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The Potential of Agricultural Conversion to Shape Forest Fire Regimes in Mediterranean Landscapes

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Abstract

In densely populated fire-prone regions, interactions between global change drivers, such as land-cover changes and climate change, may increase the frequency and severity of wildfires impacting forest ecosystems, thus diminishing their capability of provisioning key ecosystem goods and services for these societies. Yet, landscape mosaics play a crucial role in fire dynamics and behaviour. Here, we argue that promoting heterogeneous agro-forest mosaics could reduce the area affected by future fires. Specifically, we evaluated 24 landscape-scale management scenarios based on agricultural conversion, i.e. the creation of new agricultural land, that also explicitly incorporated fire suppression. Scenarios differed in the annual rate of such conversion, the spatial pattern (aggregate vs. scattered), and the location of new agricultural patches. To quantify the interactions between vegetation dynamics, fires, land-cover changes, and fire suppression, we coupled two spatially explicit models: a landscape dynamic fire-succession model and a land-cover change model. When applied to the Mediterranean region of Catalonia (NE Spain), new landscape mosaics favoured firefighting extinction capacity only after 15 years (on average) of cumulative land transformations. Agricultural conversion of at least 100 km^2 year^{-1} was required to reduce total area burnt. A conversion rate of 200 km^2 year^{-1} substantially improved fire suppression effectiveness, but subsequent conversion increases did not. When aggregated, new agriculture patches contributed more effectively to reduction in total area burnt and decreased the edge effect on remaining forest patches. Agricultural conversion in Mediterranean landscapes opens a new window for long-term spatial planning aimed at minimizing negative impacts of wildfire on forest ecosystems. These alternative strategies could help to develop landscape management practices in other fire-prone regions.

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Key words: landscape management; Mediterranean-type ecosystem; agricultural conversion; fire suppression; fire-succession model; land-cover change model; model coupling.

Highlights

- Model coupling reveals interactions between land-cover changes and fire regimes.
- Management strategies that increase agricultural areas can reduce total burnt area.
- Fire suppression effectiveness nonlinearly responds to landscape heterogeneity.

Introduction

Wildfires are an intrinsic agent of landscape change in Mediterranean-type forest ecosystems with most tree species either adapted or resistant to fires (Keeley and others 2012). Mediterranean ecosystems are found in highly humanized regions of the world (for example, the Mediterranean basin, California, or the Cape Region of South Africa). In such regions, human-related factors usually influence and drive fire regimes rather than weather conditions (for example, high temperatures and strong winds), vegetation structure and composition, or plant water stress, (Archibald and others 2009; Knorr and others 2014; Taylor and others 2016). In such human–natural systems, fire regimes ultimately emerge from cross-scale and feedback interactions between fire ignitions [mostly human caused (Ganteaume and others 2013)], prevailing fire-weather conditions, landscape mosaic configurations, and fire suppression efforts (Duncan and Schmalzer 2004; Loepfe and others 2010; Ruffault and others 2015).

Anthropic-driven changes in forested landscape composition and configuration are related to the economic development of a society from increasing demands for energy, water, and food (Lambin and others 2001; Foley and others 2005). In many regions, rapid deforestation processes, wildland-urban interface sprawl, plantations of both native and exotic species, agriculture intensification, or the rural exodus occurring in European countries since the mid-twentieth century have all shaped forested landscapes by changing both landscape mosaic composition and the spatial distribution of forest patches (Radeloff and Hammer 2005; Rudel and others 2005; Navarro and Pereira 2012). The side effects of these land-cover changes on disturbance regimes, such as fires, are starting to be assessed but are difficult to anticipate in a global change context. Human-related interventions on the landscape, such as urban expansion, silvicultural treatments, forest plantations, grazing, or agriculture intensification, continuously reshape fuel load, their spatial arrangement, and fire dynamics. For example, some authors have found that urban sprawl into semi-natural land covers nonlinearly increased the exposure of forest ecosystems to wildfires (Syphard and others 2007; Vilar and others 2016), whereas in Mediterranean fire-prone regions of southern Europe, both agriculture abandonment and afforestation have been directly associated with increases in fire activity (Moreira and others 2001; Viedma and others 2015). However, some of the human activities listed above could have a positive effect on the fire regime, in terms of area, fire size or intensity reduction. Low fuel conditions and fuel discontinuity generated by active forest management, prescribed burnings, agricultural activities, extraction of biomass for energy purposes or human-made infrastructures have the potential to influence fire dynamics (O'Donnell and others 2011; Collins and others 2015; Regos and others 2016). Even if landscape configuration and composition can drive fire spread, intensity and final burnt area, fire size and severity still depend on the weather conditions leading each fire event, which actually determine the way the fire responds to landscape features and fuel availability (Turner and Romme 1994; Moreira and others 2011).

Fuel and vegetation load patterns vary across space, thus contributing to the potential mitigation of the negative impacts of fire (Fernandes 2013). However, in most Mediterranean regions total fire exclusion has been the prevailing fire management approach to cope with wildfires during the last three/four decades. Due to improvements in firefighter training, use of technology, and increased availability of economic resources, most fires are successfully extinguished over a broad range of conditions (Donovan and Brown 2005; Fernandes and others 2016). But highly effective fire suppression in fire-adapted regions promotes fuel-load build-up, homogenizes landscapes spatially, and can trigger extreme wildfire events in the near future (Keeley 1999; Keane and others 2002). Thus, in many regions fire suppression has contributed to reducing the total number of small fires, but has failed in controlling a few large events that account for most of the burn area (Moritz 2003; Díaz-Delgado and others 2004). Yet, efficient fire suppression has been required to preserve non-fire-adapted forest ecosystems and protect the increasing wildland–urban interface where not only natural but human assets are at risk (Moreira and others 2011; Schoennagel and others 2017). To cope with future fire activity, fire suppression and fuel management at the landscape scale should converge to protect both, forest ecosystems as well as human lives and properties. Indeed, in densely populated Mediterranean-type regions, fires constitute a direct threat to human assets (i.e. properties) but also to the provisioning of multiple forest goods and services that both rural and urban communities of these regions depend on (Schröter and others 2005; Palahi and others 2008). Efforts are being made to ensure that these forest ecosystems are able to sustain the multiple needs of these communities, (for example, water availability, recreational land-use, carbon sequestration, food security) in light of future pressures exerted by climate and land-use changes. Communities are asked to design holistic fire management approaches beyond fire suppression that take into account the double dimensionality of the fire problem, the social and the environmental (Adams 2013; Fischer and others 2016). In Mediterranean regions, fire-smart management approaches will have to modify fuel composition and distribution to create more fire-resistant landscapes and communities less vulnerable to fire (Fernandes 2013; Tedim and others 2016).

Therefore, on the one hand, understanding the interactions between shifting disturbance regimes, climate warming and land-cover changes will allow us to anticipate undesirable impacts on forest ecosystem structure and better understand the function of such global change drivers co-occurring in fire-prone regions. On the other hand, this knowledge will be the basis for estimating the results of specific landscape-scale management actions and policies needed to explicitly reduce vulnerability and exposure to known (and even unknown) stressors threatening highly humanized Mediterranean regions (Stephens and others 2010; Doblas-Miranda and others 2015). The challenge, therefore, is twofold: (1) to design and plan alternative fire management approaches that create landscapes more resilient to fires (Chapin and others 2010), and (2) to use modelling approaches that replicate and estimate the effects of new fire management actions and fire suppression and capture the spatio-temporal dynamics of highly humanized fire-prone landscapes (Hantson and others 2015). Modelling frameworks combining multiple drivers of global change, accounting for spatial and temporal multi-scale interactions, and explicitly dealing with uncertainty can be part of the solution. Models have to be scenario-oriented, spatially explicit, and responsive to fire behaviour and vegetation response to fire, as well as to land-cover changes (or forest management plans) and fire suppression (IPBES 2016). In particular, stakeholders and planners need a priori evaluation of the efficiency of fire-reduction strategies within a holistic context to provide (1) insights into the cumulative impacts on the land of such policies, (2) the potential time lag between the implementation and the benefits, and (3) any apparent long-term side effects on forest structure and functioning.

Here, we assess the interactions between wildfires, land-use/land-cover (LULC) changes (for example, agriculture conversion), and fire suppression actions in Catalonia (NE Spain), a high fire risk, densely populated, forested Mediterranean region. To do so, we coupled two existing spatially explicit models, a fire-succession model (Brotons and others 2013) and a LULC change model (Aquilué and others 2017). The resulting modelling framework accounts for the spatio-temporal interactions between fire ignition, fire spread (dependent on landscape composition and species fire sensitivity), fire suppression, LULC transitions, and ecological processes (mainly post-fire regeneration and afforestation). We focus on examining alternative, landscape-scale, fire management strategies that seek to reduce vulnerability of forest landscapes to wildfires. We propose a set of scenarios that aim at changing the spatial distribution of fuel types at the landscape scale, and thus the fuel-load spatial heterogeneity across the landscape, by allocating new croplands and pastures to a Mediterranean landscape that is not currently fuel constrained (Pausas and Fernández-Muñoz 2012). We then evaluate the effectiveness of these strategies by quantifying the area suppressed by the firefighting system when using fuel-load discontinuities in relation to the amount of target burn area if these would have not been present. We specifically address two major research questions: (1) How will changing landscape configurations and active fire suppression reshape the fire regime (characterized by the total burn area and the number of large fires) in a fire-prone Mediterranean region? and (2) How will the spatial distribution of the forest cover be affected by cumulative conversions to agricultural land? The spatial arrangement and connectivity of fuels drive fire behaviour, but when connectivity is below a critical percolation threshold, fires are unlikely to spread and grow (Turner and others 2001). Indeed, fire spread patterns behave nonlinearly close to that theoretical threshold (Hargrove 2000; Miller and Urban 2000; Loehle 2004; Abades and others 2014). Therefore, we posit two contrasting hypotheses about nonlinear responses of fire suppression effectiveness across the landscape heterogeneity gradient induced by agricultural land conversion (Figure 1). According to percolation theory, new agricultural patches can have a positive, nonlinear effect on fire extinction capacity because high burnable fuels will become progressively less connected. We expect that this effect is likely to be especially weak in landscapes with little agricultural land, and likely to become stronger as agricultural land increases (Figure 1A). Conversely, in landscapes with already large amounts of agricultural land, further agricultural conversion may have a disproportional effect on fire suppression effectiveness. Eventually, landscapes will slowly reach a maximum capacity of influencing the fire regime (Figure 1B).

Materials and Methods

Study Area

Catalonia is a 32 100 km^2 fire-prone Mediterranean region in NE Spain (see Appendix S1 for a full portrait) where wildfires are the main natural disturbance triggering dominant tree species replacement and promoting landscape heterogeneity (Lloret and others 2002). Most of the ignitions are human-related, either accidentally or deliberately (Badia-Perpinyá and Pallares-Barbera 2006; González-Olabarria and others 2012). The systematic abandonment of traditional agricultural and farming activities during the mid-twentieth century has led to the colonization by scrubland and pioneer tree species of ancient croplands and pastures (Cervera and others 2019). Such recently established forests create homogeneous landscapes with fewer firebreaks, and present a fuel vertical continuity that facilitates the spread of crown fires (Lloret and others 2002). Since the 1994 and 1998 fire seasons (where c.a. 85,000 and 26,000 ha, respectively, of forest, scrublands and agricultural land were burnt), fire experts in Catalonia have devoted more effort to analysing and understanding fire behaviour according to synoptic weather conditions, topography and vegetation to improve fire suppression (Castellnou and Miralles 2009). Fire brigades are now able to anticipate fire behaviour and spread patterns and thus achieve a more successful fire suppression (Otero and Nielsen 2017). We identified Catalonia as a potential region to implement alternative fire-smart management strategies based on agricultural conversion.

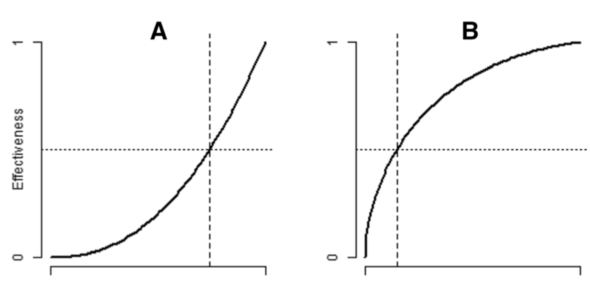

Figure 1. Two contrasting hypotheses about the nonlinear relations between fire suppression effectiveness and the amount of agriculture allocated in the landscape (that is, demand). Horizontal line is at 0.5 of effectiveness while the vertical line indicates the demand leading at 0.5 of effectiveness.

The MEDFIRE, a Fire-Succession Model

The MEDFIRE is a landscape dynamic model that integrates vegetation dynamics and fire regimes to investigate the interactions among ecological processes shaping Mediterranean landscapes (Brotons and others 2013). The fire regime is modelled by a top-down approach, in this case, the annual target area to be burned and the fire size distributions are model inputs (Appendix S2). In a given model run, the annual target area is burnt with as many fires (of a predefined target area) as needed. However, the spatial distribution of fires and the realized fire perimeters emerge from the interplay between the ignition probability and the landscape configuration itself as both forest composition and fuel abundance play key roles. In the current version, fire ignition is a function of climate, road network, and landscape mosaic (Appendix S2). Fires spread following orography, main wind direction, and the most flammable fuels (Appendix S2). Based on empirical fire data (ignition point and final shape), three main fire spread patterns, according to the dominant factor driving the spread, were identified for Catalonia: fuel-driven (convective), topography-driven, and wind-driven (Duane and others 2015). With this classification, 72 homogeneous fire regime zones in Catalonia were identified (Figure S1.3). These are regions sharing similar characteristics driving fire spread: orography, main direction of general and local winds, vegetation, and dominance of fires spreading following each of the three patterns (Castellnou and others 2009). In the model, the fire spread pattern of a simulated fire is assigned according to the location of the ignition within one of these homogeneous fire regime zones.

In our approach, post-fire regeneration and afforestation are the two most relevant ecological processes inducing changes at the landscape scale. The first is modelled by a state-transition approach. Probability of regeneration depends on the previous state (pre-fire tree species) and the presence of potential colonizers within a 2 km circular neighbourhood. This means that only species in the surrounding area are allowed to establish in the recently burnt locations. This restriction avoids the situation of having communities not observed in the study area artificially emerge on the landscape. Transition probabilities are based on empirical data from Rodrigo and others (2004) and extrapolated to the study area by Brotons and others (2013). When many species form the pool of potential states for a specific transition (13 species in the case of post-fire regeneration), a raw state-transition approach may lead to a spatially uncorrelated regeneration, particularly noticeable in large burnt areas. Because post-fire regeneration tends to occur in patchy patterns, about 40% of the burnt locations mimic the regeneration pathway of their neighbours: a burnt location randomly adopts the same state of one of its eight neighbours whenever these have already changed state (Brotons and others 2013). The annual probability of scrubland colonization by tree species was modelled as a logistic function using climatic, orographic, and forest type explanatory variables (Appendix S2).

The MEDLUC, a Land-Use/Land-Cover Change Model

The MEDLUC is a spatially explicit land-use/land-cover change model designed to reproduce any LULC transition (Aquilué and others 2017). Given a LULC map with a few discrete categories, a land transition (for example, urbanization) is the transformation of a subset of categories (for example, forest, scrublands and croplands) to a target category (for example, urban areas). The MEDLUC is based on a demand-allocation approach. That is, the demand or quantity-of-change is user defined, whereas the model spatially allocates that quantity to patches of change. A transition-potential map drives the spatial distribution of change while the allocation of transitions occurs in two phases: origination and extension of land change. A triplet of parameters controls both the speed of new patches-of-change origination and the speed of change aggregation around the first source cell (Appendix S2). A simple algorithm gives MEDLUC high flexibility to mimic a myriad of patterns of change (Aquilué and others 2017). The model has already been calibrated at 1 ha to reproduce the three main land transitions observed in Catalonia: urbanization, rural abandonment, and agricultural conversion (Aquilué and others 2017).

Coupling Fire and Land-Use Change Models

We dynamically coupled the MEDFIRE and MEDLUC models to spatialize our scenarios, that is, to allocate new agricultural land on the landscape and observe how the fire regime responded. The models share the same set of state variables: Land-cover type, time since last fire, and time since last LULC change. In the current application, the main state variable, the land-cover/forest-species map describes the composition of the Catalan territory (Figure S1.1). It details the distribution of the 12 most abundant tree species, scrublands, grasslands, and other main land-cover (arable land, permanent crops, urban areas, bare soil, and inland water). When coupling two models, all processes occur sequentially (either at uneven or regular time intervals), so the effects on the landscape accumulate. We configured the MEDFIRE time step at 1 year, whereas LULC changes occur every 5 years. Both models operate at the same spatial resolution of 1 ha.

The crucial first step when coupling the two models was to identify the processes in one of the models affected by the changes in the state variables induced by the other model, and vice versa. The next step was to design the processes to capture the dynamics of the system. In our modelling framework, fire behaviour was the bridging process between MEDFIRE and MEDLUC. Fires were sensitive to new land-cover spatial mosaics through ignition probability and fire spread. Ignition probability was a function of a pixel's neighbourhood configuration and according to calibration was higher in urban-wildland interfaces and agro-forest mosaics (Appendix S2). Fire spread was a function of tree species flammability (among other factors) making fire fronts advance faster and at a higher intensity when crossing forests and scrublands rather than croplands (Appendix S2).

Whenever rural land abandonment or agricultural conversion processes generated semi-natural or agricultural patches, respectively, these patches had to be integrated into the fire-succession model dynamics. Recently abandoned fields above an elevation of 1,500 m became alpine grasslands or scrublands. The probability of tree species colonizing the fields increased with time, as was the case for burnt scrublands. Scrublands and forests converted to agricultural land became either arable land (extensive cereals) or permanent crops (orchards) following a neighbouring rule that looks at the predominant type of agricultural land within a 500 m radius. None of the LULC change processes (urbanization, rural abandonment, and agricultural conversion) were influenced by either fire or vegetation dynamics.

A Fire Suppression Strategy Sensitive to Landscape Configuration

Here we focus on fire suppression strategies responsive to changes in landscape configuration. We built a strategy that used agricultural patches as landscape opportunities for fire suppression. We focused on the continuity of agricultural land, detecting patches rather than isolated cells because these patches constitute areas where fire intensity likely decreases and where firefighters easily access the fire front. The fire suppression rule is: once a fire front has burnt a continuous *Th* ha of agricultural land, fire suppression is activated. The MEDFIRE model mimics the spread of the fire front but records any cell reached by the fire as a suppressed cell instead of burnt, decreasing the initial target fire size (Figure 2). In this way, as a fire front advances, the model decreases both the target fire size and the annual target burn area, whether cells have been burnt or suppressed. As *Th* decreases, the smaller the patch of agricultural land required to start the suppression and the stronger the contribution of this land type to halting advancing fronts (Figure 2).

Landscape Management Scenarios

Three alternative landscape management strategies were determined according to public policies regarding land management in fire-prone landscapes. The aim of all strategies was to increase current agricultural area. Each strategy was characterized by a transition-potential map that prioritized where to allocate new croplands (Figure 3). The fire management (FM) strategy assumed a specific interest in managing land for fire prevention. Therefore, new croplands were located in high fire risk areas, especially in wildland–urban interfaces and agro-forest interfaces without any slope restriction (Eq. S2.4). The rural development (RD) strategy is related to policies for boosting the economy of marginal areas that were likely the target of past rural abandonment processes. Zones mostly covered by young forests and scrublands were prioritized to undergone change (Eq. S2.5). The crop productivity (CP) strategy is a business-as-usual scenario, where new agricultural land was placed close to the current productive areas (Eq. S2.6). In both RD and CP strategies, flat areas were more susceptible to be converted to agricultural land than steep areas, and under any strategy agricultural lands only could be allocated in elevations of at least 1250 m. The transition-potential maps were updated over time as natural areas progressively transform to agricultural areas (Eq. S2.4, S2.5, and S2.6).

We created a factorial design to investigate how much, where, and under which spatial pattern agricultural conversion influenced the fire regime (Table 1). All three strategies were tested either allocating new agricultural land following an aggregate (AGG) or a scattered (SCA) pattern (Figure S2.2). The observed rural abandonment rate was used as a reference to set the demand for agricultural conversion. In Catalonia, in a 16-year period, 1 599 km^2 was abandoned, that is ca. 100 km^2 $year^{-1}$ (CREAF 2009). We decided to test four annual demands: $D2 = 50$, $D = 100$, $2D = 200$, and $3D = 300$ km^2 $year^{-1}$ (Table 1). As the MEDLUC time step was set at 5 years, the demands actually allocated by the model were five times those mentioned above (however, for clarity we will continue to refer to these annual rates of agricultural land conversion). In all scenarios, urbanization took place at half the observed rate, that is 21.5 km^2 $year^{-1}$ (CREAF 2009). A control scenario was set at this same rate to simulate only urbanization. Each scenario (3 strategies × 4 demands × 2 spatial patterns + 1 control = 25 in total) was run 30 times for a 40-year period, from 2011 to 2050 inclusively. Because LULC changes occurred every 5 years, the landscape composition did not vary for the first 5-year period, from 2011 to 2015. In all scenarios, fire suppression threshold *Th* was set at 5 ha.

Analysis of Scenarios

To quantify the effects of LULC changes on the fire regime over time, we measured three indicators in each scenario: (1) effectiveness, defined as the ratio of suppressed area to target fire area, (2) leverage, or the amount of suppressed area in relation to the area transformed to agricultural land, and (3) the percentage of large fires (≥ 500 ha). All three variables were assessed every 5 years, at the end of the 40-year period, and for the last 20 years (from 2031 to 2050). We tested the significance of our scenarios with two ANCOVA analyses. We split the scenarios (Table 1) according to the spatial pattern

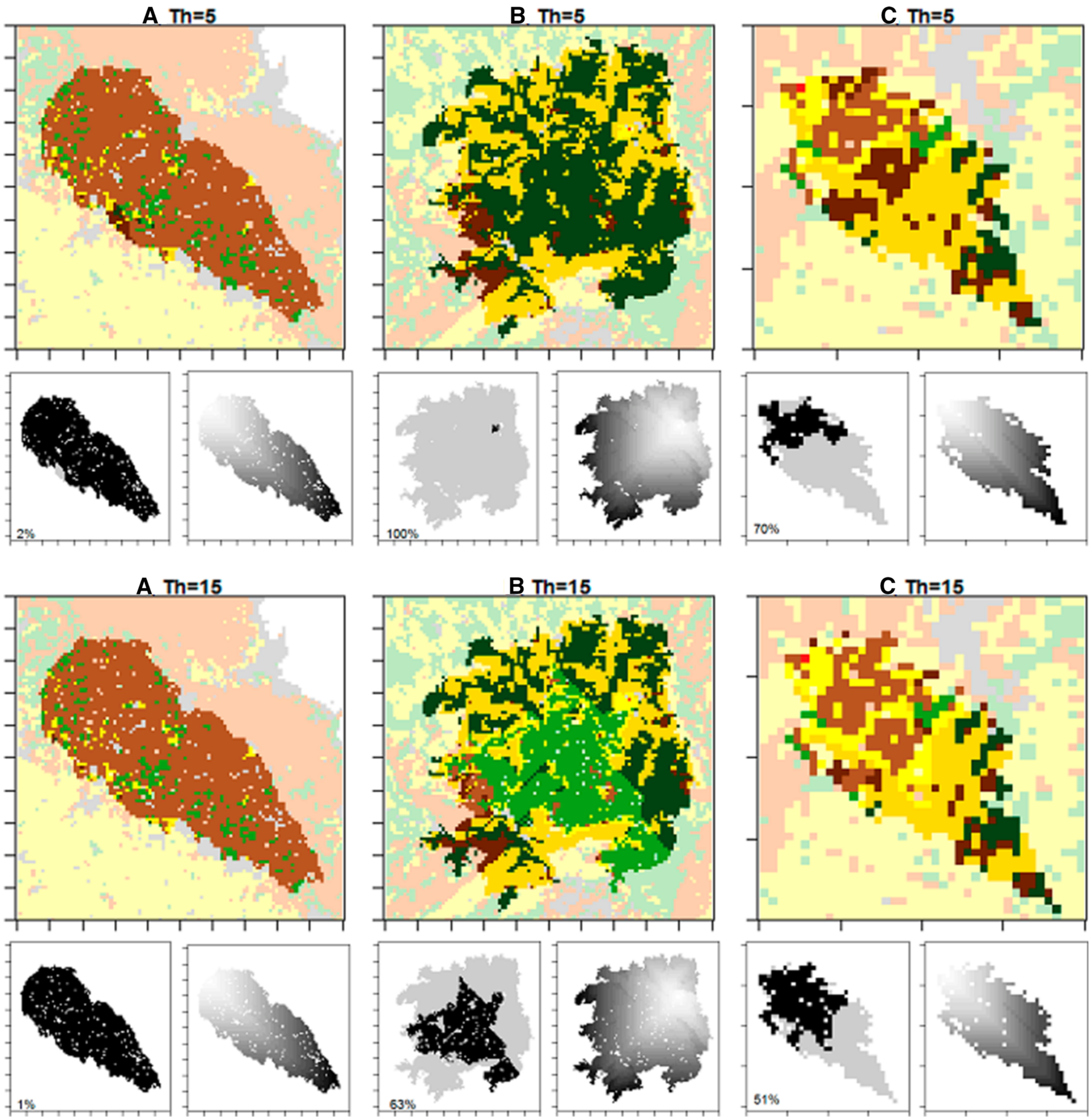

Figure 2. Two wind-driven fires (**A**, **C**) and one convective fire (**B**) suppressed at high and low levels of suppression (Th = 5 and 15 ha, respectively). For each fire, the upper panel shows the land-cover types: (1) non burnt (crop—yellow, green—forest, brown—shrub, grey—urban in pastel), (2) burnt (same colour code but darker), and (3) suppressed (same colour code but even darker). The lower left panel shows the total burnt (black) and suppressed (light grey) area with the ignition point (dark grey). The lower right panel shows the progression of the fire front (from light grey to black). Spatial resolution is 1 ha. The length of plots **A** and **B** is 100 cells, and plot C is 40 cells. The value in the lower left panel indicates the percentage of suppressed area. Fire suppression is barely activated in the 3000 ha wind-driven fire (**A**) at both thresholds because fire front advances in high intensity across scrublands and forest, burning them. The convective fire (**B**) is completely suppressed when Th is 5 ha (because the ignition point is located in the middle of an agricultural patch) but when the suppression is weaker (Th = 15 ha), the suppressed area is reduced to 63%. The 500 ha wind-driven fire (**C**) clearly benefits from the agricultural area impeding the fire advance (Color figure online).

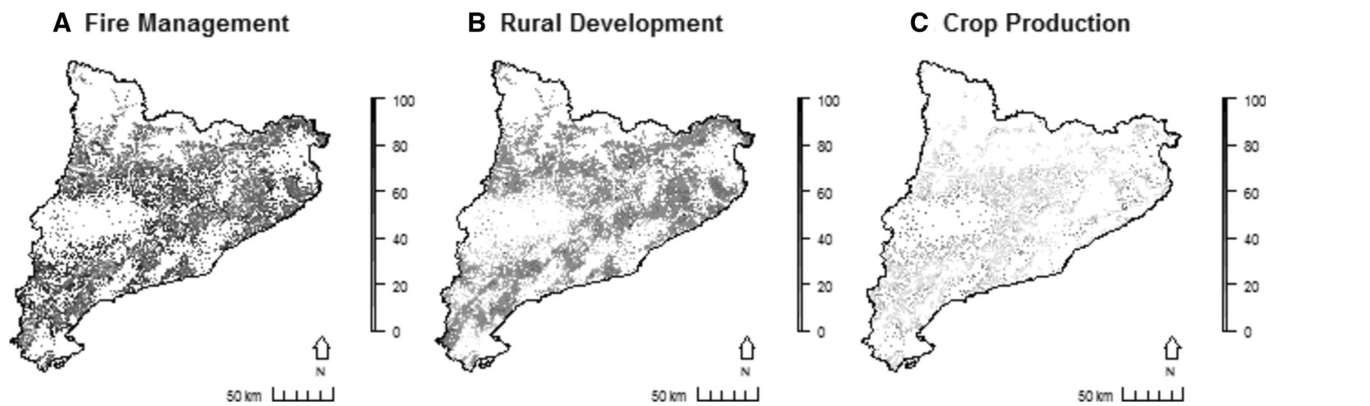

Figure 3. Initial transition-potential map (year 2010) for the fire management (**A**), rural development (**B**), for peer review and crop production (**C**) storyline, respectively.

Table 1. Identification Codes for the 24 Landscape Management Scenarios that Identify the Strategy, the Level of Demand, and the Spatial Pattern for New Agricultural Land

Scenarios	Strategies	Demand (km^2 yea^{-1})	Spatial pattern
CP_D2_AGG	Crop productivity (CP)	50 (D2)	Aggregate (AGG)
CP_D2_SCA			Scattered (SCA)
CP_D_AGG		100 (D)	Aggregate
CP_D_SCA			Scattered
CP_2D_AGG		200 (2D)	Aggregate
CP_2D_SCA			Scattered
CP_3D_AGG		300 (3D)	Aggregate
CP_3D_SCA			Scattered
FM_D2_AGG	Fire management (FM)	50	Aggregate
FM_D2_SCA			Scattered
FM_D_AGG		100	Aggregate
FM_D_SCA			Scattered
FM_2D_AGG		200	Aggregate
FM_2D_SCA			Scattered
FM_3D_AGG		300	Aggregate
FM_3D_SCA			Scattered
RD_D2_AGG	Rural development (RD)	50	Aggregate
RD_D2_SCA			Scattered
RD_D_AGG		100	Aggregate
RD_D_SCA			Scattered
RD_2D_AGG		200	Aggregate
RD_2D_SCA			Scattered
RD_3D_AGG		300	Aggregate
RD_3D_SCA			Scattered

(AGG or SCA), set the demand as the continuous variable, and the strategy (FM, RD, or CP) as the categorical variable. We determined whether the scenarios performed as well as or better than the control scenario by comparing effectiveness distributions 2-by-2 with a Wilcox test. We also verified if effectiveness improved over time by comparing the first 5-year period benefiting from changes in landscape composition, 2016–2020, with subsequent 5-year periods. To quantify the effect of LULC changes on forests, we characterized the spatial distribution of forests at the end of the period by measuring the mean patch core area and the mean shape index at the *vegueria* level (an administrative—biogeographic division of the Catalan territory, Figure S1.5). The shape index measures patch shape complexity by comparing its perimeter with that of a square of the same size

($Shape = p_i/\min(p)$, where p_i is the perimeter of patch i and $\min(p)$ the minimum perimeter possible for a maximally compact patch of the size of patch i). It is independent of patch size and increases from 1, for a square patch, as patch shape becomes more irregular.

Results

Fire suppression effectiveness increased, but not always linearly, with conversion of natural and semi-natural areas to agricultural land (Figures 4A, 5). For scenarios with a low demand of agricultural land conversion ($D2 = 50$ km^2 year^{-1} and $D = 100$ km^2 year^{-1}), effectiveness remained relatively constant over the last 30 years, except for the FM strategy that increased about 13% for the D scenario and about 9% for the RD strategy with an aggregate pattern (Figure 5). For higher demands ($2D = 200$ km^2 year^{-1} and $3D = 300$ km^2 year^{-1}), RD scenarios showed a linear increase in fire suppression effectiveness over time when spatial patterns were scattered, but effectiveness rapidly saturated (that is, no longer increased over time) when spatial patterns were aggregated (Figure 5). This saturation behaviour also applies for most FM scenarios. Although fire suppression effectiveness increased over time for most of the scenarios, a certain time was required to observe an increment of at least 5% in fire suppression effectiveness with respect to the period 2016–2020 (that is, the first 5-year period in which agricultural conversion had modified the landscape; Table 2, Figure 5). Low-demand scenarios ($D2$ and D) needed on average twice as much time as high-demand scenarios (2D and 3D) to show such increase in fire suppression effectiveness (Table 2). Thus, land-cover changes that create a landscape more heterogeneous and

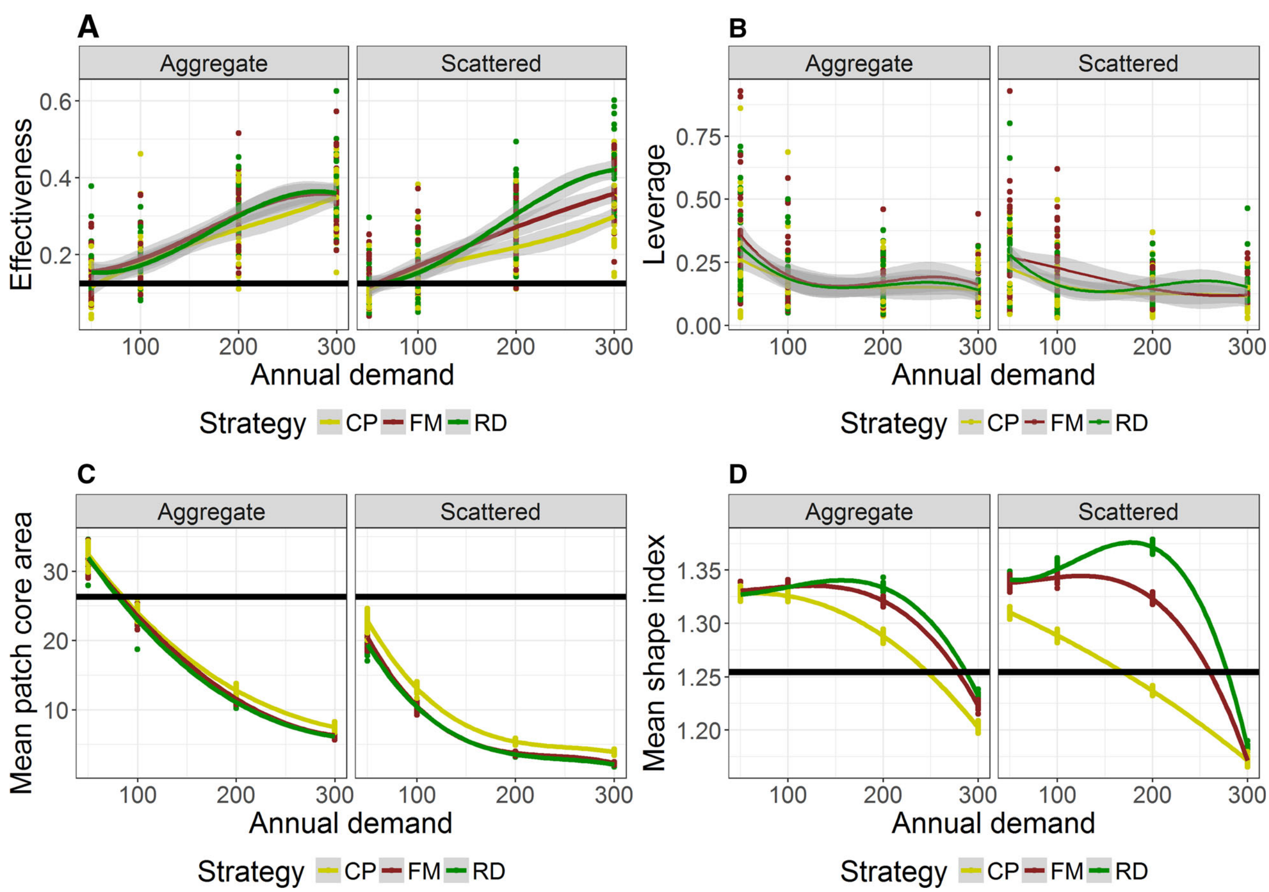

Figure 4. Relationship between (**A**) effectiveness, (**B**) leverage, (**C**) forest patches mean core area, and (**D**) forest patches mean shape index at different agricultural demands (50, 100, 200, and 300 km^2 year^{-1} are D2, D, 2D, and 3D, respectively), according to the strategy (forest management, FM; rural development, RD; and crop productivity, CP) and the spatial pattern of new agricultural patches (aggregate vs. scattered). Response variables are measured over the last 20 years of the simulated period. Solid black line in panel **A** indicates effectiveness of the control scenario with only urbanization, while in panels **C** and **D** it indicates the metric value of the reference year 2010.

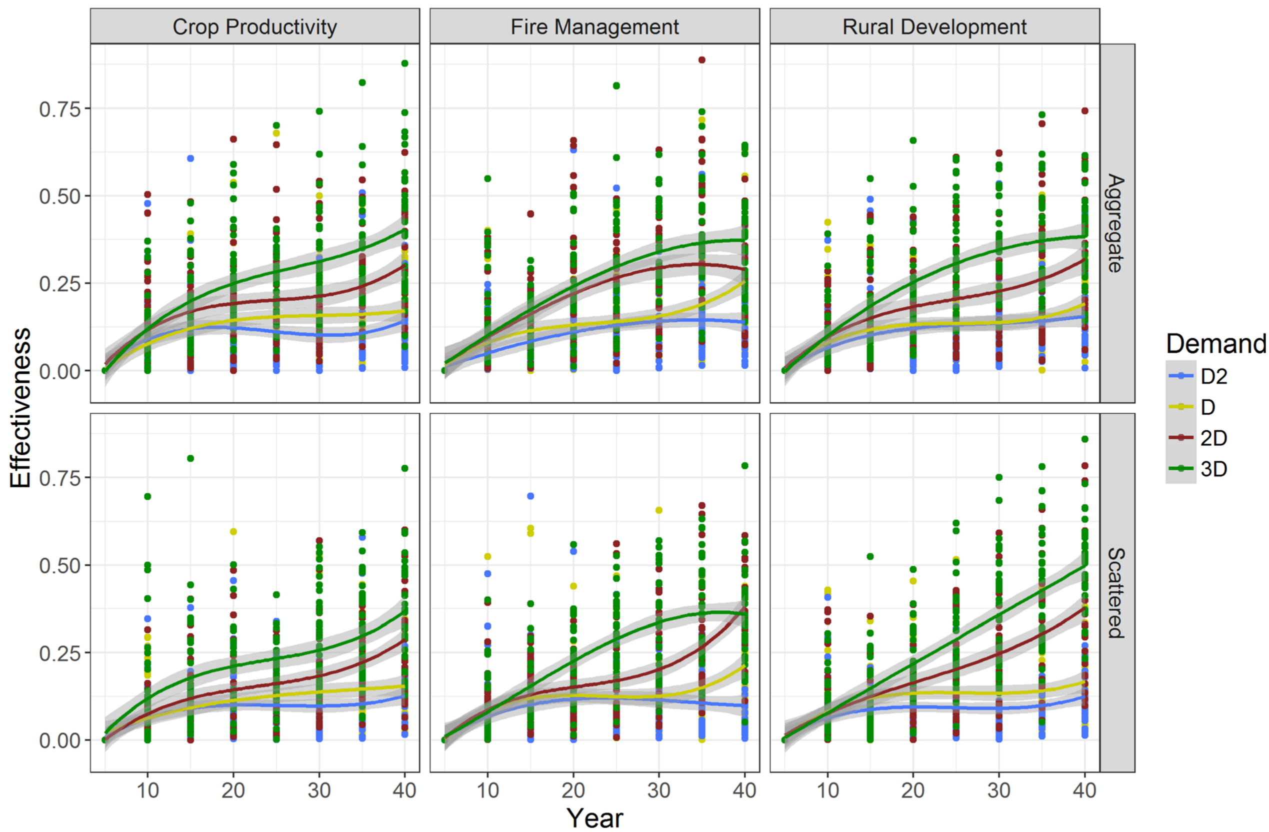

Figure 5. Cumulative effect of agricultural conversion on fire suppression effectiveness for each of the 24 landscape scenarios (3 strategies, 2 types of aggregation, and 4 levels of demand) from 2016 to 2050 inclusively.

Table 2. Number of Years Required for at Least an Increment of 5% in Fire Suppression Effectiveness with Respect to the Effectiveness of the 2016–2020 Period

Strategy		Crop productivity		Fire management		Rural development		μ_6	μ_{12}	μ_{24}
Pattern		Aggregate	Scattered	Aggregate	Scattered	Aggregate	Scattered			
Demand	*D2*		25	15		10		20	22	15
	D	10	25	25	30	25	25	23		
	2*D*	15	5	10	15	10	15	12	10	
	3*D*	5	20	10	5	5	10	9		

Average number of years needed to reach this improvement of the scenarios at the same demand level (μ_6), of the scenarios at low versus high demands (μ_{12}), and of all the scenarios (μ_{24}). Blank value means that fire suppression no increased more than 5% over all the period. Acronyms D2, D, 2D, and 3D stand for annual demand of agricultural conversion: 50, 100, 200, and 300 km^2 year^{-1}, respectively.

fragmented need to happen regularly and frequently before any new landscape configuration can have an influence on the total burnt area.

An analysis of the performance of the management scenarios over the last 20 years (of the 40-year period of agricultural conversion) showed fire suppression effectiveness of all the *D2* (= 50 km^2 year^{-1}) scenarios did not improve, on average, more than 3.5% compared to the control scenario effectiveness of 12.5% (Figure 4). Indeed, for effectiveness to be at least 10% higher than in the control scenario, annual agricultural conversion rate had to be at least of 2*D* = 200 km^2 year^{-1}. An analysis of fire suppression effectiveness over the entire 40-year period showed similar results. At the lowest agricultural conversion rate (D2) and when the allocation pattern was scattered, fire suppression effectiveness was higher than in the control scenario of only urbanization without any agricultural transition (Table S3.1). However, at this lowest agricultural conversion rate but when the allocation pattern was aggregated, effectiveness was no more than 1.7% higher than in the control scenario. At demand *D* (= 100 km^2 year^{-1}), the mean effectiveness over the 40-year period was close to the effectiveness baseline, never increasing more than 4% (Table S3.2). Agricultural demand had to be large enough (at least 2D) or twice the effectiveness of the control scenario, to have a notable effect on the fire regime. However, when demand was even greater (3D), fire suppression effectiveness was saturated for most of the scenarios, and did not increase despite the increment in new agricultural land. This tendency was shared for all the strategies under the aggregate pattern (Tables 3, 4). However, when applying a scattered pattern, only the RD strategy (Table 4) became saturated while the other two strategies (FM and CP) showed a sustained increase in effectiveness.

With regard to the effect of where (that is, strategy) and how (that is, the allocation pattern) agricultural conversion was implemented, it is evident that when agricultural land was allocated following an aggregated pattern, under all strategies (FM, RD, and CP), the new configurations equally contributed to enhancing fire suppression effectiveness (Table 3). The three strategies were equally cost-effective in reducing total burnt area (Tables 3, 4). However, when the allocation pattern was scattered, both the number of patches and the location of these patches contributed to fire suppression effectiveness (Tables 5, 6). Using this allocation pattern, at high demand (2*D* and 3*D*) the effectiveness steadily increased when patches were allocated in rural areas, whereas the effectiveness decreased when patches were allocated close to current agricultural land (Figure 4A).

The leverage variable mirrored the tendencies observed for fire suppression effectiveness (Figure 4B). When new agricultural land allocation was aggregated, this cost–benefit ratio was reduced by half from *D*2 to *D*, whereas it did not experience any change for higher demands. This means that the pressure exerted on the territory by increasing agricultural land from *D*2 to *D* over the 40 years did not result in a clear benefit to fire suppression efforts. For demands greater than D, LULC changes indicated linear benefits; the amount of land changed is directly correlated to the area suppressed (Figure 4B). Finally, the percentage of large fires (≥ 500 ha) was 15% in the control scenario,

Table 3. Analysis of Variance (Type II Tests) of the Interaction Between the Quantitative Variable (Quantity of Agriculture Conversion, that is, *Demand*) and the Categorical Variable (*Strategy*) on Effectiveness of the Scenarios when using an Aggregate Pattern

	Sum sq	*Df*	*F* value	Pr (> *F*)
Demand	2.54607	1	475.6755	< 2e−16
Strategy	0.03905	2	3.648	0.02707
Demand: strategy	0.00396	2	0.3699	0.69107
Residuals	1.82522	341		

Table 4. Coefficients and Significance of the Linear Model $effectiveness|_{aggregate\_pattern} = f\ (demand,\ strategy)$

	Estimate	Std. error	*t* value	Pr (> |*t*|)
(Intercept)	8.28e−02	9.86e−03	8.397	1.22e−15
Demand	8.84e−04	4.05e−05	21.85	< 2e−16
FM	2.49e−02	9.72e−03	2.563	0.0108
RD	2.03e−02	9.72e−03	2.093	0.037

Table 5. Analysis of Variance (Type II Tests) of the Interaction Between the Quantitative Variable (*Demand*) and the Categorical Variable (*Strategy*) on Effectiveness of the Different Strategies when Using a Scattered Pattern

	Sum sq	*Df*	*F* value	Pr (> *F*)
Demand	3.2647	1	630.303	< 2e−16
Strategy	0.1672	2	16.143	2.00e−07
Demand: strategy	0.1591	2	15.362	4.09e−07
Residuals	1.7662	341		

Table 6. Coefficients and Significance of the Linear Model $effectiveness|_{scattered\_pattern} = f\ (demand,\ strategy)$

	Estimate	Std. error	*t* value	Pr (> |*t*|)
(Intercept)	3.46e−02	1.01e−02	3.426	6.87e−04
Demand	1.00e−03	4.15e−05	24.116	< 2e−16
FM	3.73e−02	9.97e−03	3.745	2.11e−04
RD	5.33e−02	9.97e−03	5.351	1.60e−07

decreasing, on average, to 14.1% and 12.8% when the annual conversion demand was set at 2*D* and 3*D*, respectively.

Under all scenarios, the mean core area of forest patches decreased as agricultural demand increased (Figure 4C). However, when agricultural land allocation was aggregated, forest core areas were better preserved (Figure 4C). In this case, at the lowest demand level (*D*2), forests could even gain core area with respect to the initial configuration. Forest patches of different biogeographical regions were unevenly affected by agricultural conversion (Figures 6 and S3.1). Forest patches lost core area at any level of demand in central and southern coastal regions, whereas forests accumulated more core area even at *D* and 2*D* demands in mountainous regions (Figures 6 and S3.1). This occurred because the expansion of agricultural land into forests, scrublands, and grasslands was compensated by both afforestation and fire suppression. Overall, at the highest demand the forest patches became more irregular (mean shape index increased) and less complex (Figure 4D).

Discussion

Conversion of natural and semi-natural land cover to agricultural land appears to be a potential management alternative for reducing total burnt area on fire-prone, highly humanized landscapes (Moreira and Pe'er 2018). Using a modelling framework that simulates fire events, fire succession and LULC changes, we were able to assess how land-cover changes induced nonlinear responses of the fire regime of a Mediterranean region through an improvement of firefighting capabilities. An analysis of the fire regime over the last 20 years when the landscape had already undergone a substantial amount of transformation partially supported our two hypotheses (Figures 1, 4A). When land-use changes were aggregated, fire suppression effectiveness remained almost unchanged at low demands, and fire suppression levels doubled at higher demands (Figure 4A and Table S3.1). This behaviour supports in part our first hypothesis that agricultural conversion has to be relative higher to recently observed rates of change to really contribute to an improvement in fire suppression capacity (Figure 1A). However, further demand increases did not perform so efficiently; fire suppression effectiveness became saturated. The capacity of the landscape to influence the fire regime reached a saturation threshold (Figure 1B). A simulation exercise showed that under favourable weather conditions, fires can still impact and spread across the territory even in relatively fire-resistant landscapes, or low fuel-loaded landscapes (Loehle 2004). We also detected a time lag between the implementation of the land-cover transition and an increase in fire extinction capacity with respect to the control scenario without agricultural conversion (Table 2). This time lag was shorter as the rate of agricultural land conversion increased (Table S2.3). This delay effect implies a positive feedback between the amount of new agricultural land and the fire extension capacity. Forest landscapes are complex systems that tend to gradually absorb changes, as long as these are not severe and sudden (Reyer and others 2015). It is commonly observed that a time lag or resistance to change before any substantial reaction occurs (Scheffer and others 2001).

Figure 6. Proportional increase (triangles that point upwards) or decrease (triangles that point downwards) of the forest patches mean core area in the 7 vegueries (administrative—biogeographic division of Catalonia) as agricultural demand increases from $D = 100$, $2D = 200$, to $3D = 300$ km^2 year^{-1} (for the rural development strategy and the aggregate pattern of allocation). Grey background accounts for the standard deviation of the metric (that increase as grey become darker).

When the allocation of croplands was aggregated, the fire regime responded similarly (Figure 4A). We could ascribe this behaviour to the fact that the natural land available to accommodate new large agricultural patches was scarce, and became even more scarce over time (Figures S3.2, S3.3 and S3.4). When patches were large, the landscape itself had a limited capacity for these patches to extend, so the spatial distribution of new patches tended to converge across the three strategies. However, when agricultural land was sparsely allocated, the strategies that interrupt forest continuity largely contributed to reducing total burnt area (Figure 4A). Therefore, smaller agricultural patches should be allocated in strategic locations that create accessible fuel breaks in high fire risk areas to strengthen fire extinction capacity.

For the same demand, strategies using an aggregate pattern resulted, on average, in a greater benefit (Figure 5b, Table S3.2). Strategies using the scattered pattern required more LULC change effort to create potential firebreaks on the landscape. Moreover, in landscapes where the allocation of croplands was aggregated, forest core areas were better preserved, thus avoiding negative edge-effects (Brudvig and others 2012). Despite the applied transformation to agricultural lands, at intermediate demands (D), mean forest core area increased in the northern part of the study area, from west to east (Figures 6 and S3.1), where it is mostly mature forest cover (Figure S1.1). Thus, agricultural conversion could be compensated by an improved fire suppression which reduces overall fire recurrence and thus eliminates potential regeneration failure due to repeated burning (that is, forests becoming scrublands) and afforestation (that is, colonization of scrublands by woody plants). However, in south-central regions, forest cover is already quite fragmented and could not bear further pressure from agricultural conversion. In addition, afforestation in the south is slower than in the north because of higher fire recurrence and less favourable conditions (climate is drier and warmer) for forest species to establish in already stable scrubland communities (Lloret and others 2005).

A Landscape Dynamic Modelling Framework for Mediterranean Regions Integrating Natural and Anthropogenic Drivers of Change

Coupling a fire-succession with a LULC change model has proven to be a useful spatially explicit tool for exploring feedback interactions between natural and anthropogenic drivers of global change often neglected in most landscape-scale studies (Hantson and others 2015). Modelling highly humanized fire-prone landscape dynamics from a coupled human–natural systems perspective mainly means incorporating LULC changes, fire behaviour, fire suppression efforts, landscape management, and forest ecological processes. Our work is one of the first attempts to model the indirect effects of land-cover transitions on a total burnt area of an entire fire-prone forest region by including a fire suppression strategy sensitive to changes in landscape composition and configuration. In a landscape management context, other models have attempted to capture the interplay between fire behaviour and local to regional forest management policies (Mladenoff 2004; Spies and others 2017), but without explicitly including the role of fire brigades. Although Loepfe and others (2012) included the activity of fire brigades in their model to evaluate agricultural conversion as a fire-smart management strategy, they applied this approach only to three non-neighbouring municipalities of Catalonia. Because their modelling approach was applied to areas less than 1 km^2, whereas Catalonia is a 32,100 km^2 region, they could not consider fires as events spreading beyond administrative borders neither evaluate the impact of such policies at the regional and fire regime scales.

This modelling framework allows us to explore the cumulative effects of landscape changes over time. A possible next relevant question may be: How long can fire suppression efforts benefit from more fragmented and heterogeneous landscapes? However, to study long-term cumulative effects and create plausible results, landscape-scale models should explicitly include the impact of climate change on ecological processes and disturbance regimes (Keane and others 2015). Variations in temperature and precipitation would influence vegetation dynamics at the stand level, potentially altering biomass accumulation, post-fire regeneration, colonization of scrublands by woody species, and drought-induced mortality. Modelling vegetation dynamics in response to predicted climatic change has been addressed using multiple modelling approaches (from empirical-based to process-based), over a wide range of ecological scales (individuals, populations, functional types, monodominant forests), and areas (from stands to biomes) (Peng 2000; Mouillot and others 2002; Seidl and others 2012). However, all or some disturbance regimes, forest management activities, and LULC changes are missing from many of these studies (Keane and others 2015; Rammer and Seidl

2015). We plan to improve the MEDFIRE model by making forest productivity, recruitment, colonization, and mortality climate-dependent. Once coupled to the MEDLUC model, we will then explore longer timelines of human–natural systems in fire-prone regions.

Implications for Fire Management in Mediterranean Landscapes

Climate change will increase vulnerability and exposure of forest ecosystems in Mediterranean landscapes to more intense and recurrent wildfires (Amatulli and others 2013; Batllori and others 2013). Therefore, fire management will be key in improving forest resilience to better cope with future environmental conditions (Khabarov and others 2014). We propose alternative landscape-scale management options for reducing wildfires in Catalonia, and positively fostering ecosystem resilience and environmental pressures associated with global change (Chapin and others 2010). Our results suggest that increasing discontinuity in forest cover of fire-prone landscapes will reinforce fire-fighting capacity by facilitating access to the fire perimeter, reducing overall fuel-load and fire intensity, and creating firebreaks that will slow down or even stop the advancing front (Loepfe and others 2010). Thus, through changes in the spatial distribution of forest cover, agricultural conversion will prevent fires from burning out of control and diminish fire recurrence, but will not eliminate fire events from the system, which is economically unfeasible and ecologically undesirable (Donovan and Brown 2005; Moritz and others 2014). We have shown that agricultural conversion influences the final burnt area over a relatively short time span (for example, until 2050), but we have not yet explored the performance of such strategy in the long term (for example, until 2100). The benefits of using agricultural patches in forest landscapes to control the fire regime may be limited under future climatic conditions. If total burnt area in Mediterranean landscapes increase throughout this century because of climate change, our fuel-reduction strategy might fall short, and other strategies, such as prescribed burns, controlled natural fires, or even traditional grazing practices (Schoennagel and others 2017; Johnson and others 2018) may need to be implemented.

The debate continues as to whether and how fuel management can mitigate fire risk under new global conditions. There is some evidence that fuel management by itself cannot contribute to the reduction in either fire incidents or carbon emissions (Campbell and others 2012; Price and others 2015), but may control final burnt areas (Stephens and others 2009; Khabarov and others 2014). It is unlikely that silvicultural interventions, such as thinning or wood chipping, or isolated prescribed burns could reasonably modify fuel loads and forest continuity to the point of altering high intensity fires. Firstly, at least 30% of the landscape would have to be treated, resulting in perhaps unacceptable economic costs. Secondly, a random allocation of treatments greatly reduces efficiency so a careful search of optimal locations is needed. Thirdly, inadequate spatial aggregation of fuel treatments reduces the efficiency of the interventions (Finney 2001; Loehle 2004). When planning a fuel management intervention, it is important to identify the location of treatments and, to a lesser extent, their intensity (Ager and others 2010). Only a few authors have used scenario exercises to investigate the role and location of fire management interventions on the fire regime (Parisien and others 2007; Regos and others 2016). We have explicitly investigated whether the location of new agricultural areas (through the transition-potential map linked to each strategy; Figure 3) and their spatial pattern (aggregate vs. scattered; Figure S2.2) could influence the fire regime. Our results suggest that allocating crops in an aggregate pattern results in slightly more opportunities to suppress fires. If socio-economic or environmental constraints restrict the allocation to smaller scattered patches, then the spatial distribution needs to be carefully outlined and implemented. In such cases, it becomes crucial to collaborate with fire behaviour experts to identify strategic locations across the territory for fire pre-suppression activities. A strategic location for fuel management is defined as: (1) an area with a specific forest structure that if appropriately managed can modify the behaviour of a future fire and prevent it from shifting to an uncontrollable wildfire, and (2) a geographic position accessible to the firefighting crews that is also likely to receive a burning front (Syphard and others 2011). Thus, the combination of stakeholders' input and robust modelling tools for integrating multiple natural and anthropogenic drivers of change making win–win options possible for resilience-based forest management of fire-prone landscapes.

Further studies should investigate the economic viability and social acceptance of these alternative fire-reduction strategies. In addition, a detailed study of environmental and biodiversity impacts would complete the data portfolio needed to fully inform a decision-making process. Indeed, both economic and ecological trade-offs should be closely monitored over time. It is likely that socio-economic, political and conservation issues will arise when implementing such a landscape-scale management policy in a European Mediterranean region. In fact, agricultural conversion of natural and semi-natural lands will likely have many detractors. Currently, most government budgets are spent on fire suppression (to control the impact of fires) rather than on fire prevention or alternative fire management policies. However, funds could be dedicated to fostering fire-adapted landscapes and fire-resilient societies better able to cope with more severe and recurrent fire activity (Moritz and others 2014; Tedim and others 2016). For example, governments could promote regional plans that sustain rural activities in remote areas to ensure the maintenance of croplands, orchards or pastures over time. Generally, inhabitants of rural areas perceive unplanned fire incidents as dangerous and destructive. Instead, fire could be perceived as a useful tool for clearing shrubs and trees from agricultural land or from the understory in mature forests, preventing the region from burning out of control (Seijo and others 2015). However, rethinking wildfire prevention, understanding fire as a management tool and adopting landscape-scale fuel-reduction strategies remain a challenge for the general public (Fernandes 2013; Calkin and others 2015). Long-term ecological benefits and cost savings of alternative fire management policies (for example, agricultural conversion) over classic fire suppression have to be evaluated and discussed. Such discussions should consider the goods and services provided by forest ecosystems (for example, carbon sequestration, recreational uses, biodiversity conservation) and determine the ecological and economic trade-offs.

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