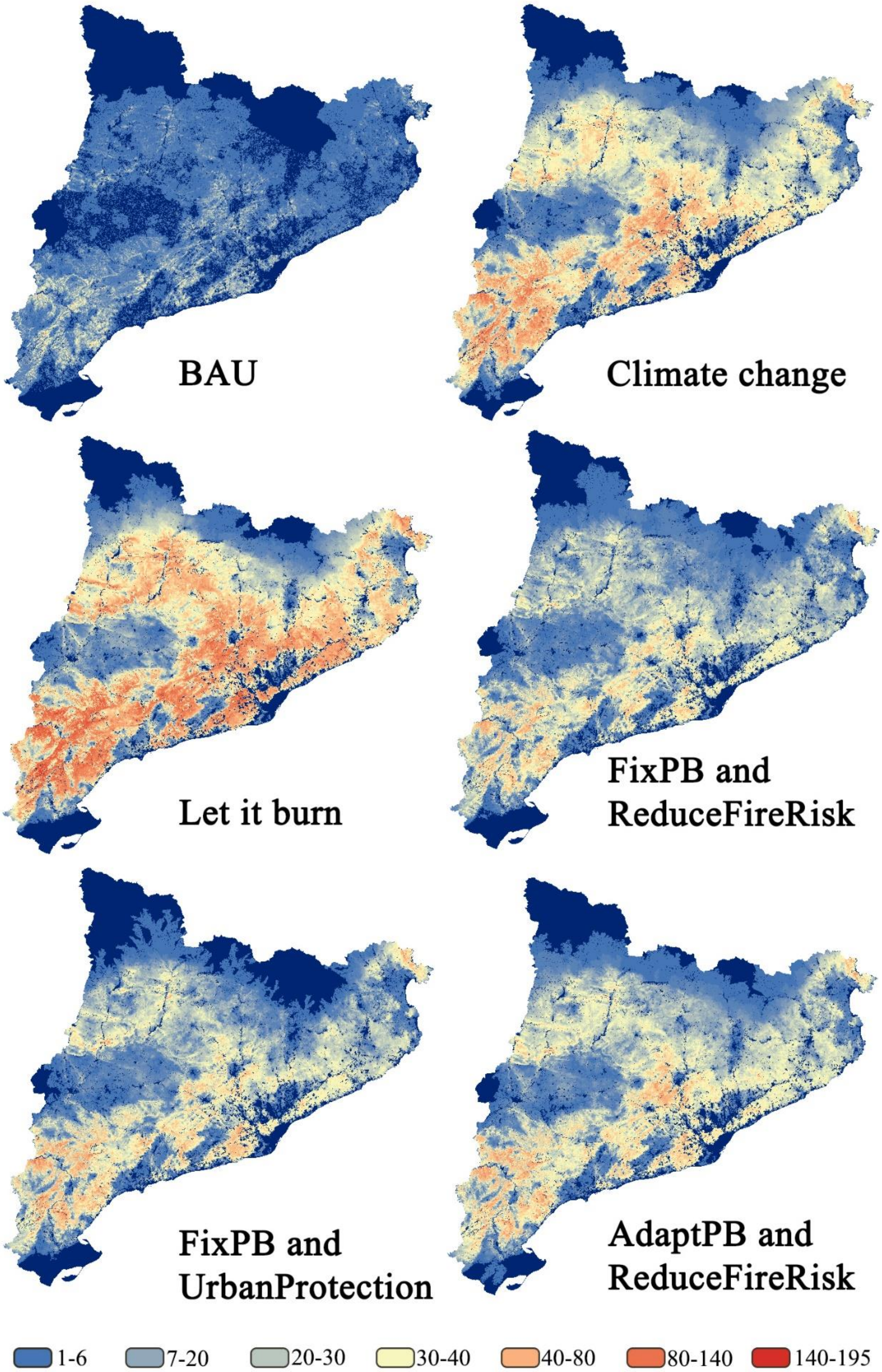

Figure S3.4. Probability of burn (%) in convective fires during the period 2016-2100 for the six scenarios (Table 1).

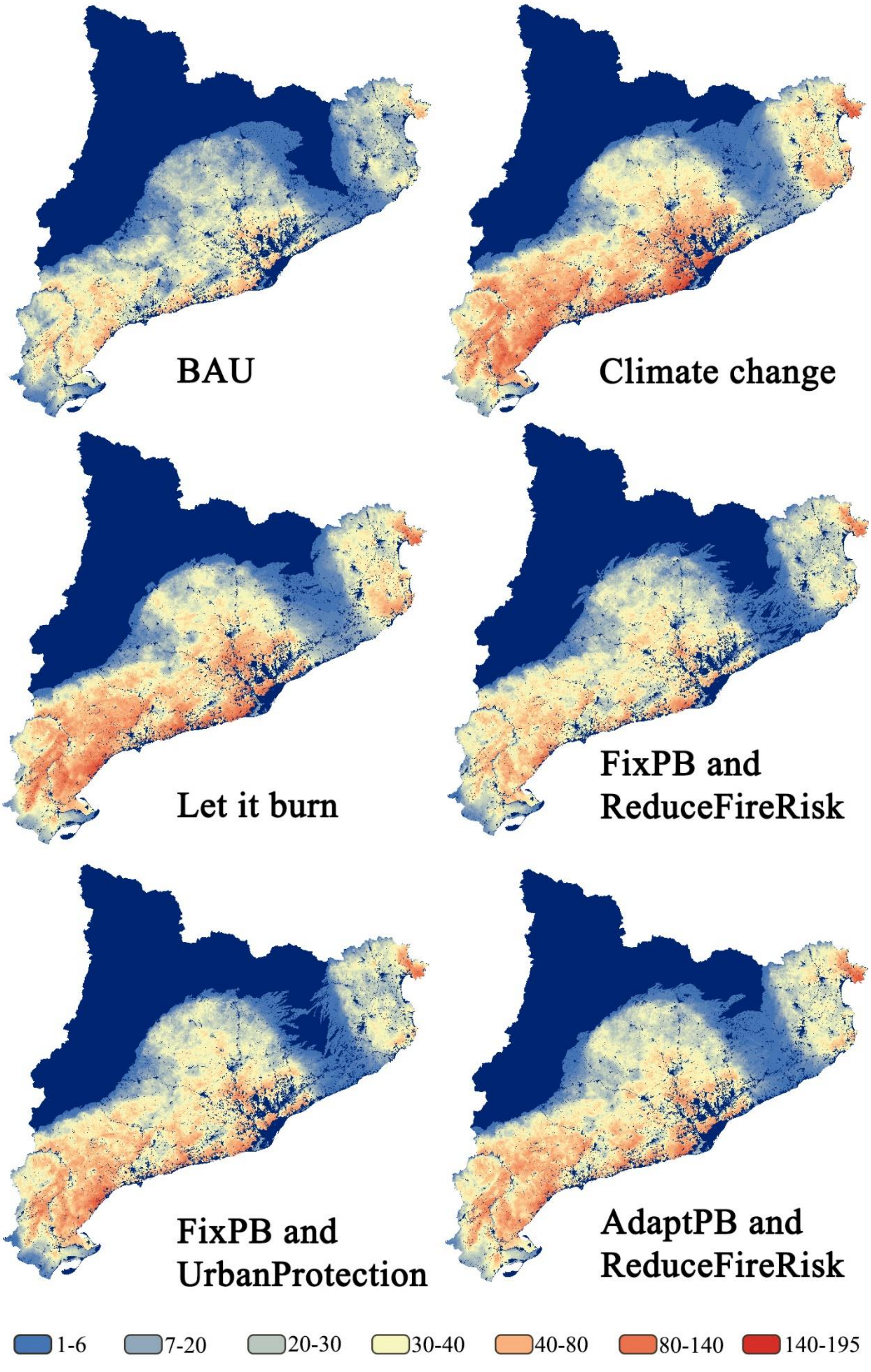

Figure S3.5. Probability of burn (%) in wind-driven fires during the period 2016-2100 for the six scenarios (Table 1).

GENERAL DISCUSSION

GENERAL DISCUSSION

Wildfires are changing and becoming more extreme. The current strategy used in many areas of the world, such as the Mediterranean basin, to control wildfires is not always successful and wildfires often surpass suppression capacity, especially in fires driven by strong winds. In this thesis, I have developed new tools and approaches to elucidate interactions in wildfire dynamics in Mediterranean regions, and I have finally integrated all this information into a flexible modelling framework that aims to anticipate changes in fire regimes and guide strategic decision making in this topic. My results show that the use of alternative fire management in Catalonia such as prescribed burning (applied under reasonable thresholds) may be a suitable strategy to mitigate negative predicted fire effects under climate change. Evidence from this work can prove very relevant to apply effective fire mitigation policies under global change.

Past and current global change impacts on the fire regime of a Mediterranean-type ecosystem

Fire is a global phenomenon that has attracted the interest of many ecologists, examining from the most detailed mechanisms behind flame creation to its wide range of ecological impacts (Bowman et al., 2009; Parisien and Moritz, 2009; Pausas and Ribeiro, 2013; Rothermel, 1983). Still, society faces new challenges that require further comprehension of fire dynamics to help decision making in an uncertain world. These challenges require the understanding of processes governing large wildfires at large and long scales, which is one of main knowledge gaps nowadays (Fernandes, 2013; Moritz et al., 2014; Schoennagel et al., 2017). Fire spread and behavior in controlled situations is widely known, but how the factors interact to promote large wildfire events requires further investigations. Here, I have provided new evidence that demonstrate how drivers operating at the landscape scale, such as climate, fire suppression or landscape structure, modulate fire activity.

In this thesis, I have developed a new quantitative approach to understand fire regimes and incorporate the implications of the fire spread pattern concept (Chapter 1, 2 and 5). Understanding and predicting fire spread patterns have allowed us to integrate a key attribute of fire regime's characterization, until now almost exclusively used in an operational suppression background. In fact, predicting fire spread patterns allows us to approach the extinction strategies taken by firefighters, which enhances the link between natural and anthropogenic drivers in modulating fire regimes. Furthermore, I have improved our current capability to predict fire spread patterns in the future by the complex interaction of climate, vegetation and suppression included in the fifth chapter of the thesis. Through the evaluation of future fire regimes according to the fire spread patterns, I open the possibility to provide management recipes that are based on the most common fire types that each region will experience in the future. Fire management, planning and prevention can feed from these outputs to better incorporate prediction tools into useful guidelines.

Certain combinations of fuel variables can promote the development of different kinds of fire spread patterns (Chapter 1). The occurrence of very intense fires relies on fuel availability at the landscape scale. A larger extension of coniferous species (more flammable than deciduous ones) and highly loaded structures are strongly related with the occurrence of convective fires. Convective fires are very intense fires that spread by massive spotting, and they need to release a lot of energy to create such an environment. Actually, in this thesis, I have been able for the first time to understand the occurrence and spread of convective fires at the landscape scale. Although they have already been described (Rothermel, 1991), the complexity associated to their behavior has limited the capacity to understand and anticipate the resulting fire patterns. Here, I show that convective fires do not only rely on large fuel loads, but they are also influenced by prevalent wind conditions and the main topography in their spread (Chapter 2). The capacity of simulating convective fires at the landscape scale enhances our prediction ability for future fire regimes and extreme fire events.

In contrast, my results point to a minor role of fuel in the spread of fire driven by wind (Chapter 2 and Chapter 4), which is in agreement with previous studies describing this process in other areas such as Californian ecosystems (Keeley et al., 1999; Moritz, 2003). Under strong wind conditions, wind pushes flames to unburnt fuels, pre-heats fuels and increases oxygen input. This ultimately increases fire intensity and spotting, and thus exacerbates fire spread without the need of high fuel loads. In Chapter 2, I show that species flammability is responsible for 21.2% of fire spread in wind driven fires, whereas it increases up to 38.7% and 47.5% in topography-driven and convective fires, respectively. Moreover, the evaluation of the effect of past fires in subsequent fires reveals that past fires become sooner flammable in windy regions than in non-windy ones (Chapter 4), suggesting that the role of fuel in fire spread lessens in these areas. However, it is important to state that in Chapter 1, I also found that wind-driven fires can depend on a minimum fuel load to spread.

It is widely recognized that weather plays a key role in extreme fire situations. In this thesis, I have proven the influence that different atmospheric configurations have on the development of large wildfires in a Mediterranean region (Chapter 3). I found six typologies of weather conditions related to large wildfires in Catalonia. These categorizations allow us to identify weather patterns that result in different fire regime attributes (location, size and frequency). Ruffault et al., 2016 extensively explored the capacity of synoptic weather characterizations as a tool to enhance the understanding of relevant fire processes in southern France, resulting in the identification of a predominant wind-driven fire regime. Working with weather variables at the continental scale allows the prediction of certain processes better than any of the component variables considered individually (Fernández-Martínez et al., 2016). I conclude that this characterization of SWT is necessary in the current fire regime change context occurring in the Mediterranean Basin.

Fire suppression shows an interacting effect with wind-driven fires. Under extreme wind conditions, fire brigades are unable to stop wind-driven fires, which can spread at speeds of up to 6 km/h. The current limit of fire suppression brigades in Catalonia is of 3-meter-high flames or a rate of spread of 2 km/h (Costa et al., 2011). The fire regime on windy days is still highly dependent on weather determinants. The dominant effect of meteorology in regions dominated by wind-driven fires raises questions over efforts to reduce fires by fuel management (Chapter 1; Jin et al., 2014; Keeley et al., 1999). Likewise, the minor role of suppression and fuel on the activity of wind-driven fires reveals a lack of control capacity for this type of fires. The most suitable solution to manage wildfires in windy regions seems to be related to the reduction of vulnerable assets (i.e. urbanizations, energy factories, etc.) and management should be directed to land-use conversion (Syphard et al., 2012).

I have also found that the drivers governing fire activity in Catalonia are dynamic and can shift over time. In this weather-dominated fire regime, past fires can modify climate influence and create windows of time when fire becomes fuel-limited (Chapter 4). The way past fires influence future fire activity can vary across different landscape attributes. Here, I purport that landscapes with a higher proportion of, and more, aggregated forests showed a stronger impact of past fires in future fires. Vegetation arrangement at the landscape scale influences fire regimes, in such a way that the mosaic created by wildfires becomes more effective for preventing new wildfires in more connected and aggregated landscapes.

Furthermore, this finding proves the capacity of past fires to become future fire inhibitors, so decreases in burnt area of past fires might result in larger areas in the future. In Catalonia, a decreasing trend in the number and area of wildfires has been recorded during last decades (Turco et al., 2013). This trend has been related to increasing efforts on fire suppression and prevention (Otero and Nielsen, 2017). Therefore, the reduction of wildfire is actually promoting the increment of future wildfire. I have shown that the mechanism underlying the fire paradox exists in Catalonia. Not all regions might show this effect, since the probability that a past fire remains in a low fuel state enough time to prevent a future new fire is dependent on other ecosystem attributes, such as fire frequency and burnt area or fuel recovery rate. This finding provides important insights to deepen fire dynamics knowledge and apply suitable fire management to control fire regimes.

Future impacts of global change on fire regimes

Global change is predicted to influence ecosystems and their processes (Doblas-Miranda et al., 2017; Lavorel et al., 2008). Fire regimes are one of the disturbances that can be influenced by anthropogenic influences: changes on climate, land-use, social practices, and vegetation can alter fire regimes as we know them today (Chapter 1, 2, 3 and 4). From all these impacts, climate seems the more impacting one and the one that local managers can less directly influence. In this thesis, I have assessed the direct impact of climate change on potential burnt areas and fire behavior (Chapter 5). Additionally, I have assessed human influences on fire regimes by the evaluation of the impacts of different fire management strategies on final burnt areas.

Results on the application of climate change scenarios point to increases in burnt area in Catalonia for the entire 21st century (Chapter 5). Although current fire suppression will be able to control a large proportion of fires, fire suppression is likely to collapse under extreme novel situations. I found that climate change is predicted to increase burnt area by 290% in respect a business-as-usual scenario, which is in agreement with prior investigations of future fire evolution. While Carvalho et al., 2008 found a potential increase of 478% of burnt area in the end of the century in Portugal, Khabarov et al., 2014 found burnt area to increase approximately 150-220 % in the whole of Europe. Flannigan et al., 2009 pointed out that the few studies that had dealt with the assessment of burnt area under future climate found extremely variable results in terms of projected changes in burnt area, probably due to differences in the spatial context and approaches used. Making projections beyond the data range increases uncertainty and decreases reliability, but it is common for this to happen under climate change projections (Amatulli et al., 2013; Khabarov et al., 2014).

Moreover, the classification of synoptic weather conditions of future summer days has revealed the appearance of novel climate conditions not registered in the past and that could open the way to novel fire regimes. Specifically, and related to the development of wildfires, I have discovered the presence of very hot anticyclonic conditions and very hot windy conditions (Chapter 5). These conditions will induce the occurrence of extreme wildfires that may represent serious threats to public safety and ecosystem integrity (Flannigan et al., 2009). The capacity of anticipation of these conditions can suppose an opportunity to prevent the occurrence of extreme large fires in Catalonia.

Importantly, the projection of future fire dynamics in Catalonia under climate change demonstrates an inhibition effect of increasing wildfires to future fires (Chapter 5). The fire leverage found in Chapter 4 of the present thesis has the power to reduce future burnt area potentials associated to climate change. It is therefore of great interest to analyze projected changes in fire, separating the influence of climate from landscape and human management and letting emerging interactions to appear, such as the capacity of past fires to limit the activity of subsequent fires in Catalonia (Chapter 5). Feedbacks between fire activity and fuel reduction can suppose an opportunity to offset climate change increasing potential risks.

Under climate change fire activity predictions, alternative management strategies are necessary to avoid negative impacts of fire. Management promoting the coexistence with fire seems to be a cost effective option for controlling fire regimes under realistic thresholds (Khabarov et al., 2014). Regos et al., 2014 found a management strategy of 'letting fires burn' to be able to offset climate change effects in Catalonia, although their strategies were poorly realistic. Here, I demonstrate that prescribed burning plans applied at sustainable and feasible levels (~15,000 ha/per year) are able to significantly reduce high-intensity fire activity in the long term. Working with prescribed burning implies that fire is not eliminated from the system, but one can be able to avoid the negative impacts of fire associated with climate change.

Other fuel management alternatives may also impact fire regimes and can help to control the increasingly hazardous situation (Schoennagel et al., 2017). Grazing is a large scale low-cost management strategy that can help to diminish fuel loads, and it can also avoid other collateral impacts of prescribed burns such as carbon emissions (Davies et al., 2015). In Catalonia, fuel mechanical treatments focused on preventing wildfires are nowadays dependent on public subsidies, which cannot offer a plausible solution to control fire regimes at the landscape scale (Altangerel and Kull, 2012). Both strategies (grazing and mechanical treatments) would however require a shift in the current economic system to revalue forest products and activate new demands allowing these management options to be economically feasible (Fight et al., 2004).

Changes in land-uses can also become an appropriate management strategy to diminish fuel at the landscape scale (Fernandes, 2013; Moreira and Pe'er, 2018). Land-use planning represents the problem and the solution of wildfire situation in many Mediterranean countries (Syphard et al., 2013). Whilst urban planning has brought humans closer to fire exposure, landscape management could reduce large wildfire hazard by promoting other alternative uses (agriculture) in strategic management points shifting wildfire spread potentials (Moreira and Pe'er, 2018). For example, Loepfe et al., 2012 demonstrated how a combination of the traditional rural mosaic could be an effective strategy to reduce wildfire impacts in a Mediterranean area.

Under this situation, it seems that the most plausible solution is to advance towards an integral holistic forest-landscape planning that allows landscapes to be resistant and resilient to large wildfires, and letting fires to be part of the same drivers of landscape modulating (Schoennagel et al., 2017). In this sense, Catalonia must change the historical negative vision of wildfires and bet for a change in how the wildfire issue is being faced, benefiting of the knowledge the country has and using quantitative tools to help making long term large scale decisions.

The evaluation of future impacts of global change in this thesis has been developed through the implementation of landscape simulation tools under different scenarios. Applying scenarios and quantitatively assessing their impacts with models is an effective way to improve environmental decision-making (Mahmoud et al., 2009). The present work gives insights to pioneer new planning and management instruments to move toward approximations that focus on landscape resilience and help fire management efficiency. The shift from a 'fire suppression era' to a 'fire regime management era' can be a very slow process due to the complexity of scale shifts, perceived risks, social acceptance and the need of different organizations to cooperate, but substantial work can be carried out to start shifting the discussion's center of gravity. I show that a shift from the fire suppression paradigm to a new, more sustainable one based on "coexist with fire", can sustain and promote an efficacious disaster risk reduction, and improve both ecosystem and society resilience.

Future perspectives

In this thesis, I have tackled global challenges of fire science that can benefit from the application of science-based management tools. But, of course, there is still long way to go. Research on the classifications of synoptic weather conditions requires further work on the characterization of sequential series of different weather types influencing wildfire activity. Fire-climate interaction investigations have lengthy paths ahead in an ongoing changing climate situation. Moreover, it is crucial that future studies focus more specifically on the indirect impacts that climate will pose to fire regimes through changing vegetation, since the change in fuel structure under global warming may have a fundamental role in shaping fire– climate relationships (Pausas and Paula, 2012). Most of the assumptions of this thesis are based on the capacity of the Catalan landscape to sustain very large fires due to high ratios of fuel accumulation. However, some studies (Batllori et al., 2013) are already pointing to a decrease in ecosystem productivity due to climate change that might result in counterintuitive effects on fire regimes at the long term. Mechanistic approaches that include the relations between vegetation and environmental conditions should be fostered. In addition, a key step in ameliorating the present modelling approach goes through incorporating a biomass variable into the model presented in Chapter 5, which can open the possibility to test other important hypothesis such as the influence of different forest structures on fire regimes, or the long-term influence of low-intensity fires in different vegetation structures.

Furthermore, the model presented in Chapter 5 opens a wide range of possibilities to investigate further interactions between fire drivers, for instance the effect of other fire management strategies on fire regimes (prescribed burning in different locations, with different frequencies, or with other species-specific restrictions, etc.). This tool allows one to test the effectiveness of different management strategies taking into account ecological considerations. It also enables one to investigate spatial variations on different types of fire spread patterns according to other type of impacts.

The ideas presented here can be applied in other regions and systems, not only with Mediterranean-type ecosystems, but also to other fire-prone areas that are undergoing important biodiversity threats as a result of changing fire regimes and that require the evaluation of the fundamentals drivers of change (Connell et al., 2017; Durigan and Ratter, 2016). Besides, further evaluations should include extended impacts of global change, such as invasive species, interaction with other disturbances (wind storms, drought, etc.), land-use changes or forest management, to have a holistic perspective of how fire regimes will be under the era of the anthropocene.

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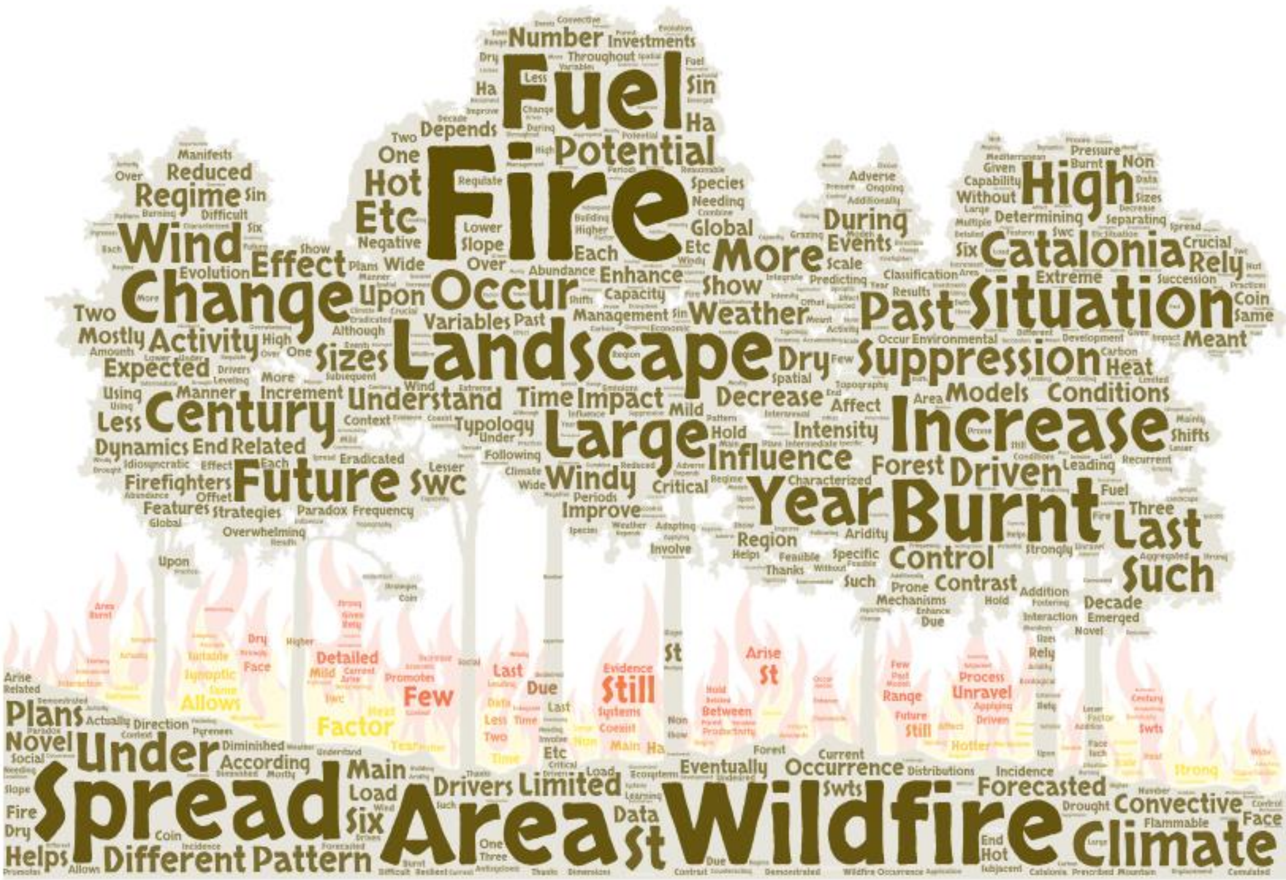
CONCLUSIONS



GENERAL CONCLUSIONS

1. Fire situation in Catalonia involved an increasing risk to society assets and natural values: an increment on fire investments has not meant a control on all extreme wildfires. Although decreasing the number of fires during last decade, large wildfires are still overwhelming firefighters capacity, especially under windy situations. Climate change is expected to increase the burnt area potential and high-intensity fires.

2. The classification of fires according to fire spread pattern helps to better understand fire regime dynamics and their potential evolution, since they unravel the mechanisms determining fire size, intensity, frequency and the kind of suppression opportunities generated for fire suppression to take place. Fire spread patterns' occurrence relies upon different landscape features, and future environmental changes will affect fire spread patterns in an idiosyncratic manner. Convective fires occur in high-load fuel landscapes and under hot conditions, and their spread mostly depends on the abundance of flammable forest species. Wind-driven fires show a weaker dependence on fuel variables. In contrast, topography-driven fire occurrence is the most widespread typology and relies upon less specific drivers, and their main spread influencing factor is slope. Modelling and predicting fire spread patterns allows us to deepen in fire regime comprehension and, eventually, improve fire planning and management. Additionally, separating wildfires according to their fire spread typology improves landscape-fire succession models without needing for detailed data accounting for physical model parameters.

3. There are six different synoptic weather conditions (SWC) leading to the development of large wildfires in Catalonia. Three are related to wind, two to heat and high-pressure systems and the last one was not characterized by any strong weather determinants. Different spatial distributions emerged from the influence of each situation. Fires occurring during mild years and under 'hot-and-dry' SWTs have been virtually eradicated from the region thanks to enhanced firefighting capability, and fire sizes in dry years have been strongly reduced. In contrast, fires occurring under windy situations have not decreased in incidence over time, and they are more difficult to control using current fire suppression strategies. The interaction of SWC with other global drivers such as fire suppression and drought conditions is crucial to understand and eventually regulate the adverse impacts of fire regime changes in a global change context.

4. Fire dynamics in intermediate positions of the aridity productivity gradient such as Mediterranean ecosystems can hold periods over which main fire limiting-factor shifts from weather to fuel. We have demonstrated that past fires influence subsequent fire activity by creating low-fuel areas. The cumulated burnt area of the last 7 years has therefore a negative impact on wildfires. This impact is higher in landscapes with more homogenous and aggregated forest cover, and is lower in landscapes with recurrent windy situations. In addition, this negative relation between past fires and future fires reveals the other face of the same coin: the smaller the burnt area in the past, the bigger the burnt area in the future. We have provided evidence of the subjacent process of the fire paradox: reducing wildfires with fire suppression in Catalonia actually promotes the future activity of fires by fuel accumulation at the landscape scale.

5. Novel climates are expected to occur in the 21st century: hotter windy situations and hotter anticyclonic situations will arise and increase throughout the 21st century. Novel climates can increase the potential of large wildfire events. Our results show that burnt area in convective and wind-driven fires will therefore increase throughout the century. However, a leveling-off in burnt area is forecasted at the end of the century, mainly because a counteracting effect of fires that decrease fuel load and increase suppression opportunities. A displacement of convective fires to non-fire prone areas in the Pre-Pyrenees mountain range is also forecasted under climate change.

6. Prescribed burning plans may be a tool to offset large wildfire events forecasted to occur during the 21st century. They can decrease high-intensity fires and smooth high interannual variability if implemented reasonably and impact forest areas of around 15,000 ha/year for all Catalonia. Their effectiveness will increase if adapting their application to ongoing fire activity, namely concentrating their application after periods of low natural fire activity. However, they also may involve undesired effects (as carbon emissions or biodiversity impact). The fostering of strategies that combine multiple fuel management practices (such as grazing, mechanical treatments, etc.) may prove be the most suitable to integrate social, economic and ecological dimensions in building resilient landscapes and learning to coexist with fire.

Fire regimes are changing or are expected to do so under global change. The main objective of this thesis is to gain a better understanding on the processes influencing fire dynamics at large scales, and to integrate them in modelling tools that help us to predict global change impacts and eventually design strategic management plans.

Results reveal that climate change, land-use changes, forest abandonment and fire suppression are altering fire regimes. This thesis provides quantitative evidence to apply efficient science-based fire management policies that may ultimately lead to a sustainable coexistence with fire.

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