Global change and the uncertain future of biodiversity in Mediterranean-type ecosystems: insights from a strategic foresight process

Memoria presentada por:

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Esta tese adícolla a miña filla Andrea

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GLOSSARY

Table. 1. The glossary briefly describes some concepts and terms that are essential in this thesis.

Active fire suppression strategy: mimics the overall efficiency of firefighters to anticipate fire behaviour and reduce the area to be burnt under determinate fire propagation conditions [1].
Adverse years: years climatically characterized by a high number of weather risk days, as opposed to years dominated by mild weather conditions (i.e. "mild years") [1].
Effectiveness: the degree to which objectives are achieved and the extent to which targeted problems are solved. In contrast to efficiency, effectiveness is determined without reference to costs. Effectiveness means "*doing the right thing.*"
Efficiency: process that uses the lowest amount of inputs to create the greatest amount of outputs. Efficiency means "*doing the thing right.*"
Ensemble: number of copies of a system, considered all at once, each of which represents a possible state that the real system might be in at some specified time [2].
Fire regime: general pattern in which fires naturally occur in a particular ecosystem over an extended period of time. Fire regimes are classified using a combination of factors including frequency, intensity, size, pattern, season, and severity [3].
Fire suppression: refers to the firefighting tactics used to suppress wildfires.
Firefighting: the act of extinguishing fires.
Forecasting: predicting future conditions based on past trends [4].
Forecast ensemble: multiple simulations (copies) across more than one set of initial conditions, model classes, parameters and predictors [2].
Horizon scanning: a tool for collecting and organizing a wide array of information to identify emerging issues [4].
Megafires: extreme fire events usually driven by critical weather conditions that lead to a concentration of numerous large fires in time and space (fire clusters) [5].
Modelling: describing a system using mathematical concepts to study the effects of different components, and make predictions about system behaviour [4].
Opportunistic fire suppression strategy: mimics firefighting actions based on the ability to take advantage of opportunities derived from old fire scars [1].
Prescribed fire: a planned fire intentionally ignited by fire managers to meet management objectives.
Scenario analysis: describe the data analysis phase of a scenario planning exercise [4].
Scenario planning: a tool encompassing many different approaches to creating alternative visions of the future based on key uncertainties and trends [6].
Simulation: using a model to imitate the operation of a system over time to explore the effects of alternative conditions or actions [4].
Storylines: narrative descriptions of plausible and alternative socio-economic development pathways that lead to different visions of future worlds [7].
Strategic foresight: a structured process for exploring alternative future states [4,8].
Target area to be burnt: hectares/year to burn according to historical fire statistics (1975–1999) [1].
Unplanned fire: a wildland fire caused by lightning or other natural causes, by accidental (or arson-caused) human ignitions, or by an escaped prescribed fire.
Vegetation encroachment: an increase in density, cover and biomass by native vegetation that promote the conversion of early-successional stages of vegetation to forest cover (i.e. secondary ecological succession) [9].
Wallacean shortfall: geographical distributions are poorly understood and contain many gaps for most of the species living on Earth [10,11].
Wildland fire: general term describing any non-structure fire that occurs in vegetation and natural fuels. Wildland fire includes both planned and unplanned fires.

ABSTRACT

Conservation needs strategic foresight leading to effectively address the ongoing challenges posed by global change. Mediterranean Basin has been identified as priority area for conservation, particularly vulnerable to the combined effects of climate change, land-use change and fire disturbance regime. The interacting effects of these drivers, and the large uncertainties associated to their forecasting, might also bring conservation opportunities to intervene through better policies. Strategic foresight exercises may offer decision-makers with tools to creatively think about the future and make decisions that create a more desirable future. In this thesis, we illustrate the role for horizon scanning, scenario planning and simulation-based scenario analysis in underpinning the strategic foresight approach — using storylines as conceptual scenarios, and simulations as numerical estimates of future environmental changes. In particular, this strategic foresight exercise contributes to opening up two promising fire management policy options ('letting unplanned fires burn' and 'forest biomass extraction for bioenergy uses') alternatives to the current fire suppression paradigm of "stopping all fires". Both fire management policies could be strategically combined in order to achieve the fuel reduction objectives required to mitigate the increasing impact of large fires caused by global change. Conservation planning may be considerably improved through the implementation of such fire management strategies. Two main emerging conservation opportunities have been identified and should be prioritized in order to effectively protect community-interest bird species in the near future: 1) promoting early-succession stages of vegetation for open-habitat dwelling species through 'letting unplanned fires burn' policies; and 2) increasing the resilience of key forest habitats to climate change for forest-dwelling species. This thesis emphasizes the need for an integrative conservation perspective wherein agricultural, forest and fire management policies should be explicitly considered to effectively preserve key habitats for threatened birds in fire-prone, highly-dynamic systems. Our findings also shed light about the importance of considering landscape dynamics and the synergies between different driving forces when assessing the long-term effectiveness of fire management at reducing fire risk and safeguarding biodiversity in Mediterranean-type ecosystems.

RESUMEN

La conservación requiere una previsión estratégica que permita abordar con eficacia los retos actuales que plantea el cambio global. La cuenca Mediterránea ha sido identificada como área prioritaria para la conservación, particularmente vulnerable al efecto combinado del cambio climático, el cambio de los usos del suelo y el régimen de perturbaciones por incendios forestales. Los efectos de la interacción de estos factores de cambio y las grandes incertidumbres asociadas a su predicción, también pueden ser vistas como una oportunidad para intervenir a través de mejores políticas de conservación. Los ejercicios de previsión estratégica pueden ofrecer a los responsables de la toma de decisiones herramientas para pensar de forma creativa y proactiva sobre el futuro y tomar decisiones que creen un futuro más deseable. En esta tesis ilustramos el papel de las actividades de 'horizon scanning', planificación y análisis de escenarios basados en simulación, en los que se sustenta el enfoque de previsión estratégica, y en la que usamos escenarios conceptuales como líneas argumentales y simulaciones como estimaciones numéricas de los futuros cambios ambientales. En particular, este ejercicio de previsión estratégica contribuye a la apertura de dos opciones de políticas de manejo del fuego prometedoras ('dejar quemar los incendios no planificados' y 'la extracción de biomasa forestal para bioenergía') alternativas al paradigma actual de 'apagar todos los incendios'. Ambas políticas de manejo del fuego podrían combinarse estratégicamente con el fin de alcanzar los objetivos de reducción de combustible requeridas para mitigar el creciente impacto de los grandes incendios causados por el cambio global. La planificación de la conservación puede ser mejorada considerablemente mediante la aplicación de estas estrategias de manejo del fuego. Dos principales oportunidades de conservación emergentes han sido identificados y deben ser priorizadas a fin de proteger de forma efectiva las especies de aves de interés comunitario en un futuro próximo: 1) la creación de etapas tempranas de sucesión de la vegetación para especies de hábitat abierto a través de políticas de 'dejar quemar incendios no planificados'; y 2) el aumento de la capacidad de resiliencia frente al cambio climático de los hábitats forestales claves para las especies más forestales. En esta tesis se hace hincapié en la necesidad de una perspectiva de conservación integral en donde las políticas agrícolas, forestales y de manejo de fuego deben ser consideradas explícitamente para preservar eficazmente hábitats clave para las aves más amenazadas en sistemas altamente dinámicos propensos al fuego. Nuestros resultados también arrojan luz sobre la importancia de considerar la dinámica del paisaje y las sinergias entre las diferentes fuerzas motrices a la hora de evaluar a largo plazo la eficacia de la gestión del fuego en la reducción del riesgo de incendios y la protección de la biodiversidad en los ecosistemas de tipo mediterráneo.

SETTING THE SCENE

Global change and conservation challenges

Global environmental change poses widespread challenges for policy and decision makers, land managers and conservation practitioners [12–14]. Climate change is a major driving force that directly, and indirectly, shapes biological communities, species and ecosystems worldwide [15–17]. Land-use and land-cover change is another important component of global change [18–20] and its combined effect with climate change and other ongoing human threats have led to substantial range contractions and species extinctions [7,21–23]. As a consequence, global biodiversity is declining at an unprecedented rate [24–26] and this decline is expected to continue over the 21st century [27–29]. However, the complex and interacting effects of both drivers, and the large uncertainties associated to their forecasting, also bring conservation opportunities [30] to intervene through better policies [28].

Mediterranean Basin has been identified as biodiversity hotspot and priority area for conservation [12,31]. The biodiversity in theses Mediterranean-type ecosystems is particularly vulnerable to the effects of climate change, land-use change, changes in fire disturbance regime, and their combined effects [32–34]. Therefore, Mediterranean Basin provides an excellent natural laboratory to study global change and its effects on biodiversity [27]. The abandonment of agricultural lands of the last decades has increased landscape homogeneity and fuel load due to vegetation encroachment processes, which in turn promotes megafires (i.e. high-intensity, large-size fires; see Table 1) [35]. Climate change has increased drought events (i.e. longer time periods with warmer temperatures and reduced precipitation) particularly during the summer, which in synergy with land-use change has altered fire regimes [3,36,37]. Huge resources were invested in fire suppression to deal with this increasing fire impact over the last decade. However, this fire suppression programs have proven to be effective in the short term but not in the longer term [38–41]. This trend is predicted to become even worse [42,43], and natural fire disturbance regime to be driven to new, uncertain states [44]. Consequently, understanding and forecasting how species respond to these novel fire regimes is essential to maximize biodiversity in fire-prone ecosystems [34,45,46]. Evaluating the relative value of fire management practices is key for ecologically sustainable management [47–50].

To make robust and effective policy decisions in conservation matter, explicit linkages between conservation action, fire management, land-use planning and their outcomes are required in Mediterranean ecosystems. Most approaches to managing ecosystems aimed at preserving biodiversity hinges on a better understanding of socio-ecological processes by examining the past. However, a forward-looking perspective, which explores a broad range of possible future trajectories of the socio-ecological system, can complement those conservation decisions exclusively based on long-term, historical approaches [51] and allows decision-makers strategically maximize benefits or minimize costs [8]. Strategic foresight was defined as *a structured process for systematically exploring alternative future states that helps decision-makers to think creatively about the future and make decisions that create a more desirable future* [4,8]. This forward-looking strategic process can be applied to conservation challenges when faced global change using scenario planning as a foresight tool [8,52,53].

The role of scenario planning in a strategic foresight process

Scenario planning is a foresight tool that encompasses many different methods to envisage alternative visions of the future based on its inherent uncertainty [4]. One of these methods consists of designing a set of contrasting scenarios to explore the uncertainty surrounding the future consequences of considering one or another decision [53]. Given the uncontrollable, irreducible uncertainty of the future, scenario planning provides a way for decision makers to develop and support more resilient and proactive conservation policy, planning, and management [8,53]. Scenario planning plays a key role in a strategic foresight process (see Cook el al. [44]), moving away from a vision focused on accurately forecasting a single future, toward a more creative perspective based on the exploration of multiple alternative and plausible future states. Thus, scenario planning stimulates decision makers to consider changes they would otherwise ignore. Simultaneously, it allows to organize these multiple alternative future into narratives (i.e. storylines) that are easier to grasp by decision makers and stakeholders [54]. This perspective strongly relies on a broad socio-ecological knowledge base of the system and a clear understanding of its dynamics and key driving factors that determine the overall logic of the storylines [54–56]. Storylines are therefore an essential part of the scenario planning and development. They are the qualitative and descriptive component of a scenario which reflect the assumptions about the driving forces of change within the scenarios or describe the potential outcomes [57]. Scenario planning can be based on purely qualitative storylines, developing narratives about how the future may evolve [54], or quantitative, using empirical models and simulations to explore uncertainty [4,52]. However, reinforcing qualitative storylines with quantitative modelling techniques and expert knowledge (SAS ‘storyline and simulation’ approach) has proven to be a successful method for integrated environmental assessment [58]. In particular, landscape-futures analysis, which combines conservation planning tools with scenario planning, has found to be an effective way to support decision-makers to achieve regional environmental targets [59].

Nowadays, scenario planning is recognized as policy support tool and methodology that can help decision makers to identify potential impacts of different policy options across a broad range of scales [27,60,61]. Indeed, scenario planning is a key component in the Millenium Ecosystem Assessment [62] as well as in IPBES Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (http://www.ipbes.net/) and is helping to achieve the targets established in the last strategic plan of the Convention on Biological Diversity [28] and to bridge the gap between scientific dialogue and policy.

Objectives

The main goal is to develop strategic foresight tools leading to effectively address the ongoing challenges posed by global change in decision-making. This thesis project should help to identify the potential solutions and opportunities arising from the combined effects of the main threats causing biodiversity losses in Mediterranean forests. More specific objectives are aimed to:

1) Identifying fire management policy options alternatives to the current fire suppression paradigm of ‘stopping all fires’ and predicting their potential effectiveness at suppressing future large fires (Chapter I and II).
2) Evaluating the potential effects of such fire management policies and their interactions with climate change on threatened birds (Chapter III and IV).
3) Predicting the future effectiveness of current protected areas network for bird conservation under climate change and novel fire regime scenarios (Chapter IV).

In addition, this thesis aims at illustrating how the strategic foresight process can be developed to identify conservation opportunities to effectively face global change in highly-dynamic, fire-prone ecosystems.

METHODOLOGY

The strategic foresight process includes the following stages (Fig. 1): 1) **Horizon scanning**: setting the scope —target species and study region; gathering and organizing information about the drivers of change, potential threats and opportunities; identifying and prioritizing future possible pathways; 2) **scenario planning**: creating alternative visions of the future based on key uncertainties and past trends, organizing these multiple alternative future into narratives (i.e. storylines); 3) **modelling and simulation**: using a model to simulate the main processes of a system over time to explore the effects of alternative fire management policies and novel environmental conditions and 4) **scenario analysis**: analysing outcomes from scenario planning and simulation exercises.

Horizon scanning —the future of Mediterranean landscapes

One of the first steps identified in a strategic foresight exercise is to determine the key components of the system, drivers, threats and opportunities, as well as the stakeholders and actors that could be involved. Collecting and organizing information about past and current trends and potential drivers of change, as well as the complex relationships between them, is therefore highly recommended to develop a successful conceptual representation of the system [4,8]. Horizon scanning activities have been applied at the regional level (Catalonia) to inform this foresight exercise [63]. In particular, workshops, fortnightly seminars, active use of blogging and micro-blogging (Twitter) and specific meetings organized within the Forestry Science Centre of Catalonia (CTFC; http://www.ctfc.cat/) between 2012 and 2014, and coordinated by our lab (Biodiversity and Landscape Ecology Lab; http://biodiversitylandscapeecologylab.blogspot.com.es/) have provided helpful knowledge and insights in this regard. These meetings involved

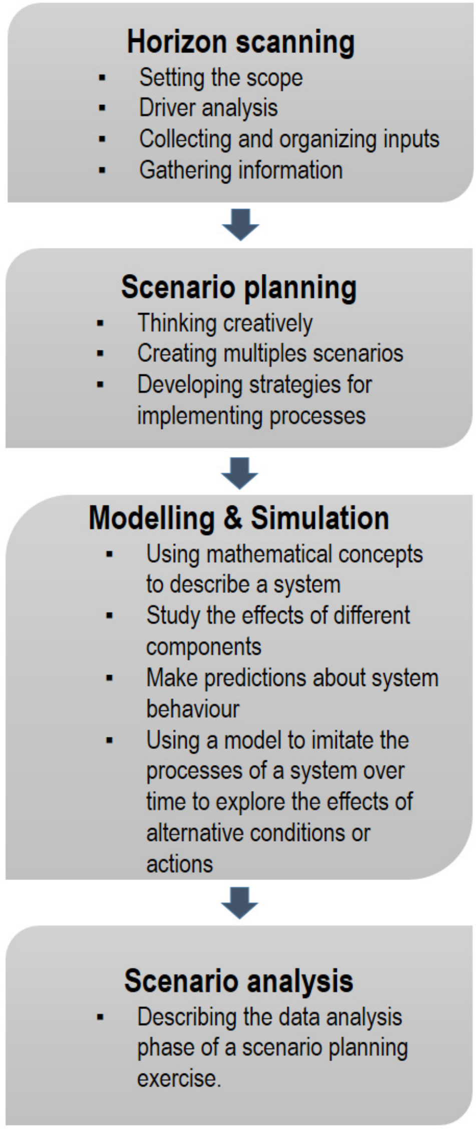

Fig.1. Stages of the strategic foresight process.

experts from different sectors (and institutions) of the agro-forestry Mediterranean systems: forest management (CTFC-CREAF), fire suppression (GRAF), forest production (Timber and Bioenergy lab-CTFC), forest policy and socioeconomic (EFIMED), fire perturbation regime (CTFC), ecosystem functioning and biodiversity (CTFC-CREAF; EBCC & ICO).

In addition, several visiting researcher from other institutions have collaborated and enhanced the discussion along this 3-year period: Brendan Wintle and David Duncan (Melbourne University), Louis Imbeau (Université du Québec en Abitibi-Témiscamingue), Marie-Josée Fortin (Toronto University), Pierre Drapeau (Université du Québec en Montreal-CEF), among others. Research stays (Université de Lausanne and Université du Québec en Montreal-CEF) carried out in the frame of this thesis project help us to gain insights from other systems and researchers (Antoine Guisan's lab and Pierre Drapeau's lab). This process was complemented by an exhaustive literature review. All these activities were used to provide plausible and simplified descriptions of how the future may develop based on a coherent and internally consistent set of assumptions about key driving forces and their relationships [57]. This information conforms the hard core of the scenario planning and development, and the conceptual representation of the system (Table 1).

Setting the scope

Birds as surrogates of biodiversity in Catalonia

There is an urgent need to identify areas of priority conservation to prevent further species extinctions [13,31,64] as well as to evaluate the effectiveness of current protected areas for safeguarding biodiversity [65–67]. However, the geographical distributions of most species are poorly understood (the so-called Wallacean shortfall) [11,10]. Consequently, biodiversity assessment often relies on single well-known, easily surveyed taxa (such as birds) assumed to be good surrogates for biodiversity as a whole. Although several studies have found birds to perform relatively poorly as biodiversity surrogates [68,69], information on the distribution of birds is more commonly available than for other taxonomic groups, mainly due to: 1) they are commonly selected as 'flagships' to promote conservation activities around the world [70]; 2) BirdLife International has identified more than 10,000 Important Bird Areas (IBAs) around the world [71], and within Europe, the EUs Birds Directive has partially based the establishment of NATURE 2000 network on special protection areas (SPAs) for birds; 3) birds react very rapidly to perturbations in their habitats because of their high mobility [72]; and 4) the increasing role of citizen-science platforms (such as eBird; openly available and broadly used by students, teachers, scientists, NGOs, etc.) which have become a major source of biodiversity data, helping to overcome the Wallacean shortfall, and having a direct impact on the conservation of birds and their habitats [73].

In Catalonia, large-scale biodiversity datasets (such as Catalan breeding and wintering bird atlases [74,75]), and ongoing monitoring programs (such as DINDIS-Bird distribution dynamics in Mediterranean landscapes affected by fires [76] or Catalan common bird survey, SOCC [77]) provide a major source of good quality data, suitable for regularly updating bird distributions at large spatial scales. Besides, the combination of spatial modelling tools with such monitoring projects has proven to be a cost-effective approach to estimate the dynamics of species distributions in space and over time [78].

Catalonia as case study: a general view from a small window

Catalonia (north-eastern Iberian Peninsula) was chosen as a study region. This area comprises a high environmental gradient that is mainly related to altitude, ranging from coastal habitats to high altitude mountain ranges (up to 3143 m a.s.l.). Climate is Mediterranean, although with more temperate climatic conditions in mountain areas.

Land-use changes linked to socio-economical drivers in this region may be representative of those that occurred in other areas of Mediterranean Europe during the last century: abandonment of traditional activities, agricultural intensification and afforestation of cultivated lands [79–81]. Nowadays, landscape in Catalonia is strongly polarized, with farmland and areas of natural vegetation each cover almost 50% of its surface area. The impact of land abandonment can be split into two different but closely-related processes: 1) agriculture abandonment as the process whereby old croplands are converted to wild open habitats such as grassland and low shrubland (i.e. primary ecological succession) [82]; and, 2) vegetation encroachment, defined as an increase in density, cover and biomass by native vegetation that promote the conversion of early-successional stages of vegetation to forest cover (i.e. secondary ecological succession). In Catalonia, vegetation encroachment is closely associated with reductions in livestock grazing and activities related to woody fuel extraction [83,84]. Recent studies have demonstrated that vegetation encroachment did have a significant impact on bird communities, whereas any relevant effect of farmland abandonment on bird populations was observed between 2002 and 2011 [9]. Forest and shrubland were the most affected by fire during the 1975– 1998 period [85].

Catalonia, as many other Mediterranean regions, has been strongly affected by wildfires during the last decades. Consequently, resources allocated to fire suppression increased in the early 80s and 90s [86]. After the occurrence of two dramatic fire events (in 1994 and 1998), fire suppression effectiveness were increased through the creation of specific technical fire brigades (GRAF) whose mission is to understand fire behaviour and anticipate changes in fire propagation [86]. At the beginning of the 21st century, prescribed burning programs were also implemented among other efforts to reduce fire risk, but not at sufficiently broad scales to achieve effective reductions due to socio-economical constraints such as bureaucracy, available funds and staff, and population suspicion [87]. Despite all these increased fire suppression and prevention efforts, wildfires continue to burn thousands of hectares in Catalonia. In particular, nowadays, Catalan fire brigades are very effective when fighting (96% of cases) low-intensity fires, letting them not to spread more than 10 ha. However, they cannot control the remaining 4%, which are the responsible of the 96% of the total area burned per year. Many authors claim that the systematic extinction of "all fires" leaves an accumulation of fuel that will be consumed in future large fires (i.e. megafires) in years with extreme fire weather conditions (fire paradox) [40,88]. This fire management policy, historically focused on extinction instead of prevention, substantially decreases small and medium fires which act as natural landscape breaks. A new debate about future fire management, in terms of extinction and prevention, finally arose between policymakers, scientific community and land managers to find cost-effective, alternative solutions to achieve the stand structure and fuel reduction objectives required to minimize the undesired impact of megafires [36,89,90].

Table 1. Table showing some of the main horizon scan activities carried out at CTFC between 2012 and 2014.

Activity	Reference	Sector	Topic	Institution
Internal seminar	De Caceres (2013). *The response of Mediterranean forest to changes in drought and fire regimes: insights from a landscape simulation model*. Seminar, 13th - December, Solsona.	Research	Landscape modelling	Forest Sciences Centre of Catalonia – CTFC
Workshop on integrating wildfire risk in the urban and spatial planning: Review of knowledge and practices	Operational tools for improving efficiency in wildfire risk reduction in EU landscapes. 12th & 13th June (2014), Solsona.	Research & Transference	Fire fighting planning	CTFC, Department of Interior from the Government of Catalonia, European Forest Institute (EFI), Fire Ecology and Management Foundation Pau Costa (PCF), King's College London (KCL)
Internal seminar	Varela (2013). *The economic evaluation of ecosystem services: experiences, opportunities and constraints for using in the Mediterranean context*. 3th July, Solsona.	Research	Economic tools and policies for sustainable forest goods and services	Mediterranean Regional Office of the European Forest Institute-EFIMED
Master student's seminar	Garcia-Candela (2012). *Modelling the Growth of species Pinus nigra and Quercus ilex in Catalonia*, 25th October. Solsona.	Academic studies	Vegetation modelling	PhD program from CREAF
Research visitor's talk	Imbeau (2012).*Research, training and technological transfer related to forestry in Québec: an overview of the Industrial Chair in Sustainable Forest* Management at UQAT. 24th 2012. Solsona.	Research	Forest management in boreal ecosystems	Université du Québec en Abitibi-Témiscamingue (UQAT)
Research stay	*Adrian Regos - Département d'écologie et évolution Ecospat – Spatial Ecology Group (Guisan's Lab) – october– november de 2013 (2 months)*	Academic & research	Biodiversity modelling & climate change	University of Lausanne (Switzerland)

Interlab meetings	*Synergies between forest biomass extraction for bioenergy and fire suppression. (2012-2014)*	Research	Forest biomass extraction for energy purposes and model implementation.	Landscape ecology and biodiversity lab & Timber and Bioenergy lab-CTFC

Scenario planning

In the Millennium Ecosystem Assessment, scenarios are described as "*…plausible and often simplified descriptions of how the future may develop based on a coherent and internally consistent set of assumptions about key driving forces and relationships*" [91]. Scenarios can be categorized as exploratory scenarios (descriptive extrapolations of the future), normative scenarios (desirable or avoidable development pathways) and business-as-usual scenarios (baseline of current trends) [57]. In this framework, storylines are an essential part of scenario planning. They are the qualitative and descriptive component of a scenario, and reflect the driving forces of change. Storyline assumptions and the relationships between different drivers were structured and described to establish internal consistency between the various statements and assumptions that underpin a storyline. This provides order to a range of potentially divergent issues allowing comparison across different narratives [57]. Thus, by using storylines it is possible to present a more precise view of the future by offering also qualitative information compared to views that presents solely quantitative data.

Along this thesis, we used a SAS approach where storylines describe those socio-ecological events found to be key in Catalonia in the horizon scanning process, and then fire simulations reinforce the storylines with numerical estimates of future environmental drivers [58,91]. Scenarios were supported by a detailed description of the storylines describing the potential future pathways in Mediterranean-type ecosystems. These storylines are based on key socio-ecological driving forces with potential to affect the landscape dynamics in Catalonia such as climate change, fire disturbance, large-scale fire management and forest harvesting for bioenergy uses. In particular, fire suppression scenarios were designed by combining different fire suppression strategies and levels of climatic severity (see scenario design in chapter I). Forest biomass extraction for bioenergy scenarios were built from three main storylines accounting for likely general strategies in large-scale forest planning (see scenario design in chapter II). These scenarios resulted from the combination of different values for the three scenario parameters: levels of fire suppression, three treatments dealing with the biomass extraction allocation, and two extraction intensities. Finally, we designed a new set of future environmental scenarios by combining the fire management policies considered in chapters I and II with two IPCC climate change scenarios (see scenario design in chapters III and IV).

Modelling and simulation —predicting the combined effects of climate and fire management on fire regime and birds

Once the storylines were conceptually developed, they were reinforced with numerical estimates of future environmental changes by combining the outcomes of Global Circulation Models (GCMs) and process-based landscape modelling tools (MEDFIRE model, [38]) throughout novel biodiversity modelling platforms (BIOMOD, [92]) (Fig. 3). These tools allow us to explicitly integrate the combined effect of fire disturbance dynamics and natural vegetation succession, in synergy with climate change for forecasting the potential responses of species between 2000 and 2050 under different climate change and alternative fire management scenarios.

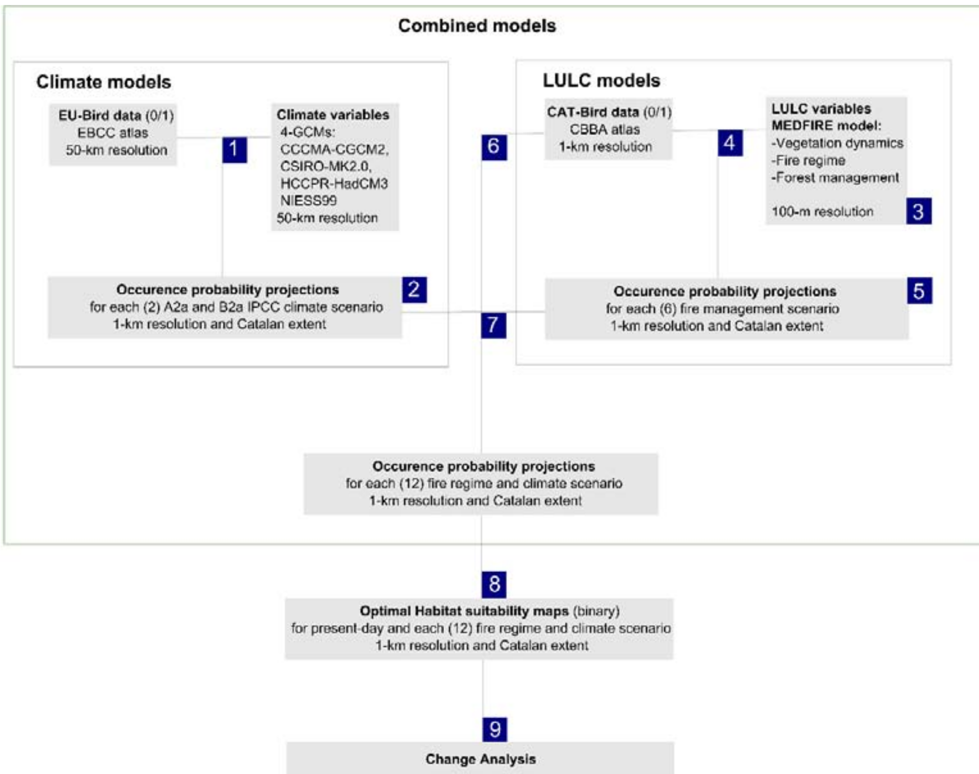

Fig. 2. Conceptual framework of the combined modelling approach developed in this thesis to address the multiscale hierarchical integration of climate and land cover information.

MEDFIRE model — A spatially-explicit tool aimed at supporting fire and forest management decisions in Mediterranean regions.

The MEDFIRE is a spatially-explicit dynamic fire-succession model that simulates land cover changes derived from vegetation dynamics, fire disturbance regime and fire suppression strategies in a Mediterranean context [38] (Fig. 4). It was designed to assess the combined effect of the drivers on fire regime at short- and medium-term timescales through a quantitative evaluation of their effects on the distribution of the annual area burnt, fire size distribution, and land cover composition. Therefore, it allows the characterization of the spatiotemporal variation in fire regime and, in turn, land cover changes under different climate scenarios and fire suppression strategies. The model was implemented using version 3.5 of the Spatially

Explicit Landscape Event Simulator (SELES) modeling platform [93]. The current version of MEDFIRE (version 3) is composed of three **sub-modules** accounting for the main dynamic processes shaping Mediterranean forests at landscape scale, i.e. (i) fire disturbance and fire suppression (fire sub-model), (ii), after-fire recovery and maturation of the vegetation (vegetation dynamics sub-model), and (iii) forest management (biomass extraction sub-model) (more details in https://sites.google.com/site/medfireproject/).

The sub-modules are sequentially executed in one-year time-steps, and all model simulations share the initial conditions for the state variables. Validation exercises carried out for different time windows with different climate and fire suppression intensities showed that the model was able to reproduce the basic descriptors of fire regime in Catalonia. The state variables that MEDFIRE uses to describe landscape context and conditions are two dynamic variables in raster format at 100-m resolution: Land cover type (LCT) and time since the last fire (TSF).

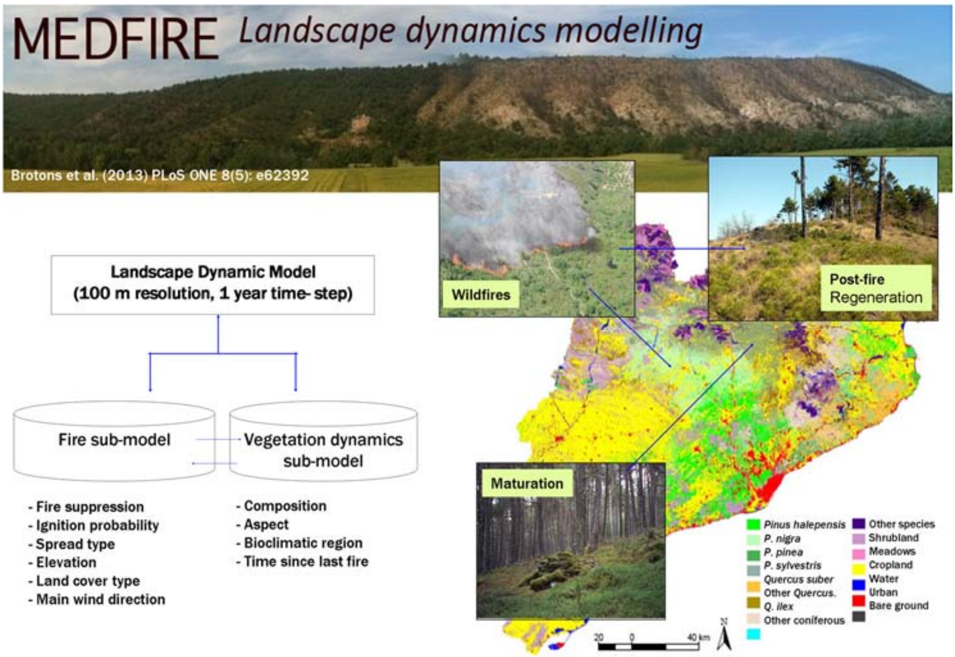

Fig. 3. Conceptual design of the MEDFIRE model. Extracted from Regos et al.[94].

See Brotons et al. [38] for a full ODD description of the model. Further information on the project in which this dynamic landscape model is embedded can be found online at https://sites.google.com/site/medfireproject/ (Fall and Fall [93] for further information on the SELES modeling platform used to implement the model).

BIOMOD — a platform for ensemble forecasting of species distributions

BIOMOD is a computer modelling platform designed for ensemble forecasting of species distributions [92]. It is implemented in a freeware, open-source R package – BIOMOD [95]. It aims to maximize the predictive power of current species distributions and the reliability of future potential distributions using different types of statistical modelling methods [96]. BIOMOD allows to model species distributions with several modelling algorithms, test models with a wide range of approaches, project species distributions into different environmental conditions. In particular, ten widely-used modelling algorithms are currently available in BIOMOD: generalized linear models (GLM), generalized additive models (GAM), generalized boosted models (GBM), flexible discriminant analysis (FDA), classification tree analysis (CTA), multivariate adaptive regression splines (MARS), surface range envelope (SRE, a.k.a. BIOCLIM), maximum entropy (MaxEnt), random forest (RF), and artificial neural networks (ANN) (more details in Thuiller et al. [92,96]).

Evaluation of model accuracy in BIOMOD can be performed with three different procedures: the area under the relative operating characteristic curve (AUC [97]), true skill statistic (TSS [98]) and Cohen's kappa coefficient [99]. BIOMOD allows *k* number of data splitting runs to be computed (i.e. data-splitting procedures), wherein a proportion of the original data are used for training the models and the remaining data are used for model evaluation. This is an alternative way when non-independent data are available for model evaluation. The variability in model accuracy arisen from data-splitting procedures should be interpreted as a measure of the sensitivity of model results to the initial conditions rather than as a measure of predictive accuracy [100].

BIOMOD2 allows different methods for computing a consensus of single-model projections using the abovementioned evaluation metrics as model weights: a weighted average value; mean, median (All), median (PCA) value of the whole predictions ensemble; or selecting the best one (more details in Marmion et al. [101]).

Dealing with the uncertainty

The future is inherently uncertain, and therefore extremely hardly predictable. This is particularly true in early-succession ecosystems, more sensitive to disturbance than mature systems [102]. In these highly-dynamic systems, scenario planning is a helpful foresight tool for making decisions, providing conservation practitioners a method for developing more resilient conservation policies [4,8]. In this thesis, we use scenario planning as an approach to management that takes uncertainty into account, wherein uncertainty is viewed as an opportunity for developing better policies and making optimal decisions [53]. This perspective considers a wide range of possible futures that include many of the key uncertainties in the system rather than focusing on the accurate prediction of a single outcome [53,54]. Thus, we get new insights in three main directions: (1) better understanding of key uncertainties of the Mediterranean ecosystems, (2) assessing the potential effects of alternative fire management strategies on fire disturbance regime and their implications into conservation planning, and (3) greater resilience of decisions to unexpected situations [53]. Besides, as our scenarios were developed considering the socio-economic and ecological dimensions of the problem, scenario planning might play a key role in guiding long-term planning for environmental decisions in Mediterranean ecosystems at different levels: (1) monitoring existing and emerging threats; (2) identifying promising new management opportunities; (3) testing the resilience of policies; and (4) defining an environmental management agenda [4].

Climate changes coupled with land-cover changes induced by fire and vegetation encroachment have been identified as the main driving forces shaping future landscapes and biodiversity in Catalonia. In this thesis, computer simulations of future environmental changes complemented scenario planning. The interacting effects of the different drivers have been hierarchically integrated in a multiscale modelling framework by combining: (1) the outcomes of different GCMs (http://ccafs-climate.org/) [103] and (2) a regional spatially-explicit dynamic fire-succession model (MEDFIRE model, [38]) throughout a (3) novel biodiversity modelling platform (BIOMOD, [92]). We explicitly dealt with the most common sources of uncertainty arising from modelling and computer simulations:

1) *Global climate models*: Applying consensus methods among climate models has been used by climatologists in order to account for uncertainties associated with different GCMs [104,105]. Recently, reducing variability across all models by deriving the central tendency of forecasts has been also adopted by ecologists in biodiversity assessments under potential climate changes [2,106]. In our case, future climate change projections were computed by averaging the outcomes of four GCMs (CCCMA-CGCM2, CSIRO-MK2.0, HCCPR-HadCM3 and NIESS99) to account for the uncertainty arising from the inter-model variability.

2) *Regional fire-succession model*: Fire is a stochastic process, driven by a complex interplay of ignition occurrence, climatic variability, local weather, topographic conditions, fuel structure, and fire suppression policies. The MEDFIRE simulation scenarios were ran several times in order to consider such stochasticity. We used the results of individual replicates (hereafter 'runs') as sample. With a large enough number of runs, statistical significance is almost guaranteed because of reduced variation around the mean. For selecting an appropriate number of runs we did sensitivity analysis. In particular, 10 replicates was found to be a number large enough to take into account such uncertainty, since the increase in the sample size does not introduce changes to our results and main conclusions. In addition, we also found that the computing time increases considerably with the number of replicates from about 12 hours for each scenario in 100-runs case to about 60 hours in 500-runs case. Following White et al. [107], the results derived from our simulations were always interpreted using the box-plots comparison. According to these authors, modellers should abandon frequentist statistical hypothesis tests (e.g. ANOVA) to interpret simulation model results and focus on evaluating the magnitude of differences between simulations (e.g. box-plots). They consider frequentist statistical tests inappropriate for two reasons: i) *p*-values are determined by statistical power (i.e. runs or replications), which can be arbitrarily high (or low) in a simulation context, producing minuscule *p*-values regardless of the effect size. ii) The null hypothesis of no difference between treatments (e.g. parameter values) is known *a priori* to be false, invalidating the premise of the test. Use of *p*-values is problematic (rather than simply irrelevant) because small *p*-values lend a false sense of importance to observed differences.

3) *Biodiversity models*: Combining different modelling algorithms has been proposed as an approach to adjust inherent uncertainty of individual models, and to determine an optimal solution from an ensemble of predictions [2,96]. Divergent forecasts have been often observed in studies comparing alternative modelling techniques to assess potential shifts induced by global change in the distributions of biodiversity. Some of these studies found that predicted distribution changes could range from a 92% loss to a 322% gain for one species depending on the applied modelling algorithm [108]. These studies challenge the common practice of relying on one single method to make forecasts of the responses of species to global environmental change scenarios. Thus, recent studies have advocated the use of multiple models within an ensemble

forecasting framework [92,100]. In our case, instead of selecting the 'best' model from an ensemble, we generated a 'consensus' forecast from the resulting projections. In addition, ensemble models, built on a series of competing models each with a different combination of environmental predictors, may provide more informative and ecologically correct predictions [96]. We used the BIOMOD2 modelling tool [92] for fitting ensemble models on target species. Five widely-used modelling algorithms implemented in BIOMOD2 were used: (1) Generalized Linear Models (GLM), (2) Generalized Additive Models (GAM), (3) Classification Tree Algorithms (CTA), (4) Generalized Boosted Regression Models (GBM), and (5) Random Forest (RF).

The area under the curve (AUC) of the receiver-operating characteristic (ROC) was used as a means to evaluate the performance of the models [109]. We used a 10-fold split-sample procedure keeping 30% of the initial data out of the calibration for the subsequent validation of the predictions. We randomly repeated this procedure 10-fold to produce predictions independent of the calibration data [97]. The weighted average approach was applied for computing a consensus of any single model with AUC > 0.7 using AUC values as model weights, which increases significantly the accuracy of species distribution forecasts [101].

Scenario analysis

The scenario analysis was based on regional landscape simulations wherein the combined effect of fire disturbance regime, vegetation dynamics and fire management policies was taken into account under a context of climate warming and land abandonment. The MEDFIRE model was an essential tool for effectively simulating changes in landscape composition derived from vegetation dynamics and fire disturbances, at large temporal and spatial scales. However, the implementation of a new sub-module into the model ('Biomass extraction' sub-module) as well as other changes in state variables, parameters and outcome tables were required, leading to a new version of the model. In particular, the implementation of 'Biomass extraction' sub-module as an integrated process on the MEDFIRE model enabled to define a firefighting strategy based on this forest management practice and, therefore, to be able to translate the conceptual narrative in a numerical estimate of the process. In addition, it was also necessary to develop an integrated modeling framework in which the main drivers of change (namely climate change and fire-induced land cover changes) were combined to effectively simulate the potential change of habitats and their effects on the target species' distribution under our future environmental scenarios.

RESULTS

The results are structured in four chapters:

- Chapter I: Using unplanned fires to help suppressing future large fires in Mediterranean forests
- Chapter II: Synergies between forest biomass extraction for bioenergy and fire suppression in Mediterranean ecosystems: insights from a storyline-and-simulation approach
- Chapter III: Fire management, climate change and their interacting effects on birds in complex Mediterranean landscapes: dynamic distribution modelling of an early-successional species — the near-threatened Dartford Warbler (*Sylvia undata*)
- Chapter IV: Predicting the future effectiveness of protected areas for bird conservation in Mediterranean ecosystems under climate change and novel fire regime scenarios

CHAPTER

I

USING UNPLANNED FIRES TO HELP SUPPRESSING FUTURE LARGE FIRES IN MEDITERRANEAN FORESTS

By

Adrián Regos, Nuria Aquilué, Javier Retana, Miquel De Cáceres & Lluís Brotons (2014)

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Using Unplanned Fires to Help Suppressing Future Large Fires in Mediterranean Forests

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Abstract

Despite the huge resources invested in fire suppression, the impact of wildfires has considerably increased across the Mediterranean region since the second half of the 20th century. Modulating fire suppression efforts in mild weather conditions is an appealing but hotly-debated strategy to use unplanned fires and associated fuel reduction to create opportunities for suppression of large fires in future adverse weather conditions. Using a spatially-explicit fire–succession model developed for Catalonia (Spain), we assessed this opportunistic policy by using two fire suppression strategies that reproduce how firefighters in extreme weather conditions exploit previous fire scars as firefighting opportunities. We designed scenarios by combining different levels of fire suppression efficiency and climatic severity for a 50-year period (2000–2050). An opportunistic fire suppression policy induced large-scale changes in fire regimes and decreased the area burnt under extreme climate conditions, but only accounted for up to 18–22% of the area to be burnt in reference scenarios. The area suppressed in adverse years tended to increase in scenarios with increasing amounts of area burnt during years dominated by mild weather. Climate change had counterintuitive effects on opportunistic fire suppression strategies. Climate warming increased the incidence of large fires under uncontrolled conditions but also indirectly increased opportunities for enhanced fire suppression. Therefore, to shift fire suppression opportunities from adverse to mild years, we would require a disproportionately large amount of area burnt in mild years. We conclude that the strategic planning of fire suppression resources has the potential to become an important cost-effective fuel-reduction strategy at large spatial scale. We do however suggest that this strategy should probably be accompanied by other fuel-reduction treatments applied at broad scales if large-scale changes in fire regimes are to be achieved, especially in the wider context of climate change.

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Introduction

Wildland fires are a major component of disturbance regimes in many regions [1]. While climate and vegetation characteristics have been described as major determinants of fire regimes, in the Mediterranean Basin and similar regions where human influence is widespread, fire regimes emerge as a complex process in which landscape planning, economic activities and fire management can override the influence of natural factors [2,3,4].

Despite the huge amount of resources invested in fire prevention and suppression, the impact of wildfires has considerably increased since the second half of 20th century across different Mediterranean regions [1,3,5]. Fire suppression efforts have been stepped up in recent years, but while they appear to successfully deal with wildfires in mild weather conditions, there are doubts over the efficiency of these policies in climatically-adverse conditions [6,7,8]. Recent wildfires tend to be larger and more severe as a consequence of an increase in fuel accumulation and continuity (induced mainly by the abandonment of agriculture and livestock, and active afforestation policies) [3,9,10] coupled with drier and warmer climatic conditions [5]. In addition, the expansion of populations and the wildland–urban interface has also contributed to more fire ignition events [11].

In mesic regions of the Mediterranean basin (typically the Eastern Iberian Peninsula), fuel is now less limiting, and fire regimes appear to be mainly driven by the occurrence of climatically adverse conditions [12]. Different strategies can be envisaged to reduce the growing impact of wildfires in the Mediterranean region. Fire suppression policies have traditionally focussed on the preventive early detection of ignitions, but measures have recently shifted towards strategic planning and anticipation of fire spread to make optimal use of firefighting resources [13]. Other issues have been recognized as key, such as the management of fuel to reduce fire intensity and the extent and impact of large fires, but they pose difficulties in terms of effective implementation at large spatial scales [14,15,16,17]. Fuel reduction may increase the chances of suppressing large fires in adverse climate conditions [8,18]. Forest management (including grazing) has been proposed as a measure for reducing the accumulation of forest fuel. However, land abandonment is widespread in most regions affected by fire, and all available evidence suggests that forests are expanding in most of the Mediterranean [19,20]. Prescribed fires are increasingly used to reduce fuel, but many countries face strong public opposition to this preventive action, making prescribed fires more difficult to apply at large scales for efficient fuel reduction than in other regions with Mediterranean-type climate, such as Australia [16,21,22].

Given that wildfires are currently seen as one of the main drivers of forest landscape changes in many Mediterranean regions, wildfires occurring in mild weather conditions could become a tool to regulate the impact of undesired, destructive, large fires taking place in climatically adverse conditions [6,23]. Modulating fire suppression efforts in less adverse climatic conditions could allow a strategy to use unplanned fire events and the associated fuel reduction to create opportunities for efficient suppression of large fires in future adverse conditions [6,24]. While such a strategy has the potential to control and reduce fuel using the current pattern of ignitions, any attempt to change the basic firefighting principle of tackling "all fires" as soon as possible would obviously meet with controversy, especially since very little information is available on the potential effectiveness of such a fire management strategy. Here, we address these questions using landscape simulations under different scenarios combining fire suppression strategies and climatic severity. Specifically, we investigate the potential of this opportunistic strategy for reducing the impact of large fires in climatically adverse conditions. We also assess what amount of area would need to be burnt in mild weather conditions to obtain reductions in the area burnt by large fires under a future climatic warming scenario. Finally, we discuss the spatial scale at which this strategy may be implemented, and its possible future socio-economic implications.

Material and Methods

Study area

The study area was Catalonia, a region located in northeastern of Spain with a land area of 32,115 km^2 and an altitude that ranges from sea level to 3102 m. Catalonia has a typical Mediterranean climate with low winter precipitation and hot and dry summers. Moreover, its complex topography induces major variability in climatic and fire weather conditions across the territory. The vegetation is mostly comprised of forest and shrubland. Evergreen species occur in 60% of the total forest area, 73% of which is occupied by conifers (mainly *Pinus sylvestris*, *Pinus halepensis* and *Pinus nigra*), with sclerophyllous and deciduous species (*Quercus ilex*, *Quercus faginea* and *Quercus suber*) covering the remaining 40% [25]. According to the CORINE land cover map [26], shrubland of diverse species (and mainly evergreen) composition covers 37% of the total wildland area (Fig 1). Forest and shrubland were the most affected by fire during the 1975–1998 period [27].

During the same period, wildfires burnt about 13% of the wildland area (around 250,000 ha), and both the frequency of fire events and area burnt have increased since the pre-1970 period [12,27]. This shift in fire regime was mainly driven by the increase in fuel amount and continuity following rural land abandonment across Catalonia during the pre-1970 period [10,28]. As a consequence, resources allocated to fire suppression increased in the early 80s (*Focverd I* fire suppression program) and 90s (*Focverd II*) [29]. After 1999, fire-fighting capacities were improved through the creation of specific technical fire brigades (GRAF) whose mission is to understand fire behaviour and anticipate changes in fire propagation [29]. At the beginning of the 21st century, prescribed burning programs were also implemented among other efforts to reduce fire risk, but not at sufficiently broad scales to achieve effective reductions [13]. Despite all these increased fire suppression and prevention efforts, wildfires continue to burn thousands of hectares in Catalonia every year. In addition, the aridity trends observed over recent decades point to an increase in the number of dry days per summer [5].

MEDFIRE simulation model

The MEDFIRE model [4,30] is a spatially-explicit landscape model that is able to mimic changes in landscape composition derived from vegetation dynamics and fire disturbances.

We present here a **short overview** of the model. The complete description, calibration, and validation processes for the study area can be obtained from previous published work [4]. The model was implemented using the version 3.5 of SELES modelling platform [31] (http://www.seles.info/). The current version of MEDFIRE (version 2) has two main sub-models [4]: (i) after-fire succession and maturation of vegetation (vegetation dynamics sub-model), and (ii) wildfire disturbance (fire sub-model) (more details in https://sites.google.com/site/medfireproject/). The main purpose of the model is to examine the spatial interaction between wildfires, vegetation dynamics and fire suppression strategies. It was designed to assess how different drivers affect fire regime at short- and medium-term timescales through a quantitative evaluation of their effects on the distribution of the annual area burnt, fire size distribution, and landscape composition. Validation exercises carried out for different time windows with different climate and fire suppression data showed that the model was able to reproduce the basic descriptors of fire regime in our study area [4].

The **state variables** that MEDFIRE uses to describe landscape context and conditions are spatially explicit variables in raster format at 100 m resolution. Land cover type (LCT) and time since last fire (TSF) are dynamic variables, while the static variables are: ignition probability, bioclimatic region, fire spread type (relief- or wind-driven), elevation, aspect and main wind direction.

The **fire sub-model** uses a top-down approach: for each time-step (a year), fires are simulated until the potential annual area to be burnt is reached. Potential annual area refers to the area that is expected to burn according to the historical fire data (1975–99 period). According to previous research [5], climatically adverse years are characterized by a high number of weather risk days (hereafter referred to as "adverse years"), as opposed to years dominated by mild weather conditions (hereafter called "mild years"). Thus, potential burnt area and fire size distributions depend on the climatic severity of the summer. For each simulated fire, the model chooses an ignition location used to establish the fire spread type [32]. The spread rate is a function of TSF (as a proxy of fuel accumulation), LCT flammability (of burnable land covers), aspect and wind direction (in wind-driven fires) or topography (in relief-driven fires). Fire spread rate was parameterized in a calibration exercise comparing model outputs with historical fire data [4]. In the absence of fire suppression, all the pixels that could be reached within the timespan of the fire are recorded as burnt (i.e. post-fire transitions may occur, and the TSF is set to 0). Otherwise, if fire suppression occurs, the pixels recorded as burnt include only a subset of pixels that were not affected by fire suppression, and therefore the final fire size will be smaller than was potential. We assume that long-term droughts or long periods with high temperatures or strong winds can be predicted and, therefore, high-risk fire conditions can be anticipated before an ignition takes places thus permitting firefighters to distinguish fire conditions. Thus, although the model assumes that climate is the main driver of fire regime, key elements of fire regime such as fire size can be modulated by fire suppression.

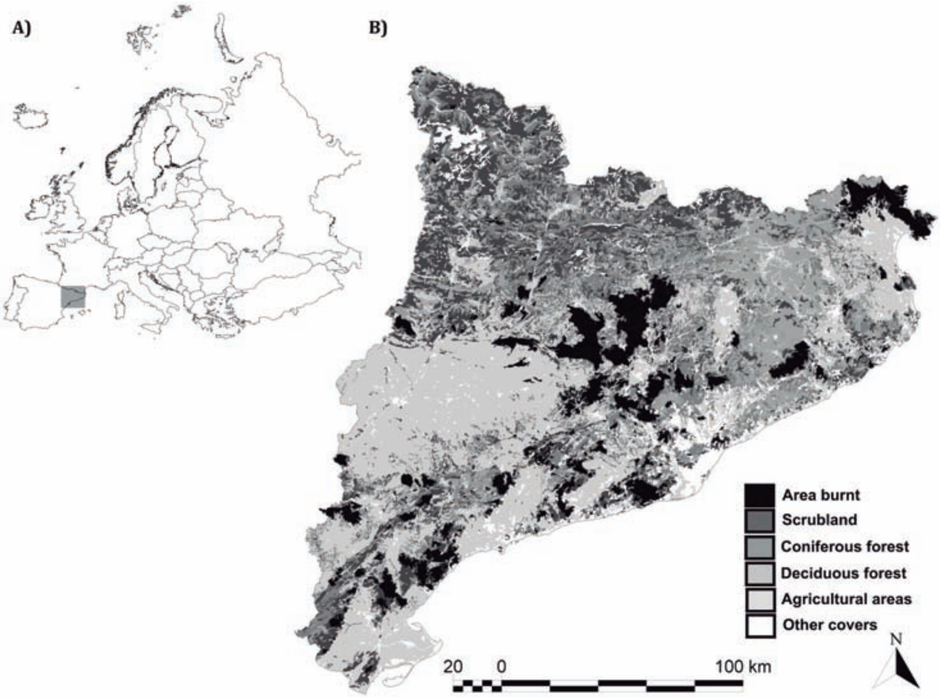

Figure 1. Location of the study area. Geographic location of the study area in south-western Europe (A). Land covers affected by fires between 1980 and 2000 in Catalonia (B).
doi:10.1371/journal.pone.0094906.g001

The **vegetation dynamics sub-model** assumes that forest cover types are relatively stable, so a type-conversion can only occur after burning. Succession without burning can occur only from shrubland to forest. This land cover change takes place depending on the availability of mature forest in neighbouring cells and the TSF of shrubland that will potentially change. Once a cell is burnt, this sub-model updates the land cover according to two post-fire regeneration approaches:

- Applying non-spatial stochastic transitions, using a multinomial distribution with transition probabilities previously published by others [33] that depend on pre-fire cover class as well as on other factors such as aspect, bioclimatic region and TSF.
- By neighbourhood species contagion, considering the neighbours that were also burnt in the current year and shared the same pre-fire cover class. It is important to note that the model cannot handle the complexity derived from possible within-stand heterogeneity since each cell can only be described by a single dominant tree species.

Fire suppression strategies in MEDFIRE

Two fire suppression strategies are implemented in the MEDFIRE model:

- **The opportunistic strategy** mimics firefighting actions based on the ability to take advantage of opportunities derived from old fire scars. These fires provide firefighting opportunities since they are easy to detect by fire brigades and they strongly decrease fuel load and therefore fire intensity. The implementation of the opportunistic strategy in MEDFIRE suppresses burning in a cell whenever its TSF is below a pre-specified threshold (expressed in years) (Fig. 2).
- **The active fire suppression strategy** mimics the overall efficiency of firefighters to anticipate fire behaviour and reduce realized area burnt under determinate fire propagation conditions. This strategy was implemented through two different processes. First, we induced increases in the potential annual area to let burn so as to reproduce the effects of not suppressing small fires and therefore increase the total number of fires in a given scenario. By default, the MEDFIRE model simulates fires until the potential annual area to be burnt is reached, and so increases in potential area burnt result in a larger number of fires per year. Second, we introduced the concept of opportunities tied to fire-specific thresholds in spread rate. In areas in which spread rate is below a pre-specific threshold, firefighters are able to stop the fire spreading, which leads to decreases in the final area burnt [4].

Scenario definition

We assessed the effectiveness of an opportunistic fire suppression policy based on whether or not to allow unplanned fires to burn in mild weather conditions through scenarios characterized by a progressively decreasing active fire suppression policy (Fig. 3). Specifically, we designed eighteen future scenarios by combining

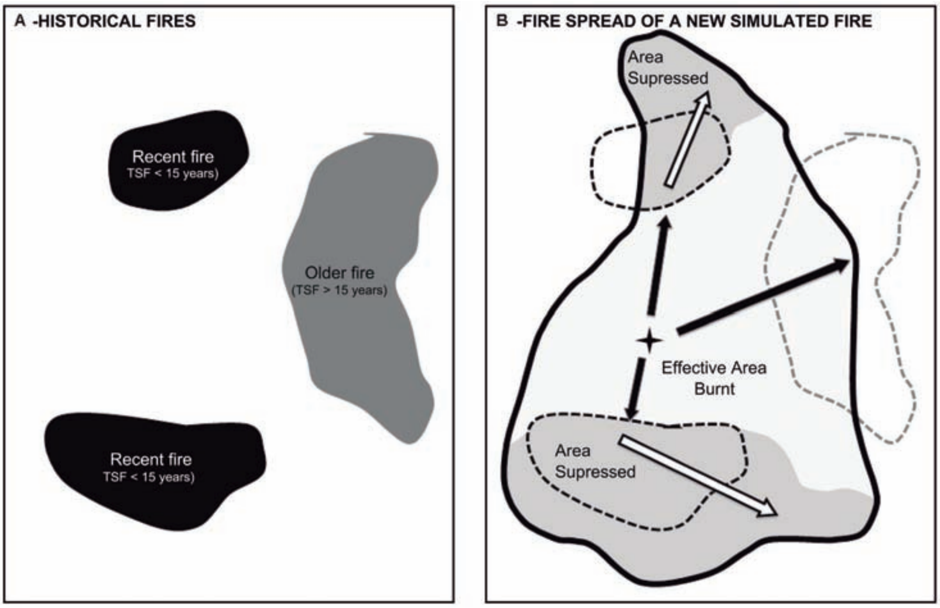

Figure 2. The figure, modified from previous work [4]**, illustrates the effects of opportunistic fire suppression on realized area burnt.** (A) Historical fires in a region, where black patches are recent fire scars with time since last fire less than 15 years and grey patches correspond to older fire scars. (B) Fire spread of a new simulated fire in the area. Potential area (thick black line) is larger than the final area burnt due to opportunistic fire suppression generated by recent fires in (A). Suppressed areas are shown in grey and main spread axes are arrowed. Spread occurring within final area burnt (black arrows) and potentially within the suppressed area (white arrows) is shown.
doi:10.1371/journal.pone.0094906.g002

different fire suppression strategies and levels of climatic severity (Tables 1 and 2). We considered **nine different treatments of active fire suppression** (acting only in years with mild climatic conditions) corresponding to situations of variability in general fire suppression efforts. The nine treatments were defined by combining three levels of potential area to be burnt with three levels of active suppression using spread rate thresholds: (a) the first three levels were simulated through variability in potential area to burn. Baseline annual distributions of area burnt were derived from 1975-99 wildfire statistics (using a lognormal distribution fitted for the available data). To reproduce the effects of not suppressing small fires (leading to increases in the total area burnt), we modified the mean of the lognormal distribution of area burnt in mild years according to the decreasing efforts of firefighters to suppress small fires: (1) *High* 7.74 (~6,500 ha/year); (2) *Average* 9.14 (~26,000 ha/year); and (3) *Low* 9.81 (~52,000 ha/year) (Tables 1 and 2). (b) The second three levels were defined using specific spread rate thresholds to reduce the final area burnt: (1) strong active suppression of opportunities corresponding to spread rate of heading fires, or descending fronts in pine forests (fire spread threshold 90); (2) medium active suppression of opportunities corresponding to spread rate in agricultural cover and sclerophyllous forest (fire spread threshold 40); (3) no active suppression of opportunities (fire spread threshold 0) (Tables 1 and 2). **Opportunistic fire suppression** was only allowed in climatically adverse years and was characterized by the number of years since the last fire in which the fire scars can be used as fire suppression opportunities by firefighters. In all simulation scenarios, the opportunistic fire suppression strategy was limited to fire scars generated in the last 15 years. The ongoing climatic trends show an increase in the number of years with very high fire-risk days [5]. Finally, we used **two climatic treatments** describing whether the percentage of adverse years (*i.e.* with dry and hot summers) will remain stable in the future (35% is the percentage of adverse years in the period 1980–1999) or is set to increase (up to 70%), following recent research [4] (Tables 1 and 2). Five hundred replicates of each scenario were simulated for a 50-year period (2000–2050).

Evaluation of simulation results

To evaluate the effect of opportunistic fire suppression strategies under the different scenarios, we calculated area suppressed as the difference between potential area to be burnt in a year and the final area burnt. We also tracked the area suppressed in adverse years according to the origin of the fire scar that created the firefighting opportunity: (1) scars of fires simulated in climatically adverse years, (2) scars of fires simulated in climatically mild years, and (3) scars of historical fires (those affecting the region before the simulation started, i.e. the 1975–99 period). The means and standard deviations of all these variables were used to describe the fire regime obtained under each simulated scenario. All statistical analyses were performed using R software, version 3.0.2 [34].

Results

Effects of decreasing fire suppression in mild weather on later undesired large fires

Scenarios with no and medium active fire suppression in mild years (see scenarios charted with white and light-grey box-plots in Fig. 4, A2) showed an increase in fire suppression opportunities in

Figure 3. Decision-making process for an opportunistic fire suppression policy based on whether or not unplanned fires should be let to burn in mild weather conditions.
doi:10.1371/journal.pone.0094906.g003

adverse years compared to scenarios characterized by strong fire suppression (see dark grey box-plots in Fig. 4, A2). Specifically, the area suppressed in adverse years by opportunistic strategies increased from 18% to 29% in scenarios with strong active fire suppression (dark-grey box-plots in Fig. 4, A2), and from 22% to 50% with no active firefighting in mild years (white box-plots in Fig. 4, A2). Moreover, the opportunities derived from historic fire scars were the same in all scenarios (Fig. 5C), showing that the increased efficiency of the opportunistic strategy came from simulated fires.

Looking at the amount of area that would need to be burnt per year to reduce the impact of large fires in extreme fire weather, results show that the reference scenarios built on historical wildfire statistics (scenarios labelled *high* from 1 to 3, burning approxi-

Table 1. Description of the variables and levels used in the scenarios characterization.

Variables	Levels	Description
Active fire suppression	90	Strong active suppression corresponding to spread rate of heading fires or descending fronts in pine forests
	40	Medium active suppression corresponding to spread rate in agricultural cover and sclerophyllous forest
	0	No active suppression
Potential area to burn	6,500 (high)	Hectares/year to burn in climatically mild years according to historical fire statistics (1975–1999). Period characterized by strong efforts of firefighters to suppress small fires (*Focverd I* and *II* fire suppression programs)
	26,000 (average)	Hectares/year to burn in mild years considering an average efforts of firefighters to suppress of small fires
	52,000 (low)	Hectares/year to burn in mild years considering relatively little effort of firefighters to suppress small fires
Opportunistic fire suppression	15	Number of years since the last fire after which fire scars can be used as fire suppression opportunities by fire brigades
Climatic severity	35	Percentage of adverse years for the simulation period (2000–2050) according to the trends recorded in the period 1980–1999
	70	Percentage of adverse years for the simulation period (2000–2050) factoring in climatic warming

doi:10.1371/journal.pone.0094906.t001

Table 2. List of simulation scenarios describing parameters used to reproduce active firefighting strategies and climate severity.

ID	Factors		
	Active Fire Suppression		Climatic Severity
	Potential annual area to burn (ha/year)	Spread rate threshold	Adverse years (%)
	Mild years	*Mild years*	
1	6,500	90	35
2	6,500	40	35
3	6,500	0	35
4	6,500	90	70
5	6,500	40	70
6	6,500	0	70
7	26,000	90	35
8	26,000	40	35
9	26,000	0	35
10	26,000	90	70
11	26,000	40	70
12	26,000	0	70
13	52,000	90	35
14	52,000	40	35
15	52,000	0	35
16	52,000	90	70
17	52,000	40	70
18	52,000	0	70

Potential annual area to burn follows a lognormal distribution (with mean 7.74 and standard deviation 1.43 in mild years fitted from 1975–99 wildfire statistics). The mean of that distribution is used as a scenario parameter with three possible values: (1) **High**-7.74 (~6,500 ha/year), (2) **Average**-9.14 (~26,000 ha/year), and (3) **Low**-9.81 (~52,000 ha/year).
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mately 6,500 ha/year in mild years) allowed opportunistic suppression of 18–22% of the target annual area in adverse years (Fig. 4, A2). If mean area burnt in mild years was increased to 26,000 ha/year by decreasing efforts to suppress small fires (scenarios labelled *average* from 7 to 9), the area suppressed in adverse years would increase to 26–37% (Fig. 4, A2). Finally, when mean area burnt in mild years was increased to 52,000 ha/year due to a fire suppression policy aimed at engineering a shift in fire regime towards a higher number of small fires (scenarios labelled *low* from 13 to 15), the percentage of area suppressed in adverse years also increased to figures of up to 29–50% (Fig. 4, A2). However, while the opportunities derived from fires simulated in mild years (see scenarios 1–3 compared to scenarios 7–9 and 13–15 in Fig. 5, B) increased as the final annual area burnt in these years grew, the opportunities generated in earlier adverse years decreased (see scenarios 1–3 compared to scenarios 7–9 and 13–15 in Fig. 5, A). This increase in fire suppression opportunities was therefore partially modulated by the decrease in opportunities from adverse years.

Interaction between fire suppression and climatic severity

To evaluate the interaction between fire regime, fire suppression and climate warming, we compared scenarios with the same set of parameters while varying the percentage of adverse years from 35% up to 70% (see Table 1). When the number of years with adverse conditions increased, counterintuitive effects appeared on the potential opportunistic fire suppression strategies. Thus, the area suppressed was higher in the simulated scenarios under climate warming (scenarios 4–6 in Fig. 4, A2) than under the current climatic regime (scenarios 1–3 in Fig. 4, A2). Climate warming induced a greater area suppressed by opportunities derived from fires simulated in adverse years (compare scenarios under climate warming, boxed in a thick line, and scenarios without climate warming, boxed in a thin line, in Fig. 5, A). However, when we considered a more severe fire regime in mild years (~52,000 ha/year, scenarios with label *low*), the area suppressed was lower in scenarios with climate warming (scenarios 10–12 and 16–18 in Fig. 4, A2) than scenarios without climate warming (scenarios 7–9 and 13–15 in Fig. 4, A2). This increase in area burnt in mild years again led to a greater area suppressed by opportunities derived from fires simulated under mild weather conditions (compare scenarios labelled *high* and *low* in Fig. 5, B). However, it is also remarkable that climate change also led to fewer years with mild fire weather conditions, thus reducing the window of opportunity for the creation of opportunities under these conditions (compare scenarios with climate change, boxed in a thick line, against scenarios without climate warming, boxed in a thin line, in Fig. 5, B).

Discussion

We have shown that relaxing fire suppression efforts under relatively controlled conditions (opportunistic fire suppression policy) has the potential to substantially reshape fire regimes and decrease the amount of area burnt under undesired, extreme climate conditions. However, the potential of this strategy is

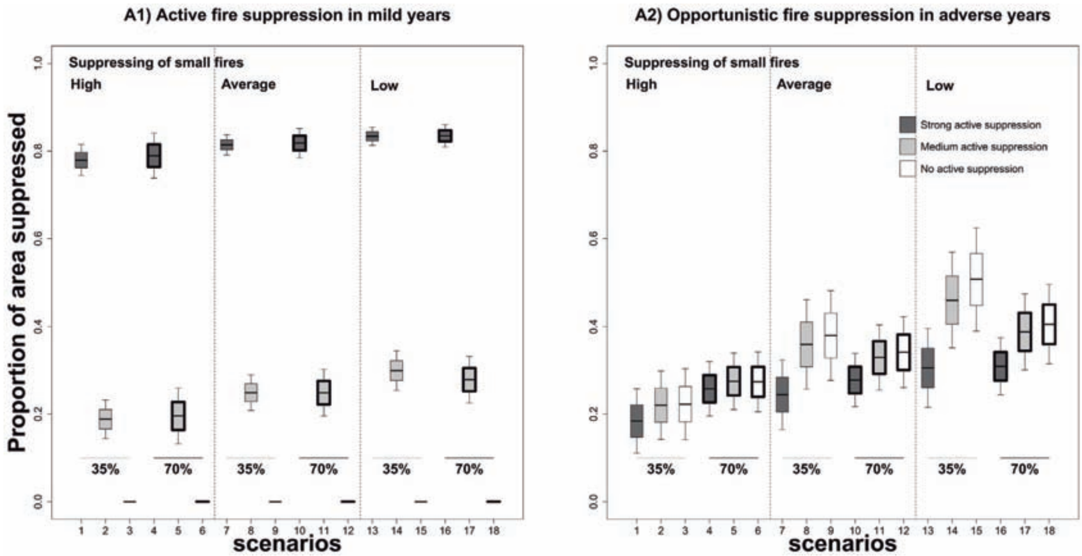

Figure 4. Proportion of area suppressed in relation to potential area to burn. Area suppressed by active fire suppression strategies in mild years (A1) and opportunistic fire suppression strategy in adverse years (A2). Potential annual area in mild years follows a lognormal distribution with means of 7.74 (**High** ~6,500 ha/year), 9.14 (**Average** ~26,000 ha/year), and 9.81 (**Low** ~52,000 ha/year), to reproduce a decreasing effectiveness of firefighter efforts to suppress small fires. Simulation scenarios characterized by thresholds of 90% in active fire suppression of mild years are represented in dark-grey box-plots, in light grey by thresholds of 40%, and in white of 0%. Box-plot elements are as follows _ lower and upper whiskers: approximately 68% of all data values (**mean ± SD**, standard deviation); lower and upper midhinges: the **mean ±** ½ **SD**; central black line: the **mean**. Box outline width represents the percentage of adverse years used in the simulations, i.e. 35% (thin width) and 70% (thick width).
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somewhat limited due to the complexity of the interactions between fuel availability, fire impact, and fire suppression strategies.

Potential of opportunistic strategy for reducing the impact of large fires

Given the growing impact of wildfires, the effect of fire exclusion has been extensively studied and debated in many different

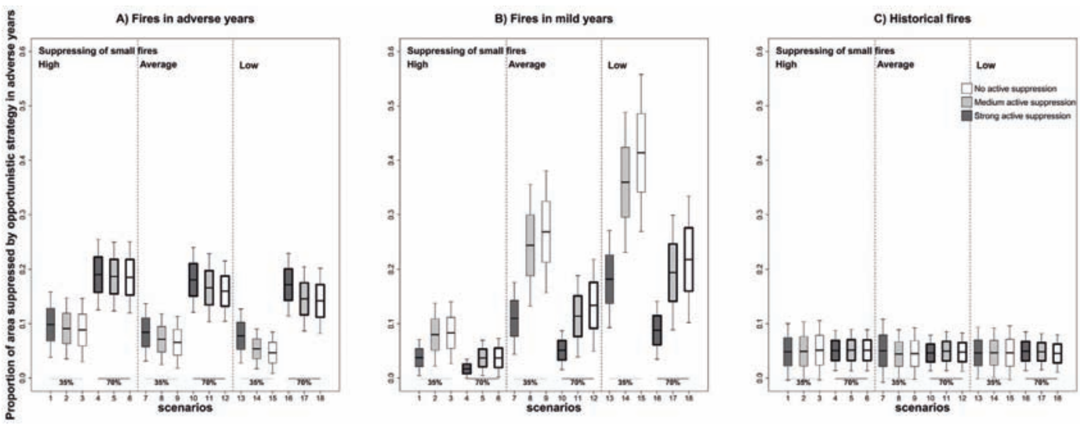

Figure 5. Proportion of area suppressed (in relation to potential annual area) by opportunistic fire suppression strategy in adverse years. Area suppressed by firefighting opportunities derived from: (A) fires in adverse years, (B) fires in mild years, (C) historical fires. Simulation scenarios characterised by thresholds of 90% in active fire suppression of mild years are represented in dark-grey box-plots, in light-grey by thresholds of 40%, and in white of 0%. The labels *high*, *average* and *low* refer to the distribution of potential annual area in mild years (see Fig 4 for more details). Box-plot elements and box-plot outline width are as in Fig. 4.
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Mediterranean ecosystems for decades now [2,35,36]. Many authors claim that the systematic extinction of ''all fires'' leaves an accumulation of fuel that will be consumed in future large fires in years with extreme fire weather conditions (fire paradox) [35,37,38]. Recent studies carried out in the Mediterranean basin using fire-succession models have demonstrated that high fire suppression efforts may lead to a slightly higher proportion of large and more intense fires [2,39]. Our results concur with this hypothesis, since scenarios with strong active fire suppression in mild weather did lead to increases in the area burnt by large fires in adverse conditions due to feedbacks in the dynamics of fuel accumulation (Fig. 4). In addition, we demonstrated that relaxing the fire suppression efforts in mild years, in which benign fire weather conditions allow firefighters to tackle any fire event efficiently, provided additional fire scars associated to fuel reduction. These new burnt-area patches generated potential firefighting opportunities for later adverse years (Fig. 5, B). In our particular case, the area suppressed in adverse years by opportunities derived from fires simulated in mild years increased considerably, as the final annual area burnt in these years was higher (Fig. 5, B). In the reference scenarios derived from statistics on wildfires between 1975 and 1999 (which burnt 6,500 ha/year in mild years), the area suppressed by opportunities derived from previous fire scars only accounted for 22% of the potential annual area in adverse years (Fig. 4). This suggests that the current high-efficiency fire suppression policy may be decreasing the opportunities that arise from past fires. Our results showed that a progressive increase of area burnt in mild years by relaxing fire suppression efforts led to a reduction in area burnt in adverse years: a decrease of an additional 15% (up to 37%) would require a four-fold increase in the final annual area burnt in mild years (i.e. to 26,000 ha/year), whereas a decrease of an additional 23% (up to 50%) would require an eight-fold increase (i.e. to 52,000 ha/year). Therefore, to effectively reduce large fires under adverse weather conditions, we need to allow burning across larger areas in mild years. Bear in mind that reductions in the total area burnt in adverse weather conditions do not come for free _ here, the reductions involved a loss of future opportunities for firefighting (Fig. 5, A) [4]. Therefore, the amount of area treated in mild conditions has to be very high to reduce the amount of area burnt in adverse climate conditions and compensate for the loss of opportunities derived from fires avoided in such adverse conditions.

Fire management based on climate-adapted modulation of fire suppression shares some overlap with the management policy of prescribed burnings implemented in other Mediterranean ecosystems [15,21,22]. Both prescribed burning and the use of unplanned fires resulting from decreasing suppression efforts are tactics that use fire as a tool to fight larger wildfires and that aim to increase the effectiveness of fire suppression through fuel reduction [8,18]. Recent studies [2,39] used a simulation model to investigate whether large fires in the Mediterranean region are consequence of large fire suppression programs or, conversely, are driven by extreme fire weather conditions. Their results suggest that, although the total area burnt is much the same regardless of whether or not fire suppression or prescribed fire policies are used, prescribed burning does reduce fire intensity. Here, we show that like prescribed burning, unplanned fire events could be used to reduce fuel accumulation and fire intensity to create opportunities for effective fire suppression of large fires in future adverse conditions. We therefore suggest that designing treatments to minimize adverse fire effects may be a more effective strategy than designing treatments that attempt to extinguish ''all fires''.

Moreover, in our study and in the current fire regime context, unplanned fires increase landscape heterogeneity but do not seem enough to offset the decade-long general trend towards homogenization due to land abandonment and the coalescence of natural vegetation patches [28,40]. This landscape homogenization process is driving an increase in fuel continuity [41] and consequently fire spread and intensity [10,12,42]. To offset this ongoing trend and create new fire suppression opportunities, we envisaged a fuel-reduction strategy based on relaxing fire suppression efforts in mild years to create a novel fire regime with a large number of smaller fires. Our results have demonstrated that this strategy is associated with effective reductions in the area burnt by fires in adverse years. Thus, decreasing fire suppression in mild weather conditions may create landscapes in which wildfires occur with less devastating consequences. Fire may itself play a key role in maintaining these novel landscapes.

Opportunistic fire suppression under climatic warming scenarios

The interaction between area burnt, fire suppression and climate warming had counterintuitive effects on the potential for opportunistic fire suppression strategies to reduce the amount of area burnt in climatically adverse years. The area burnt in adverse years in scenarios with climate warming is consistent with climate change bringing warmer and drier summers and increased fire weather risk [43,44]. Overall, our results are in agreement with the trends reported for recent decades in the Mediterranean basin [5,45]. However, the area burnt in the simulated scenarios under climate warming was lower than expected due to increases in the area suppressed by opportunities derived from simulated fires in adverse years (Fig. 5, A). At the same time, climate warming also implies a lower number of mild years and therefore fewer windows for creating the opportunities targeted. In this context, exponentially larger areas need to be burnt in mild years to create additional fire suppression opportunities (Fig. 5, B). On the other hand, recent studies carried out in regions with Mediterranean climatic conditions highlight the role of landscape structure in shaping current and future fire–climate relationships at regional scale, and suggest that the future changes in fire regime under global warming may be different from what it is predicted by climate alone [46]. We argue that opportunistic fire suppression policies have the potential to substantially effect changes in this fire–climate relationship through the novel landscapes created by relaxing active fire suppression efforts in mild weather conditions. We also suggest that, given the large annual area burnt required to prevent large fires in adverse fire weather years, the spatial allocation of firefighting efforts and fire suppression resources will be a keystone for the optimization of this fuel-reduction strategy and its successful implementation in future firefighting programs forced to deal with climate change.

Implications for the future: some considerations

The effectiveness of this opportunistic fire suppression strategy is still relatively low compared to other fuel reduction strategies applied in different Mediterranean-type ecosystems [15,18,47]. In Australia, where prescribed burning is used as a cost-effective fuel-reduction treatment, previous works [22] found that three units of prescribed fires were required to reduce one unit of unplanned fire area. This negative relationship was stronger in the tropical savannas of northern Australia, where prescribed early-dry-season burning was able to substantially reduce late-dry-season fire area by direct one-to-one replacement [16]. In Australian eucalypt forest, other authors [21] found that each unit area reduction in unplanned fire required about four units of prescribed fire. We argue that strategic placement of these fuel treatments (*i.e.* prescribed burning or thinning followed by prescribed burning) is the likely key to effective implementation. In fact, recent research [48] found that strategic placement of fuel treatments reduced the predicted growth rates of simulated fires under adverse weather conditions more effectively than random placement in three study areas of western USA. Random placement of fuel treatments required about twice the treatment rate of optimally-placed fuel treatments to yield the same reduction in predicted fire growth rates [48]. However, opportunistic fire suppression is based on unplanned fire occurrence. Unplanned fires tend to be determined by the spatial arrangement of ignition factors. In Mediterranean countries where natural ignitions are scarce, fire regime is strongly linked to human activities, with the result that fire scars are not randomly distributed in the space but follow the auto-correlated pattern of human activities [1,49,50]. Therefore, we suggest that the identification of spatio-temporal patterns of fire occurrence at regional scales in these systems may optimize the opportunities created by unplanned fires, and thus mitigate the heavy impact of the undesired large fires in extreme fire weather.

From a purely economic standpoint, opportunistic 'let-burn' fire suppression strategies have a further benefit tied to the fact that they curb the economic losses caused by large fires while also saving on fire suppression resources. In fact, a recent study suggests that the potential savings associated to opportunistic strategies could be substantial [23]. The authors simulated unplanned fires at landscape scale over a 100-year period using existing models of fire behaviour, vegetation and fuel development and fire suppression effectiveness to estimate suppression costs using a suppression cost model. They found that estimated future suppression cost savings were positively correlated with fire size. Others authors [51] studied different spatial factors influencing large wildland fire suppression expenditures, and they also found that fire size and private land had a strong effect on expenditures. Note that just a tiny fraction of fires (around 1%) accounts for 85% of suppression expenditure in the western USA [6]. Given that the land in our study area is mainly privately-owned, we suggest that an opportunistic strategy aimed at mitigating large wildfires by relaxing efforts to suppress small fires could enable huge suppression savings. However, this strategy also implies large areas burnt in mild weather conditions. The decision on whether a particular fire should be let to burn must be made by weighing up the potential benefits in terms of the landowners' management objectives and the potential cost of damage from unsuppressed fire [52]. It is the net benefit of allowing a fire to burn that is the relevant criterion [23,53]. Therefore, factoring in the potential socio-economic and ecological costs (such as soil loss, destruction of wildlife habitat, loss of timber value, infrastructure and human life) and benefits discussed here is essential for identifying candidate areas suitable for using unplanned fires as a management tool.

To conclude, we suggest that to achieve the stand structure and fuel reduction goals required to minimize large fires in extreme fire weather, this strategy could be accompanied by other fuel-reduction treatments such as large-scale forest thinning or biomass extraction. Further studies are needed to assess the impact of novel fuel-reduction treatments on fire regime. Moreover, the possible impacts of these fire management options on biodiversity and a variety of ecosystem services should be carefully evaluated before cost–benefit analyses can be developed. These potential fuel-reduction treatments should therefore also be evaluated in terms of social, economic and environmental cost–benefit trade-offs.

Author Contributions

Conceived and designed the experiments: LB AR. Performed the experiments: AR NA LB. Analyzed the data: AR NA JR MC LB. Contributed reagents/materials/analysis tools: AR NA MC JR LB. Wrote the paper: AR NA JR MC LB.

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CHAPTER

II

SYNERGIES BETWEEN FOREST BIOMASS EXTRACTION FOR BIOENERGY AND FIRE SUPPRESSION IN MEDITERRANEAN ECOSYSTEMS: INSIGHTS FROM A STORYLINE-AND-SIMULATION APPROACH

By

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Running title: BIOMASS EXTRACTION IN FIRE-PRONE ECOSYSTEMS

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Keywords: Fire suppression, forest fires, forest harvesting, MEDFIRE fire-succession model, Mediterranean basin, process-based model, renewable energy, scenarios-based analysis, landscape simulations.

ABSTRACT

Increases in fire impacts over many regions of the world have led to large-scale investments in fire suppression efforts. There is increasing recognition that biomass extraction for energy purposes may become an important forest management practice in fire-prone ecosystems. However, at present very few studies have explicitly assessed biomass extraction as a fuel treatment at landscape scale. Here, we use a landscape fire-succession model in Catalonia (NE Spain) to quantitatively evaluate the potential effects of a biomass extraction-based strategy on essential fire regime attributes after considering different levels of fire suppression, biomass extraction intensity and spatial allocation of such efforts. Our findings suggested that the effectiveness (area suppressed in relation to expected area to burn) at suppressing wildfires was determined by extraction intensity, spatial allocation of the extraction effort, and the fire suppression levels involved. Thus, the highest suppressed-area values were found with lower harvesting intensities, especially under high fire suppression capabilities and strategies focused on bioenergy goals (figures close to 70%). However, the efficiency (area suppressed in relation to managed area) was higher when the treatments were based on the fire prevention strategy and focused on high-fire-risk areas (up to 25%) than with treatment designed for energy reasons (lower than 3%). Our results suggest that large-scale biomass extraction may be needed if significant changes in fire regimes are to be expected. We conclude that biomass extraction for energy purposes has the potential to induce significant changes in fire regimes and can therefore be considered a cost-effective landscape-level fuel-reduction treatment.

INTRODUCTION

Every year in the Mediterranean basin, thousands of hectares of forest and shrubland are burnt by wildfires, causing major ecological and socio-economic impacts and often human casualties (Moreira and others 2011; Keeley and others 2012). Climate warming, land use/land cover changes and human action such as fire suppression policies or afforestation programs have reshaped the frequency and severity of wildfires in the Mediterranean Basin over the last few decades (Piñol and others 1998; Moreira and others 2011; Brotons and others 2013). First, the absence of grazing following a generalized abandonment of traditional livestock practices has spurred the recovery of vegetation over large spatial scales (Alcamo and others 1996; Pausas and others 2008). Furthermore, in some areas old croplands have been reforested by extensive pine plantations bringing general increases in forest area (Rounsevell and others 2006; de Chazal and Rounsevell 2009; Stellmes and others 2013). The land abandonment that occurred in these systems coupled with large-scale reforestation has led to a build-up of continuous and homogenous fuel beds that are prone to burn due to shrub encroachment and forest regeneration. These new vegetation patterns, coupled with large scale changes in the distribution of human activities at the wildland-urban interface has induced radical changes in fire regimes in the western Mediterranean region, bringing increased fire risk, higher burning frequencies, and larger burnt areas (Piñol and others 1998; Badia and others 2011; Gonzalez-Olabarria and others 2012).

Weather and climate are key factors affecting fire ignition, behavior and severity (Benson and others 2008), since both short- and long-term atmospheric conditions have a profound influence on meteorological fire risk (Amraoui and others 2012). In Mediterranean ecosystems, most of the burnt area is caused by a very small number of fires larger than 1,000 hectares (Piñol and others 1998; Díaz-Delgado and others 2004; Moreira and others 2011). These undesired large fires are driven by low fuel moistures and strong winds, and under these extreme fire weather conditions the current firefighting capabilities and capacities are strongly constrained. At landscape-scale, fire regime results from a complex interplay of ignition frequency, climatic seasonality (with longer dry seasons) and fuel structure (Moreira and others 2011; Keeley and others 2012). From a fire management perspective, fuel complex and load are the only variables affecting fire behavior that can be adequately managed. This has prompted several authors to suggest reducing the impact of large fires hinges on considering different fuel reduction-related strategies (Stephens and others 2009; Alvarez and others 2012; McIver and others 2012). Indeed, in Mediterranean regions, once the ignition occurs, fuel load and connectivity are more relevant in driving fire activity than the occurrence of weather conditions (Pausas and Paula 2012). Prescribed fire is an attractive fuel-reduction treatment for forest managers since it is likely to be naturally closer to the process it is designed to replace than other possible fire surrogates (McRae and others 2001; Reiner and others 2009), and more effective at reducing fire spread than mechanical treatments alone (Van Wagtendonk 1996; Agee and Skinner 2005). Nevertheless, when fire managers attempt to implement prescribed burning programs, they are often constrained by socio-economic and territorial issues (Stephens and others 2012) that challenge the controlled burn strategy, especially in areas with private property such as those dominating the western Mediterranean region (Winter and others 2002; Brunson and Shindler 2010; Bradstock and others 2012). As a result, mechanical treatments (such as forest thinning or mastication) are an important part of the treatment regime as they help to reduce fuels and overcome the risks and constraints imposed by prescribed burning (Sturtevant and others 2009; McIver and others 2012).

However, not all fuel reduction surrogates have the same effect on potential fire behavior (Stephens et al., 1998). Typical fuels treatment uses silviculture for industrial uses of wood to improve the stand and, in turn, reduce crown fuels. However, biomass extraction for energy purposes takes all harvested (even all fine fuels) material off site decreasing the original surface fuels and reducing further wildfire hazard and likelihood of crown fire as well as surface fire. Current bioenergy trends and thermal conversion technologies are able to use wood chips from full trees. In this full-tree harvesting system, trees are felled and extracted without being delimbed or topped. This harvesting system is perceived as better for the creation of fire suppression opportunities that can be exploited by firefighters to reduce the impact of undesired large fires (Agee and Skinner 2005; Stephens and others 2009). Several studies have highlighted the potential of fire suppression to modify fire regimes (Minnich and Chou 1997; Piñol and others 2005; Brotons and others 2013; Regos and others 2014).

There is increasing recognition that biomass extraction for energy may become, in addition to an energy source, a critical forest management alternative in fire-prone landscapes if reduction in the size and severity of wildfires is a policy-relevant goal, given that the current fire suppression systems have reached their limits and are systematically overwhelmed when faced with extreme fire weather conditions (Becker and others 2009; Evans and Finkral 2009; Abbas and others 2011; Verón and others 2012). However, to date, no quantitative studies have assessed the effectiveness of biomass extraction for bioenergy as a fuel treatment at landscape scale. Therefore, there is still no clear picture of how biomass extraction interacts with fire suppression strategies at landscape level and whether this strategy can be successfully considered in a decision-making process where the goal is to mitigate large fires.

The aim of this work is to evaluate, using a dynamic landscape fire-succession model, the potential effects of forest biomass extraction as fuel-reduction treatment on a central attribute of fire regime—burnt area. Specifically, we assess how (i) different levels of fire suppression, and (ii) the intensity and (iii) spatial allocation of forest biomass extraction could affect (a) the effectiveness (which, here, refers to area suppressed in relation to expected area to burn) of this fuel-reduction strategy to mitigate large forest fires, and (b) the efficiency (which, here, refers to area suppressed in relation to area to be managed) of each treatment. Finally, we discuss the advantages and disadvantages of biomass extraction strategies in shaping current fire regimes in the Mediterranean region, and introduce key socio-economic and ecological issues that should be addressed in future research to facilitate its potential implementation.

MATERIAL AND METHODS

Study area

The study was conducted on Catalonia, a Mediterranean region located in the northeastern Iberian Peninsula (Fig. 1a). This region is currently extensively covered by forest (39.6%) and shrubland (16.8%) (CREAF 2009; Ibañez and Burriel 2010). Coniferous forests (mainly *Pinus sylvestris*, *Pinus halepensis* and *Pinus nigra*) occupy 58.4% of the total forested area, the broad-leaved species (*Quercus ilex* and *Quercus suber*) represent 28.9% while mixed forests cover 12.6% (CORINE 2006). The average slope of Catalan forests is 46.6% (66% of forests are in areas with less than 30% of average slope), which must also be taken into account as an important physical constraint for forest biomass extraction in some areas. In total, 87% of forest surface in Catalonia belongs to private owners, and 89.2% of the properties are smaller than 10 ha.

Comparison of the Second and Third National Forest Inventories of Spain (IFN-2 and IFN-3, Villaescusa and Díaz, 1998; Villanueva, 2005) reveals that the forest biomass stands in Catalonia are growing 2.7 millions m^3/yr (Fig. 1c). The annual increment averaged for Catalonia is 3.16 m^3/ha/yr. Moreover, IFN-3 shows that the number of trees in Catalan forests is biased in reference to the ideal distribution, since there is an excess of small-diameter trees. According to government data, average forest resource exploitation between 2000 and 2010 was 155,000 m^3 per year of firewood and 550,900 m^3 per year for industrial use, which gives a total (705,900 m^3) that comes to just 20% of forest growth. Therefore, current forest harvesting levels could be increased four-fold and idem for yearly harvested surface.

In Catalonia, wildfires are extensive in pine forests and shrublands, while deciduous forest rarely burn (Fig. 1b). Focusing in the 1975–98 period, conifer forest was the land cover most affected by fire (43% of total burnt area), followed by shrubland (31%), broad-

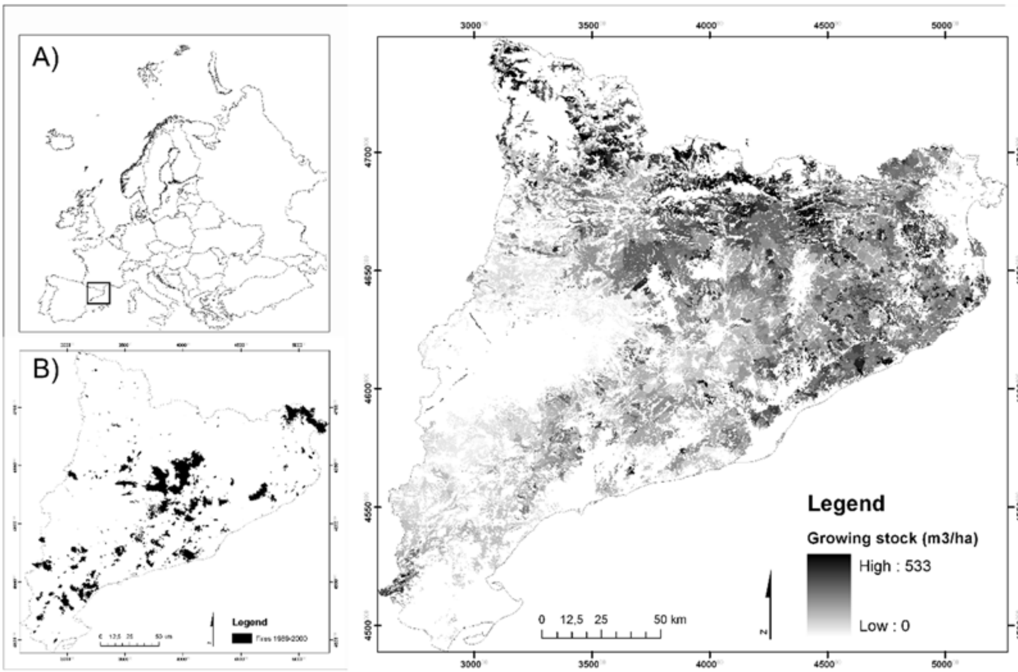

Fig. 1. Location of the study area (A), wildfires occurred in the study area between 1989 and 2000 (B), and growing stock (expressed in m³/ha) (C).

leaved forest (7%) and grassland (3%) (Díaz-Delgado and others 2004). Catalonia is characterized by a complex topography that induces major variability in climatic and fire weather conditions across the territory. Areas below 1000 m asl and with slopes steeper than 20% are most prone to burn. From a climatic viewpoint, fires are more prone to occur in localities with the highest solar radiation levels, medium-rank mean annual precipitation and mean annual temperatures in the range 11-15ºC (Díaz-Delgado and others 2004).

The MEDFIRE model

MEDFIRE is a **dynamic landscape model** designed to mimic the main ecosystem processes in Mediterranean landscapes (Brotons and others 2013; De Cáceres and others 2013; Regos and others 2014). The main purpose of the model is to examine the spatial interactions between wildfires, vegetation dynamics and biomass extraction over short- and medium-term time scales through quantitative evaluation of the effects on landscape composition and fire regime (Brotons and others 2013). The model assumes that the main driver of fire regime is climate, but it can be modulated by fire suppression and forest management strategies (see Appendix S1 for a more detailed description of the model). Calibration and validation exercises carried out for different time windows under different climate and fire suppression scenarios showed that the model was able to reproduce the fire regime for Catalonia (Brotons and others 2013).

The **state variables** that MEDFIRE uses to describe landscape context and conditions are spatially explicit variables in raster format at 100 m resolution. Land cover type and time since the last disturbance, either natural (fire) or human-caused (biomass extraction), are dynamic variables. Other static variables that complete landscape characterization for the considered processes are elevation, aspect, slope, distance to roads, fire risk, main wind direction, solar radiation, and annual precipitation (more details in Brotons *et al.*, 2013).

Biomass extraction in the MEDFIRE model is applied as an annual target area to be managed (ha/year). We assume a constant annual biomass extraction rate (equals to the inter-annual increment, expressed in m^3/ha/year), so the annual target area to manage only depends on a pre-determined harvesting intensity (m^3/ha) and the total area available for biomass extraction (ha) (see more details in Table 1 and Appendix S1). To achieve the annual target area to manage, treated patches are placed over the landscape according to a biomass extraction probability accounting for harvesting constrains (e.g. slope, species and distance to roads) (Perpiñá and others 2009; Abbas and others 2011; Wendland and others 2011; Levers and others 2014). Biomass extraction is not allowed in restricted areas and is limited to zones not recently burnt nor managed (as post-fire management is not included in the scope of this research). The final size of a managed patch is then selected from a predetermined normal distribution bounded by minimum and maximum patch sizes according to the data from the regional government for the 2000–2010 period (GENCAT, 2013). The shape of managed patches directly derives from a process of random growth from an initial extraction point to any of the eight neighbors and further spread according to harvesting constrains until the target area is reached (further details in Appendix S1). Forest harvesting intensity is implemented in the model through a simplified two level categorization: 1) high intensity level (69.5 m^3/ha) and 2) low intensity level (34.7 m^3/ha) (Table 1 and Appendix S2). The high-intensity level corresponds to treatments wherein all available biomass yearly in an area is harvested, while the low intensity level corresponds to an amount of biomass harvested half of the high-intensity treatment. The low-intensity harvesting level requires therefore, the double of harvested area per year to achieve the same stand of biomass and the period of time between harvests is half of the time than when applying a high intensity level.

Fire disturbance is modeled using a mixed top-down, bottom-up approach. For each time-step (one year), fires are simulated until the potential annual area to be burnt is reached. Potential annual area refers to the area that is expected to burn according to historical fire data (1975–99 period). The model also mimics the ability of firefighters to take advantage of opportunities in areas where forest biomass has been reduced (i.e. fires or biomass extraction treatments). The **fire suppression** opportunities derived from these fuel reduction processes are therefore able to constrain final fire sizes, making final values of this fire regime component an emergent

Fig. 2. Typical appearance of an area dominated by *Pinus halepensis* before extracting (A) and after extracting (B) biomass.

property of the model (Brotons and others 2013; Regos and others 2014). Opportunities are defined as instances in which fire brigades can control and extinguish a given fire. Specifically, MEDFIRE allows fire suppression whenever the time since last extraction at the cell level is below a pre-specified threshold (expressed in years). The implementation of the mechanical extraction of biomass for bioenergy purposes in our model implies that all fine fuels (branches and shrubs) are also removed thus significantly reducing fuel load in a given area (as illustrated in Fig. 2a and b, see also Appendix S2). This treatment effectively redistributes fire suppression opportunities at the landscape level by altering fire behaviour in two different ways: changing fire spreading rates and reducing the likelihood of crowning behaviour (Agee and Skinner 2005; Reinhardt and others 2008; Cochrane and others 2012). In particular, the potential for crown fires is expected to decrease in low-density stands due to the lower canopy bulk density (Fig. 2b) (Stephens 1998; Graham and others 1999; Alvarez and others 2012), but this treatment also creates firefighting opportunities because the control of understory shrubs can decrease surface fire intensity (Castedo-Dorado and others 2012). Although the magnitude of this effect should be estimated at stand-level, spatial attribution at landscape-level of suppressing fires at any treated location due to fuel reduction treatments can only be dealt with probabilistically. To our knowledge, there still is a lack of quantitative assessments of how forests managed for biomass extraction decrease fire risks through changes in fire spread that allow firefighters to stop the fire (Alvarez and others 2012; Castedo-Dorado and others 2012). We therefore considered a wide range of fire suppression effectiveness to deal with the uncertainty in the relationship between biomass extraction and fire suppression opportunities (see scenario section). Fire suppression effectiveness was implemented in the model as a probability that firefighters effectively use an opportunity derived from a management action (i.e. biomass extraction) and therefore effectively constrain further spread of the fire from that location.

Previous studies determined that a period of 30 years is required for the canopy to close in Mediterranean forests after disturbance (Espelta and others 1995; Broncano and others 2005). Although in high-intensity treatment all annually available biomass in an area is harvested, we finally assumed, to be conservative, a shorter period (15-year, corresponding to 2/3 of the rotation period between harvests) as the time window of the opportunity to affect fire behavior. Low-intensity harvesting levels imply half of the amount of harvested material per hectare, so the time window for using harvested areas as firefighting opportunities will be, logically, half of the time when applying a high intensity level (7-years period).

Scenario design

Scenario storylines

Forest biomass extraction scenarios were built from three main storylines accounting for likely general strategies in large-scale forest planning. These three storylines were:

1) *Renewable energy—no subsidies (Renew)*: biomass extraction treatment costs and their spatial patterns are strongly influenced by factors such as site conditions, harvesting methods, distance to target area to manage, productivity of the machinery, number of machines,

biomass production per hectare, and the operator's skill, among others (Perpiñá and others 2009; Abbas and others 2011; Wendland and others 2011; Levers and others 2014). To take into account these logistic and economic constraints, we designed a set of scenarios characterized by forest harvesting in optimal areas (i.e. favorable site conditions avoiding steep slopes and with small extraction distances) thus assuming a cost-effective forestry biomass harvesting. Moreover, harvesting biomass as fuel could facilitate energy consumption savings in local communities, among other socioeconomic and environmental benefits (Mason and others 2006; Becker and others 2009).

2) *Renewable energy—subsidies (RenewSub)*: from an energetic viewpoint, the expected future increase of petrol and fossil fuel prices can potentially stimulate harvesting of forest biomass for bioenergy. On these lines, in September 2009 the European Parliament approved its directive 2009/28/EC on the promotion of the use of energy from renewable sources. This EU directive establishes the general potential of a 20% share of energy from renewable sources in gross final consumption of energy in the EU. In Spain, as member state, different support mechanisms will be applied at national level in order to guarantee that the EU directive becomes fully functional (MINECO 2013). Consequently, energy forecasts for 2020 are to increase the contribution of energy from biomass. By 2015, 12 million m^3 of forest biomass must be assigned to power generation—6.4 million to be used directly (from forests and wooded areas) and the remaining 5.6 million to be used after an industrial process. In fact, Catalonia has recently approved a forest harvesting strategy pegged to specific targets for biomass-derived energy (GENCAT 2014).

To achieve a 20% share of energy from renewable sources as established by European, National and Regional standards, we envisaged another set of scenarios based on an additional forest biomass extraction also from sub-optimal areas but financially subsidized by the government.

3) *Fire Prevention (FireP)*: when the implementation of fuel treatments at landscape scale is financially limited, land managers will often prioritize fuel treatments in areas of higher fire risk. To address these issues and test the effectiveness of this strategy from a prevention viewpoint, we defined an additional set of scenarios in which biomass extraction was exclusively applied to areas showing the highest fire risk.

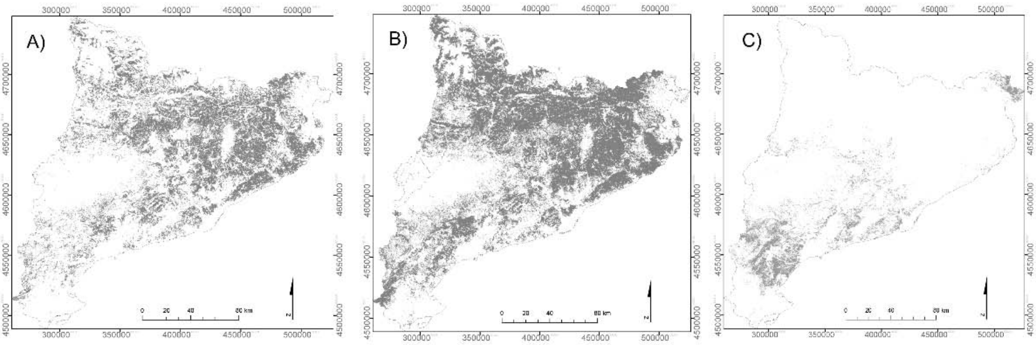

Fig. 3. Areas where biomass extraction takes place according to the three storylines: Optimal area fitting that slope is < 30% and distance to roads is < 400 m, whereas protected areas are also excluded (A). Suboptimal areas (areas with slope > 30% and distance to roads > 400 m, and within protected areas) are not excluded (B). Optimal areas where fire risk is high (C).

Scenario implementation

We designed and implemented **eighteen** forest biomass extraction **scenarios** by combining different target areas to manage and three levels of fire suppression effectiveness under the three storylines defined above (Tables 1 and 2). The target area to be managed depends on intensity of extraction and on variability in the spatial constraints affecting the final area for biomass extraction (Table 1). All scenarios were characterized by a **biomass extraction rate** equal to the annual increment averaged for Catalonia (3.16 m^3/ha/year), thus assuming sustainable extraction of the resource (details in Appendix S2). One hundred replicates of each scenario were simulated for a 50-year period (2000–2050).

Variable	Value	Label	Description
Biomass extraction rate	3.16 m^3/ha/year		Sustainable extraction rate, equal to the average annual increment derived from the comparison between IFN2 (1986–1996) and IFN3 (1997–2008).
Intensity of extraction	69.5 m^3/ha 34.7 m^3/ha	High-Int Low-Int	High-intensity extraction was estimated from the available forest biomass feedstock per year (2,714,100 m^3/year), considering a rotation period of 22 years and a technically available surface (859.000 ha) (more details in Appendix S2). Low-intensity extraction is half of the high-intensity treatment.
Area for biomass extraction	859,000 ha	Renew	Optimal area for biomass extraction fitted that slope is < 30% and distance to roads is < 400 m, whereas protected areas are also excluded.
	1,385,000 ha	RenewSub	Additional biomass extraction in suboptimal areas: slope > 30% and distance to roads > 400 m, including protected areas.
	245,000 ha	FireP	Optimal areas where fire risk is high.
Target area to be managed	39,043 ha/year	High-Int + Opt	Target areas to manage (hectares/year) were calculated according to the equation: ([*Area for biomass extraction*

	78,086 ha/year	Low-Int + Opt	(ha)]*[*Biomass extraction rate* (m^3/ha/year)]) / [*Intensity* (m^3/year)] (see more details in Appendix S1).
	11,105 ha/year	High-Int + FireRisk	
	22,211 ha/year	Low-Int + FireRisk	
	62,849 ha/year	High-Int + SubOpt	
	125,698 ha/year	Low-Int + SubOpt	
Fire suppression	90%	High-FS	A wide range of fire suppression effectiveness levels were considered to deal with the uncertainty in the relation between biomass extraction and fire suppression opportunities as well as the possible variability related with firefighting skills and the amount of funding or resources invested in fire suppression.
	40%	Medium-FS	
	10%	Low-FS	

Table 1. Description of the variables, labels and values used in the MEDFIRE scenarios characterization. **Abbreviations:** Hectares (ha); IFN (National Forest Inventory); High-Int (High-intensity), Low-Int (Low-intensity); Renew (biomass extraction in optimal areas), RenewSub (also in suboptimal areas), FireP (in areas at high fire risk); FS (Fire suppression).

The eighteen scenarios resulted from the combination of different values for the three scenario parameters (Tables 1 and 2):

– Three levels of **fire suppression** covering a wide range of effectiveness were considered to deal with the uncertainty in the relationship between biomass extraction and fire suppression opportunities as well as possible variability related to firefighting skills and amount of funding or resources invested in fire suppression: (1) high fire suppression effectiveness (according to this level of fire suppression, corresponding to a high capacity to control and extinguish a given fire, a fire simulated by the model will be suppressed in 90% of opportunities effectively leading to fire constrained); (2) medium fire suppression effectiveness (40% of opportunities), and (3) low fire suppression effectiveness (10% opportunities).

– Three treatments dealing with the **biomass extraction allocation** were designed, each determining where harvesting activities are restricted according to storyline (Fig. 3). In the *Renew* storyline, extraction took place in areas where slope was < 30% and distance to roads was < 400 m, and was excluded in protected areas like national and natural parks (total extent of about 859,000 ha) (Fig. 3a). In the *RenewSub* storyline, we relaxed the biomass extraction constraints to also allow actions in areas with slope > 30, distance to roads > 400 m and within protected areas (total extent of about 1,385,000 ha) (Fig. 3b). In the *FireP* storyline, biomass extraction is limited exclusively to high fire risk areas (total extent of 244,800 ha) (Fig. 3c).

– Two **extraction intensities** were considered, as this is a factor that determines the amount of harvestable target area every year and defines the available opportunities for fire suppression. In the high-intensity treatment *High-Int* (69.5 m^3/ha), extractions were implemented with long rotation periods (22 years) and over a small overall yearly area. In contrast, the low-intensity treatment *Low-Int* (34.7 m^3/ha) involved shorter rotation periods and a larger area. Thus, under the *Renew* storylines, and considering a sustainable biomass extraction rate (3.16 m^3/ha/yr), we needed to manage 39,043 ha every year (annual target area to manage) with high-intensity extraction, while for low-intensity treatments 78,086 ha/year were required to achieve the same amount of biomass. For scenarios from the *RenewSub* storyline, the area to manage yearly increased to 62,849 ha with high-intensity extraction and to 125,698 ha with low-intensity extraction. Finally, for scenarios derived from the *FireP* storyline, the yearly area to manage was 11,105 ha under high-intensity extraction and reached 22,211 ha under the low-intensity extraction.

ID	Target area to manage (ha/year)	Intensity of extraction (m^3/ha)	Area for biomass extraction	Fire suppression
1	39,043	*High-Int*	Renew	90
2	39,043	*High-Int*	Renew	40
3	39,043	*High-Int*	Renew	10
4	78,086	*Low-Int*	Renew	90
5	78,086	*Low-Int*	Renew	40
6	78,086	*Low-Int*	Renew	10
7	62,849	*High-Int*	RenewSub	90
8	62,849	*High-Int*	RenewSub	40
9	62,849	*High-Int*	RenewSub	10
10	125,698	*Low-Int*	RenewSub	90
11	125,698	*Low-Int*	RenewSub	40
12	125,698	*Low-Int*	RenewSub	10
13	11,105	*High-Int*	FireP	90
14	11,105	*High-Int*	FireP	40
15	11,105	*High-Int*	FireP	10
16	22,211	*Low-Int*	FireP	90
17	22,211	*Low-Int*	FireP	40
18	22,211	*Low-Int*	FireP	10

Table 2. List of MEDFIRE scenarios describing parameters used to reproduce fire suppression and biomass extraction. **Abbreviations:** High-Int (High-intensity), Low-Int (Low-intensity); Renew (biomass extraction in optimal areas), RenewSub (also in suboptimal areas), FireP (in areas at high fire risk).

Evaluation of simulation results

The **effectiveness** of forest biomass extraction as a fuel-reduction strategy to suppress wildfires was assessed by comparing the percentage of suppressed area derived from the biomass extraction opportunities (hereafter referred to as suppressed area) to the potential area to be burnt obtained if each fire would have burnt without fire suppression effort. To evaluate which treatment was more efficient at reducing wildfires, we also calculated suppressed area in relation to managed area for each scenario (hereafter refers as **treatment efficiency**). We used the mean and standard deviations of these variables obtained under each simulated scenario. R-based package was used to analyze MEDFIRE outputs (R software, version 3.0.2; package 'medfire', version 2.0) (R Core Team 2014).

RESULTS

The reduction in area burnt by wildfires depended on fire suppression levels, intensity and spatial placement of the biomass extraction (Fig. 4). Moreover, treatment efficiency was clearly higher for the biomass extraction scenarios that aimed to reduce fuel accumulation in high risk areas (Fig. 5).

Effects of fire suppression levels

The fire suppression levels considered for each scenario had a major impact on the effectiveness of biomass extraction at suppressing wildfires. Thus, the suppressed area under low fire suppression levels ranged between 4% and 7% (see scenarios with white box-plots in Fig. 4). Under moderate fire suppression levels, suppressed area increased up to 19–27% (see scenarios with light grey box-plots in Fig. 4), while in scenarios with high fire suppression levels, suppressed area achieved values close to 70% (see scenarios with dark grey box-plots in Fig. 4).

Effects of spatial placement of biomass extraction

The scenarios from the *Renew* storyline, in which biomass extraction took place in optimal areas, showed maximum suppressed area values of about 50–61% (scenarios 1 and 4, respectively, in Fig.4a).
Looking at the *RenewSub* storyline, where biomass extraction included sub-optimal areas, the suppressed area reached up to 69% (scenarios 7 and 10 in Fig. 4b). Nevertheless, it should be noted that these scenarios also involve a much higher extent to be managed than scenarios with more restrictive spatial constrains. When the spatial allocation of biomass extraction was restricted to high fire risk areas, i.e. scenarios from the *FireP* storyline, the suppressed area was considerably less, at about 40–47% (scenarios 13 and 16, respectively, in Fig. 4c). However, considering the area to be managed, the results suggested that the most efficient treatments were those where biomass extraction was implemented on high risk areas (compare scenarios from the *FireP* storyline with those from the *Renew* storylines in Fig. 5).

Effects of intensity of biomass extraction

In general, scenarios with low-intensity extraction (34.7 m^3/ha) showed slightly higher suppressed area values than those characterized by high-intensity extraction (69.5 m^3/ha) (compare scenarios tagged *High-Int* and *Low-Int* in Fig. 4), except for scenarios under the *RenewSub* storyline which showed similar figures (see scenarios 7-12 in Fig. 4). Thus, in the scenarios derived from the *Renew* storyline, the suppressed area slightly increased from 5–50% in scenarios with high-intensity extraction (scenarios 1-3 in Fig. 4a) to 7–61% in scenarios with low-intensity extraction (scenarios 4-6 in Fig. 4a).
For scenarios from the *RenewSub* storyline in which the area to be managed is considerably higher than in the *Renew* storyline, extraction intensity did not have any effect on suppressed area (see scenarios 7-12 in Fig. 4).
Finally, for scenarios derived from the *FireP* storyline with high-intensity treatments (scenarios 13-15 in Fig. 4c), the suppressed area was 4–40% while under lower intensity treatments suppressed area was 4–46% (scenarios 16-18 in Fig. 4c). Therefore, in this case, although suppressed area increased by 6% under high fire suppression levels, it remained unchanged under lower fire suppression levels.

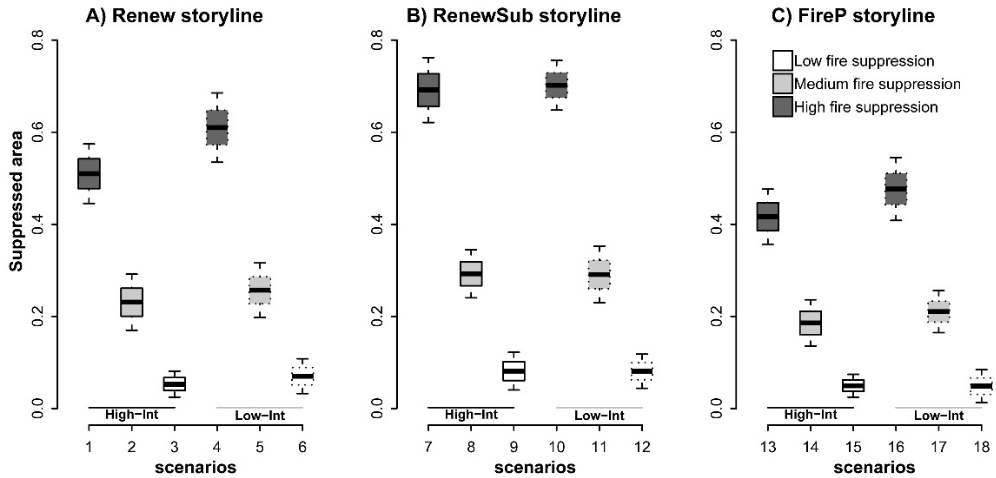

Fig. 4. Effectiveness (area suppressed in relation to the potential area to be burnt) for each biomass extraction scenario under the three storylines: (A) biomass extraction takes in optimal areas, (B) suboptimal areas and (C) optimal areas where fire risk is high. Scenarios characterized by high, moderate and low fire suppression are represented in dark-grey, light-grey and white box-plots, respectively. Continuous-outline boxes represent high-intensity biomass extraction scenarios (*High-Int*) whereas discontinuous-outline boxes refer to low-intensity treatments (*Low-Int*). Box-plot elements—lower and upper whiskers represent approximately 68% of all data values (mean ± SD, standard deviation), lower and upper hinges represent the mean ± ½ SD, and central black line represents the mean.

DISCUSSION

Our findings suggest that biomass extraction has the potential to substantially contribute to changes in fire regimes and decrease the amount of burnt area by using the fire suppression opportunities created by this forest harvesting tactic. Nonetheless, the **effectiveness** of this fuel-reduction strategy is strongly determined by the intensity and spatial allocation of the extraction and how firefighters can use the opportunities created by biomass extraction as fire suppression strategy. Moreover, the **efficiency** of this forest management at suppressing wildfires is clearly related to the objectives for which the treatment is designed.

Potential effects of fire suppression on biomass extraction-based fuel-reduction strategies

Recent studies advocate the interpretation of fire regime as a dynamic process strongly influenced by changes in landscape, climate and socioeconomic factors (James and others 2010; Moreira and others 2011; Keeley and others 2012; Brotons and others 2013). In the Mediterranean region, fire suppression plays a key role in these dynamic processes, to the point that the current fire regime cannot be explained without factoring in the effects of fire exclusion (Piñol and others 2005, 2007; Brotons and others 2013). In this sense, our results are in agreement with these previous studies, highlighting the key role played by fire suppression in modulating fire regime. Specifically, our results suggest that the **effectiveness** of forest biomass extraction for bioenergy as a fuel-reduction strategy designed to reduce the impact of wildfires is strongly dependent on fire suppression investments and capabilities and on the relationship between biomass harvesting and the creation of fire suppression opportunities (Fig. 4). To our knowledge, there still is a lack of quantitative assessments of how forests managed for biomass extraction decrease fire risks through changes in fire spread that allow firefighters to stop the fire. We therefore encourage the development of new studies at finer scales to clarify this linkage. Despite this uncertainty, and even considering moderate-fire suppression scenarios (see scenarios with light grey box-plots in Fig. 4), our findings clearly support the view that biomass extraction for bioenergy can be considered by policymakers as a viable strategy to reduce large fires. This forest harvesting practice should therefore be taken into account in future fire suppression plans in addition to conventional fuel-reduction treatments such as prescribed burning, mastication, timber harvesting or the alternative 'let-burn' strategies in order to effectively reduce the impacts of large fires (Fernandes and Botelho 2003; Agee and Skinner 2005; Houtman and others 2013; Regos and others 2014).

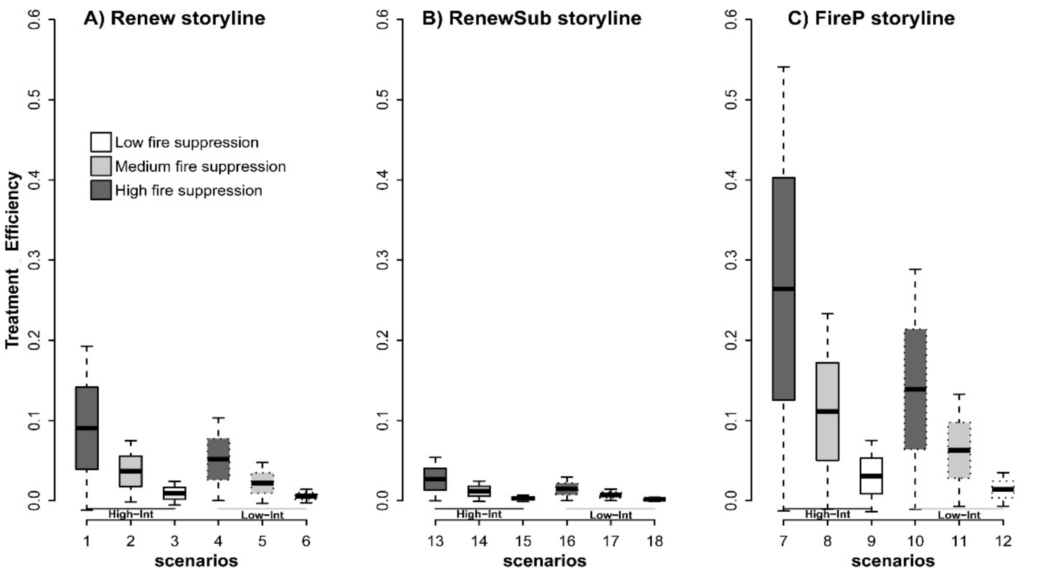

Fig. 5. Treatment efficiency (area suppressed in relation to the area managed) for each biomass extraction scenario under the three storylines. Box-plot characteristics are as in Fig. 4

Effects of spatial allocation of forest harvesting on biomass extraction-based fuel-reduction strategies

Despite a number of studies, the crucial issue of the best placement of fuel-reduction treatments on the landscape remains a largely unanswered question (Finney and others 2007; Parisien and others 2007). Our findings shed more light on this particularly important question. When forest biomass extraction takes place in optimal areas for harvesting activities, biomass extraction provides large fire suppression opportunities (suppressing 50–61% of the potential area to be burnt) to reduce the impact of wildfires (see scenarios included in the *Renew* storyline). According to our results, strategies aimed at obtaining maximum revenues from biomass extraction suppressed a larger area than strategies based on prevention and focused on high fire risk areas (compare *Renew* storyline and *FireP* storyline scenarios in Figs. 4A and C).

Nonetheless, taking into account the total area managed in each treatment, we can conclude that an extraction of forest biomass in areas at higher probability of fire occurrence is a more efficient allocation strategy for avoiding large wildfires (compare *Renew* storyline and *FireP* storyline scenarios in Fig. 5a, c). Finally, according to our simulation outcomes, the scenarios wherein biomass extraction for energy use also exploits sub-optimal areas achieved the highest suppressed area, at values close to 70% under high fire suppression levels (scenarios included in the *RenewSub* storyline in Fig. 4b). Nonetheless, achieving such suppression values hinges on being able to manage 4–9% of the whole forest area every year. This would imply huge investments in forest biomass extraction, especially in the sub-optimal areas where its implementation would be very costly as unsuitably placed.
Thus, our findings reveal that the **efficiency** of this forest harvesting strategy at suppressing wildfires depends on the allocation of extraction (clearly related to the objectives for which the treatment is designed), while the amount of suppressed area (i.e. **effectiveness**) depends more strongly on the extent of area to be treated. This conclusion is line with previous studies highlighting that a high proportion of the landscape (> 30%) should be managed to achieve a substantial reduction in the fire propagation conditions, and that treatments aimed to create fire resilient landscapes are less efficient if they are randomly applied (Finney 2003; Parisien and others 2007; Bradstock and others 2012).

Effects of forest harvesting intensity on biomass extraction-based fuel-reduction strategies

When trees of intermediate size are mechanically cut but all harvested material is taken off site, as is commonly proposed with biomass extraction for energy purposes, the original surface fuel load decrease and further wildfire hazard and the likelihood of crown and surface fire can be reduced (Stephens 1998; Evans and Finkral 2009). Taking these issues into consideration, harvesting actions for energy could be a well-adapted fuel reduction strategy for creating fire-resilient stands in Catalonia, since it implies keeping only a few big trees and removing all harvested material to reduce surface fuels, increasing height to live crown, and decreasing crown density (Fig. 2). However, according to our results, the effectiveness of forest biomass extraction at reducing wildfires also depends on extraction intensity. Thus, the suppressed area is slightly higher with lower harvesting intensities, especially under high fire suppression capabilities (see scenarios 1 and 4 in Fig. 4) and strategies designed to prevent large fires (see scenarios 13 and 16 in Fig. 4). This could be explained by the fact that high intensities, which are more profitable for the forest contractor, are executed with long rotation periods and in a smaller overall yearly area, whereas low felling intensities have shorter rotation periods and the yearly treated area is larger. Therefore, large managed areas increase the **effectiveness** of the biomass extraction at suppressing wildfires, despite the reduction in time window of opportunities for fire suppression. However, the **efficiency** of this strategy is higher with high felling intensities as the area treated is considerably smaller than in low-intensity treatments (Fig. 5).

Socio-economic and ecological considerations: scope for further research

Taking into account some of the considerations mentioned above, we suggest that enhancing biomass use as a way to reduce wildfire effects hinges on first weighing up the costs and benefits of different incentive or investment options relative to their margin of gain. Recent studies have highlighted that the benefits that can be obtained from reducing the impact of crown fires by applying large-scale fuel-reduction treatments as well as the negative effects of large wildfires are currently underestimated (Mason and others 2006). In fact, the cost of firefighting should be considered as a consequence of not investing in reducing fuel loads. At the same time, the inclusion of the market value of ecosystem services preserved by fuel-reduction activities has been recently endorsed as a policy option to stimulate biomass utilization (Nechodom and others 2008). In addition, biomass extraction brings socioeconomic benefits tied to its use as energy, thus further encouraging its utilization. Therefore, we suggest that cost/benefit analysis broadened to include market and nonmarket considerations should be incorporated into any decision-making process aimed at mitigating the devastating impact of forest fires.

From an ecological viewpoint, some limitations of MEDFIRE model, inherent to any spatial modelling exercise, must be taken into account to avoid wrong decisions based on misunderstanding conclusions. The reduction of tree density generates a crown fuel extraction, reducing crown fire hazard and increasing the fire suppression opportunities (Castedo-Dorado and others 2012). However, an opening of canopy could also generate the increase of understory shrub cover, changing a low dangerous forest fuel model into a very dangerous forest fuel model in few years. The static state of some variables into the MEDFIRE such as fire risk or ignition probability is another important challenge to address in future versions of the model, especially in current context of ecological perturbations (wildfires and biomass extraction) and climatic change. Besides, although two types of forest harvesting intensity have been considered, the MEDFIRE model is not currently designed to deal with differences between even and uneven-age stands, or with the presence of mixed forest. The type of forest and the way to plan the treatments could strongly modify the fire suppression effectiveness and fire risk. These ecological issues are not implemented in the MEDFIRE as they are beyond the scope of the present research and represent challenges to be addressed in the near future.

CONCLUDING REMARKS

In face of global change, and given the important role of anthropogenic disturbances in influencing fire regime, studies that include only one driver are likely to inadequately assess potential strategies to mitigate the impact of wildfires. Fire regime is a dynamic process strongly influenced by changes in landscape, climate and socioeconomic factors. The spatial interactions between wildfires, vegetation dynamics and human actions (in our case, fire suppression policies and forest biomass extraction for bioenergy) should therefore be addressed over short- and medium-term timescales through the regional narrative storyline and simulation approach. For this purpose, qualitative storylines accounting for likely general strategies in regional-scale forest planning were defined and translated into quantitative forest biomass extraction scenarios using landscape fire-succession model simulations. Given the persistent uncertainty due to a lack of quantitative assessments of how forests managed for biomass extraction decrease fire risks through changes in fire spread that allow firefighters to stop the fire, we encourage the development of new studies at finer scales to clarify this linkage. To deal with this uncertainty, we assessed the effect of a wide range of fire suppression policies. Our findings clearly support the view that biomass extraction for bioenergy can be considered by policy makers as a viable strategy to reduce large fires. We also addressed the effect of spatial allocation of biomass extraction considering three plausible and simplified descriptions of how the future may develop based on a coherent and internally consistent set of assumptions on the key driving forces of forest harvesting and its relationships with possible socio-economic and energy policies. In light of our results, a large fraction of the landscape should be effectively managed in order to achieve an appreciable reduction of area burnt; however, the efficiency of this forest harvesting effort in suppressing wildfires depends on the allocation of extraction (clearly related to the objectives for which the treatment is designed). Our results also suggested that harvesting for energy could be a well-adapted fuel reduction strategy for creating fire-resilient stands in Mediterranean regions, but the effectiveness of this strategy at reducing wildfires also depends on intensity of extraction. This valuable information for forest and fire managers will be a keystone for the optimization of this fuel-reduction strategy and its successful implementation in future firefighting programs forced to deal with global change. Finally, we suggest that cost/benefit analysis broadened to include market and nonmarket considerations should be incorporated into any decision-making process aimed at mitigating the devastating impact of forest fires in order to facilitate its potential for implementation. These recommendations are not restricted to our study region but could extend to multiple spatial, temporal and socio-political scales, since this fuel-reduction strategy presents strong synergies with social and energy-based policies, helping to bridge the gaps between forest policies, fire management and renewable energy strategies.

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SUPPORTING INFORMATION LEGENDS

Appendix S1: Model overview and biomass sub-model description

Appendix S2: Forest biomass in Catalonia—Description

For online publication only

APPENDIX S1: MEDFIRE model description

This appendix presents an overview of the MEDFIRE model and its sub-models, and describes the conceptual and implementation details for the recently developed *Biomass extraction* sub-model as well as the specifications guiding the initialization of the sub-model variables.

See Brotons *et al.* (2013) for a full description of the model (ODD) (Grimm *et al.*, 2010). Further information on the project in which this dynamic landscape model is embedded can be found online at https://sites.google.com/site/medfireproject/. See Fall and Fall (2001) for further information on the SELES modeling platform used to implement the model.

The MEDFIRE model

The MEDFIRE model is a raster-based, **dynamic fire-succession model** designed to mimic the main ecosystem processes of Mediterranean landscapes. The main purpose of the model is to examine spatial interactions between wildfires, vegetation dynamics and biomass extraction over short- and medium-term time scales through quantitative evaluation of the effects on landscape composition and fire regime. The model was implemented using version 3.5 of the SELES modeling platform (http://www.seles.info/). The current version of MEDFIRE is composed of three **sub-modules** accounting for the main dynamic processes shaping Mediterranean forests at landscape scale, i.e. (i) fire disturbance and fire suppression (fire sub-model), (ii), after-fire recovery and maturation of the vegetation (vegetation dynamics sub-model), and (iii) forest management (biomass extraction sub-model). The sub-modules are sequentially executed in one-year time-steps, and all model simulations share the initial conditions for the state variables.

The **state variables** are spatial variables that describe the landscape context and conditions related to the modeled processes. The dynamic spatial variables are: Land cover type (LCT), describing the main land covers and dominant tree species in forested areas; Time since last fire (TSF), indicating the number of years since the last fire episode; Time since last management (TSM), indicating the number of years since the last management intervention; Biomass extraction probability (BEP), accounting for the harvesting drivers; Biomass productive state (BPS), estimating forest-wide growth conditions. The static variables that complete the landscape characterization are: ignition probability, bioclimatic region, fire spread type (percentage of relief- or wind-driven fires over a region), elevation, aspect, main wind direction, slope, solar radiation, annual precipitation, distance to roads, and fire risk. Fire risk variable shows the locations where a fire is likely to start, and from where it can easily spread to other areas. The Catalan regional government has developed this raster layer considering historical ignition records, composition and structure of the vegetation, topography and climatic factors (Moreno *et al.*, 2006).

Fire sub-model

The fire sub-model is responsible for simulating the impact of a given fire regime in the landscape of a given area. This landscape event is scheduled once every year in summer. The sub-model begins by determining either from a preselected distribution or an input table whether the current summer is climatically wet (normal) or dry (adverse). Then, a total annual extent to be burnt is drawn from a statistical distribution, which differs depending on whether the summer is climatically normal or adverse (*AnnualBurnDistNorm* and *AnnualBurnDistSevr*). For each fire, the sub-model stochastically selects the target fire size, an ignition point and the fire-spread type (either relief- or wind-driven). As for the total annual extent to be burnt, distinct fire size distributions are used for climatically normal and adverse years (*FireSizeDistNorm* and *FireSizeDistSevr*). If fire suppression is not active, the fire is allowed to spread from its ignition point until the burnt extent equals the target fire size. In contrast, if fire suppression is active not all the cells potentially affected by a fire will be effectively burnt. Ignitions are generated and fires spread one after the other sequentially until the total annual extent to be burnt is reached. All burnable land cover types (see Table 1 in Appendix 3), effectively or non-effectively burnt, are counted when calculating total burnt extents.

1. *Ignition point*: Ignition points are restricted to occur in cells with burnable land cover type (*LCT*) (i.e. urban, water and rock covers are excluded). Ignition points are stochastically determined by randomly picking a grid cell with weights given by $W_{Ignition}$ (Bar Massada *et al.*, 2011). This value is derived from an input layer that describes a basic probability of ignition for each grid cell (*ProbIgnition*).

2. *Fire spread and burning*: Before starting a new fire, a value for its fire size is drawn from a statistical fire size distribution. This value sets the target extent to be burnt. The process of fire spread is as follows based on He & Mladenoff (1999). A given cell that is set to burn is called an *active cell*. The first active cell is the grid cell selected as ignition point. For each active cell, its eight immediate neighbors are considered as cells where the fire can spread. We refer to these as *spreading cells*. For every spreading cell, the model calculates a spread rate ($SR > 0$), which is a dimensionless number but is used to determine the order in which spreading cells are processed (removed from the event queue). Cells with low *SR* values are processed later than those with high *SR* values. When a given spreading cell is processed, the model then calculates the probability of burning ($P_{burning}$) and determines whether the cell burns or not using a Bernoulli trial. If the cell burns it becomes an active cell, and the spreading algorithm is processed for that cell. Otherwise the fire front at this point is stopped. The spatial pattern of a given fire arises as a result of differences among cells in the rate of spread and probability of burning. In other words, different combinations of spread rate and propensity to burn control fire shape and the proportion of unburned islands. Fires generally burn until their burnt extent equals the pre-specified fire size. Hence, the fire extent may be reached before slow-spreading cells are processed. Once the target extent is reached, all active cells on the front are stopped and the fire is completed. To ensure that fires do no stop before the target extent is reached, cells on the front that do not burn are kept in a randomly sorted list and the fire front is re-ignited if needed from these cells. Otherwise, these remain unburned.
Two basic fire spread patterns are considered: relief-driven base versus wind-driven base spreads (Rothermel, 1972). The fire spread type layer (*SpreadType*) contains the proportion of topographic fires for each cell in the grid. A Bernoulli trial for the ignition location with the probability of relief-driven fires taken from this proportion is used to determine the specific spread type for each simulated fire. To model the influence of fuel in the rate of spread, a *Base*

value is modified according to a *Fuel* multiplier as a proxy of fuel load and aspect of the *spreading cell* following the spread rate formulation in He *et al.* (2005) and Sturtevant *et al.* (2010). The *Base* and *Fuel* values are combined to calculate the rate of spread (*SR*) as:

$$SR = 1 - e^{-(Base \cdot Fuel)} \qquad \text{(A1)}$$

being higher for uphill fronts, wind-aligned fronts, southern slopes and higher for specific *LCT* covers and fuel loads (He & Mladenoff, 1999; Piñol *et al.*, 2005; Millington *et al.*, 2009). Whether a cell burns or not mainly depends on the spread rate. Slower fires are assumed to be more likely to go out due to local conditions (slow fires are most likely lower intensity, such as heading downhill, against the wind, across lower flammable types, etc.). The probability of burning is simply calculated as:

$$P_{burning} = SR^{SR\_BurnExp} \qquad \text{(A2)}$$

where exponent *SR_BurnExp* (≥ 0) controls the relationship between spread rate and probability of burning.

a. *Relief-driven Base spread*: The basic spread rate in a relief-driven fire is modeled as follows: First, the difference in altitude between the spreading cell and the active cell is assessed using *Elevation* spatial variable. This difference allows calculating the slope of the burning front (*estFireSlope*), which is afterwards bounded between –0.5 and +0.5 (±50%). The slope of the burning front is used to calculate a base rate of spread following:

$$Base = (1+rSlope)^{(estFireSlope+0.5)} \qquad \text{(A3)}$$

where *rSlope* (≥ 0) specifies the extent to which slope modulates the spread rate. Note that *Base* = 1 when the slope of the burning front is -0.5 (downhill) and *Base* > 1 for higher values of slope.

b. *Wind-driven Base spread*: The basic spread rate for a wind-driven fire is calculated taken into account the local wind direction since it has significant effect on fire spread (Sharples *et al.*, 2010). First, *fire spread direction* is defined as the vector from a *fire anchor point* to the spreading cell. The model then measures the angle in degrees (*degreesOffWind*) between the *fire spread direction* and the main wind direction (given at cell level by *Wind* spatial variable). This value, which ranges from 0 to 180 degrees, is used to calculate the basic spread rate following the function:

$$Base = (1+rWind)^{((180 - degreesOffWind)/180)} \qquad \text{(A4)}$$

where *rWind* (≥ 0) specifies the extent to which *degreesOffWind* modulates the spread rate. Using this formula, *Base* = 1 when the fire is spreading against the wind (*degreesOffWind= 180*) whereas *Base* > 1 for fire fronts with lower angles between the main wind direction and the direction of fire spread. The initial fire anchor point for any fire is the ignition point. As fire spreads, however, if the local fire spread direction deviates significantly (> 45 degrees) from the direction from the anchor point (e.g. due to barriers such as urban or rock, or due to slower spread or local fire extinctions), the anchor point is updated. In this way broad scale fire direction can reduce bias from spreading within a grid (to eight neighbours on 45 degree angles), yet local effects that influence direction can be included to ensure fire direction responds to landscape structure. The fire anchor points tends to be located in areas that cause discontinuous changes in fire direction, such as non-burnable LCTs, areas with slower spread or low probabilities of burning, areas with local fire suppression, etc). After passing such areas, fire spread rate increases again in the direction of the wind.

c. *Fuel load spread*: Fuel load (*Fuel*) is calculated using the *LCT*, *TSF* and *Aspect* values of the *spreading cell*. *TSF* values are re-scaled to the [0-1] interval and the result is stored as *TSFExp*. Aspect is used to modulate fuel load by setting *AspExp* = -1 when the spreading cell is oriented to North, *AspExp* = +1 when it is oriented to South and *AspExp* = 0 otherwise. Each burnable *LCT* has its corresponding *flammability* quality parameter, f_{LCT} ($\geq$ 1). The fuel load is then calculated as:

$$Fuel = (1 + rAspect\ )^{AspExp} \cdot (1 + rTSF\ )^{TSFExp} \cdot (rLCT\ \cdot f_{LCT}) \quad \text{(A5)}$$

where *rAspect*, *rFuel* (both ≥ 0) and *rLCT* (> 0) specify the extent to which differences in *Aspect*, *TSF* and *LCT flammability*, respectively, modulate the fuel load.

3. *Fire suppression*: Two distinct fire suppression strategies are implemented, both related to the concept of firefighting opportunity. The active fire suppression strategy concerns opportunities generated in areas where *SR* is lower than a pre-specified threshold (*SRthreshFF*). The passive fire suppression strategy is related to opportunities given by low fuel loads and consists in suppressing the fire whenever *TSF* or Time since last management (*TSM*) is lower than a pre-specified threshold (*TSFtreshFF; TSMtreshFF*). For any of the two fire suppression strategies, if a cell is said to burn but complies with the required condition it will not burn. However, the model allows the fire to continue spreading from that cell (but without effectively burning), so that areas that would have been reached via spread beyond the suppression opportunity point also do not burn.

4. *Fire effects*: Cells that are effectively burned have *TSF* set to 0. The fire extent is calculated as the number of cells that effectively burned plus the number of cells that would have burned but did not because of fire suppression of all burnable *LCT* cells reached via spread.

Vegetation dynamics sub-model

The vegetation dynamics sub-model is responsible for updating the *LCT* state variable. This landscape event is scheduled once every year at the end of the year. The two ecological processes implemented in this sub-model are: (1) vegetation regeneration following fire disturbances (i.e., post-fire vegetation transitions); (2) natural succession from shrubland to forest (only changes between shrubland and forest classes are allowed and other natural covers are considered stable).

1. *Post-fire vegetation regeneration:* Post-fire changes in *LCT* represent the outcome of vegetation regeneration dynamics after the impact of fire in a given area. Only those cells that have burnt in

the current year are allowed to undergo a *LCT* change. Post-fire transitions in dominant species are implemented according two approaches: non-spatial stochastic transitions or neighborhood species contagion. This is implemented by allowing the updated *LCT* value of some target cells to be based on the current *LCT* values of their neighbors. Otherwise, a non-direct, deterministic regeneration approach is applied defining post-fire changes as transition probabilities (Balzter, 2000) based on data from Rodrigo *et al.* (2004). Whether neighbor contagion transitions happen is determined using a Bernoulli distribution with success probability *pNeighbContag*.

a. *Spatially autocorrelated transitions*: When neighbor contagion is used, any neighbor (at 150 m radius) of the target cell available is considered appropriate for contagion if: (1) were also burnt this year; (2) have the same pre-fire *LCT* and *TSF* values; and (3) their *LCT* value has been already updated. The updated *LCT* value is copied from a neighbor randomly chosen among those that are appropriate for contagion. If none of the neighbors is considered appropriate for contagion then the transition is not spatially autocorrelated.

b. *Non-spatially autocorrelated transitions*: Post-fire *LCT* transition probabilities (*postFireSucc*) depend on the pre-fire *LCT* value and are regionalized following the bioclimatic regions (*BioRegion* spatial variable). Given that transitions after fire are also known to depend on time since the previous last fire (Díaz-Delgado *et al.*, 2002), we applied a different transition probability table for recent re-burnt areas (*postFireSuccReburnt*) when less than *CanopySeedAge* years have passed between the last fire event and the current one. Vegetation regeneration patterns are strongly linked to aspect value (Pausas *et al.*, 1999). Accordingly, we increased the amount of transitions to shrubland in southern slopes using an aspect factor (*SppAspectFactor*).

2. *Succession from shrubland to forest*: Each year, shrubland cells are allowed to become forests. The probability of becoming forested ($P_{shrub2forest}$) is calculated as a logistic function:

$$\mathrm{logit}(P_{shrub2forest}) = a + b \cdot TSF_{shrub} \cdot ForNeigh \quad \text{(A6)}$$

where *ForNeigh* is product of the proportion of neighbors (150 m radius) that are considered adult forests (i.e. cells which *LCT* is a tree species and its $TSF \geq MatureForest$), TSF_{shrub} represents the age of the shrubland itself, and *a* and *b* are, respectively, the intercept and slope of the linear predictor. In the case that shrubland becomes a forest, the dominant tree species is chosen using a multinomial distribution where the probabilities are calculated using the number of adult forests of each *LCT* among the neighbors (150 m radius) of the target cell. The number of neighbors of each forest type is weighted by a seed pressure factor (*SeedPressure*) since not all tree species have the same colonization capability of new areas in a Mediterranean landscape (Verdú, 2000).

Biomass extraction sub-model

The **biomass extraction sub-model** is tasked with simulating a forest management plan based on harvesting biomass in selected forest areas and defined by the annual biomass extraction rate and intensity of extraction. This landscape event is scheduled once every year, before the fire season starts.

The procedure is designed to restrict the biomass extraction process to locations satisfying a set of spatial constraints defining the available area for biomass extraction (*ExtractArea* variable, expressed in hectares). By default, biomass extraction can take place in any forested area, but spatial constraints can be applied to exclude protected areas or restrict harvesting activities in target locations. This sub-model aims to allocate annual biomass demand over the area available for biomass extraction, but instead of requiring an annual harvestable volume (whose units are m^3/year), it requires an annual biomass extraction rate (*ExtractRate*) that express the volume to be harvested per hectare each year (m^3/ha/year). To mimic the effect on forests stands of a variety of biomass extraction techniques, the sub-model uses the intensity-of-extraction variable (*ExtractIntens*) that dictates the maximum harvestable volume per unit of area (m^3/ha). Thus, the annual volume to be harvested (i.e. *ExtractArea x ExtractRate*) at intensity *ExtractIntens* defines the annual target area to be managed (*ManagedArea* in ha/year).

The sub-model begins by drawing a target area (*TargetPatchArea*) from a managed patch size distribution and selecting an initial location according to the Biomass extraction probability (BEP) that accounts for the main factor driving a harvesting intervention on Mediterranean forest lands. In the current version, BEP depends on the spatial constants slope, risk of fire and distance to roads (or paths), and the dynamic variable LCT (describing the dominant tree species in forested areas and the main land covers). The managed patch size distribution follows a normal distribution *N*(*MeanSizePatch*, *SdSizePatch*) bounded by *MinSizePatch* and *MaxSizePatch,* estimated from Autonomous Government data for the 2000–2010 period. From this initial location, the future managed patch has to grow to reach the *TargetPatchArea* spreading to any of the eight neighbors according to BEP. Spreading does not occur in areas where extraction is not allowed nor in recently-managed zones or recent burnt zones, so the state variable Time since last management (TSM) must be greater than *BiomassAgeReturn*, and Time since last fire (TSF) must be greater than *ForestAgeReturn* for neighboring cells. Since forest landscapes are not homogeneous and forest stand quality varies across them, the sub-model has not been designed to effectively manage as many cells as the *TargetPatchArea* dictates, but the effective managed area will depend on the Biomass productive state (BPS) of the forest stands. The productive state of forested cells is characterized by tree species, solar radiation and annual average precipitation. Thus, when spreading reaches a new cell, the patch area (*PatchArea*) is not directly incremented by one unit but by the equivalent effective unit described by BPS. As the BPS variable is greater than 1 for high-productive stands and smaller than 1 for less-productive stands, less spatial area is managed in high-productive stands to reach the same target area as in a low-productive stand. The spreading process stops when the equivalent effectively managed area *PatchArea* is equal to or greater than the *TargetPatchArea* independently of spatial managed area. The sub-model sequentially simulates as many managed clusters as needed to reach the annual target area to be managed.

Simulating biomass extraction as an integrated process on a dynamic fire-succession landscape model, as can be achieved by the MEDFIRE model, gives the chance to define a firefighting strategy based on this forest management practice. The model considers that managed patches are opportunities to stop fire from spreading further as low fuel loads in harvested stands reduce fire intensity. The opportunities generated by the extraction of forest biomass may be used for a period of time *FFOppor* that depends on the intensity of extraction.

The variables *ExtractArea*, *ExtractRate*, *ExtractIntens* (and consequently *ManagedArea* = [*ExtractArea x ExtractRate*] / *ExtractIntens*), and *FFOppor* are scenario parameters used to translate a storyline scenario to a quantitative MEDFIRE model scenario. The set of complementary sub-model variables are similarly initialized for any model scenario, as shown in Table S1.1.

Tables

Table S1.1. Description and default values for Biomass extraction sub-model variables.

Variable	Value	Description
MeanSizePatch	10 ha	Mean of the patch size distribution following a normal distribution
SdSizePatch	20 ha	Standard deviation of the patch size distribution following a normal distribution
MinSizePatch	4 ha	Minimum of the patch size distribution
MaxSizePatch	80 ha	Maximum of the patch size distribution
BiomassAgeReturn	22 year	Period of time after harvesting that biomass extraction cannot take place (rotation period)
ForestAgeReturn	30 year	Period of time after fire that biomass extraction cannot take place

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APPENDIX S2: Forest biomass in Catalonia—Description

This appendix gives technical details on the figures calculated and criteria considered for estimating the forest biomass technically available for Catalonia, as well as intensities and rotation period considered in our simulations.

To estimate the forest biomass, data were processed from the Spanish National Forest Inventory (IFN3 and 2; Villanueva, 2005), the Land Cover Map of Catalonia (CREAF, 2009; Ibañez & Burriel, 2010) and the OrGest map (Vericat *et al.*, 2010; Piqué *et al.*, 2011).The following constraints were applied to define the final technically available forest biomass (859,000 hectares):

- Canopy cover fraction (FCC) over 70%
- Main species, whose occupancy area is larger than 1.000 hectares, were selected
- Protected areas were excluded
- Accessibility, as buffer distances described in Table S2.1

Forest managers from the Autonomous Government were consulted to help establish the accessibility conditions required for exploitable areas (Table S2.1).

Table S2.1: Buffer distances (expressed in meters) for slope classes and regions of Catalonia

Buffer distance from forest roads	General	Central Catalonia	Pyrenean area
Slope <30 %	400	400	500
Slope 30-60 %	75	150	300
Slope >60 %	35	75	75

Available biomass can be split into two categories: energy uses (primary forest biomass) and industrial uses (packaging, construction, etc.). The assumptions for splitting the available forest biomass are shown in Table S2.2.

Table S2.2: Assumptions for differentiation of biomass use

Biomass for energy	Biomass for industrial use
Stem + thick branch biomass of conifer trees under DC20	Stem from conifer species over DC20 cm
Thick branch biomass of conifer trees over DC20	
Stem + thick branch biomass of *Quercus* species	

Acronyms: DC20 refers to the diameter class of 20 cm.

Current bioenergy trends and thermal conversion technologies allow the use of wood chips from full trees. In this full-tree **harvesting system**, trees are felled and extracted without being delimbed or topped. This harvesting system is perceived as better for the creation of fire suppression opportunities, with good potential synergies with understory grazing. The calculations of the harvesting potential for bioenergy (stem plus thick-branch biomass as shown in Table S2.2) have been obtained by adopting this harvesting system as reference. However, the full-tree system might not be used in practice in every biomass exploitation due to technical (terrain or stand difficulties, skillness of companies, intermediate storage availability, etc.), environmental (nutrient exports) or economic reasons (not enough critical mass to justify this harvesting system over the full-stem harvesting system in which trees are felled, delimbed and topped at forest).

We thus calculated **technically available forest biomass feedstock** of 2,714,100 m^3 per year on 859,000 hectares for both industrial and energy uses, allowing a sustainable biomass extraction rate (BER) of 3.16 m^3/ha/yr. Specifically, 989,600 m^3 per year are classified as energy assortments and 1,724,500 m^3 per year as industrial assortments. However, the current exploitation in Catalonia is between 600,000 and 880,000 m^3, (average of 705.900 m^3 per year, meaning a BER of 0.82 m^3/ha/yr in the technically available surface, 859.000 ha) according to Autonomous Government databases for 2000–2010 period (GENCAT, 2013), so the current exploitation could be increased almost four- fold to match available growing volumes.

- BER $_{[\text{industry uses}]}$ = available forest biomass feedstock per year (1,724,500 m^3/yr)/ technically available surface (859.000 ha) = 2.1 m^3/ha/yr
- BER $_{[\text{energy uses}]}$ = available forest biomass feedstock per year (989,600 m^3/yr)/ technically available surface (859.000 ha) = 1.15 m^3/ha/yr
- BER $_{[\text{total}]}$ = BER $_{[\text{industry uses}]}$ + BER $_{[\text{energy uses}]}$ = 3.16 m^3/ha/yr

Forest harvesting intensity has been simplified, for the whole region to two intensity levels: 1) high intensity level (High-Int) and 2) low intensity level (Low-Int) (i.e. half of the high-intensity treatment). One assumption for the high-intensity level is that all the technically available biomass per year is effectively harvested (2,714,100 $m^{3/}$/year). The period between harvests (or rotation period), area to be treated each year, and harvesting intensity are interrelated. Thus, rotation period was chosen as a function of the profitability of the harvest for forest companies, which usually need to harvest more than 45 fresh tons per hectare. This dictates a rotation period between harvests of 22 years, with a mean intensity of 25.4 m^3/ha of biomass for energy and 44.1 m^3/ha for industry uses, totalizing 69.5 m^3/ha. This figures were calculated according to the following expressions:

- High-Int $_{[\text{industry uses}]}$ = [available forest biomass feedstock per year (1,724,500 m^3/yr) * rotation period (22 yr)] / technically available surface (859.000 ha) = 44.16 m^3/ha
- High-Int $_{[\text{energy uses}]}$ = [available forest biomass feedstock per year (989,600 m^3/yr) * rotation period (22 yr)] / technically available surface (859.000 ha) = 25.4 m^3/ha
- High-Int $_{[\text{total}]}$ = H-Int $_{[\text{industry uses}]}$ + H-Int $_{[\text{energy uses}]}$ = 69.5 m^3/ha

The low-intensity harvesting level imply half of the amount of harvested material per hectare (34.75 m^3/ha), but also a higher amount of harvested (treated) area per year when the total harvest of 2,714,100 m^3/year is to be reached. The period of time between harvests will be, logically, half of the time when applying a high intensity level.

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CHAPTER

III

FIRE MANAGEMENT, CLIMATE CHANGE AND THEIR INTERACTING EFFECTS ON BIRDS IN COMPLEX MEDITERRANEAN LANDSCAPES: DYNAMIC DISTRIBUTION MODELLING OF AN EARLY-SUCCESSIONAL SPECIES — THE NEAR-THREATENED DARTFORD WARBLER (SYLVIA UNDATA)

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REVIEW

Fire management, climate change and their interacting effects on birds in complex Mediterranean landscapes: dynamic distribution modelling of an early-successional species—the near-threatened Dartford Warbler (*Sylvia undata*)

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Abstract The current challenge in a context of major environmental changes is to anticipate the responses of species to future landscape and climate scenarios. In the Mediterranean basin, climate change is one the most powerful driving forces of fire dynamics, with fire frequency and impact having markedly increased in recent years. Species distribution modelling plays a fundamental role in this challenge, but better integration of available ecological knowledge is needed to adequately guide conservation efforts. Here, we quantified changes in habitat suitability of an early-succession bird in Catalonia, the Dartford Warbler (*Sylvia undata*), which is globally evaluated as Near Threatened in the IUCN Red List. We assessed potential changes in species distributions between 2000 and 2050 under different fire management and climate change scenarios, and described landscape dynamics using a spatially-explicit fire-succession model that simulates fire impacts in the landscape and post-fire regeneration (MEDFIRE model). Dartford Warbler occurrence data were acquired at two different spatial scales from: (1) the Atlas of European Breeding Birds (EBCC) and (2) the Catalan Breeding Bird Atlas (CBBA). Habitat suitability was modelled using five widely-used modelling techniques in an ensemble forecasting framework. Our results indicated considerable habitat suitability losses (ranging between 47 and 57 % in baseline scenarios), which were modulated to a large extent by fire regime changes derived from fire management policies and climate changes. Such result highlighted the need for taking the spatial interaction between climate changes, fire-mediated landscape dynamics and fire management policies into account for coherently anticipating habitat suitability changes of early-succession bird species. We conclude that fire management programs need to be integrated into conservation plans to effectively preserve sparsely forested and early succession habitats and their associated species in the face of global environmental change.

Keywords Bird conservation · Global change scenarios · Multiscale hierarchical modelling · MEDFIRE model · Fire-prone ecosystems · Forest biomass extraction

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Introduction

The current challenge in a context of major environmental changes is to accurately forecast how the interaction between climate change and other ongoing human-induced threats affects biodiversity (De Chazal and Rounsevell 2009; Garcia et al. 2014; Stralberg et al. 2014). Species distribution models (SDMs) may play a fundamental role in this challenge, but we need to integrate more ecology in model building and develop a more coherent model validation before species distribution modelling may be of use in a dynamic ecological context (Guisan and Thuiller 2005; Elith et al. 2006; Guisan and Rahbek 2011).

Mediterranean landscapes are highly dynamic systems (Keeley et al. 2012). Climate change is one of the most powerful driving forces of these dynamics and, in the Mediterranean basin, its severity has markedly increased in recent years (IPCC 2007). However, climate change impacts on biodiversity are often also indirect through changes in disturbance regimes (Clavero et al. 2011; De Cáceres et al. 2013; Turco et al. 2014). Fire is a critical factor in the Mediterranean and is likely to drive landscape change effects over large areas. The description and analysis of landscape patterns associated to fire dynamics have received some attention (Lloret et al. 2002; Moreira et al. 2011, and references therein). However, knowledge about how the temporal and spatial arrangement of habitats arising from wildfires affects biodiversity in complex, human-dominated landscapes is astonishingly poor (Richards et al. 1999; De Cáceres et al. 2013; Kelly et al. 2014), with the exception of within-habitat succession-related recovery of communities after disturbance events (Loyn 1997; Zozaya et al. 2011; Nimmo et al. 2012; Santos et al. 2014; Lindenmayer et al. 2014; among others). In this work, we present recent advancements on habitat and bird modelling responses to fire and climate changes in Catalonia (north-east Iberian Peninsula) in which SDMs applications have played a major role. We focus on the spatial interactions among climate change, fire-conducted landscape dynamics and fire management actions with a future perspective. We used 'forecasting' techniques that identify the events leading from the current situation to a plausible future outcomes (Cook et al. 2014). Based on a storyline and simulation approach, we combined climate projections from global circulation models (GCMs) and fire simulation outcomes from a dynamic fire-succession model (MEDFIRE model) to develop a set of potential future trajectories.

Our main goal is to assess the effects of several fire management strategies on an early-succession bird species, the Dartford Warbler (*Sylvia undata*), as a 'model' study under a climate change context in order to provide insights into a conservation planning process aimed at preserving biodiversity in the face of global change. The Dartford Warbler was recently evaluated on a global scale as Near Threatened in the IUCN Red List, since it is declining at a moderately rapid rate (Birdlife International 2014). Declines in the core populations in Spain are largely responsible for the estimated overall decline of the species (Birdlife International 2004a, b). As a consequence, this species is considered of conservation concern in Europe (more than 95 % of the global population; Species of European Concern category 2 vulnerable, Annex 1 of the European Habitats Directive). The drivers of this population decline are not entirely clear but may include habitat degradation and modification (Van den Berg et al. 2001) and climate changes (Bibby 1978). In fact, climate-related changes in the species' Mediterranean stronghold could be particularly important, and the species could suffer a considerable range loss by the end of the century (Huntley et al. 2007). Changes in the pattern and frequency of wildfires may be a threat, although the species often colonises early successional habitat created by such fires (Pons and Prodon 1996; Herrando et al. 2001; Moreira et al. 2003; Pons et al. 2012). In particular, we ask the following questions: (1) how will climate change synergically with fire-conducted vegetation dynamics affect the distributional range of Dartford Warbler over the next 50 years?; and (2) can fire management offset distributional shifts caused by climate change and natural succession processes?

Methods

Study region and bird data

The study was conducted in Catalonia, a core region in the distribution of the genus *Sylvia* (Shirihai et al. 2001), dominated by a Mediterranean climate and located in north-eastern Spain (Fig. 1). Fire is a major landscape driver in the study region, with about 25 % of the wildland area affected by fires during 1975–2010 (Díaz-Delgado et al. 2004) (Fig. 1). Most fires in the region are severe, including crown fires that strongly affect both forest canopy and undergrowth, and cause widespread tree mortality (Rodrigo et al. 2004).

Dartford Warbler occurrence (presence/absence) data were acquired at two different spatial scales from: (1) the EBCC Atlas of European Breeding Birds (EBCC; Hagemeijer and Blair 1997); these data record the occurrence of breeding by each species in the 3,165 50-km^2 squares of a Universal Transverse Mercator (UTM) grid, largely during the late 1980s and early 1990s; and (2) the Catalan Breeding Bird Atlas (CBBA; Estrada et al. 2004). The CBBA resulted from a large-scale survey that between 1999 and 2002 covered the whole of the Catalonia using grid-based 10 km UTM squares. A total of 3,076 1 km^2 (approximately 9 % of the total area) were selected to conduct standardised intensive surveys of species presence

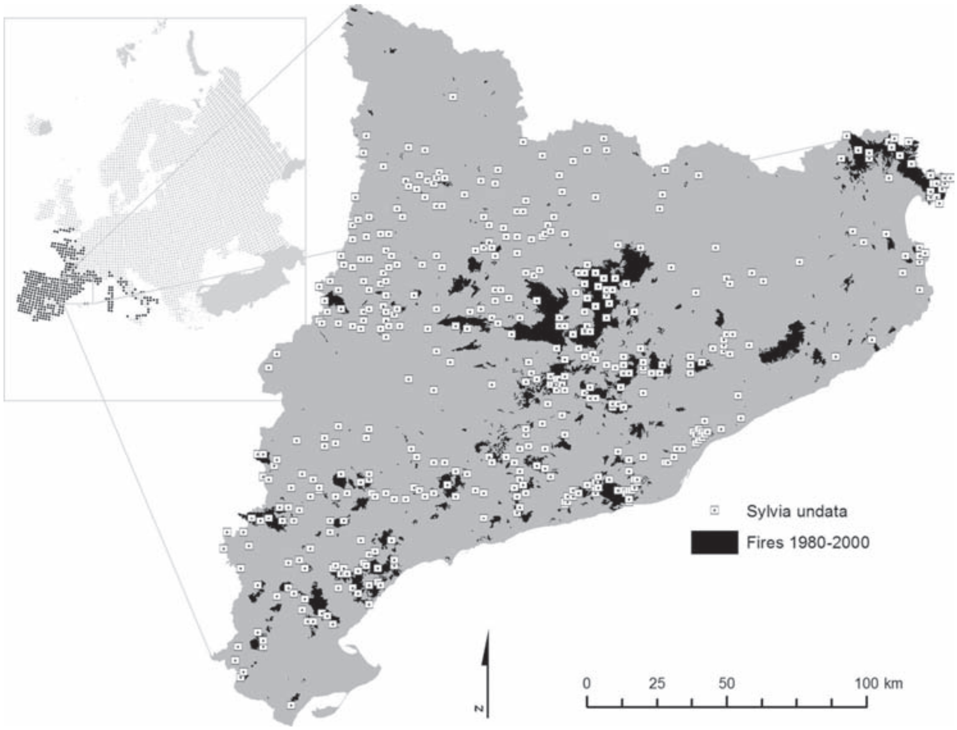

Fig. 1 Location of study region. Presence of Dartford Warbler (*Sylvia undata*) in Europe (*black dots*) at 50-km^2 resolution. Presence of Dartford Warbler in Catalonia (*white squares*) at 1-km^2 resolution and distribution of wildfires between 1980 and 2000

in a stratified fashion to cover the main habitat types present within each of the 10-km^2 squares (Hirzel and Guisan 2002).

Scenario design

We designed 12 future environmental scenarios by combining four strategies of potential fire management aimed at mitigating the impact of large fires in Mediterranean-type novel forest ecosystems and two IPCC climate change scenarios (see Table 1). A set of fire management scenarios assumes that forest biomass extraction would reduce the impact of wildfires in forested areas, while fires would freely burn the shrubland and cropland areas (Evans and Finkral 2009; Becker et al. 2009; Abbas et al. 2011). In particular, we developed four scenarios wherein the annual area treated for biomass extraction is changing in extent and allocation (for more details, see scenarios 1–4 in Table 1). Moreover, we also envisaged a set of four exploratory scenarios characterised by decreasing fire suppression levels in years with mild weather conditions (scenarios 5–8 in Table 1). Fire management options based on 'let-burn' fire suppression strategies in mild years were found to have the potential to substantially reshape fire regimes and decrease the amount of area burnt under undesired, extreme climate conditions (Houtman et al. 2013; Regos et al. 2014). Furthermore, we designed another set of two scenarios representing business-as-usual trajectories (baseline of current trends) including the fire suppression policies currently implemented in Catalonia (scenarios 9 and 10 in Table 1). Another set of exploratory scenarios was characterized by no suppression as an extreme reference trajectory to the current trend (scenarios 11 and 12 in Table 1). All scenarios were implemented under two climate baselines (A2a and B2a). Each fire management strategy supports particular fire mosaics that comprise different arrangements of fire age-classes in the landscape, also affecting land cover-type dynamics.

The modelling framework

To quantify changes in distributional range of Dartford Warbler under fire management and climate change scenarios, we used a multiscale hierarchical modelling approach. Climate and land cover variables at different scales were integrated into the same modelling framework in

Table 1 List of future scenarios designed for Catalonia

ID	Scenario	Storyline	IPCC	Incentive/constrains
1	BioFS + A2	Forest harvesting in optimal areas from an environmental and economic viewpoint (~39,000 ha extracted annually)	A2a	Forest biomass extraction is not allowed in protected areas
2	BioFS + B2		B2a	Forest biomass extraction is not allowed in protected areas
3	BioFS + A2 plus	Forest harvesting in optimal areas from a logistic and economic viewpoint (~62,000 ha extracted annually)	A2a	–
4	BioFS + B2 plus		B2a	–
5	UnFS + A2	An opportunistic fire suppression strategy based on low decreasing active firefighting efforts in controlled "mild" fire weather conditions to provide further firefighting opportunities in adverse years	A2a	6,500 ha/year to burn in climatically mild years
6	UnFS + B2		B2a	6,500 ha/year to burn in climatically mild years
7	UnFS + A2 plus	An opportunistic fire suppression strategy based on high decreasing active firefighting efforts in controlled "mild" fire weather conditions to provide further firefighting opportunities in adverse years	A2a	52,000 ha/year to burn in climatically mild years
8	UnFS + B2 plus		B2a	52,000 ha/year to burn in climatically mild years
9	Base + HighFS + A2	Strong active suppression corresponding to current fire suppression levels	A2a	–
10	Base + HighFS + B2		B2a	
11	NoFS + A2	No fire suppression	A2a	–
12	NoFS + B2		B2a	–

Each scenario is a combination of a climatic baseline (A2a and B2a) and fire management strategy (BioFS, UnFS, HighFS and NoFS)

three steps: (1) climate envelope models were calibrated at a European scale to capture the climate niche and physiological tolerance range of the species (Pearson et al. 2004) and then directly downscaled at the Catalan scale; (2) land-cover models were calibrated and projected at the Catalan scale; and (3) a final third set of models was performed using as predictors the outcomes of climate and land cover models developed in the two first steps.

Environmental data

Environmental predictors used in the distribution models for each scale (European and Catalan) were selected according to our research goals and the previous ecological knowledge available for Dartford Warbler (Pons and Prodon 1996; Herrando et al. 2001; Pons et al. 2012). We followed Pearson et al. (2004) and used climate variables to model the distribution of Dartford Warbler in the whole of Europe, as this extent encompasses more than 95 % of global distribution and thus allows us to capture the whole of the species' realized climatic niche. Climate predictors were selected by expert knowledge and according to previous scientific literature: (1) maximum temperature of warmest month; (2) minimum temperature of coldest month; and (3) annual precipitation. Three additional predictors were also considered after testing multicollinearity problems (Spearman's rho correlation coefficient <0.7); (4) mean diurnal range; (5) precipitation seasonality; and (6) precipitation in warmest quarter. The current climatic data were obtained from the WorldClim database (http://www.worldclim.org/current/) and future climatic projections from the International Center for Tropical Agriculture (ICTA) (http://ccafs-climate.org/) (IPCC 2007). These current climatic data were generated by interpolated climate data from the 1950–2000 period. Future climate change projections were computed from an average ensemble (ENS) model of four GCMs (CCCMA-CGCM2, CSIRO-MK2.0, HCCPR-HadCM3 and NIESS99) to account for the uncertainty arising from the inter-model variability. These projections were available at 30 arc-s (~1 km) resolution by the application of delta downscaling method on the original data from the IPCC Fourth Assessment Report (provided by ICTA) for time-slide 2050 (2040–2069).

Fire-mediated landscape dynamics were addressed at the Catalan scale using a landscape dynamic modelling approach. We used a MEDFIRE simulation model, a spatially-explicit dynamic fire-succession model designed to integrate climatic and anthropogenic drivers and allow the investigation of their combined effect on fire regimes and land cover at short- and medium-term time-scales in a Mediterranean context (Brotons et al. 2013). This model allows the prediction of changes in landscape properties and composition derived from spatial interactions between wildfire, vegetation dynamics and fire management strategies (a detailed description of the model can be found in

Brotons et al. 2013 and Regos et al. 2014). In the MEDFIRE, the potential burnt area and fire size distributions depend on the climatic severity of the year: (1) A2-IPCC scenarios: the probability of a year being adverse (characterized by higher proportion of large wildfires compared to the distribution corresponding to mild years) increases from 0.30 to 0.59 for time-slice 2050 (2040 and 2069); and (2) B2-IPCC: the probability of a year being adverse increases from 0.30 to 0.62 for time-slice (more details in supplementary Appendix 1). Initial landscape composition and properties are represented by means of two raster dynamic layers at 100-m resolution for year 2000: Land cover type (LCT) and time since last fire (TSF). Information of landscape composition is obtained from the land cover categories: (1) coniferous and (2) oak tree species, (3) shrubland as dynamic variables, and (4) cropland as a static variable. Detailed knowledge of the fire-mediated properties of landscapes is achieved through proportional extent of different three fire age-classes: (5) older vegetation (>30 years since fire) (6) mid-age vegetation (10–30 years since fire), and (7) recently burnt vegetation (<10 years since fire). All spatial layers were simulated 10-fold under each of the fire management scenarios for - year 2050 using the MEDFIRE model. The percentage of area covered by each variable was calculated within 1 km × 1 km cells to match them with the bird data resolution.

Model fitting and evaluation

Combining different modelling algorithms has been proposed as an approach to adjust inherent uncertainty of individual models, and to determine an optimal solution from an ensemble of predictions (Araújo and New 2007; Thuiller et al. 2009). Ensemble models, built on a series of competing models, each with a different combination of environmental predictors, may provide more informative and ecologically correct predictions (Thuiller 2003). We used the BIOMOD2 modelling tool (Thuiller et al. 2009; BIOMOD package is available at http://r-forge.r-project.org/projects/biomod/) for fitting ensemble models on the Dartford Warbler. We fitted models using five distinct techniques: (1) generalized linear models (GLM) (McCullagh and Nelder 1989); (2) generalized additive models (GAM) (Hastie and Tibshirani 1990); (3) classification tree algorithms (CTA) (Breiman et al. 1984); (4) generalized boosted regression Models (GBM) (Friedman et al. 2000); and (5) random forest (RF) (Breiman 2001). The area under the curve (AUC) of the receiver-operating characteristic (ROC) was used as a means to evaluate the performance of the models (Elith et al. 2006). We used a 10-fold split-sample procedure keeping 30 % of the initial data out of the calibration for the subsequent validation of the predictions. The European projections downscaled at the Catalan level were validated against the occurrence data of CBBA. We applied the weighted average approach for computing a consensus of any single model with AUC >0.7 using AUC values as model weights, which significantly increases the accuracy of species distribution forecasts (Araújo and New 2007; Marmion et al. 2009). Response curves for each algorithm used for building the final models were represented in three-dimensional plots using the Evaluation Strip method proposed by Elith et al. (2005). This method enabled us to compare the predicted responses from the different statistical approaches on the same data and to infer the importance of each predictor in the final model.

Boolean maps (presence/absence) were calculated from the probability layers to define two levels of habitat suitability (HS) for each projection, using two thresholds with applied ecological meaning: (1) we defined as species distribution areas (in terms of prevalence of the data used in the model development) those with habitat suitability values above the lowest 10 % HS percentile of available occurrences (Thresh1; hereafter "DIST"); and (2) within these distribution areas, we applied a second level threshold aimed at identifying optimal habitat suitability areas for the species. These were defined by setting a new threshold from the average of the suitable values within the DIST (Thresh2; hereafter "OpHS"). Optimal HS may be interpreted in the context of the European Birds directive as the best areas for the species and therefore those potentially to be included within Natura 2000 sites (Herrando et al. 2011; Arcos et al. 2012). In total, we projected 480 potential distribution maps for future environmental conditions (12 scenarios × 10 replicates × 2 steps × 2 thresholds).

Evaluation of potential changes

We counted the grid cells (100 ha) with probability values larger than each pre-specified presence threshold to estimate the extent of areas predicted as DIST and OpHS. We calculated the predicted gains and losses between 2000 and 2050 for each scenario from the models derived from land cover predictors (step 2) and from land cover and climate predictors (step 3) in order to infer the effect of climate in combination with fire-conducted landscape dynamics.

Results

The predictive accuracies of Dartford Warbler ensemble forecasts were good ($AUC_{LCT} = 0.898$). The inclusion of climate envelopes into the land cover ensemble models further improved their modelling performance ($AUC_{LCT+CLIM} = 0.947$). The high accuracy performance

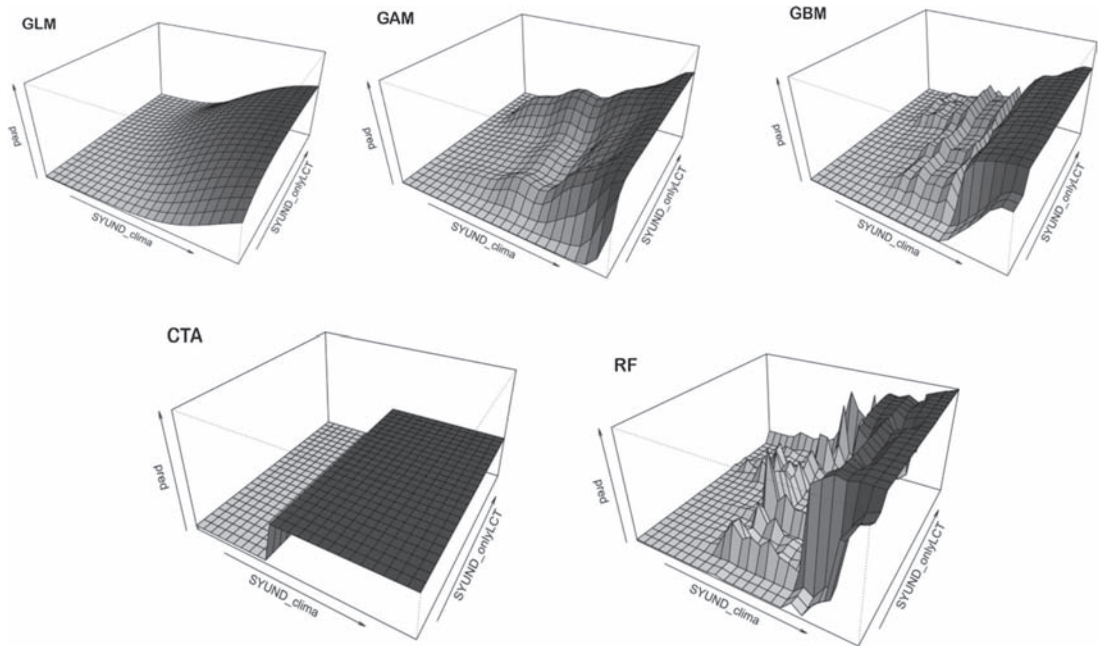

Fig. 2 Reponses to climate and land cover predictors at Catalan scale for the five algorithms considered: generalized linear models (GLM), generalized additive models (GAM), generalized boosted regression models (GBM), classification tree algorithms (CTA), and random forest (RF). Axes labels: the probability of occurrence (*pred*), climate (*SYUND_clima*) and land cover (*SYUND_onlyLCT*) predictors. The unit of measurements ranges between 0 and 1

obtained at the European scale ($AUC_{EU-CLIM} = 0.995$) shows a strong correlation between Dartford Warbler occurrence and the selected climate variables. However, the accuracy of climate models downscaled at a regional level was very low ($AUC_{CAT-CLIM} = 0.57$). This is in agreement with the importance of predictors in the final model (see response curves in Fig. 2) showing that landscape properties and composition are constraining the final Dartford Warbler distribution at finer scales.

The results derived from the analysis of different scenarios showed a strong effect of fire management strategy on Dartford Warbler potential distribution area. The DIST of Dartford Warbler decreased up to 40 % under the current fire suppression levels between 2000 and 2050 (see scenarios Base + HighFS in Figs. 3, 4). The optimal habitat suitability (OpHS) under these scenarios showed an average decrease of 56 %. The losses in habitat suitability decrease as fire suppression levels tend to be relaxed and annual burnt area increases (see scenarios Base + HighFS, UnFS and UnFS plus in Figs. 3, 4). Fire suppression strategies based on letting unplanned fires burn in mild weather conditions has the potential to create sparsely forested and early-succession habitats and increase the distribution range of the species (Figs. 3, 4), thus partially offsetting the overall trend of forest expansion recorded over the next 50 years in business-as-usual scenarios (Table 2). The decrease in optimal habitat suitability ranged between 20 and 43 % under biomass extraction scenarios (BioFS scenarios in Figs. 3, 4), thus slightly lower values than in scenarios with the current high fire suppression levels (Base + HighFS). Climate changes had a clear effect on Dartford Warbler distribution area (compare land cover and climate models with land cover models in Fig. 3). We found stronger declines in habitat suitability under IPCC scenario A2 than B2 (compare A2 and B2 scenarios in results of land cover and climate models; Fig. 3). The direct effect of climate change on Dartford Warbler distribution was clearly stronger than its indirect effect through the changes in fire regime (compare A2 and B2 scenarios of land cover and climate models with land cover models; Fig. 3).

Discussion

The European breeding population of the Dartford Warbler, which constitutes more than 95 % of the global population, was supposed to undergo a considerable

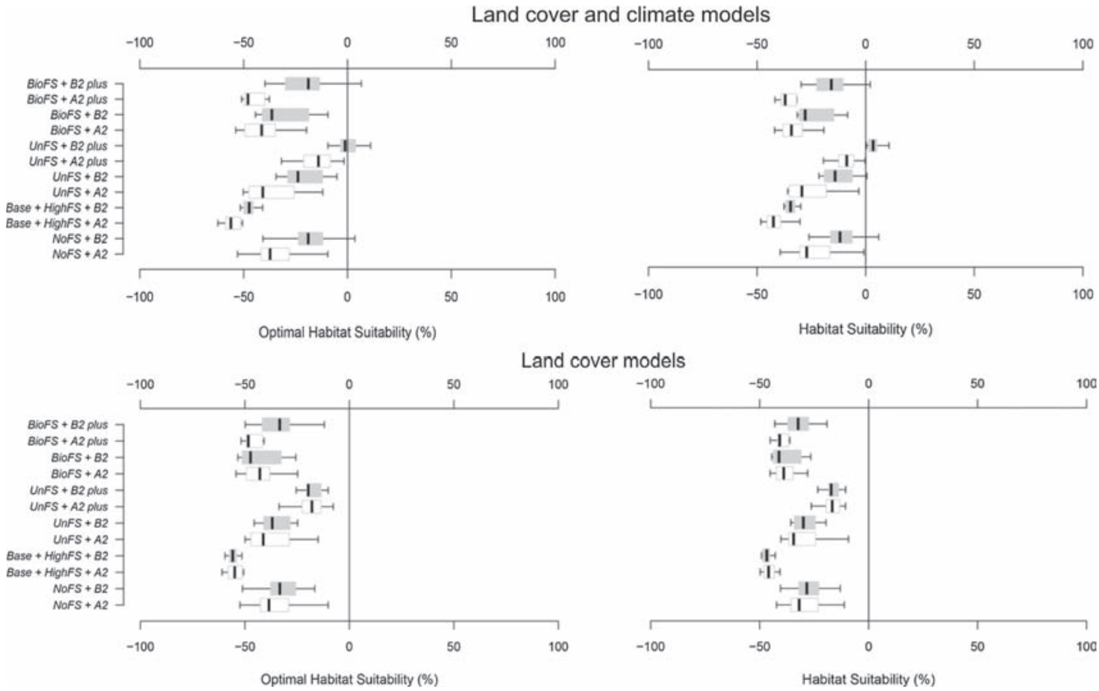

Fig. 3 Predicted changes (expressed in %) in optimal habitat suitability (calculated after applying Thresh2 to the probability layers) and habitat suitability (calculated after applying Thresh1) between 2000 and 2050 under each future scenario obtained from models exclusively performed with land cover variables (land cover models) or considering the interaction between climate and land cover change (land cover and climate models). The scenarios are described in Table 1

decline during the 1970–1990 period (Tucker and Heath 1994). The population trend for the species as shown by the Pan-European Common Bird Monitoring Scheme suggests that it declined by 17 % in the period 1998–2011 PECBMS (2013), so it has recently justified uplisting the species to a higher threat category (Birdlife International 2014). The stronghold of the species is located in Spain which holds 983,000–1,750,000 pairs (Martí and Del Moral 2003), but the populations there have declined by an average of 4.6 % (95 % CI: 6.2–3.1) per year during 1998–2011 according to the Spanish common bird monitoring scheme (SACRE) (SEO/BirdLife 2010). Our study also predicts large habitat suitability losses in Catalonia mainly derived from successional losses and land abandonment (ranging between 47 and 57 % in baseline scenarios), but these losses can be strongly modulated by fire regime shifts conducted by fire management, together with climate change. Our results thus highlight the need to take the spatial interaction among climate change, fire-mediated landscape dynamics and fire management policies in highly dynamic and fire-prone ecosystems into account to accurately predict habitat suitability changes of early-succession bird species in a context of global change.

The amount of area burnt by wildfires has decreased in Catalonia since the introduction of new fire suppression policies and the creation in 1999 of a specific technical fire brigades (GRAF) (Brotons et al. 2013). According to our projections, the habitat suitability of Dartford Warbler will strongly decrease between 2000 and 2050 due to pine and oak forest expansion caused by natural succession processes favoured by these high fire suppression levels (Fig. 3; Table 2). This decline could only be counterbalanced by a large-scale change in the use of forests and open habitats in the region or by progressive decrease in fire suppression levels and a subsequent increase in the annual burnt area (Figs. 3, 4). The use of unplanned fires resulting from decreasing suppression efforts are tactics that use fire as a tool to fight larger wildfires, and that aim to increase the effectiveness of fire suppression through fuel reduction (Regos et al. 2014). Unplanned fires increase landscape heterogeneity, offsetting the decade-long general trend towards homogenization due to land abandonment and the coalescence of natural vegetation patches (Table 2). Thus, early-successional species such as Dartford Warbler could be favoured in the future by this fire management policy, especially in those areas strongly affected by land

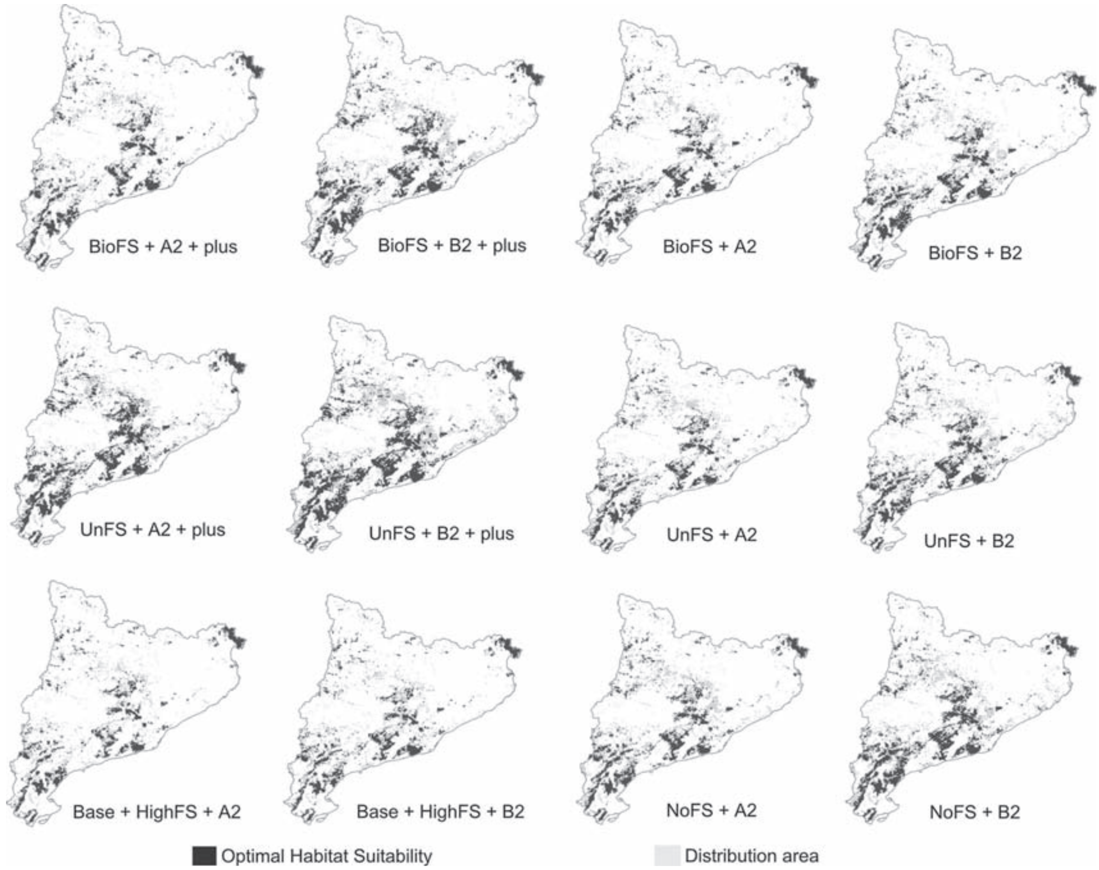

Fig. 4 The potential distribution areas (*grey*) and optimal habitat suitability (*black*) in 2050 under future scenarios. The maps were generated from averaging the probability layer and applying subsequent thresholds (Thresh1 and 2, respectively) for each 10 replicates performed in each scenario simulation. The scenarios are described in Table 1

abandonment processes. Forest biomass extraction for bioenergy purposes has also been proposed as a fuel-reduction treatment aimed at suppressing forest fires (Evans and Finkral 2009; Becker et al. 2009; Abbas et al. 2011). This forest management option may help in reducing the impact of wildfires in forested areas, while fires could burn the shrubland and cropland areas to a greater extent. Nevertheless, it is also important to note that forest biomass extraction (or logging) can increase the density of vegetation in lower forest layers, potentially increasing vegetation flammability but also providing temporary habitat for other shrubland species (Stephens 1998; Fenton et al. 2009; King et al. 2011). Our simulations showed that fire suppression strategies exclusively focused on forest areas have the potential to counterbalance the negative effect of shrub–forest succession on the distribution of the Dartford Warbler, but not to the same degree as those scenarios that include a larger number of fire events and a greater area burnt (Fig. 3). Landscape gradients induced by fire may potentially enhance the resilience of threatened open-habitat bird species by increasing the range of potential habitat used and their ability to colonize recently burnt areas (Brotons et al. 2005; Vallecillo et al. 2007). In particular, the Dartford Warbler can colonize burnt areas as soon as the second year after fire, even when it was absent before (Pons et al. 2012). However, the effects of wildfires on open-habitat-dwelling species hinge on the frequency and extent of burnt areas. If a fire regime characterized by small- and medium-sized fires prevails over the long term, local-scale heterogeneity introduced into the landscape may favour metapopulation dynamics for such species by maintaining a dynamic pool of suitable habitat patches that are colonized after perturbation from nearby suitable habitats. In contrast, a spread of extensive wildfires will

Table 2 Predicted changes (%) of different habitats and landscape properties in Catalonia (north-east Spain) under 12 future scenarios

	Coniferous	Oak	Shrub	Recently burnt	Mid-age	Old-age
BIOFS + A2	9.69	26.69	−44.53	−0.82	72.99	−2.31
BIOFS + B2	8.96	26.96	−43.86	4.51	73.70	−2.57
BIOFS + A2 PLUS	11.91	25.91	−46.59	−8.78	58.06	−1.47
BIOFS + B2 PLUS	8.98	26.61	−43.48	−12.61	133.10	−3.70
UNFS + A2	9.60	27.09	−44.87	9.68	110.07	−3.98
UNFS + B2	9.14	27.55	−44.81	3.21	120.71	−4.03
UNFS + A2 PLUS	−1.76	30.26	−33.36	71.87	266.16	−11.82
UNFS + B2 PLUS	−1.72	30.62	−33.84	28.88	298.96	−10.92
NOFS + A2	5.15	28.66	−40.76	27.53	138.19	−5.69
NOFS + B2	4.65	28.98	−40.45	34.71	136.35	−5.96
BASE + HIGHFS + A2	18.68	23.89	−53.30	−61.72	−22.51	3.53
BASE + HIGHFS + B2	18.57	24.06	−53.35	−61.16	−25.71	3.60

The habitats are: (1) coniferous and (2) oak tree species, and (3) shrubland; and the fire-mediated properties of landscapes: (4) recently burnt vegetation (<10 years since fire) (5) mid-age vegetation (10–30 years since fire), and (6) older vegetation (>30 years since fire). The scenarios are described in Table 1

initially favour open-habitat birds, but the habitat may soon turn unsuitable until new perturbations generate open habitats again (Brotons et al. 2005; Watson et al. 2012; Taylor et al. 2013; Kelly et al. 2014). This emphasises the importance that fire management might have on long-term preservation of these species associated with early-successional stages in highly dynamic environments. Besides, it is also important to keep in mind that wildfires could negatively affect forest-dwelling birds, which would have major implications for conservation for other threatened and endangered species. Previous studies have already proved that large-scale forest maturation and spread due to land abandonment processes have counteracted the potentially negative effects of fires on forest bird distributions in the Mediterranean Basin (Herrando and Brotons 2002; Gil-Tena et al. 2009). Since vegetation encroachment has been a major driving force for the avifauna in Catalonia over the last decade (Herrando et al. 2014), fire management programs aimed at effectively preserving open-habitat species could be reasonably integrated into current conservation plans without large negative impacts for forest species across the region. The removal of snags after a fire by extensive application of post-fire management practices such as salvage logging has negative impacts on forest birds in Mediterranean ecosystems, but also positive effects on a number of open-habitat species (Rost et al. 2012, 2013). On these grounds, we suggest that managers maintain some standing dead trees during post-fire logging operations to provide suitable habitat for the widest range of species (Rost et al. 2012). Nonetheless, further research considering a broader community perspective would be highly desirable in order to provide new insights that could help decision-making processes in conservation.

Regarding the effect of climate, our models showed that it is a main factor in determining the Dartford Warbler's distribution at large scales. Conversely, at regional scales, the species distribution is strongly constrained by landscape properties and composition (Figs. 2, 3). Nevertheless, the inclusion of climate at a regional scale also increased the predictive accuracies of the final model: the combined effect of both factors, climate and landscape, provides better predictive capabilities, as has already proved for other taxa, scales and regions (Pearson et al. 2004; Lomba et al. 2010; Cumming et al. 2013). Our simulations showed a larger loss in habitat suitability on Dartford Warbler distribution under IPCC scenario A2 than B2, mostly owing to the direct effect of climate change rather than to the indirect effect through the changes in the fire regime (Fig. 3).

In addition, an indirect effect of climate through the changes in natural succession could be affecting the response of the species to the newly burnt areas. In the driest areas of Catalonia, it has been found that the species colonises later, or remains confined to unburnt patches. The peak of highest abundance may occur as soon as the fourth year after fire or later, up to the ninth year (Pons and Clavero 2010). This delayed response was likely due to the slow plant regeneration resulting from a colder climate and higher grazing pressure in the mountain area (Pons et al. 2012). This mountain area is distributed across the northernmost part of Catalonia which is also the area less affected by fires (see Fig. 1; Díaz-Delgado et al. 2004). We suggest that, in addition to the fire management strategies discussed here, prescribed burning programs in mountain areas could help to maintain this species in the north of Catalonia.

Conclusions

Deeper insights on the temporal and spatial factors that interact to determine current landscape patterns and species responses are essential if we want to understand and manage the future outcome of biodiversity responses in Mediterranean systems. The generality of these constraints suggest that successful application of species distribution modelling to the prediction of species distribution dynamics in other conditions should be developed under a similar integrative, ecologically sound framework. In particular, our findings suggest that fire management programs must be integrated into conservation plans to effectively preserve sparsely forested and early-succession habitats and their associated species in the face of global change.

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SUPPORTING INFORMATION

Fire management, climate change and their interacting effects on birds in complex Mediterranean landscapes: dynamic distribution modelling for a model early-successional species–the near-threatened Dartford Warbler (*Sylvia undata*)

Appendix 1 – Detailed description of the climate scenarios: Linking IPCC's scenarios with MEDFIRE model simulations.

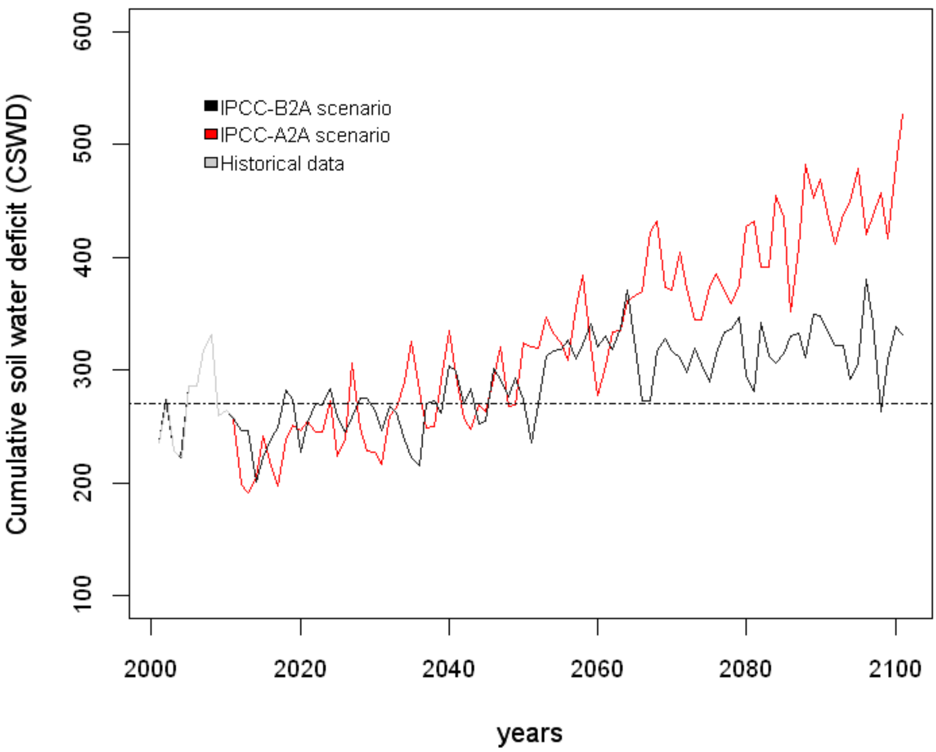
The IPCC's Special Report on Emissions Scenarios (SRES) (IPCC 2000) describes the relationships between the forces driving GHG emissions and their evolution during the 21st century. The scenarios defined in the SRES range from fossil-fuel intensive to alternative futures involving rapid adaptation of new technologies. We selected A2 and B2 scenarios as they describe a "regionalisation" leading to a heterogeneous world development opposed to "globalization" tending to a homogeneous world development described in the A1 and B1 storylines. A2a describes a highly heterogeneous future world with regionally oriented economies. The main driving forces are a high rate of population growth, increased energy use, land-use changes and slow technological change. The B2a is also regionally oriented but with a general evolution towards environmental protection and social equity.

In the MEDFIRE model different fire size distributions are used depending on the climatic severity of the year. Adverse years are characterized by a high number of weather risk days (Piñol et al. 1998). Therefore, the distribution of fire sizes corresponding to adverse years specifies a higher proportion of large wildfires compared to the distribution corresponding to normal (non-adverse) years (Brotons et al. 2013). The potential total area to be burnt is also drawn from a statistical distribution that differs between adverse and mild years.
In order to develop coherent and plausible climate scenarios in our fire simulations we need to define climatic treatments that can encompass possible future trends in fire regimes for the study area according to the IPCC-SRES climate scenarios (A2a and B2a "regionalization" storylines). For this purpose, according to the methodology developed in De Cáceres et al. (in prep) we calculated a *Cumulative soil water deficit* (CSWD; in mm of water) index based on regional climatic records for the period 1980–2010 and determined which years could be considered as meteorologically adverse (Fig. 1).

Cumulative soil water deficit (CSWD; in mm of water) is defined as the average between the annual cumulative soil water deficit of the current and preceding years. We adopted a Thornthwaite-type (Thornthwaite and Mather 1955) approach to estimate CSWD and calculated its value accounting for the effects of slope and aspect on potential evapotranspiration and within-catchment water redistribution. Historical records of total area burned and fire sizes were assembled for years of the 1975 – 1999 period (Díaz-Delgado et al. 2004; González-Olabarria and Pukkala 2007). Assuming that drier years imply lower fuel moisture and usually lead to larger impact of summer wildfires(Pausas and Paula 2012), we used a threshold of 270 mm in the CSWD regional average to separate years with 'mild' summer conditions and years having 'adverse' summer conditions (exceptionally dry years that can lead to very large convective fires).

We then estimated the historical trend in the probability of having an adverse year, and used the resulting trend to define two climatic treatments: 1) A2: the probability of a year being adverse (*Pad-yr*) increases from 0.30 to 0.59 for time-slice 2050 (2040 and 2069); 2) B2: the probability of a year being adverse increases from 0.30 to 0.62 for time-slice 2050 (2040 and 2069).

Fig. 1. Historic (2000 – 2010) and predicted (2010 – 2100) sequence of cumulative soil water deficit (regional averages) for IPCC-A2a and IPCC-B2a scenarios in Catalonia. The dashed line shows the reference value (270) considered as threshold that enabled us to define every year as adverse or mild.



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CHAPTER

IV

PREDICTING THE FUTURE EFFECTIVENESS OF PROTECTED AREAS FOR BIRD CONSERVATION IN MEDITERRANEAN ECOSYSTEMS UNDER CLIMATE CHANGE AND NOVEL FIRE REGIME SCENARIOS

By

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BIODIVERSITY RESEARCH

Predicting the future effectiveness of protected areas for bird conservation in Mediterranean ecosystems under climate change and novel fire regime scenarios

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ABSTRACT

Aim Global environmental changes challenge traditional conservation approaches based on the selection of static protected areas due to their limited ability to deal with the dynamic nature of driving forces relevant to biodiversity. The Natura 2000 network (N2000) constitutes a major milestone in biodiversity conservation in Europe, but the degree to which this static network will be able to reach its long-term conservation objectives raises concern. We assessed the changes in the effectiveness of N2000 in a Mediterranean ecosystem between 2000 and 2050 under different combinations of climate and land cover change scenarios.

Location Catalonia, Spain.

Methods Potential distribution changes of several terrestrial bird species of conservation interest included in the European Union's Birds Directive were predicted within an ensemble-forecasting framework that hierarchically integrated climate change and land cover change scenarios. Land cover changes were simulated using a spatially explicit fire-succession model that integrates fire management strategies and vegetation encroachment after the abandonment of cultivated areas as the main drivers of landscape dynamics in Mediterranean ecosystems.

Results Our results suggest that the amount of suitable habitats for the target species will strongly decrease both inside and outside N2000. However, the effectiveness of N2000 is expected to increase in the next decades because the amount of suitable habitats is predicted to decrease less inside than outside this network.

Main conclusions Such predictions shed light on the key role that the current N2000 may play in the near future and emphasize the need for an integrative conservation perspective wherein agricultural, forest and fire management policies should be considered to effectively preserve key habitats for threatened birds in fire-prone, highly dynamic Mediterranean ecosystems. Results also show the importance of considering landscape dynamics and the synergies between different driving forces when assessing the long-term effectiveness of protected areas for biodiversity conservation.

Keywords
biodiversity management, bird conservation, hierarchical approach, land abandonment, land cover change, MEDFIRE model, multiscale modelling, species distribution models, vegetation dynamics.

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INTRODUCTION

Global change poses a daunting challenge to any large-scale planning effort, such as the implementation of biodiversity conservation and management strategies (Kukkala & Moilanen, 2013). In a dynamic socio-ecological system, traditional conservation approaches based on the selection of static protected areas (hereafter PAs) are increasingly questioned due to their limited ability to incorporate the future impact of changing conditions (e.g. climate change, land cover change) on biodiversity (Rayfield *et al.*, 2008; Le Saout *et al.*, 2013; Leroux & Rayfield, 2014). Although protected areas have proven to be effective for the protection of species against ongoing human threats, many species might shift their distributions outside existing protected areas under climate change scenarios (Araújo *et al.*, 2004, 2011; Alagador *et al.*, 2014). This issue may raise particular concern in highly dynamic environments such as fire-prone ecosystems where climate change could act in synergy with vegetation encroachment following land abandonment and move natural fire regimes out of their historical range (Pausas & Fernández-Muñoz, 2011; Batllori *et al.*, 2013).

Wildland fires are a major component of disturbance regimes in Mediterranean-type ecosystems world-wide (Keeley *et al.*, 2012). Current global circulation models (GCMs) and climate change scenarios forecast higher burning frequencies and larger burnt areas due to greater severity of weather conditions in the future (Piñol *et al.*, 1998; De Groot *et al.*, 2013; Flannigan *et al.*, 2013). Current fire suppression policies will be challenged in the future and alternative fire management strategies will likely be applied to achieve the stand structure and fuel reduction objectives required to minimize the impact of undesired fires (Liu *et al.*, 2010; McIver *et al.*, 2012; Moritz *et al.*, 2014). However, it is still largely unknown how these new fire management strategies could impact on ecosystems and biodiversity. In particular, the effectiveness of PAs for biodiversity conservation in a medium-term future has never been evaluated under novel fire regime scenarios and fire management strategies.

In Europe, Natura 2000 (hereafter N2000) is a network of PAs that constitutes the backbone of biodiversity conservation. N2000 is, however, implemented in a static manner and the degree to which it will be able to meet its conservation objectives under changing conditions in the future remains a major question (Hole *et al.*, 2009; Trouwborst, 2011; Van Teeffelen *et al.*, 2014). N2000 is based on the Birds Directive (79/409/EEC, amended in 2009: 2009/147/EC) and the Habitats Directive (92/43/EEC, consolidated in 2007) of the European Union. This network is targeted at ensuring the long-term survival of Europe's most valuable and threatened species and habitats listed in the annexes of these two directives. N2000 is not a system of strict nature reserves where all human activities are excluded: the emphasis of the system relies on the sustainability of future management within the PAs, both from ecological and socio-economical perspectives. Therefore, a better understanding of the interactions between climate change and large-scale future land management and of their future effects in terms of biodiversity conservation inside these PAs is needed at the earliest (Le Saout *et al.*, 2013; Virkkala *et al.*, 2013; Coetzee *et al.*, 2014).

Comparing changes in biodiversity inside and outside PAs has proved to be an efficient option in assessing the protection effectiveness and reporting on the initial status of biodiversity (Johnston *et al.*, 2013; Barnes *et al.*, 2015). Such an approach may help assess whether N2000 is fulfilling the requirements of European Commission's conservation policy goals and to provide a starting point for future evaluations of the network. The future effectiveness of the PAs has been already evaluated under climate change (Araújo *et al.*, 2007; D'Amen *et al.*, 2011; Johnston *et al.*, 2013) and land use change (Pouzols *et al.*, 2014) scenarios at large scales for a variety of species groups, but their interactions at fine scale in dynamic landscapes have not been considered yet. In fire-prone ecosystems like in the Mediterranean region, the effect of wildfires and fire suppression policies should be explicitly considered as they are expected to interact closely with climate change and to produce a range of positive and negative effects on biodiversity (Taylor *et al.*, 2013; Vallecillo *et al.*, 2013; Kelly *et al.*, 2014). In this respect, forest management practices and vegetation encroachment in previously abandoned cultivated areas are key driving forces as they may affect natural fire regimes and, in turn, land cover dynamics in the short to medium term (e.g. James *et al.*, 2007; De Cáceres *et al.*, 2013; Herrando *et al.*, 2014).

Here we integrated climate change scenarios at continental scale with simulations of vegetation dynamics at regional scale in a hierarchical manner to evaluate the future combined effect of multiple driving forces on a sample of conservation interest bird species. We used a storyline-and-simulation approach (De Chazal & Rounsevell, 2009) where storylines describe potential fire suppression and land management policies in a Mediterranean-type ecosystem, and simulations reinforce storylines with numerical estimates of future environmental changes. We predicted changes in the distribution of 23 bird species of conservation interest included in the Birds Directive under climate change and novel fire regime scenarios between 2000 and 2050. We focused on the distribution changes in bird species that are expected to respond to fire, vegetation encroachment and climate change in the future. Based on the future predictions, we assessed the long-term effectiveness of N2000 in allowing the future persistence of relevant habitats for these target species in Catalonia. To evaluate whether N2000 will ensure its key conservation role in the next decades, we tested the hypothesis that relevant habitats for the target bird species will be more efficiently preserved within this network of PAs than in areas without such a European protection status.

METHODS

Study area

The study was conducted in Catalonia, a region located in north-eastern Spain with a typical Mediterranean climate (Fig. 1). Its complex topography induces an important geographical variability in climate and weather conditions. The vegetation mainly includes forest and shrubland (CORINE, 2006), two land cover types that are most affected by fire (Díaz-Delgado *et al.*, 2004). Land abandonment due to the cessation of agricultural activities over the last decades has been followed by the conversion from abandoned open land (i.e. shrublands) to forest habitats (Herrando *et al.*, 2014). The interaction among such vegetation encroachment, fire suppression and climate change induces important modifications of the fire disturbance regime in this Mediterranean study region (Brotons *et al.*, 2013).

There are 115 Sites of Community Importance (SCIs) designed for the protection of habitats and species of Community interest (Habitats Directive) and 73 Special Protection Areas (SPAs) designed for the protection of birds of Community interest (Birds Directive) in Catalonia (Fig. 1). SCIs and SPAs cover 32% and 28% of the region, respectively, and their total combined extent is 10,624 km^2, 87% of which is covered by both SCIs and SPAs (GENCAT, 2013).

Bird data

We used presence/absence data for breeding bird species at two different spatial extents and resolutions: (1) European extent at a 50 km resolution and (2) Catalan extent at a 1 km resolution.

At the European level, bird data were obtained from the *EBCC Atlas of European Breeding Birds* (EBCC; Hagemeijer & Blair, 1997, available at http://s1.sovon.nl/ebcc/eoa/). This dataset documents the occurrence of breeding bird species in the 3165 50 km resolution squares in Europe according to a Universal Transverse Mercator (UTM) grid. Field data were mostly collected during the late 1980s and early 1990s.

At the Catalan level, bird data were obtained from the *Catalan Breeding Bird Atlas* (CBBA; Estrada *et al.*, 2004, available at http://www.sioc.cat/atles.php). The CBBA resulted from a large-scale survey conducted between 1999 and 2002 to cover the whole of the Catalonia using a grid system with 10 km resolution UTM squares. A total of 3076 1 km resolution squares (*c.* 9% of the total area) were selected to conduct standardized intensive surveys of species presence in a stratified fashion to cover the main habitat types present within each of the 10 km resolution squares (Hirzel & Guisan, 2002).

Among the 214 bird species that commonly breed in Catalonia, we only selected those included in the Annex I from the Birds Directive (European Parliament, 2010). We chose this set of species as indicators of conservation value at the European level, as they have a legal conservation status in Europe. From this set, we removed those species with < 30 occupied 1 km squares in Catalonia to ensure sufficient information is available for further analyses. As we focused here on the combined effect of climate change, vegetation encroachment due to land abandonment and fire regime on

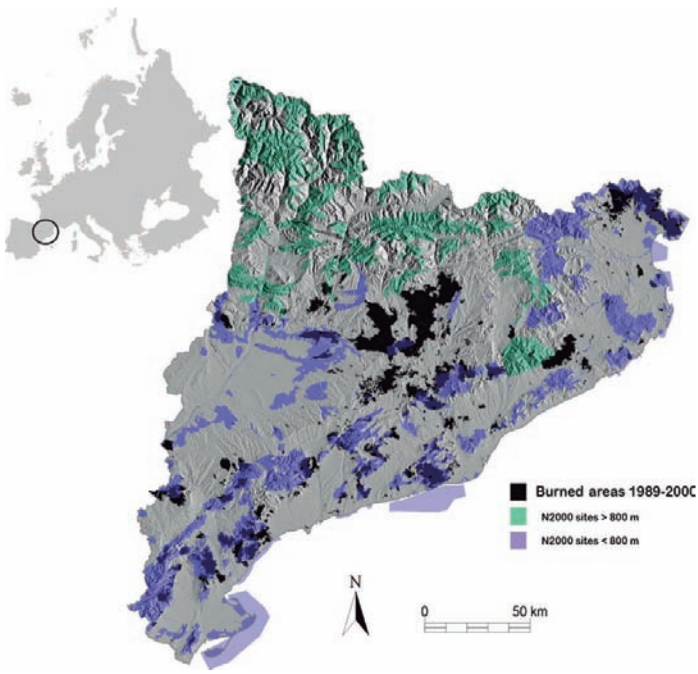

Figure 1 Location of the study area in Europe (black circle) and spatial distribution of the N2000 sites and wildfires occurred in Catalonia between 1989 and 2000.

birds, we also excluded those species that are not breeding in habitat types along the gradient from abandoned open land to forest. Hence, we focused on 23 species exhibiting different degrees of specialization from open habitats (i.e. early-successional stages and sparsely vegetated areas) to forest.

Climate data

We obtained current climate data (period 1950–2000; hereafter 2000s) from the WorldClim database (www.worldclim.org/current) and future climate scenarios (period 2040–2069; hereafter 2050s) from International Center for Tropical Agriculture (CIAT) (http://www.ccafs-climate.org). Future climate change projections were computed for A2 and B2 IPCC-SRES scenarios from an average ensemble model of four GCMs (CCCMA-CGCM2, CSIRO-MK2.0, HCCPR-HadCM3 and NIESS99) to account for the uncertainty arising from the intermodel variability (see Appendix S1). These four GCMs were selected as they provide a range of variability with respect to annual temperature and cumulative precipitation predictions (Naujokaitis-Lewis *et al.*, 2013). These projections were available at 30 arc seconds (*c.* 1 km) resolution and were resampled by estimating mean value within the specified grid cell to match the resolution of bird data in Europe and in Catalonia.

Landscape data

We used the MEDFIRE model to simulate future land cover changes derived from spatial interactions among fire regime, vegetation dynamics and fire management policies (Brotons *et al.*, 2013; De Cáceres *et al.*, 2013; Regos *et al.*, 2014). MEDFIRE is based on observed time series to simulate the future effect of primary processes driving vegetation dynamics and fire regime in the landscape (see Appendix S2). Vegetation encroachment due to land abandonment (hereafter land abandonment) is explicitly integrated into MEDFIRE to simulate the succession from abandoned open land to forest and its interaction with fire regime. To deal with the stochastic nature of wildfires, the land cover layers were then simulated 10 times (hereafter runs) for 2050 under the different combinations of six fire management scenarios and two climate change scenarios (Table 1, Appendix S2). To describe predicted vegetation changes under each scenario, we used the outputs of the simulation runs and we calculated the area occupied by each land cover type. Some land cover types do not influence fire dynamics (i.e. water, rocks and urban areas), whereas farmland was assumed to be static but to allow fire to spread through it. Fire can affect farmlands, but they do not directly shift to other habitat types after fire unless an additional land use change occurs.

Modelling framework

To estimate potential changes in habitat suitability for the target species between 2000 and 2050, we used a hierarchical approach integrating climate and land cover change scenarios at different scales in the same modelling framework (more details in Appendix S3). This approach required the following steps:

Step 1. – Climate models at the European level

We fitted species distribution models from EBCC bird data and climate variables at the European scale (hereafter climate models) to estimate the bioclimatic envelope of each species (Araújo *et al.*, 2005a; Barbet-Massin *et al.*, 2012). Model predictions under both current and future climate conditions were directly downscaled (Araújo *et al.*, 2005b; McPherson *et al.*, 2006) within the 1 km resolution squares in Catalonia.

Step 2. – Land cover models at the Catalan level

Higher resolution models for the target species were built from the CBBA bird data and land cover variables derived from the MEDFIRE model at the Catalonia level (hereafter land cover models). We predicted the probability of occurrence within each 1 km resolution square in Catalonia under current and future land cover scenarios.

Step 3. – Combined models at the Catalan level

Combined climate and land cover models (hereafter combined models) were built using the same dependent variables (bird occurrence from CBBA) and the same resolution (1 km) and extent (Catalonia) as in *Step 2*. They were developed using two predictors: (1) the outcomes of the climate model at 1 km resolution (*Step 1*) and (2) the outcomes of the land cover model at 1 km resolution (*Step 2*).

All the models were trained using five widely used algorithms (GLM, GAM, CTA, GBM and RF) implemented in the BIOMOD2 library in R (Thuiller *et al.*, 2009). We used a repeated (10 times) split-sample approach to produce predictions independent of the training data. Each model was fitted using 70% of the data and evaluated using the area under the curve (AUC) of a receiver operating characteristics (ROC) (Fielding & Bell, 1997) calculated on the remaining 30%. We applied an ensemble-forecasting framework by computing a consensus of single-model projections (from models with AUC > 0.7 using AUC values as model weights) using a weighted average approach (Araújo & New, 2007; Marmion *et al.*, 2009).

To quantify the changes in the effectiveness of N2000 between 2000 and 2050, high-quality habitats (hereafter optimal habitats) for the species need to be firstly identified. Probability outputs were hierarchically ranked in two levels of increasing suitability (Herrando *et al.*, 2011; Arcos *et al.*, 2012) (see Appendix S4 for a sensitivity analysis in selecting thresholds). These optimal habitat areas can be interpreted as critical habitats for our study species in line with the conservation mandate of the European directives.

Table 1 List of fire regime scenarios simulating future land cover changes in the study area. Each scenario is a combination of a climate (A2 and B2) and a fire management (BioFS, UnFS or HighFS) treatment. Asterisks indicate the business-as-usual scenarios. For more details, see Regos *et al.* (2015) and Appendix S2

ID	Scenario acronym	Scenario description	Storyline	Incentives/Constrains
1	BioFS + A2	Forest harvesting in optimal areas from an environmental and economic viewpoint (*c.* 39,000 hectares annually extracted) + climate trend according to the A2 IPCC-SRES climate scenario	Forest biomass extraction	Forest biomass extraction is prohibited in protected areas
2	BioFS + B2	Forest harvesting in optimal areas from an environmental and economic viewpoint (*c.* 39,000 hectares annually extracted) + climate trend according to the B2 IPCC-SRES climate scenario	Forest biomass extraction	Forest biomass extraction is prohibited in protected areas
3	BioFS + A2 plus	Forest harvesting in optimal areas from a logistic and economic viewpoint (*c.* 62,000 hectares annually extracted) + climate trend according to the A2 IPCC-SRES climate scenario	Forest biomass extraction	Forest biomass extraction is allowed in protected areas
4	BioFS + B2 plus	Forest harvesting in optimal areas from a logistic and economic viewpoint (*c.* 62,000 hectares annually extracted) + climate trend according to the B2 IPCC-SRES climate scenario	Forest biomass extraction	Forest biomass extraction is allowed in protected areas
5	UnFS + A2	An opportunistic fire suppression strategy based on lowly decreasing active firefighting efforts in controlled 'mild' fire weather conditions to provide further firefighting opportunities in adverse years + climate trend according to the A2 IPCC-SRES climate scenario	Let-burn	6500 hectares annually burnt in climatically mild years
6	UnFS + B2	An opportunistic fire suppression strategy based on lowly decreasing active firefighting efforts in controlled 'mild' fire weather conditions to provide further firefighting opportunities in adverse years + climate trend according to the B2 IPCC-SRES climate scenario	Let-burn	6500 hectares annually burnt in climatically mild years
7	UnFS + A2 plus	An opportunistic fire suppression strategy based on highly decreasing active firefighting efforts in controlled 'mild' fire weather conditions to provide further firefighting opportunities in adverse years + climate trend according to the A2 IPCC-SRES climate scenario	Let-burn	52,000 hectares annually burnt in climatically mild years
8	UnFS + B2 plus	An opportunistic fire suppression strategy based on highly decreasing active firefighting efforts in controlled 'mild' fire weather conditions to provide further firefighting opportunities in adverse years + climate trend according to the B2 IPCC-SRES climate scenario	Let-burn	52,000 hectares annually burnt in climatically mild years
9*	Base + HighFS + A2	Strong active fire suppression management corresponding to currently implemented strategy + climate trend according to the A2 IPCC-SRES climate scenario	Stop all fires	–
10*	Base + HighFS + B2	Strong active fire suppression management corresponding to currently implemented strategy + climate trend according to the B2 IPCC-SRES climate scenario	Stop all fires	–
11	NoFS + A2	No fire suppression strategy + climate trend according to the A2 IPCC-SRES climate scenario	No suppression	–
12	NoFS + B2	No fire suppression strategy + climate trend according to the B2 IPCC-SRES climate scenario	No suppression	–

Evaluation of simulation outcomes

To disentangle the relative role of climate change and land cover change in shaping the future distribution of the target species, we categorized the distribution change of the different species to each of these driving forces as positive, negative or neutral. To do so, we first estimated for each species the number of squares with optimal habitats in 2000 and for each scenario in 2050 according to the climate, land cover and combined models. Second, we calculated the relative changes in this number of squares between 2000 and 2050 (see Appendix S5). The number of species expected to be potentially affected by fire-induced land cover changes within a general context of climate change and land abandonment was estimated using generalized linear models (GLMs) with a Gaussian error distribution and 'identity' link function (Guisan *et al.*, 2002) (see Fig. S5.2). The effects were considered as significant at $P < 0.05$, and the number of species associated with a significant effect of fire suppression strategies in these GLMs was counted.

To summarize the response of bird species assemblages under each scenario, we counted the number of species predicted to gain or lose < 20%, between 20 and 50%, or more than 50% of squares with optimal habitats between 2000 and

2050, inside and outside N2000. To assess the extent to which N2000 will likely be able to maintain its role to ensure the persistence of key habitats for the target species under climate and land cover change scenarios, we first calculated the percentage of squares with optimal habitats inside N2000 relative to those in the whole study area and we used this percentage as a measure of effectiveness of N2000 in 2000 (Eff_{2000}) and in 2050 (Eff_{2050}). We tested whether the results inside and outside N2000 were significantly different using a Wilcoxon signed rank test for paired samples. Second, increase or decrease in effectiveness was estimated from the difference between Eff_{2050} and Eff_{2000} for each species under each scenario (Appendix S6). Third, we calculated the number of species for which N2000 is expected to increase or decrease in effectiveness by < 5%, by 5% to 10% and by more than 10% between 2000 and 2050.

In addition to a global analysis of the results over the whole N2000 network, we also explored the geographical variation in the decrease/increase of the number of squares with optimal habitats for the species and in the effectiveness of N2000 along the latitudinal/altitudinal gradient in Catalonia. We split the N2000 sites into two sets of PAs associated with different elevation ranges: (1) above 800 metres (> 800 m) and (2) below 800 metres (< 800 m) (Fig. 1). This elevation threshold was used to distinguish between PAs predominantly located in mountain areas (north of Catalonia) from those in the lowlands (south). The results obtained above and below 800 m were compared through a Wilcoxon signed rank test for paired samples.

RESULTS

Model accuracy

Climate models calibrated at the European scale efficiently captured the climate envelope of the species (mean $AUC_{EU\text{-}CLIM} = 0.97$), but when they were compared to the known distribution of the species in Catalonia, they fit only weakly because of low specificity values (mean $AUC_{CAT\text{-}CLIM} = 0.54$, Table 2). At such resolution, the distribution of the species is also constrained by land cover related factors, but downscaled climate models were considered as useful as they were able to capture the broad climate envelope of the species (mean sensitivity values above 0.70). The predictions based on climate variables could be subsequently refined with the inclusion of land cover variables at the Catalan level, as indicated by the higher predictive accuracy of the combined models (mean $AUC_{CLIM+LCT} = 0.93$) than that of the models based on land cover variables only (mean $AUC_{LCT} = 0.89$) (Table 2).

Table 2 Evaluation of predictive performance for ensemble models built with land cover variables only (Land cover), climate variables only downscaled from the European to the Catalan level (Climate) and with climate and land cover variables according to a multiscale hierarchical integration approach (Combined) for each bird species. AUC values are calculated for land cover, climate and combined models, whereas sensitivity and specificity are given only for climate models

Species	Acronym	AUC			Sensitivity	Specificity
		Land cover	Climate	Combined	Climate	Climate
Anthus campestris	ANCAM	0.912	0.590	0.957	0.91	0.18
Aquila chrysaetos	AQCHR	0.863	0.800	0.952	0.56	0.79
Bubo bubo	BUBUB	0.838	0.550	0.891	0.25	0.65
Caprimulgus europaeus	CAEUR	0.701	0.610	0.727	0.95	0.20
Circaetus gallicus	CIGAL	0.676	0.580	0.708	0.84	0.25
Dryocopus martius	DRMAR	0.913	0.910	0.98	0.89	0.84
Emberiza hortulana	EMHOR	0.926	0.600	0.969	0.66	0.54
Falco peregrinus	FAPER	0.818	0.540	0.859	0.99	0.00
Galerida theklae	GATHE	0.919	0.790	0.958	0.90	0.53
Gypaetus barbatus	GYBAR	0.926	0.840	0.984	0.25	0.96
Gyps fulvus	GYFUL	0.868	0.560	0.941	0.32	0.80
Hieraaetus fasciatus	HIFAS	0.98	0.750	0.997	0.91	0.39
Hieraaetus pennatus	HIPEN	0.901	0.650	0.971	0.61	0.68
Lanius collurio	LACOL	0.898	0.870	0.969	0.98	0.52
Lullula arborea	LUARB	0.76	0.670	0.883	0.94	0.14
Milvus migrans	MIMIG	0.811	0.550	0.866	0.60	0.38
Milvus milvus	MIMIL	0.936	0.750	0.991	0.82	0.68
Neophron percnopterus	NEPER	0.905	0.580	0.968	0.21	0.76
Oenanthe leucura	OEURA	0.997	0.770	0.999	0.77	0.62
Pernis apivorus	PEAPI	0.868	0.730	0.926	0.63	0.69
Pyrrhocorax pyrrhocorax	PYRAX	0.91	0.660	0.963	0.64	0.64
Sylvia undata	SYUND	0.898	0.570	0.947	0.81	0.29
Tetrao urogallus	TEURO	0.976	0.960	0.997	0.88	0.90
Mean		0.878	0.690	0.930	0.71	0.54

Predicted changes in habitat suitability for birds

A wide range of bird responses to climate change, to land cover change and to their combined effect were found. Overall, a larger number of species were predicted to show a negative than a positive response to climate change and to land cover changes (see effects of both drivers on Fig. 2 and Table S5.1). The combined effect of climate and land cover change in the future was therefore predicted to be negative for most of the target species (Fig. 2): only 3 and 1 species were predicted to show a neutral or positive response, respectively. For most species, a stronger effect (either positive or negative) of climate change was expected under the A2 than under the B2 scenario (Fig. 3 and Table S5.2). According to the results of the GLMs, 18 species of the 23 studied ones will potentially be affected by decisions in relation to the implementation of future fire suppression strategies within the general context of climate change and land abandonment, especially in lowland areas below an average elevation of 800 metres (Fig. S5.1 and S5.2).

Overall, the amount of optimal habitat in N2000 was significantly larger than non-protected areas in 2000 (Wilcoxon signed rank test, $P < 0.05$) and especially in 2050 ($P < 0.001$). Our results showed a strong decrease in the number of squares with optimal habitats for the target species between 2000 and 2050, both inside and outside N2000 (Fig. 3a,b). Inside N2000, although the amount of optimal habitat above and below 800 metres was not found to be significantly different ($P > 0.05$), the largest decreases were predicted in PAs below 800 metres, indicating a latitudinal/altitudinal gradient in the expected changes (Fig. 3c,d). Changes in the amount of optimal habitats largely varied among species and scenarios (see details in Appendix S5). The smallest decreases were predicted under scenarios of fire suppression strategies based on letting unplanned fires burn during mild weather conditions (UnFS plus in Fig. 3). This strategy is predicted to be particularly effective to counterbalance the negative effect of land abandonment in areas below 800 metres for open-habitat bird species such as the Ortolan Bunting (*Emberiza hortulana*) or the Dartford Warbler (*Sylvia undata*) (Fig. S5.1). The greatest number of species with decreasing amount of optimal habitats was found under business-as-usual scenarios (Base + HighFS scenarios in Fig. 3a,b). A great number of species were also predicted to undergo a decrease in the amount of optimal habitats outside PAs under forest biomass extraction scenarios (Fig. 3b), but this decrease is expected to be slightly smaller inside PAs (Fig. 3a).

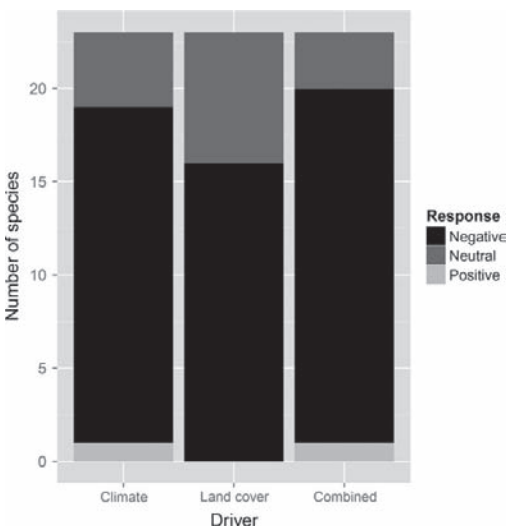

Figure 2 Number of species predicted to have a positive, negative or neutral response across the alternative climate, land use or combined models between 2000 and 2050. See detailed results for each species in Table S5.1.

Predicted changes in N2000 effectiveness

The future effectiveness of N2000 was expected to largely depend on the target species and the scenario of environmental change (Fig. 4a). Overall, the number of squares with optimal habitats for the target species is predicted to decrease less inside than outside N2000 (Fig. 4a,b). Hence, the effectiveness of N2000 will likely increase between 2000 and 2050, especially at elevations higher than 800 m (Fig. 4b). The potential of fire management policies to indirectly affect this effectiveness through fire-induced changes in the amount of optimal habitats will be higher in areas below 800 m (Figs 4c and S3).

DISCUSSION

Losses and gains in habitat suitability

To our knowledge, the present study is one of the most ambitious attempts so far to forecast biodiversity changes (i.e. multispecies responses) based on simulations of future vegetation dynamics and fire disturbance under climate change in a fire-prone Mediterranean region. The multiscale approach we implemented allowed us to predict the future changes in habitat suitability for conservation-concern bird species as a response to climate change and vegetation dynamics driven by fire-related disturbance regime and land abandonment. Our findings show that although the future response of the species to these changes is species specific, large decreases in the amount of optimal habitats are expected for most of the species (Fig. 3). In addition, our results also indicate that such a decrease in habitat suitability will be driven by both climate and land cover changes (Fig. 2). Interestingly, the response of a high number of species to these changes is predicted to vary substantially depending on the fire management practices that will be implemented in the future (Fig S5.2).

Despite the huge resources invested in fire suppression over the last decades in the Mediterranean region, wildfires

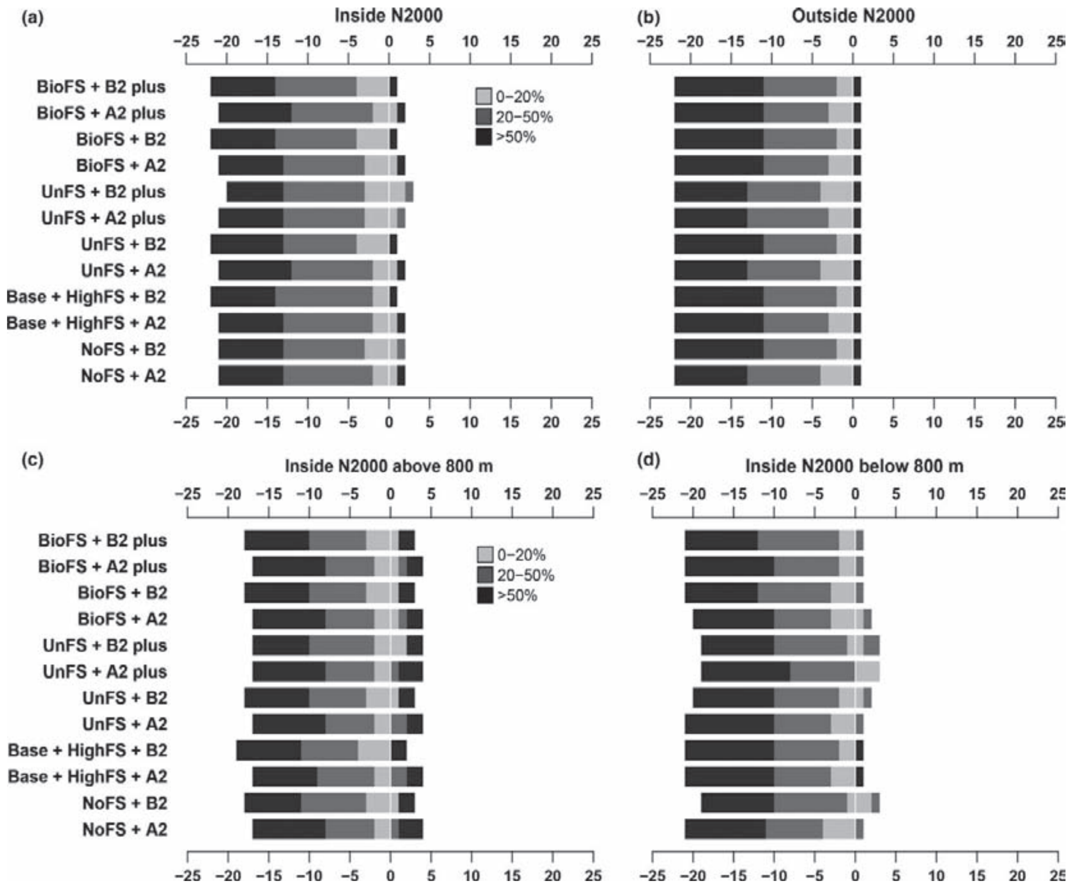

Figure 3 Number of species predicted to gain (positive values) or lose (negative values) < 20% (low-light grey), between 20 and 50% (medium-light grey) and more than 50% (dark grey) of their optimal habitats between 2000 and 2050 under each future scenario (see Table 1 for acronyms): (a) inside N2000, (b) outside N2000, (c) inside N2000 above 800 m and (d) inside N2000 below 800 m. Bar length reflects mean number of species across the different MEDFIRE runs simulating land cover changes.

are expected to increase their impact as a result of an interaction between vegetation encroachment due to land abandonment (Loepfe *et al.*, 2010; Moreira *et al.*, 2011) and harsher (i.e. drier and/or warmer) climate conditions (Piñol *et al.*, 1998; Turco *et al.*, 2014). The fire management option that is typically implemented in the study area involves large fire suppression efforts regardless of the climatic severity of the year. It is expected that this strategy will continue to be applied in a near future. According to our simulations, the greatest number of species with a decreasing amount of optimal habitats in the future is predicted under these business-as-usual scenarios (Base + HighFS scenarios). This pattern results from a combination between a negative effect of land abandonment and fire suppression strategies on open-habitat species and a negative impact of climate change on cold-dwelling forest species (Fig. 3 and Table S5.1).

Reducing fire suppression efforts in mild weather conditions is an alternative but hotly debated strategy that consists in using unplanned fires and associated fuel reduction to create opportunities for suppression of large fires in future adverse weather conditions (Regos *et al.*, 2014). Our projections revealed that the negative impact of land cover change on open-habitat bird species such as the Ortolan Bunting or the Dartford Warbler (De Cáceres *et al.*, 2013; Regos *et al.*, 2015) is expected to be significantly less important when projecting species distribution changes under such a novel fire management strategy (Fig. S5.2). There are more opportunities to create new open habitats for these species through changes in fire regime below than above 800 metres elevation (Figs 3d and S5.1), where a larger number of fire events are predicted. These findings are consistent with previous studies suggesting that heterogeneous landscapes induced by fire management aimed at creating uneven shrubland patches may potentially enhance the resilience of threatened open-habitat species in an overall land abandonment context (Brotons *et al.*, 2005; Vallecillo *et al.*, 2007; Zozaya *et al.*, 2010).

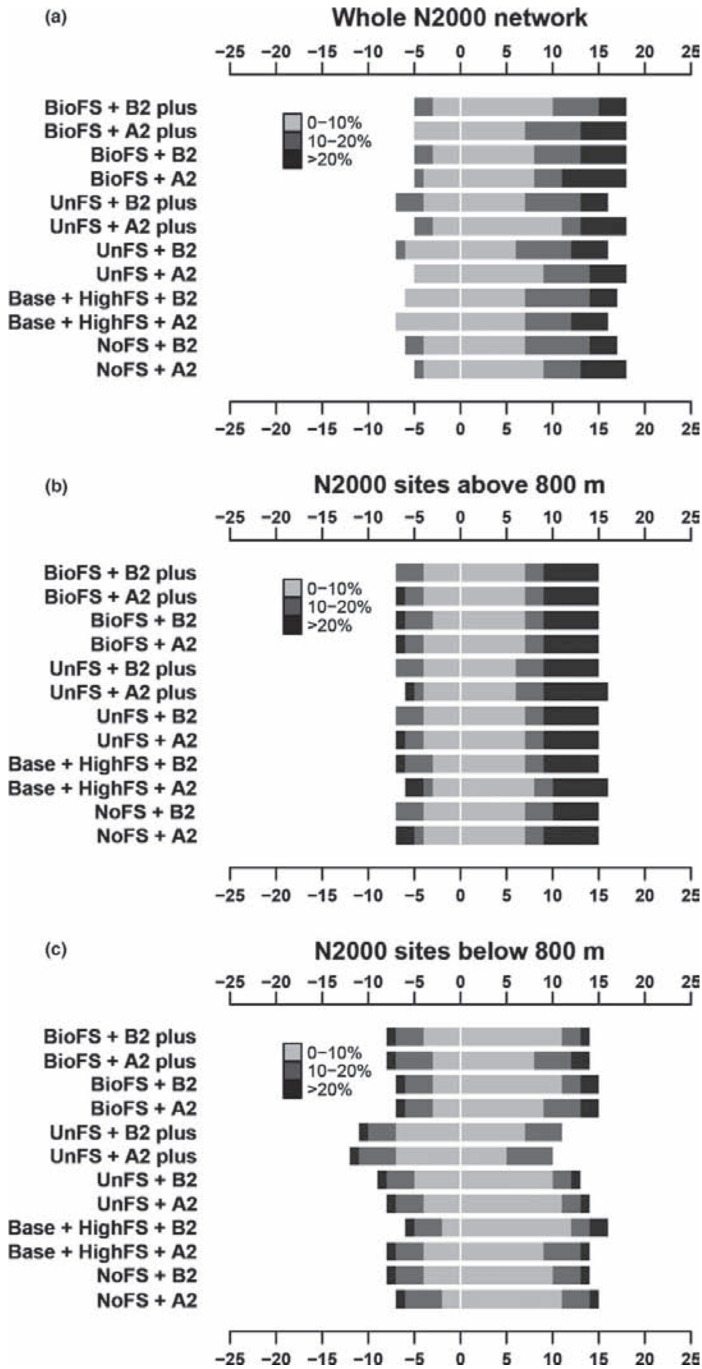

Figure 4 Number of species for which N2000 effectiveness is predicted to increase (positive values) and decrease (negative values) by < 5% (low-light grey), by 5–10% (medium-light grey) and by more than 20% (dark grey) between 2000 and 2050 for each future scenario (see Table 1 for acronyms): (a) whole N2000 network, (b) N2000 sites above 800 m and (c) N2000 sites below 800 m. Bar length reflects mean number of species across the different MEDFIRE runs simulating land cover changes.

The obtained projections and the relative roles of the various drivers were different for forest-dwelling birds. For this group of species, climate change was predicted to override the effect of fire management in the future. Scenarios based on forest biomass extraction for energy purposes (Evans & Finkral, 2009) were included in the analysis because we expected forest birds to benefit from such fire management strategy in the future through a reduction in the impacts of wildfires in forested areas. However, for those species, the decrease in habitat suitability under biomass extraction scenarios was only slightly, and not significantly, lower than in business-as-usual scenarios (Base + HighFS scenarios in Fig. 3). In addition, when the direct impact of climate change is taken into account in our multiscale combined models, forest specialist species, such as the Western Capercaillie (*Tetrao urogallus*) or the Black Woodpecker (*Dryocopus martius*), were predicted to be almost insensitive to the different fire suppression strategies (Fig. S5.2). Those species are distributed in the northernmost areas, that is the least fire-affected areas in Catalonia (Díaz-Delgado *et al.*, 2004 and Fig. 1), and climate change is therefore expected to have the strongest effect in determining their future distribution. As a result, such forest species are predicted to undergo decreases in the amount of their optimal habitats over the next decades primarily due to climate-induced north- and upward shifts in their distribution. It is not surprising to find large decrease in habitat suitability for cold-dwelling forest species in a context of climate warming (Huntley *et al.*, 2008), especially for those species that have in north of Spain the southern margin of their distributional range (e.g. Black woodpecker; Hagemeijer & Blair, 1997).

Overall, our projections suggest that fire management practices aimed at decreasing fire impact through the creation of new early-successional stages and sparsely vegetated areas by letting unplanned fires burn during mild weather conditions are the best option to help reduce the decline of open-habitat species in a context of land abandonment. At the same time, such strategy is not expected to have negative side effects on forest specialist species: future habitat suitability for these species is mostly driven by climate change (negative effect) and forest expansion under land abandonment (positive effect) (see also Gil-Tena *et al.*, 2009). Conservation efforts for these forest specialist species should focus on increasing the resilience of key forest habitats (*Pinus sylvestris* and *P. uncinata*) to climate change. Such regional objectives may be potentially achieved through adaptive forest management (Gil-Tena *et al.*, 2010; Keskitalo, 2011; Kolström *et al.*, 2011).

The role of N2000 in the near future

Our results provide the first assessment of the future effectiveness of the currently established protected areas for the conservation of bird species targeted by N2000 under different combinations of climate and novel fire regime scenarios. The effectiveness of N2000 for the protection of the target conservation interest bird species will likely increase over the next decades as the proportion of optimal habitats within N2000 relative to the whole of Catalonia is predicted to increase (Fig. 3). This result highlights the key role that the current N2000 network will play in the near future to maintain suitable habitats for open-habitat and forest bird species of European conservation interest in fire-prone, highly dynamic Mediterranean ecosystems. In a context of climate change and especially in lowland areas, this effectiveness may be considerably improved through the implementation of novel fire management strategies that are not in line with those that have been typically implemented so far (Fig. 4c).

Our results suggest that climate-induced north- and upward shifts in the geographical distribution of a large sample of species will take place in the region. As it has also been shown at the European level (Araújo *et al.*, 2011; Thomas & Gillingham, 2015), mountain areas will therefore likely remain a stronghold for most of the cold-dwelling species in Catalonia. As mountains are well covered with protected areas in Catalonia, this could explain that the effectiveness of N2000 is predicted to be higher at sites above 800 metres for these species. As for warm-dwelling bird species, they were predicted to mostly benefit from climate change but, above all, such open-habitat species were expected to undergo strong declines due to land abandonment processes in lowland areas. For the conservation of their suitable habitats in the future, N2000 is predicted to be less efficient and novel fire management policies would be particularly relevant.

Recent studies assessing present and future effectiveness of PAs for biodiversity conservation under climate change have found discrepancies among taxa (Maiorano *et al.*, 2006; Araújo *et al.*, 2007; Lisón *et al.*, 2013). For instance, while some studies reported larger decrease in suitable habitats for birds outside than inside PAs (Araújo *et al.*, 2011; Virkkala *et al.*, 2013; Gillingham *et al.*, 2015), other authors drew attention to the limited effectiveness of PAs in protecting amphibians and lichen species (D'Amen *et al.*, 2011; Rubio-Salcedo *et al.*, 2013). This pattern might be explained by the lack of consideration for non-charismatic species groups in the design of PAs. The bird-targeted SPAs in Catalonia cover 87% of the whole of N2000, which indicates a large overlap with SCIs and contributes to explaining the important role that N2000 will likely play for bird conservation in the near future in Catalonia. Besides, SCIs are indirectly protecting relevant habitats for most of the target species. A multitaxa approach is now warranted to address the impact of global change on a variety of species associated with a range of ecological requirements and life history traits, as birds may perform only fairly as surrogates of biodiversity (Larsen *et al.*, 2012).

Although the effectiveness of N2000 is expected to increase in the future (Fig. 4), the total amount of optimal habitats for conservation interest birds will strongly decrease both inside and outside the network. First, this sheds light on the need to implement proactive conservation strategies inside N2000 so as to maintain and improve biodiversity conservation under changing environmental conditions (Heller & Zavaleta, 2009; Bush *et al.*, 2014). Second, our simulations showed an even more important decrease in habitat suitability in the unprotected areas surrounding the PAs (Fig. 3b). Population viability can decline considerably as a result of large losses on temporal availability of optimal habitats due to the loss of connectivity between patches, often exacerbated by dispersal constraints (Gil-Tena *et al.*, 2012; Mazaris *et al.*, 2013; Saura *et al.*, 2014). Such habitat loss outside PAs could compromise the future chances to ensure species conservation status within the conservation network (Cabeza, 2003; Cabeza & Moilanen, 2003; Rayfield *et al.*, 2008). Biodiversity management actions should also focus on maintaining suitable habitats in unprotected areas if we are to guarantee the medium- and long-term conservation of bird diversity (Brambilla *et al.*, 2014).

This study offers novel insights into how fire management policies in interaction with land abandonment and climate change might strongly impact on future biodiversity conservation in fire-prone Mediterranean ecosystems. Based on a hierarchical modelling approach integrating climate and land cover change scenarios at different scales, we draw attention to the key role that the current N2000 network might play in the near future. We also emphasize the need for an integrative and proactive conservation perspective wherein agricultural, forest and fire management policies should be considered inside and outside N2000 to effectively maintain key habitats for threatened birds in these types of ecosystems. In the light of our results, we underline the need for an explicit consideration of landscape dynamics when forecasting the future effectiveness of a network of protected areas in a context of global change.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Appendix S1. Detailed information on climate scenarios: degree of similarity among the four GCMs and the multimodel mean consensus GCM.

Table S1. The Pearson correlation quantifies the similarities in spatial patterns between each individual general circulation model (GCM) variable and the multimodel mean ensemble for the same variable for the 2050 for two emission scenarios (A2a and B2a).

Appendix S2. Detailed information on land cover scenarios: storylines and simulations.

Appendix S3. Complete description of the modelling framework —uncertainties and limitations.

Appendix S4. Complete description of binary conversion procedure: Sensitivity analysis in selecting thresholds.

Figure S4. Predicted percentage of change in the effectiveness of N2000 for preserving the optimal habitats for the target species between 2000 and 2050 from different thresholds in binary conversion.

Appendix S5. Changes in habitat suitability for each bird species under climate and/or land cover change scenarios.

Table S5.1. Predicted percentage of gains and losses in the amount of optimal habitats for the target species between 2000 and 2050 averaged across the different scenarios of future environmental changes.

Table S5.2. Predicted percentage of gains and losses in the amount of optimal habitats for the target species between 2000 and 2050 under A2 and B2 climate change scenarios.

Figure S5.1. Predicted percentage of gains and losses in the amount of optimal habitats for the target species between 2000 and 2050 in N2000 sites above and below an average elevation of 800 metres under each scenario of future change according to the combined models.

Figure. S5.2. Predicted percentage of gains and losses in the amount of optimal habitats for the target species between 2000 and 2050 inside N2000 under each scenarios of future change and according to the combined models and the land cover models.

Appendix S6. Changes in the effectiveness of N2000 for the conservation each bird species under climate and land cover change scenarios.

Figure S6. Predicted percentage of change in the effectiveness of N2000 for preserving the optimal habitats for the target species between 2000 and 2050 under each scenario of future environmental changes according to the combined models.

BIOSKETCH

Adrián Regos is a PhD student in the InForest Research Unit (Biodiversity and Landscape Ecology lab) at the Forest Science Centre of Catalonia (CEMFOR-CTFC). His thesis is focused on the combined effects of global change drivers on biodiversity in fire-prone ecosystems. In his thesis, he combines scenario planning tools, landscape simulations and biodiversity modelling platforms to predict shifts in the spatial patterns of bird communities under future climate and fire-induced land cover scenarios (https://adrianregosresearch.wordpress.com/).

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Author contributions: A.R., L.B. and A.G. conceived the ideas; M.D., N.T., A.G. and L.B. supervised the research, and A.R. run the analysis and led the writing with contributions from all authors.

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SUPPORTING INFORMATION

Predicting the future effectiveness of protected areas for bird conservation in Mediterranean ecosystems under climate change and novel fire regime scenarios

APPENDIX S1: Detailed information on climate scenarios: degree of similarity among the four GCMs and the multimodel mean consensus GCM.

We obtained current climate data (period 1950–2000) from the WorldClim database (www.worldclim.org/current) and future climate scenarios (period 2040-2069) from International Center for Tropical Agriculture (CIAT) (http://www.ccafs-climate.org). CIAT data are based on the baseline data reflecting current climate conditions from WorldClim. We first selected three climate variables that play a key role on the distribution of the bird species (Crick, 2004; Araújo et al., 2005a; Thuiller et al., 2014): maximum temperature of warmest month, minimum temperature of coldest month and annual precipitation. Then we consider the other climate variables available in WorldClim to capture other dimensions of the climate niche, and in turn, increase the accuracy of our models and subsequent projections. To avoid multicollinearity problems all pairs of variables were tested for pair-wise correlation. We additionally included in the final set of climate variables only those ones with a correlation coefficient lower than 0.7: mean diurnal range (mean of monthly (max temp - min temp), precipitation seasonality (coefficient of variation) and precipitation of the warmest quarter. Future climate change projections were computed for A2 and B2 IPCC-SRES scenarios from an average ensemble model of four GCMs (CCCMA-CGCM2, CSIRO-MK2.0, HCCPR-HadCM3 and NIESS99) to account for the uncertainty arising from the inter-model variability. These four GCMs were selected as they provide a range of variability with respect to annual temperature and cumulative precipitation predictions (Liu et al., 2010a; Naujokaitis-Lewis et al., 2013). These projections were available at 30 arc-seconds (~1 km) resolution and were resampled by estimating mean value within the specified grid cell to match the resolution of bird data in Europe and in Catalonia.

We used the spatial Pearson correlation to quantify the similarities in spatial patterns between individual GCMs for a given variable and the mean of that variable. Values range between -1 and 1, with values close to 1 indicating agreement among variables between GCMs. Based on this correlation coefficient, there was generally a high degree of similarity among the four GCMs and the multimodel mean consensus GCM for the majority of the climate variables (Table S1). Of all GCMs, the NIES99 GCM consistently had the highest values across all variables, indicating the least divergence from the consensus except for precipitation of warmest quarter in B2. The largest deviations were evident for precipitation seasonality, especially for the HADCM3 GCMs.

Table S1. The Pearson correlation quantifies the similarities in spatial patterns between each individual general circulation model (GCM) variable and the multimodel mean ensemble for the same variable for the 2050 for two emission scenarios (A2a and B2a). *Acronyms*: BIO2 = Mean Diurnal Range (Mean of monthly (max temp - min temp)); BIO5 = Max Temperature of Warmest Month; BIO6 = Min Temperature of Coldest Month; BIO12 = Annual Precipitation; BIO15 = Precipitation Seasonality (Coefficient of Variation); BIO18 = Precipitation of Warmest Quarter.

Emission Scenarios	GCM	BIO2	BIO5	BIO6	BIO12	BIO15	BIO18
A2	CCCMA	0.9985	0.9924	0.9994	0.9996	0.9640	0.9915
	CSIRO	0.9987	0.9974	0.9994	0.9996	0.9826	0.9874
	HADCM3	0.9972	0.9850	0.9997	0.9988	0.9167	0.9976
	NIES99	0.9990	0.9952	0.9997	0.9994	0.9424	0.9897
B2	CCCMA	0.9988	0.9954	0.9997	0.9998	0.9451	0.9917
	CSIRO	0.9989	0.9984	0.9990	0.9997	0.9684	0.9946
	HADCM3	0.9975	0.9900	0.9997	0.9992	0.9089	0.9929
	NIES99	0.9992	0.9962	0.9998	0.9997	0.9547	0.9877

SUPPORTING INFORMATION

Predicting the future effectiveness of protected areas for bird conservation in Mediterranean ecosystems under climate change and novel fire regime scenarios

APPENDIX S2: Detailed information on land cover scenarios: storylines and simulations.

In this appendix we provide a detailed description of landscape simulations and the storylines underlying the potential future land cover pathways in Mediterranean-type ecosystems. These storylines are based on the key socio-ecological driving forces that have the potential to affect landscape dynamics in the study region, such as climate change, fire disturbance regime, large-scale fire management, land abandonment and forest harvesting for bioenergy uses (see also Regos *et al.* 2015).

STORYLINES

The description of four regional storylines developed for Catalonia is supported by previous collaborative works wherein conservation ecologists, forest engineers and technical fire brigades (GRAF) were involved (Brotons *et al.* 2013; Regos *et al.* 2014):

1) **Stop all fires**

Increased fire risk, higher burning frequencies and larger burnt areas are expected in the Western Mediterranean region due to vegetation encroachment following land abandonment, coupled with increasingly severe weather. Current fire management option based on suppressing "all fires" is characterized by high fire suppression levels regardless of the climatic severity of the year. It is expected that this strategy will continue to be applied in a near future.

2) **No suppression**

Nowadays, firefighters have become more efficient at suppressing small and low-intensity fires, but the number of large and high-intensity fires has considerably increased during the last decades. According to "fire paradox" (Minninch, 1983) large fires are a modern artefact induced by successful fire exclusion along the 20th century. Assuming a paradigm shift in fire management, we envisaged another set of baseline treatments embodying the 'no fire suppression' strategy as a counterpoint to the current trend.

3) **Let-burn**

Rural communities have traditionally used fire in rangeland management and agriculture, as well as in forests, and the long fire history in the Mediterranean region has created ecosystems that need fire for their sustainability. An opportunistic fire suppression strategy based on reducing active firefighting efforts in controlled "mild" weather conditions provides further firefighting opportunities in adverse years (Houtman *et al.*, 2013; Regos *et al.*, 2014). Here it is considered as a possible pathway that the fire management policies might follow in the next decades.

4) **Forest biomass extraction**

The biomass harvesting as a fuel could reduce energy consumption in local communities, among other socioeconomic and environmental implications at regional level (Mason *et al.*, 2006; Becker *et al.*, 2009; Evans & Finkral, 2009; Abbas *et al.*, 2011). In Catalonia, a forest harvesting strategy has been recently approved and includes specific targets for biomass-derived energy (GENCAT, 2014). Its effectiveness of this fuel-reduction treatment for suppressing wildfires has been recently shown in Catalonia (Regos et al. submitted). We designed a set of scenarios characterized by forest harvesting in optimal areas from a logistic and economic viewpoint (i.e. favourable site conditions with gently slopes and small extraction distances) assuming thus a cost-effective forestry biomass harvesting. An additional set of scenarios was designed to represent an environmental perspective wherein biomass extraction is prohibited in protected areas.

Scenario design and implementation can be found in Regos *et al.* (2015).

LANDSCAPE SIMULATIONS

We used the MEDFIRE model to simulate future land cover changes derived from spatial interactions among fire regime, vegetation dynamics and fire management policies (Brotons *et al.*, 2013; De Cáceres *et al.*, 2013; Regos *et al.*, 2014). MEDFIRE is a spatially explicit dynamic fire-succession model designed to integrate climate and anthropogenic drivers. It allows examining their combined effect on fire regime and, in turn, on land cover at short- and medium-term time scales in a Mediterranean context. MEDFIRE is based on observed time series to simulate the future effect of primary processes driving vegetation dynamics (i.e. natural succession, post-fire regeneration and maturation processes) and fire regime (i.e. fire ignition, fire spread, fire suppression and fire effects) in the landscape. In the MEDFIRE model, fires are simulated until the potential annual area to be burnt is reached. Potential annual area refers to the area that is expected to burn according to the historical fire data (1975–99 period). According to previous research (Piñol *et al.*, 1998), climatically adverse years are characterized by a high number of weather risk days ('adverse years'), as opposed to years dominated by mild weather conditions ('mild years'). Thus, potential burnt area and fire size distributions depend on the climatic severity of the year: (1) the probability of a year being adverse increases from 0.30 to 0.59 for time-slice 2050 in A2 emission scenarios; and from 0.30 to 0.62 for time-slice 2050 in B2 emission scenarios (more details in Regos et al., 2015). Vegetation encroachment due to land abandonment (hereafter land abandonment) is explicitly integrated into MEDFIRE to simulate the succession from abandoned open land (i.e. shrubland) to forest and its interaction with fire regime. Land cover in 2000 was represented by means of two raster layers at 100-m resolution: land cover type (LCT) and time since last fire (TSF). In particular, the model assumes that forest cover types are relatively stable, so a type-conversion can only occur after burning. Succession without burning can occur only from shrubland to forest. This land cover change takes place depending on the availability of mature forest in neighbouring cells and the TSF of shrubland that will potentially change. Post-fire transitions in dominant species are implemented according to two approaches: non-spatial stochastic transitions or neighbourhood species contagion.

To deal with the stochastic nature of wildfires, the land cover layers were then simulated 10 times (hereafter runs) for 2050 using MEDFIRE model under the different combinations of 6 fire management scenarios and 2 climate change scenarios (Table 1, Appendix S1 and Regos *et al.* 2015 for the detailed description of the scenarios). To describe predicted vegetation changes under each scenario, we used the outputs of the simulation runs and we calculated the area occupied by each land cover type. Some land cover types do not influence fire dynamics (i.e. water, rocks and urban areas), whereas farmland was assumed to be static but to allow fire to spread through it. Fire can affect farmlands but they do not directly shift to other habitat types after fire unless an additional land use change occurs. A transition from farmland to shrubland requires a land use change that was not simulated in the context of the present study. Detailed estimates of future land cover were obtained considering the following categories: (1) coniferous tree species (mainly dominated by *Pinus halepensis*, *Pinus nigra*, *Pinus pinea*, *Pinus sylvestris*) (2) deciduous tree species (*Quercus ilex* and *Quercus suber*), (3) shrubland and (4) farmland (represented by different types of cropland). Additional variables were measured to represent other fire-mediated land cover properties such as the vertical structure or the maturation of the vegetation by calculating the coverage of three different age-classes of the vegetation: (5) older vegetation (>30 years since fire), (6) mid-age vegetation (10–30 years since fire), and (7) recently burned vegetation (<10 years since fire). To match bird data resolution in Catalonia, we calculated the area covered by each variable within 1-km resolution squares.

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SUPPORTING INFORMATION

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APPENDIX S3: Complete description of the modelling framework —uncertainties and limitations.

Modelling framework

In order to estimate potential changes in habitat suitability for the target species between 2000 and 2050, we used a hierarchical approach integrating climate and land cover change scenarios at different scales in the same modelling framework. This approach required the following steps:

Step 1. – Climate models at the European level

We fitted species distribution models on climate variables at the European scale (hereafter climate models) to estimate the bioclimatic envelope of each species (Araújo et al., 2005a; Barbet-Massin et al., 2012). The European extent encompasses most of the distribution of the target species (Del Hoyo et al., 2006; Huntley et al., 2007). We trained the climate models with bird occurrence data from the EBCC database at 50-km resolution, using five different modelling techniques available in the BIOMOD2 package (Thuiller et al., 2009) in R (R Core Team, 2013): Generalized Linear Models (GLM), Generalized Additive Models (GAM), Classification Tree Algorithms (CTA), Generalized Boosted Regression Models (GBM), and Random Forest (RF). The original dataset was split into two subsets: 70% of the data was used for training the models and the remaining 30% for testing their performance. To produce predictions independent of the training data, we repeated this procedure 10-fold (Fielding & Bell, 1997). We applied an ensemble forecasting framework by computing a consensus of single-model projections using the area under the receiver operating characteristic curve (AUC, a measure of model accuracy) as model weights in a weighted averaging approach (Araújo & New, 2007; Marmion et al., 2009). Only models with AUC values above 0.7 were used in the averaging procedure. Model predictions under current climate conditions and for each scenario under future conditions were downscaled to the 1-km resolution squares in Catalonia. In particular, we applied a widely-used downscaling process consisting of projecting directly distribution models calibrated at course scales onto finer-resolution grids (Araújo et al., 2005b; McPherson et al., 2006; Fernandes et al., 2014). Current predictions on the test datasets were compared to bird occurrence data from the CBBA to evaluate model accuracy: AUC, specificity and sensitivity values were calculated using the R-based ‘PresenceAbsence’ package (Freeman & Moisen, 2008; R Core Team, 2014).

Step 2. – Land cover models at the Catalan level

Higher resolution models for the target species in the study area were built using the same ensemble forecasting approach as described above, but we only included land cover variables derived from the MEDFIRE model at the Catalan level (hereafter land cover models). We used bird occurrence data from the CBBA to train the models and we predicted the probability of occurrence within each 1-km resolution square in Catalonia under current and future land cover scenarios. Current predictions on the test datasets were compared to bird occurrence data from the CBBA to evaluate model accuracy based on the AUC values.

Step 3. – Combined models at the Catalan level

Combined climate and land cover models (hereafter combined models) were built using the same dependent variables (bird occurrence from CBBA) and the same resolution (1-km) and extent (Catalonia) as in *Step 2*. They were developed using two predictors: 1) the outcomes of the climate model at 1-km resolution (*Step 1*); and 2) the outcomes of the land cover model at 1-km resolution (*Step 2*). This approach is adapted from the well-established hierarchical approach (Pearson et al., 2002, 2004), but it differs from the latter in that the outcomes of both climate and land cover models are incorporated as two separate predictors in the final model. This allows a balanced contribution of each type of drivers in shaping the predicted distributions of the species. We assessed the accuracy of the combined models from the AUC values.

In total, the outcomes obtained from the hierarchical modelling were: 1) two climate models for the two emission scenarios (A2 and B2); 2) twelve land cover models for the twelve novel fire regime scenarios (resulting from the interaction of six fire management and two climate scenario) (Table 1), and 3) twelve combined models obtained from integrating outcomes of climate and land cover models.

Uncertainties and modelling limitations

In this study, we use a storyline-and-simulation approach wherein uncertainty is viewed as an opportunity for developing better policies and making optimal decisions (Alcamo, 2008; Cook et al., 2014b). We envisaged a wide range of possible futures that include many of the key uncertainties in the system rather than focusing on the accurate prediction of a single outcome. These foresight exercises help to support more proactive conservation policies when faced the inherent uncertainty of the future (Bush et al., 2014; Cook et al., 2014a) .

However, some limitations of our approach should be considered to avoid misleading conclusions. Our projections take into account the combined effect of climate change and fire-induced land cover changes, but neglect some issues that are still challenging SDM-based approaches such as the effect of dispersal constraints, biotic interactions (Davis et al., 1998; Araújo & Guisan, 2006), as well as other specific threats (e.g. poisoning of raptors) (Ogada et al., 2015). Moreover, climate has also direct effects on the phenological and physiological response of species (Bellard et al., 2012; van Teeffelen et al., 2014). For instance, global warming can affect food availability and chick survival rates (Both & Visser, 2005; Visser & Both, 2005). Therefore, although the habitat area remains constant, habitat quality cannot be guaranteed. In addition, the reliability of biodiversity projections can be also compromised by three main sources of uncertainty: (1) the general circulation models (GCM) selected, (2) the inherent stochasticity of fire dynamics, and (3) the modelling algorithm applied. Here, future climate change projections were computed by averaging the outcomes of four GCMs to account for the uncertainty arising from the inter-model variability. Applying consensus methods (e.g. by deriving the central tendency of forecasts) among climate models has been recently adopted by ecologists in biodiversity assessments under potential climate changes for reducing variability across all models (Buisson et al., 2010; Naujokaitis-Lewis et al., 2013). However, it is important to bear in mind that, using a central tendency of forecasts, the effects of extreme climate regime scenarios can be hidden (Beaumont et al., 2008). Moreover, fire is a stochastic process driven by a complex interplay of ignition occurrence, climatic variability, local weather, topographic conditions and vegetation structure, as well as fire management policies (Keane et al., 2004). Our fire simulation scenarios were computed several times in order to consider such stochasticity. Thus, although computing a central tendency of forecasts helps drawing conclusions, we should also take into account that extreme fire events can also be masked in our simulations. Finally, the combination of different modelling algorithms has been adopted to adjust inherent uncertainty of individual models for each target species (Araújo & New, 2007; Thuiller et al., 2009). Our ensemble models, built on a series of competing models, each with a different combination of environmental predictors, may provide more informative and ecologically correct predictions (Thuiller 2003). However, they should be interpreted with caution as these approaches not reduce the uncertainties, but the likelihood of making conservation decisions based on inaccurate forecasts (Araújo & New, 2007).

The selection of thresholds (see Appendix S4) has been shown to contribute greatly to model uncertainty (see, e.g., Nenzén & Araújo, 2011). However, when the objective involves identifying 'critical habitat' for species conservation, binary conversion is fully justified by the objective (Guillera-Arroita et al., 2015). The 10th percentile is a widely-used measure since the lower percentile, the lower the error of omission (the model predicts absence in areas where the species is found), and the greater the sensitivity of the model (Pearson et al., 2007). Thus, we adopted a more conservative outlook of the loss of habitat for many species, which is very appropriate given the abovementioned uncertainty (Fig. S4.). Moreover, as we work with relative (instead of absolute) units of change, and thresholds are equally applied inside than outside of N2000, changes in the effectiveness estimated from different thresholds are not large enough to affect our conclusion on the increasing role of N2000 in the near future (Fig. S4.).

In addition, the spatial mismatch between the resolution of European climate models and Catalan land cover models might bring some uncertainty about the reliability of our projections (Seo et al., 2009). Although, potential errors in the downscaling processes are associate to the presence of false positives (Araújo et al., 2005b), our downscaling climate models were considered as useful since they were able to capture the broad climate envelope of the species and the predictions could be subsequently refined with the inclusion of land cover variables at the regional level. Our results are in line with those suggesting the potential usefulness of downscaled projections to guide regional conservation actions (Barbosa et al., 2010; Bombi & D'Amen, 2012; Keil et al., 2013).

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SUPPORTING INFORMATION

Predicting the future effectiveness of protected areas for bird conservation in Mediterranean ecosystems under climate change and novel fire regime scenarios

APPENDIX S4: Complete description of binary conversion procedure: Sensitivity analysis in selecting thresholds.

To quantify the changes in the effectiveness of N2000 between 2000 and 2050, high quality habitats (hereafter optimal habitats) for the species need to be firstly identified. We applied cut-off points or thresholds that convert maps with continuous suitability habitat values into maps with more areas hierarchically prioritised according to their relevance for the species. Thus, probability outputs were hierarchically ranked in two levels of increasing suitability. Among the different methods available to transform model probability outputs into maps of suitable-unsuitable areas (Liu et al., 2005), we followed Arcos et al. (2012) and Herrando et al. (2011). Thus, for all species, the threshold below which the absence areas for species are defined corresponds to the average tenth percentile of the data used for developing the models (i.e. 10% of the presence data with the lowest suitability). (Pearson et al., 2007). The average mean of the values within the areas above the first threshold provided a second threshold allowing the identification of optimal habitat areas (i.e. areas with habitat quality above the mean), which can be interpreted as critical habitats for our study species in line with the conservation mandate of the European directives.

This appendix provides a sensitivity analysis assessing the effects of the selection of different cut-off points or thresholds that convert continuous, probability maps into categorical maps for which optimal habitat is identified. In particular, we used the average of 10^{th} percentile of the data used for developing the models (i.e. 10% of the presence data with the lowest suitability); the average of 20^{th} percentile of the data (i.e. 20% of the presence data with the lowest suitability, and the lowest suitability value of the presence data as first threshold (see Methods section for a detailed description of procedure). The Fig. S4 shows the changes in the effectiveness of N2000 to preserve the optimal habitats for six representative species (i.e. covering the different pattern of response to our future scenarios) of the whole suite of target species.

The results showed that the direction of the effect (positive/negative) and the response patterns under different scenarios for the species analyzed remained unchanged across the different thresholds used. Our conclusions are therefore consistent independently of the use of different thresholds. While differences between thresholds in species habitat availability inside and outside protected areas were minor in terms of changes in protected area effectiveness, it is interesting to note that in larger thresholds (20^{th} percentile), were more restrictive in selecting optimal habitats for species and reduce the overall amount of species habitat preserved in protected areas.

We finally chose the percentile 10^{th} as threshold for the following reasons:

1) The 10th percentile is a widely-used measure since the lower percentile, the lower the error of omission (the model predicts absence in areas where the species is found), and the greater the sensitivity of the model (Pearson et al., 2007).
2) Applying low percentiles allow us to adopt a more conservative outlook of the loss of habitat for many species which is very appropriate given the inherent uncertainty associated to modeling approaches.
3) As we work with relative (instead of absolute) units of change and the thresholds are equally applied inside than outside N2000, we found minimal changes in the effectiveness between thresholds so our conclusions on the increasing role of N2000 in the near future remains the same (see fig. S4 in the new appendix S4).

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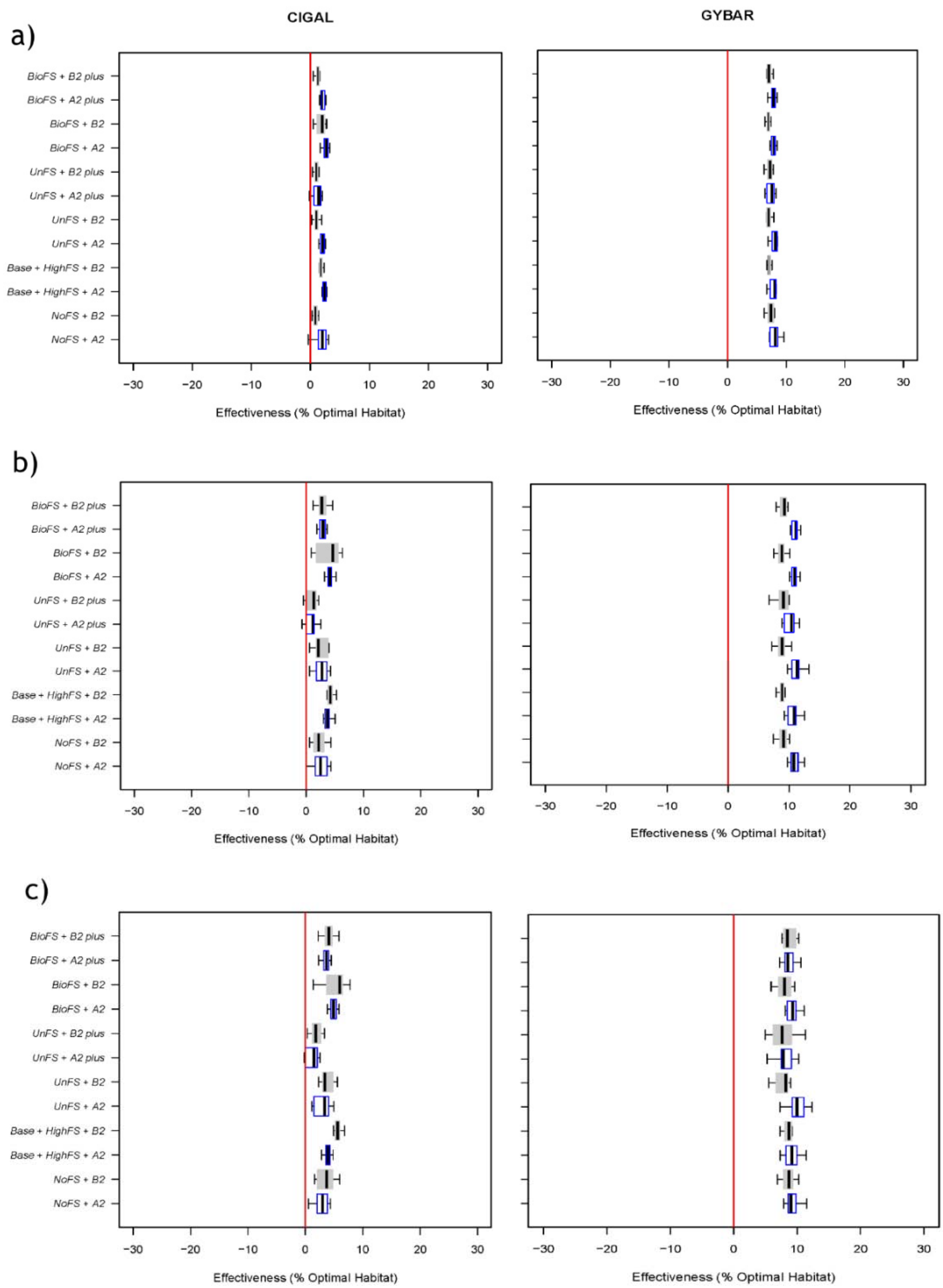
Figure S4. Predicted percentage of change in the effectiveness of N2000 for preserving the optimal habitats for the target species between 2000 and 2050 under each scenario of future environmental changes according to the combined models and using: a) the lowest suitability value of the presence data, b) the average of 10th percentile and c) the average of 20th percentile as a first threshold. The whiskers indicate the 5% and 95% percentiles, the hinges indicate the first and third quartiles (in white and grey for A2 and B2 climate change scenarios, respectively) and the central black line indicates the median value across the different MEDFIRE runs simulating land cover changes. See Tables 1 and 2 for scenario and species acronyms, respectively.


a)
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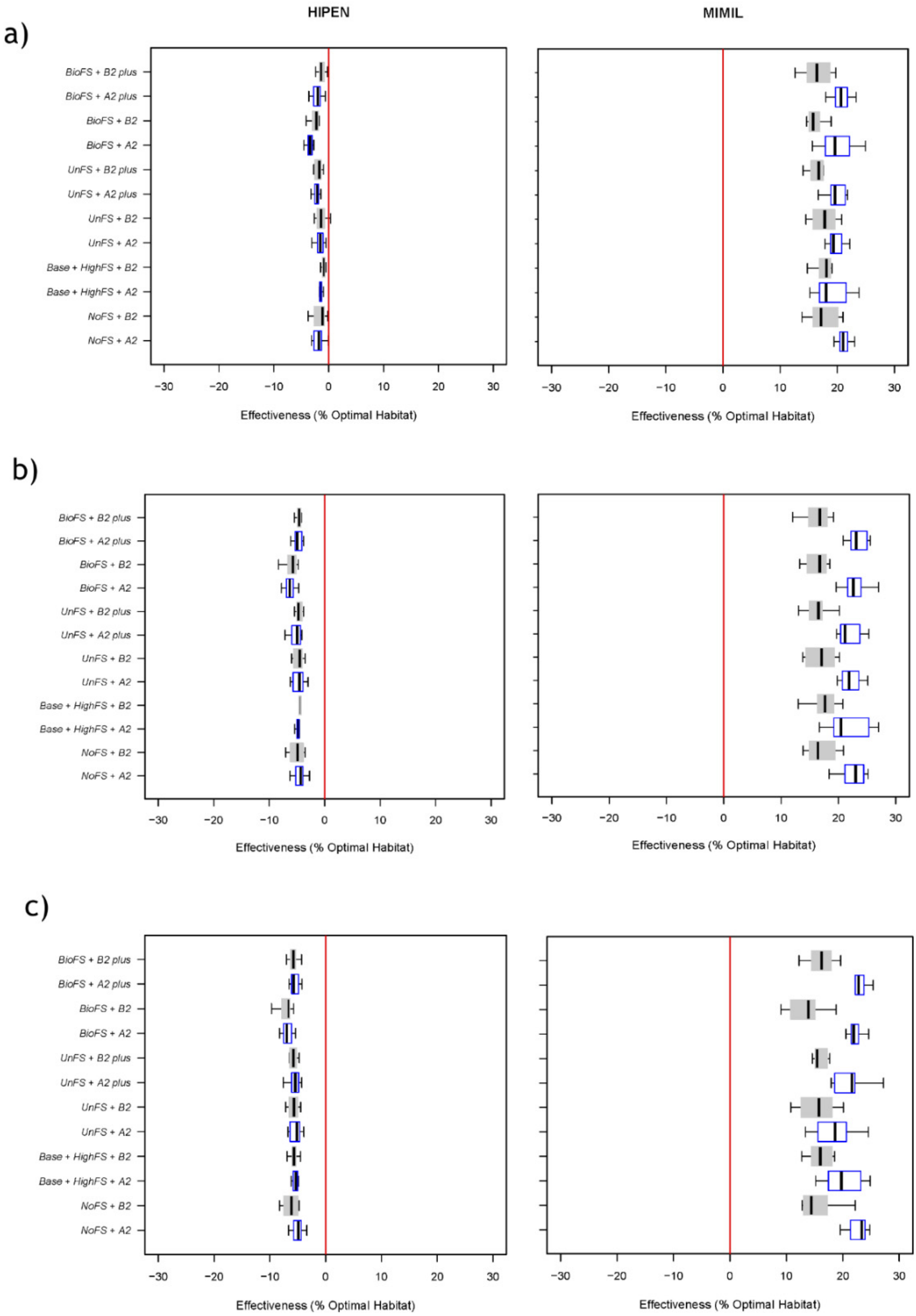
Effectiveness (% Optimal Habitat)



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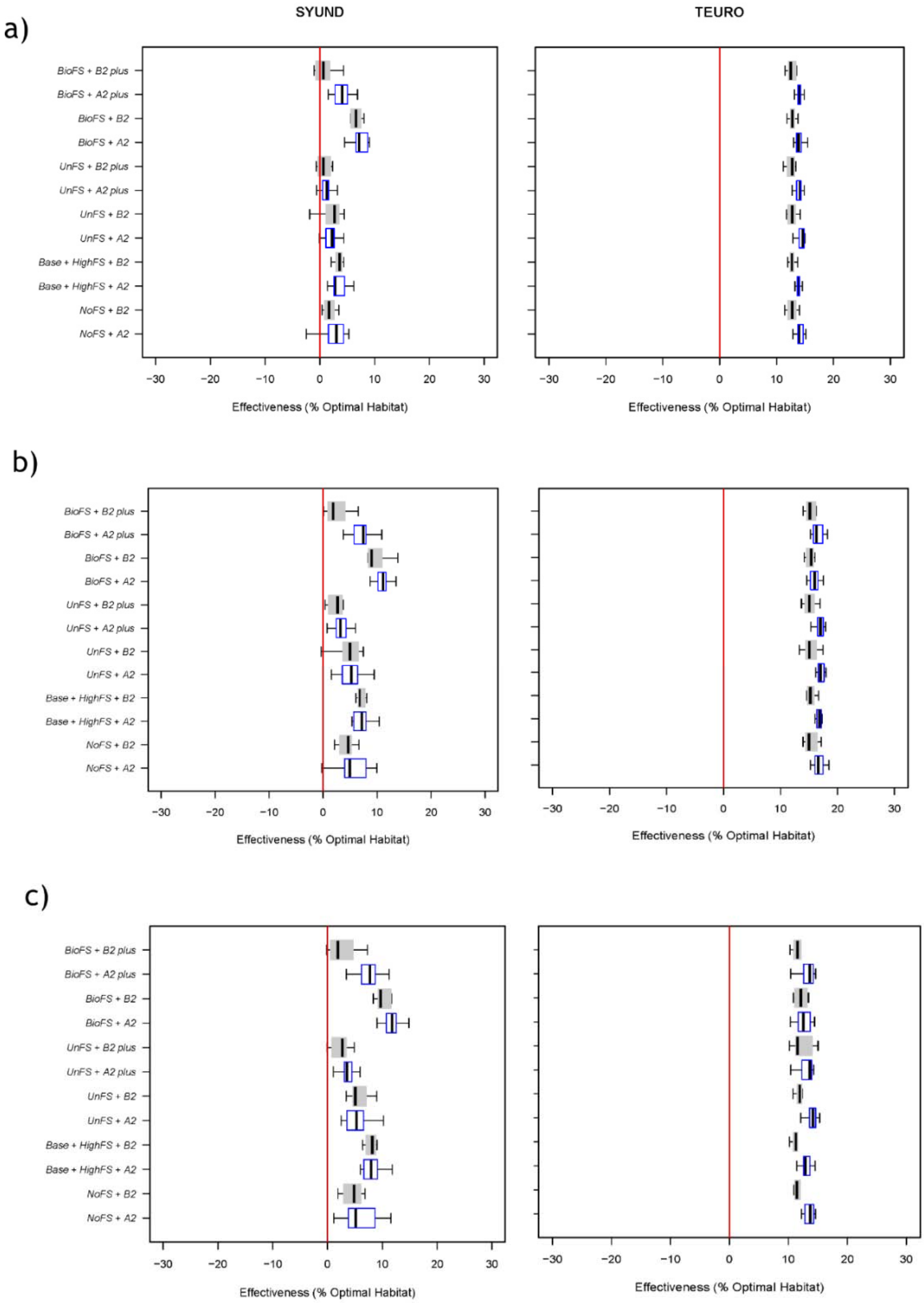
Effectiveness (% Optimal Habitat)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Effectiveness (% Optimal Habitat)
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c)

SUPPORTING INFORMATION

Predicting the future effectiveness of protected areas for bird conservation in Mediterranean ecosystems under climate change and novel fire regime scenarios

APPENDIX S5: Changes in habitat suitability for each bird species under climate and/or land cover change scenarios.

This appendix provides details on the relative change in the amount of optimal habitats for the 23 species analyzed in our study between 2000 and 2050 under each scenario of future environmental changes in Catalonia. Based on the outcomes from climate models, land cover models and combined models, we counted the number of species predicted to show a positive (on average more than 20% of gains among the different scenarios), negative (on average more than 20% of losses) or neutral (on average less than 20% of gains and losses) response to climate change, to land cover change and to its combined effect with climate change (Table S5.1). Table S5.2 documents the relative changes predicted from climate models under A2 and B2 scenarios. The number of species expected to be potentially affected by fire-induced land cover changes within a general context of climate change and land abandonment were estimated using Generalized Linear Models (GLMs) with a Gaussian error distribution and 'identity' link function. The relative change in the amount of optimal habitats for each species between 2000 and 2050 according to the predictions derived from the combined models was included as dependent variable. Fire suppression strategies scenarios (6 levels: see storylines in Appendix S1 and Table 2), climate change scenarios (2 levels: A2 or B2) and their interactions were used as explanatory variables. These models allowed us to dissociate the effect of climate change from that of fire suppression strategies on the future changes in the amount of optimal habitats for the target species. The effects were considered as significant at $p < 0.05$ and the number of species associated with a significant effect of fire suppression strategies in these GLMs was counted.

Fig. S5.1 illustrates the predicted changes inside N2000 above and below an average altitude of 800 meters as derived from the combined models. Fig. S5.2 synthesises the overall changes predicted from the combined and land cover models.

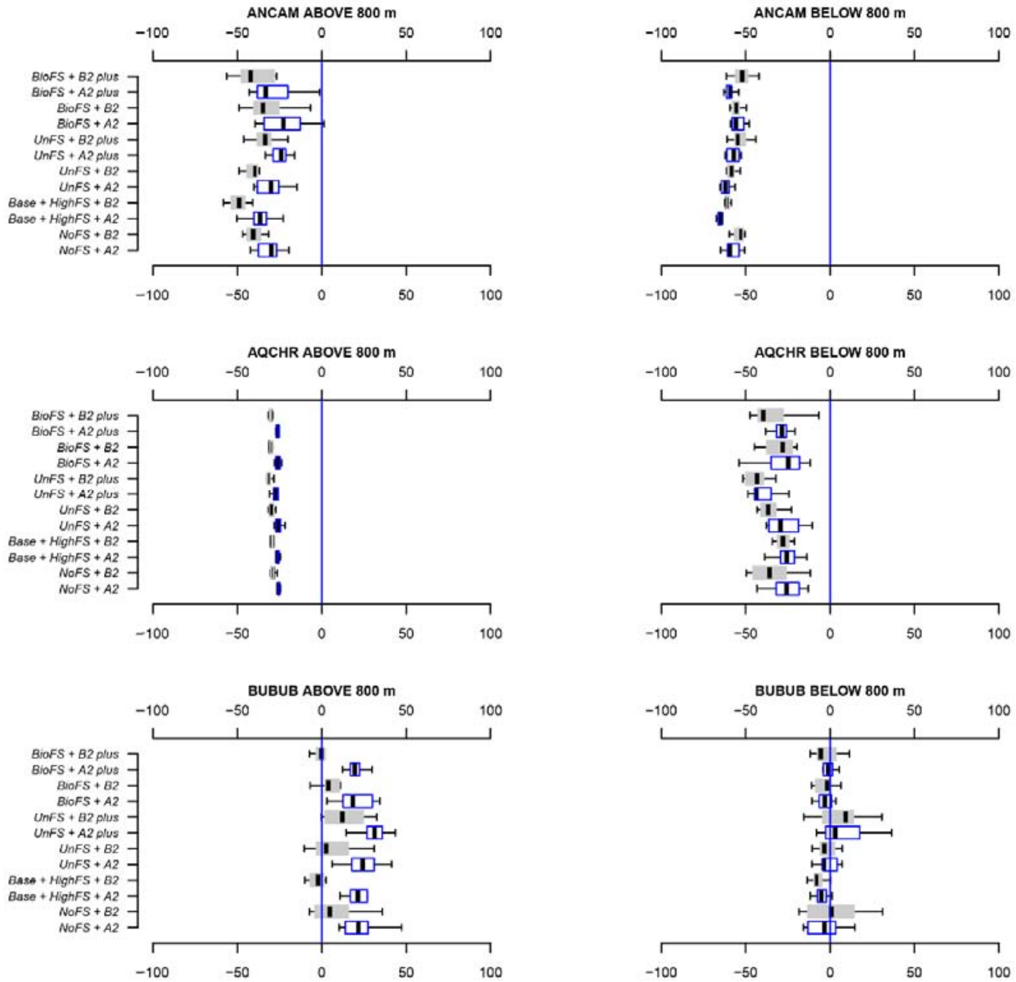
Table S5.1. Predicted percentage of gains and losses in the amount of optimal habitats for the target species between 2000 and 2050 averaged across the different scenarios of future environmental changes. Based on the outcomes from climate models, land cover models and combined models, we counted the number of species predicted to show a positive (on average more than 20% of gains among the different scenarios), negative (on average more than 20% of losses) or neutral (on average less than 20% of gains and losses) response to climate change, to land cover change and to their combined effect (counterbalancing or additive effect). See Tables 1 and 2 for scenario and species acronyms, respectively.

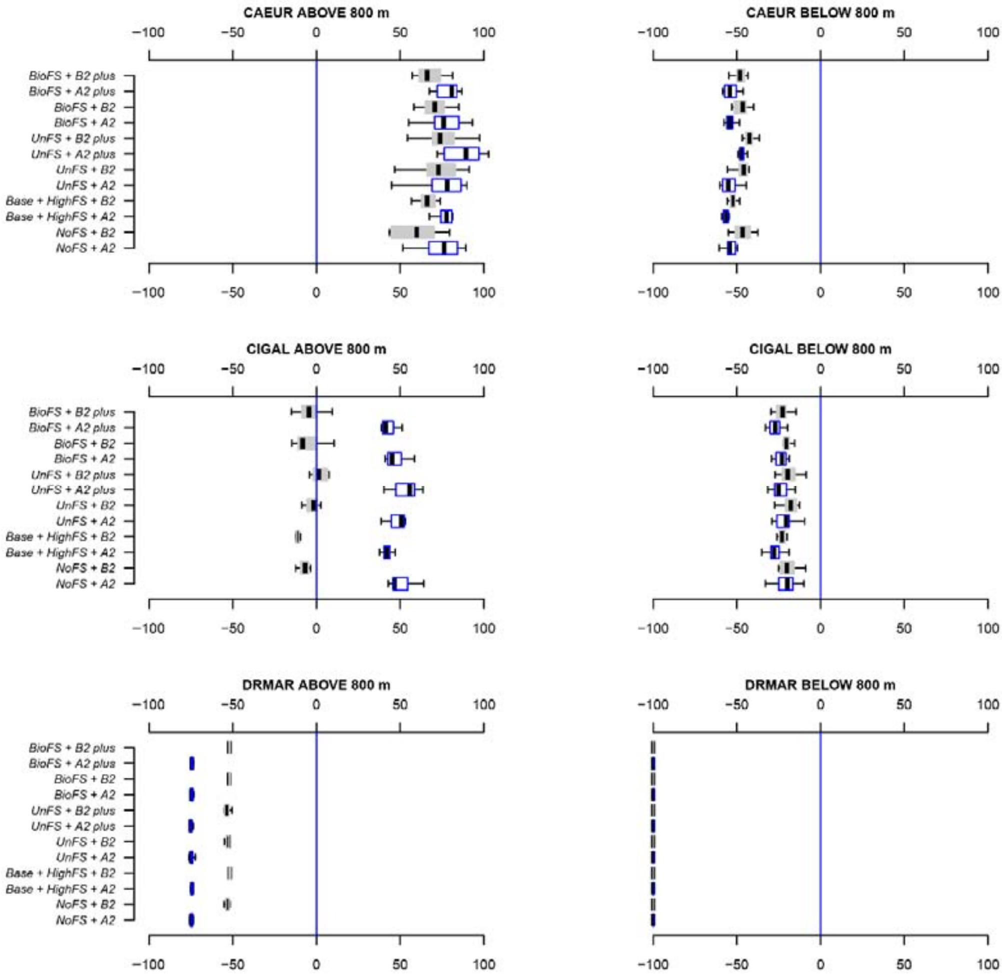
	CLIMATE		LAND COVER		COMBINED	
	Mean	Response	Mean	Response	Mean	Response
ANCAM	-77,81	negative	-57,17	negative	-55,30	negative
AQCHR	-56,88	negative	-29,76	negative	-28,57	negative
BUBUB	-31,07	negative	-14,25	neutral	1,93	neutral
CAEUR	-77,18	negative	16,86	neutral	-25,78	negative
CIGAL	14,28	neutral	-31,08	negative	-13,32	neutral
DRMAR	-74,46	negative	-4,88	neutral	-64,47	negative
EMHOR	-49,35	negative	-44,58	negative	-52,45	negative
FAPER	-99,09	negative	-25,11	negative	-36,21	negative
GATHE	-20,95	negative	-47,19	negative	-56,81	negative
GYBAR	-47,06	negative	-32,29	negative	-13,25	neutral
GYFUL	17,73	neutral	-38,72	negative	-40,73	negative
HIFAS	-50,80	negative	-58,20	negative	-81,70	negative
HIPEN	1,35	neutral	-12,23	neutral	52,37	positive
LACOL	-24,31	negative	-48,33	negative	-44,79	negative
LUARB	-74,39	negative	-13,48	neutral	-38,74	negative
MIMIG	-53,36	negative	-45,76	negative	-45,42	negative
MIMIL	-59,58	negative	-39,90	negative	-53,68	negative
NEPER	36,37	positive	-42,05	negative	-27,46	negative
OEURA	-18,14	neutral	-69,61	negative	-80,92	negative
PEAPI	-79,99	negative	-1,21	neutral	-26,67	negative
PYROC	-92,66	negative	-37,36	negative	-53,13	negative
SYUND	-75,48	negative	-33,89	negative	-23,26	negative
TEURO	-49,71	negative	4,69	neutral	-44,89	negative

Table S5.2. Predicted percentage of gains and losses in the amount of optimal habitats for the target species between 2000 and 2050 under A2 and B2 climate change scenarios. See Table 2 for species acronyms.

	A2	*B2*
ANCAM	-78,75	-76,87
AQCHR	-46,14	-67,62
BUBUB	-31,85	-30,30
CAEUR	-79,19	-75,17
CIGAL	19,93	8,64
DRMAR	-81,53	-67,40
EMHOR	-46,13	-52,57
FAPER	-100,00	-98,19
GATHE	-28,79	-13,11
GYBAR	-88,47	-5,65
GYFUL	22,27	13,19
HIFAS	-67,04	-34,56
HIPEN	-0,84	3,54
LACOL	-23,61	-25,02
LUARB	-78,22	-70,57
MIMIG	-59,73	-47,00
MIMIL	-66,78	-52,38
NEPER	52,35	20,40
OEURA	-18,28	-18,00
PEAPI	-87,81	-72,17
PYROC	-98,60	-86,72
SYUND	-97,13	-53,83
TEURO	-47,22	-52,21

Fig S5.1. Predicted percentage of gains and losses in the amount of optimal habitats for the target species between 2000 and 2050 in N2000 sites above (left) and below (right) an average altitude of 800 meters under each scenario of future change according to the combined models. The whiskers indicate the 5% and 95% percentiles, the hinges indicate the first and third quartiles (in white and grey for A2 and B2 climate change scenarios, respectively) and the central black line indicates the median value across the different MEDFIRE runs simulating land cover changes.




CAEUR ABOVE 800 m
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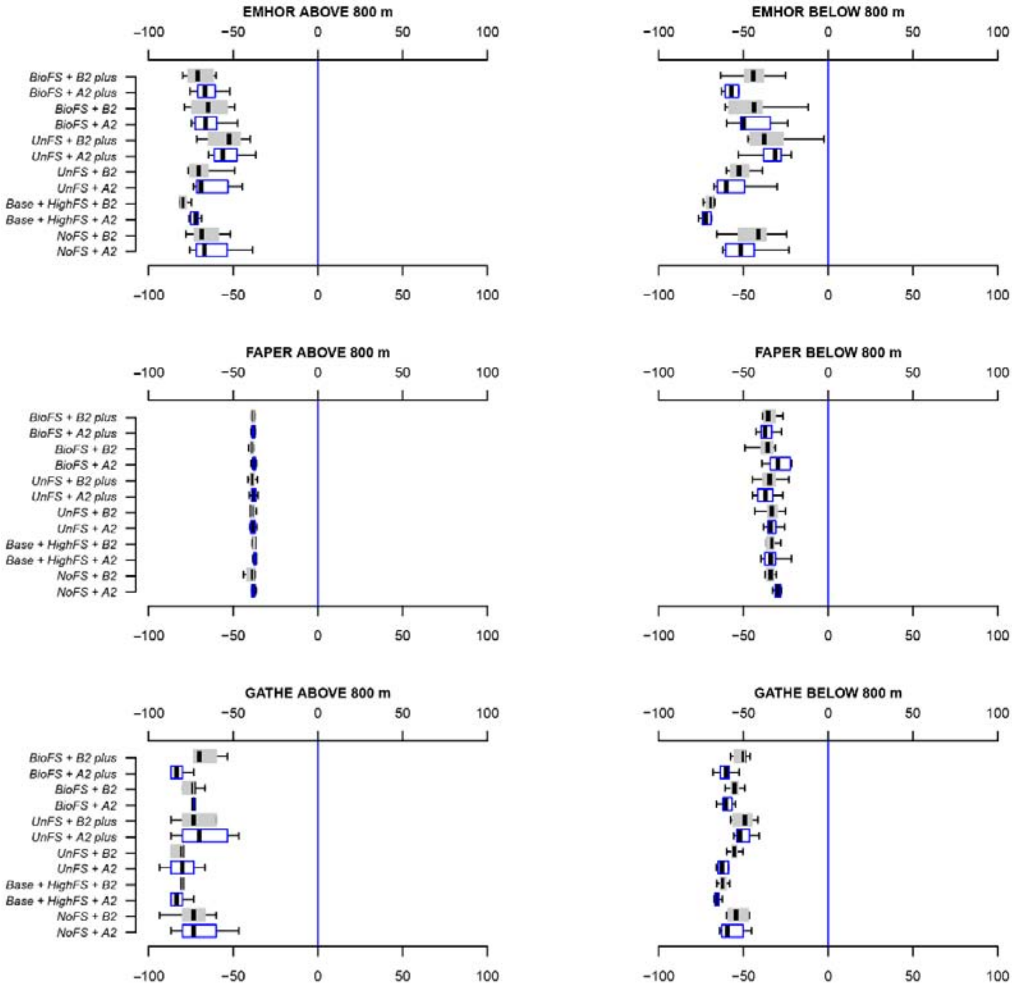
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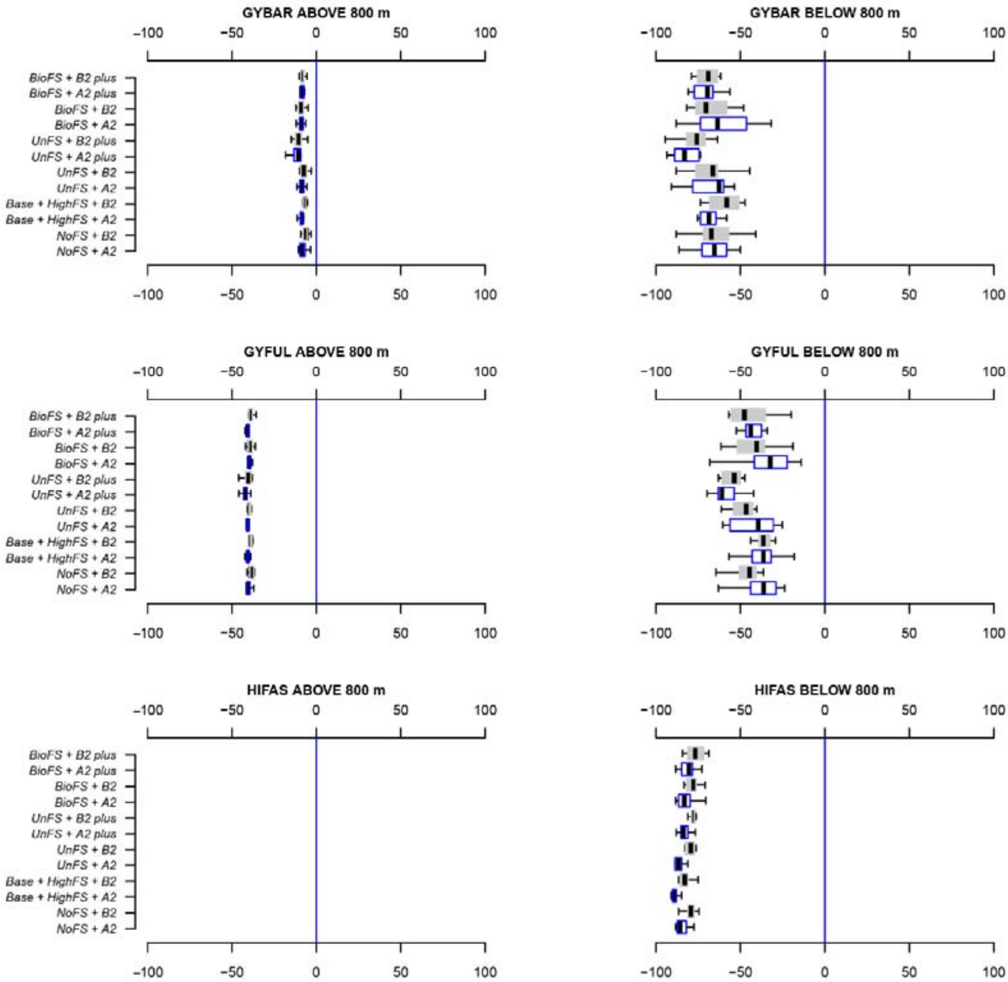
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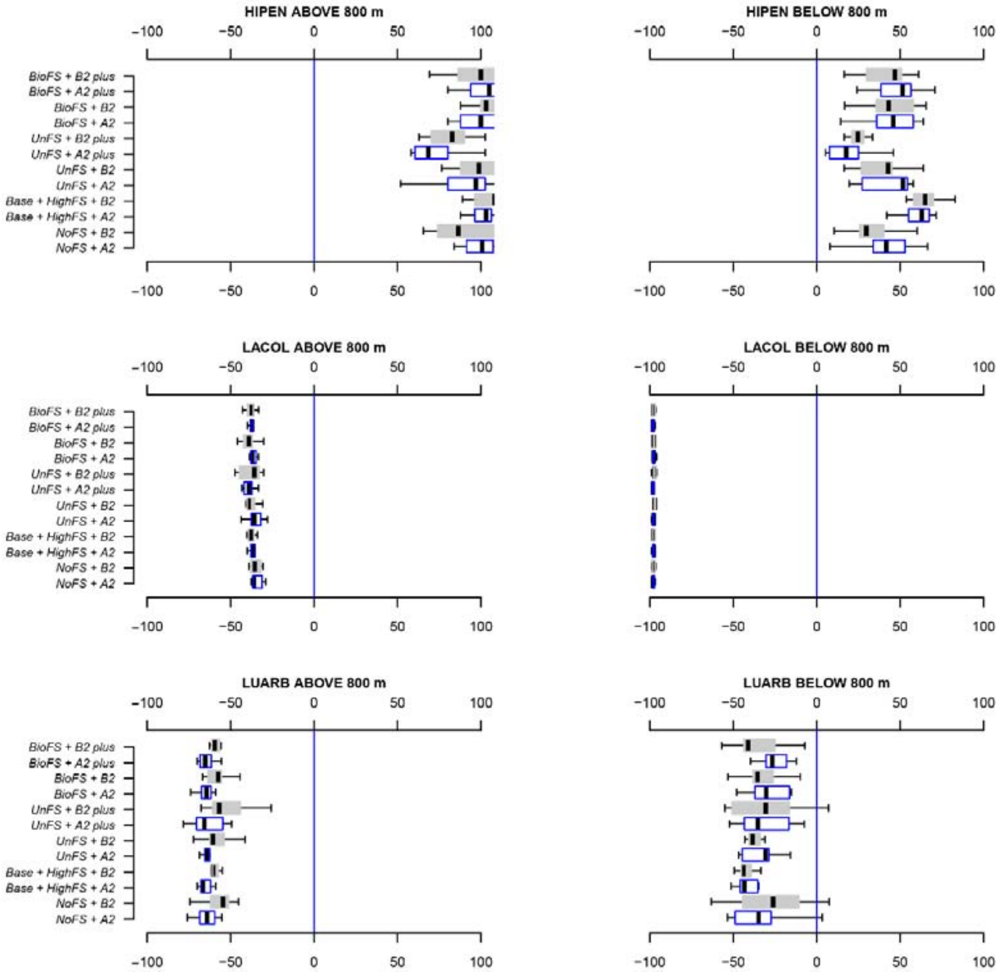
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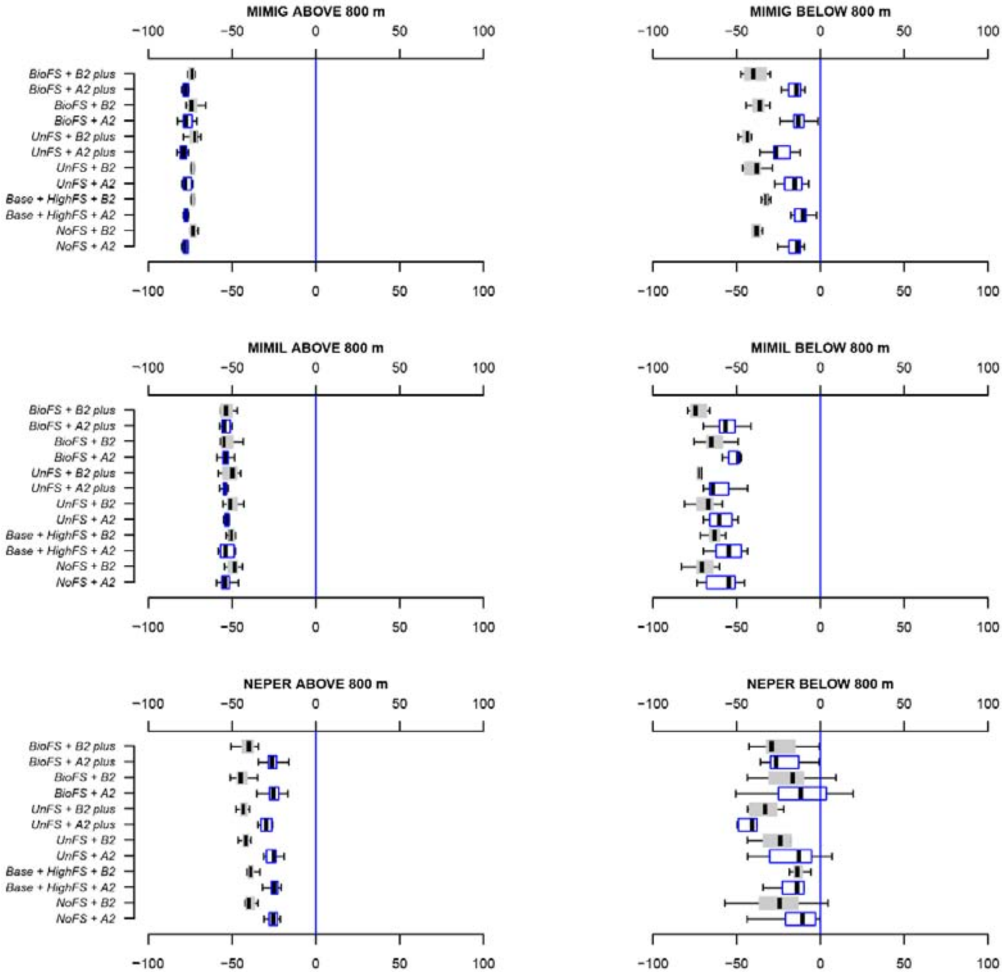
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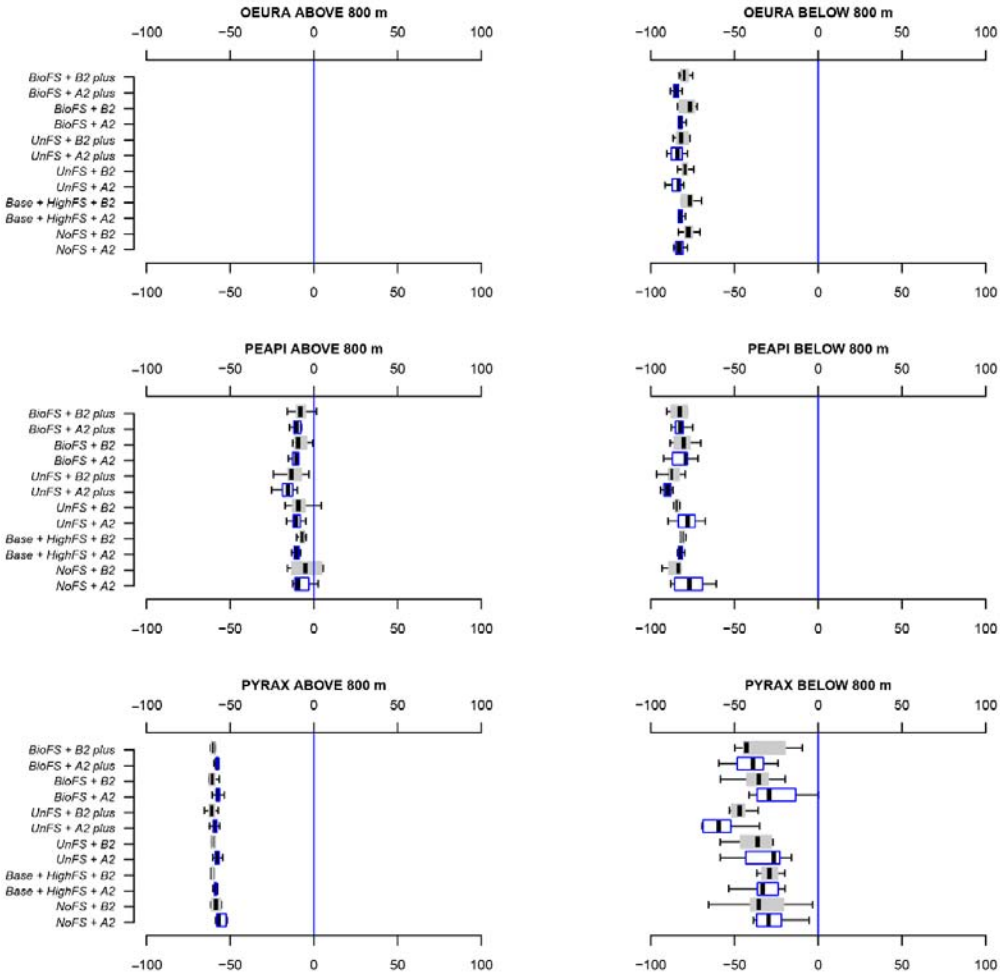
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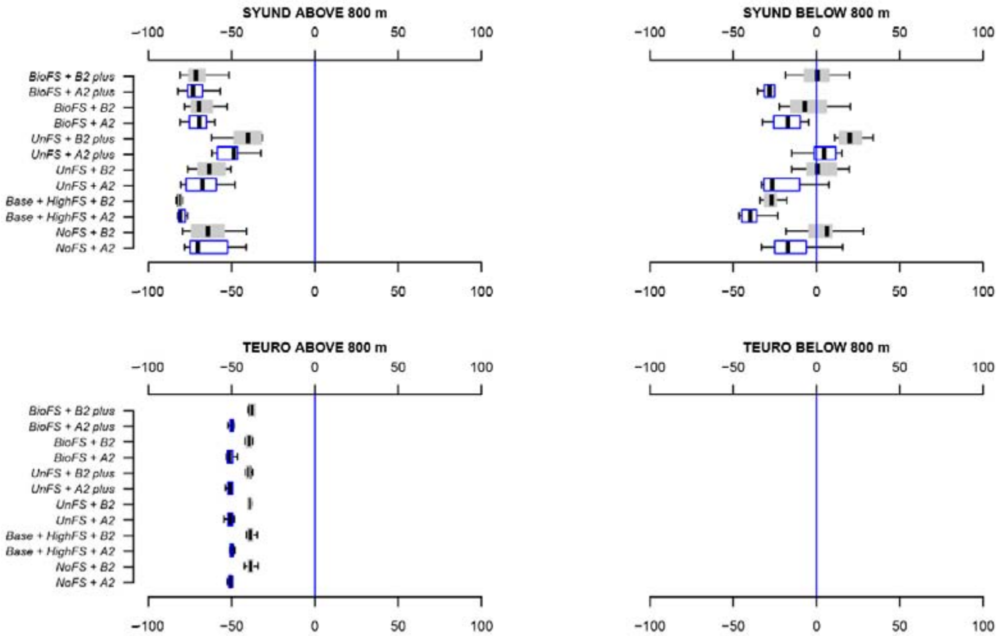
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UnFS + A2
Base + HighFS + B2
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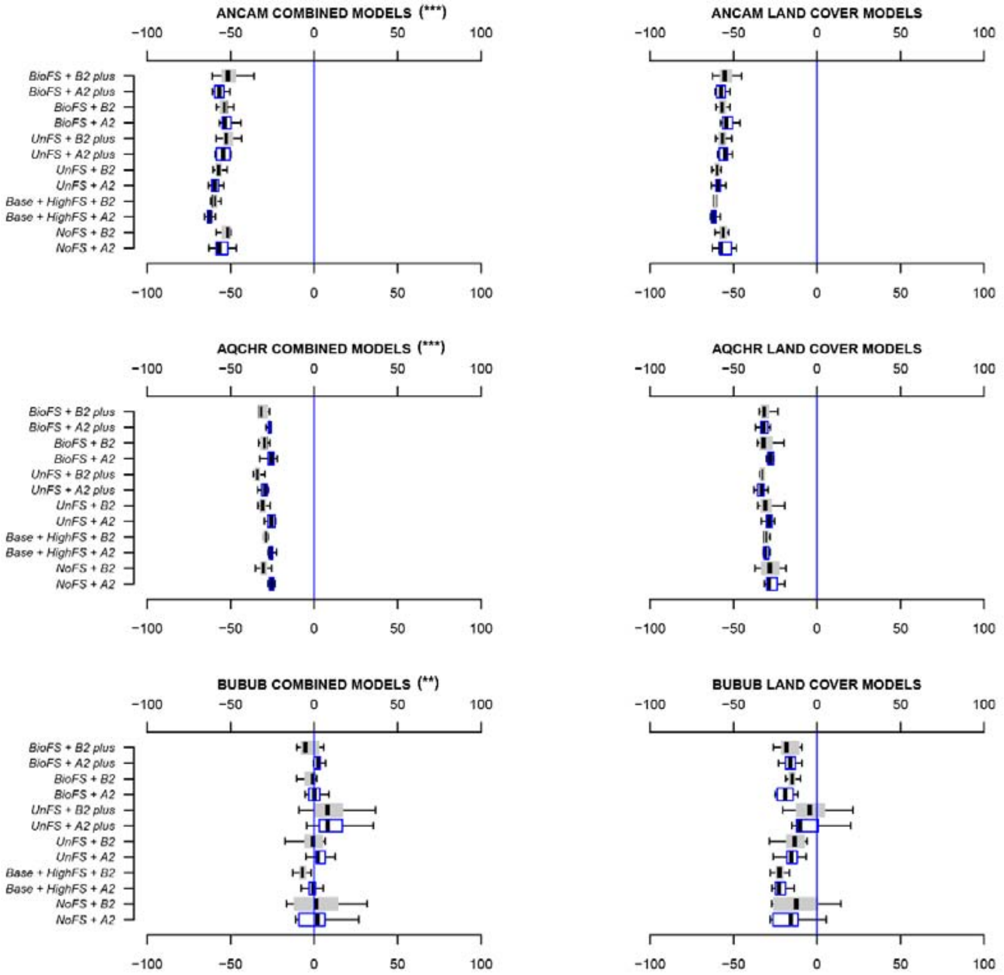
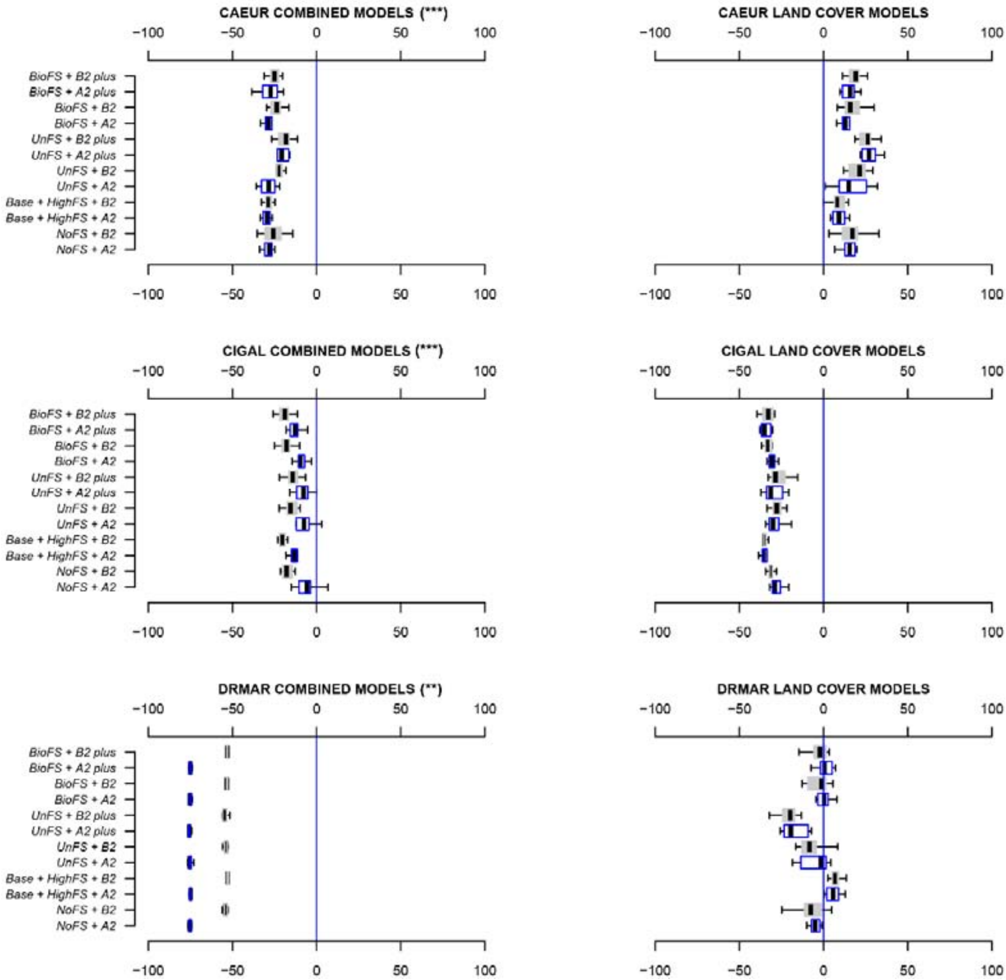
Fig. S5.2. Predicted percentage of gains and losses in the amount of optimal habitats for the target species between 2000 and 2050 inside N2000 under each scenarios of future change and according to the combined models (left) and the land cover models (right). The whiskers indicate the 5% and 95% percentiles, the hinges indicate the first and third quartiles (in white and grey for A2 and B2 climate change scenarios, respectively) and the central black line indicates the median value across the different MEDFIRE runs simulating land cover changes. The stars between brackets after species names in the outcomes of the combined models (left) indicate the significance level ('***' < 0.001, '**' <0.01, '*' <0.05, 'N.S.' non significant) for the effect of fire suppression strategies on future gains and losses in the amount of optimal habitats as evaluated by the GLMs.

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CIGAL LAND COVER MODELS
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BioFS + A2 plus
BioFS + B2
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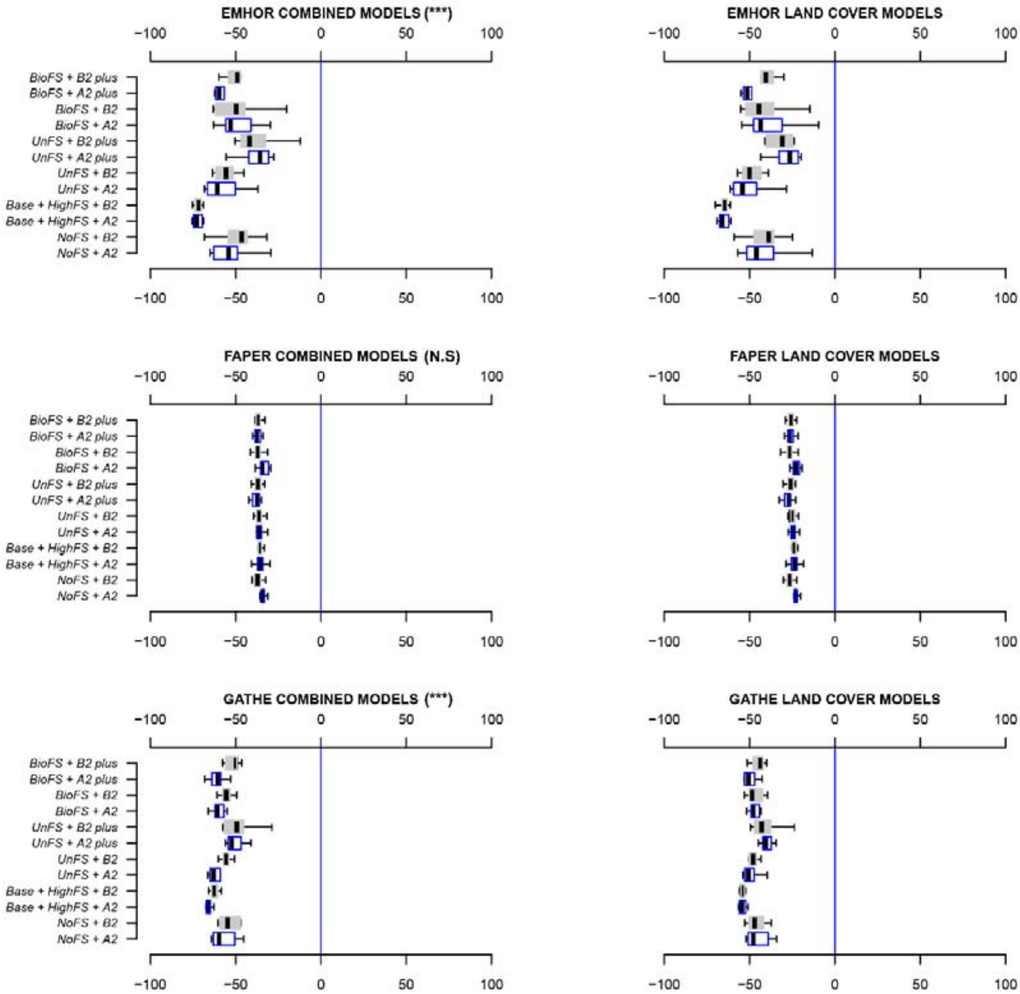
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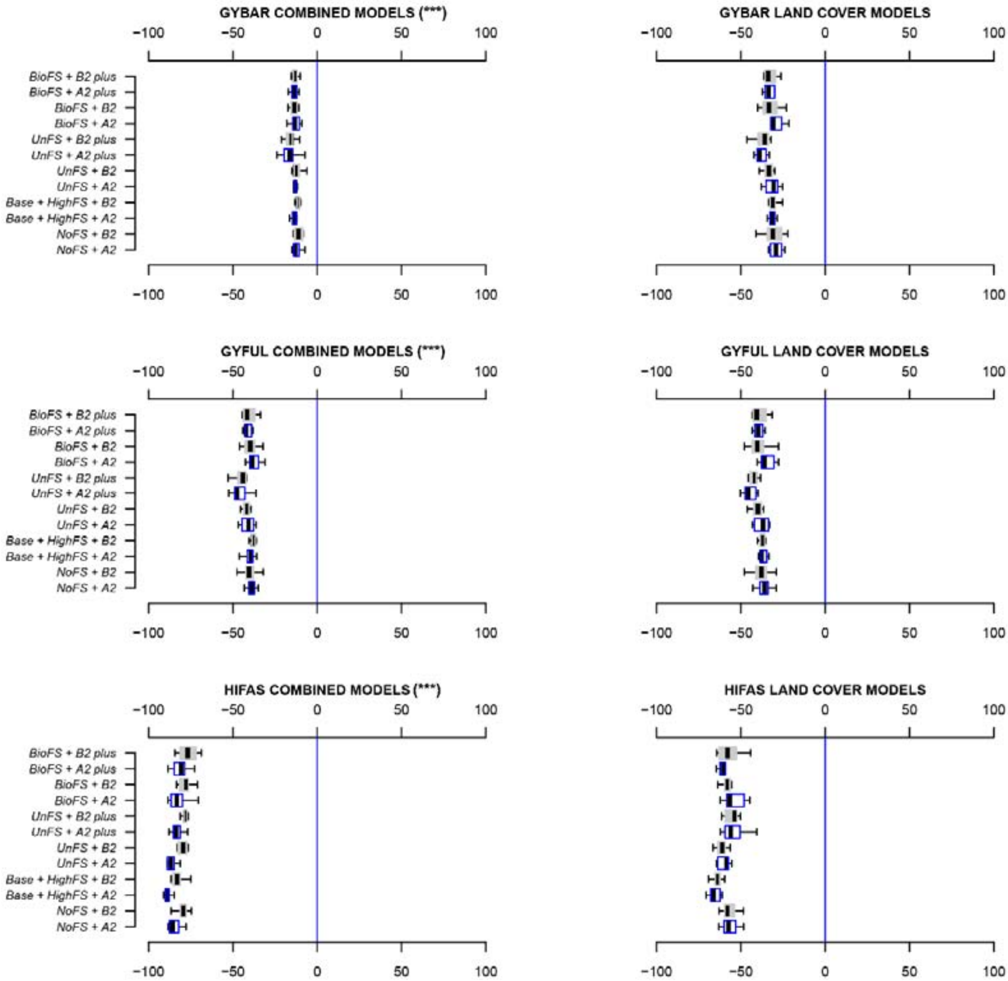
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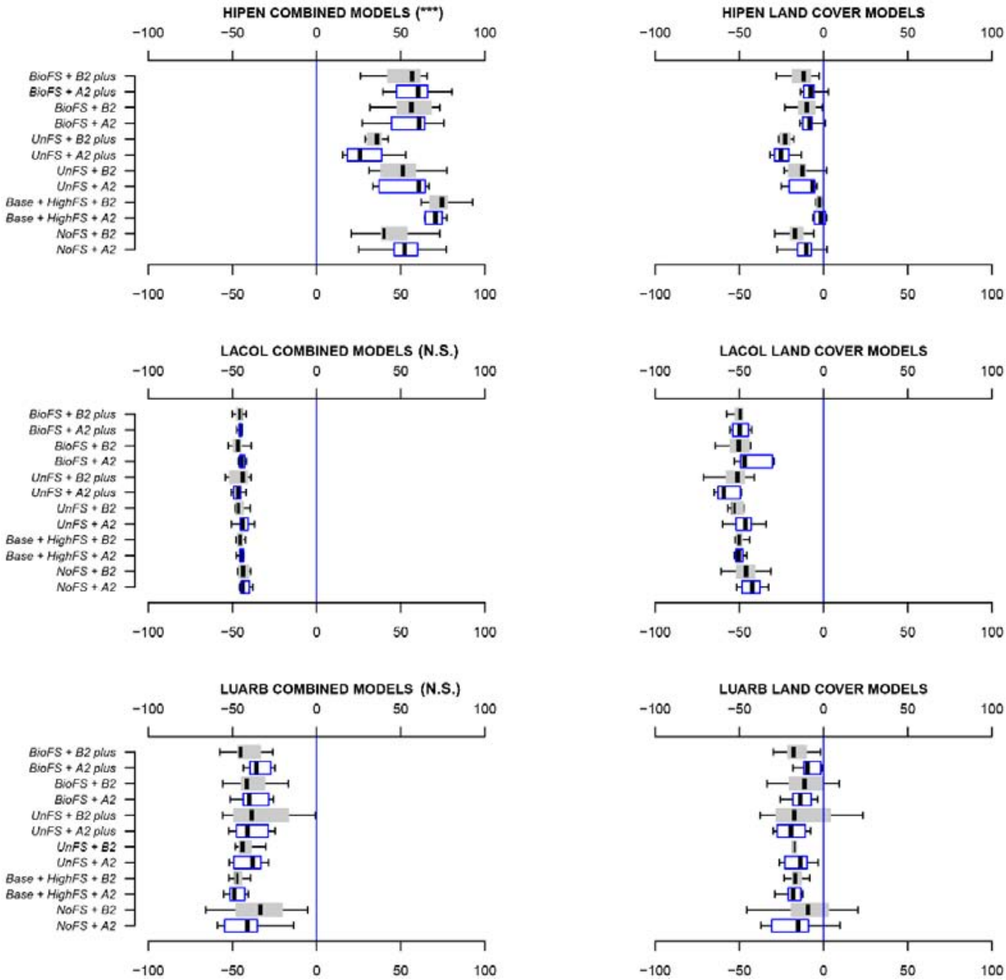
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LUARB LAND COVER MODELS
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BioFS + B2 plus
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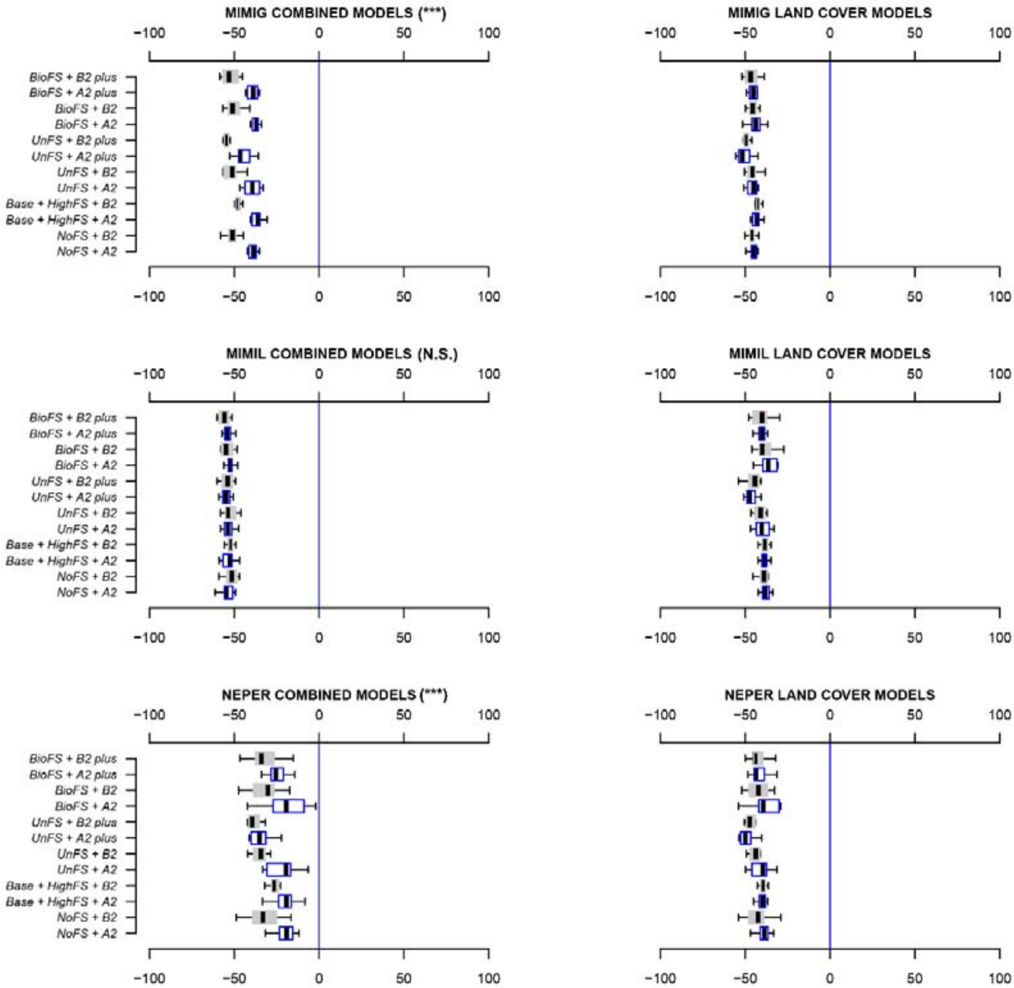
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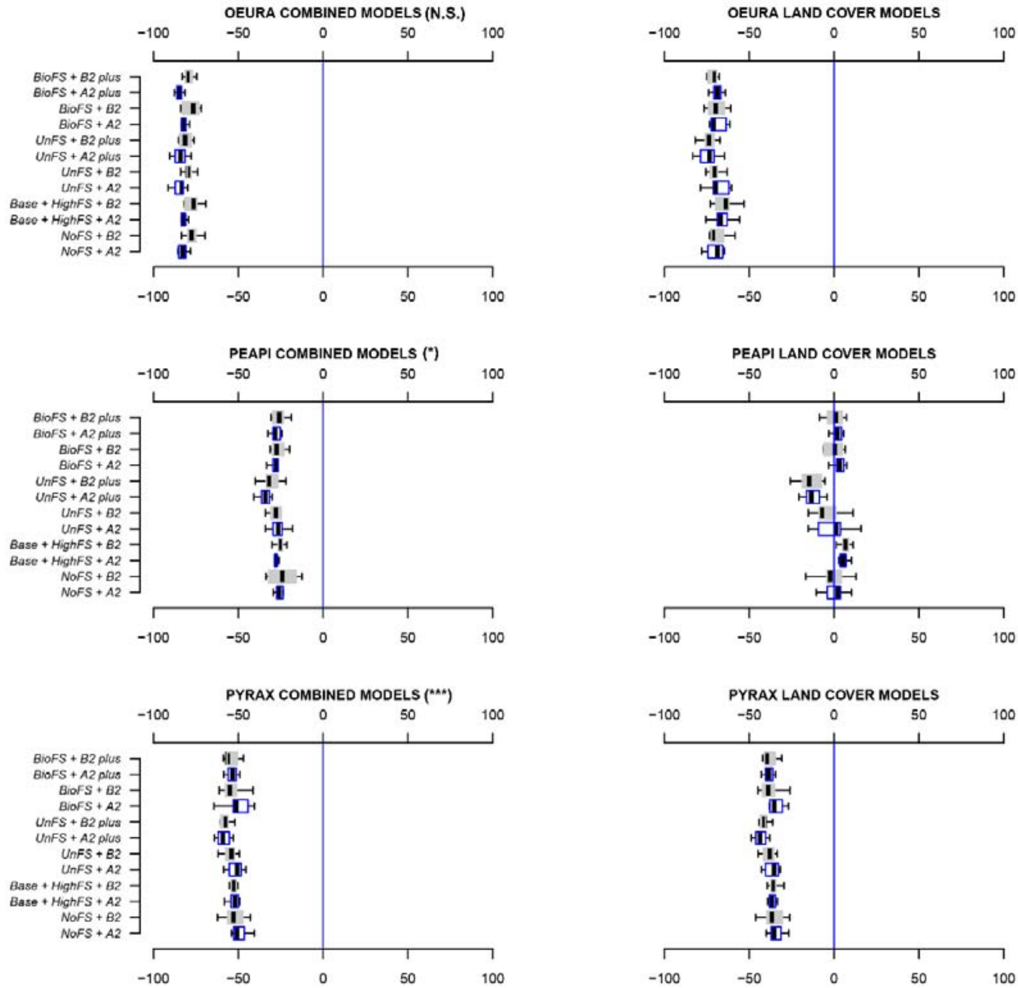
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PEAPI LAND COVER MODELS
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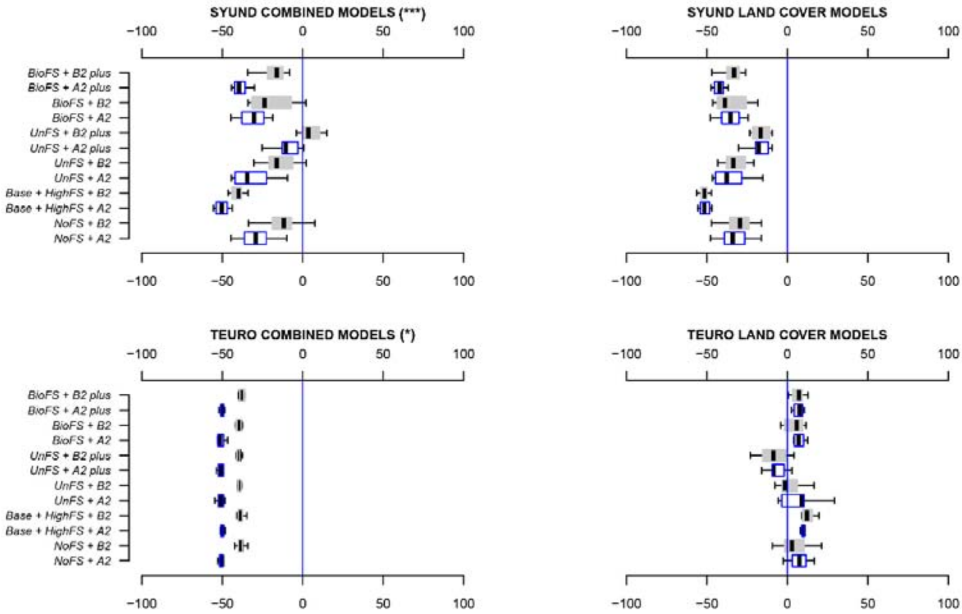

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TEURO COMBINED MODELS (*)
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SUPPORTING INFORMATION

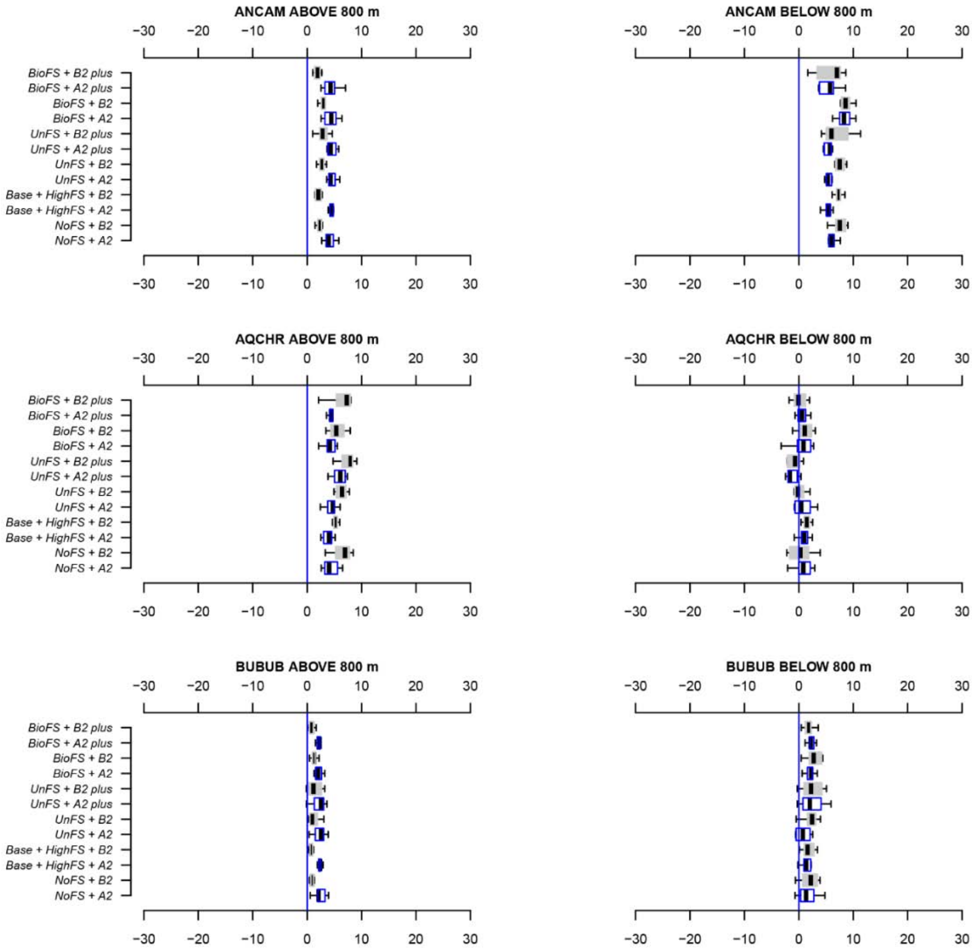
Predicting the future effectiveness of protected areas for bird conservation in Mediterranean ecosystems under climate change and novel fire regime scenarios

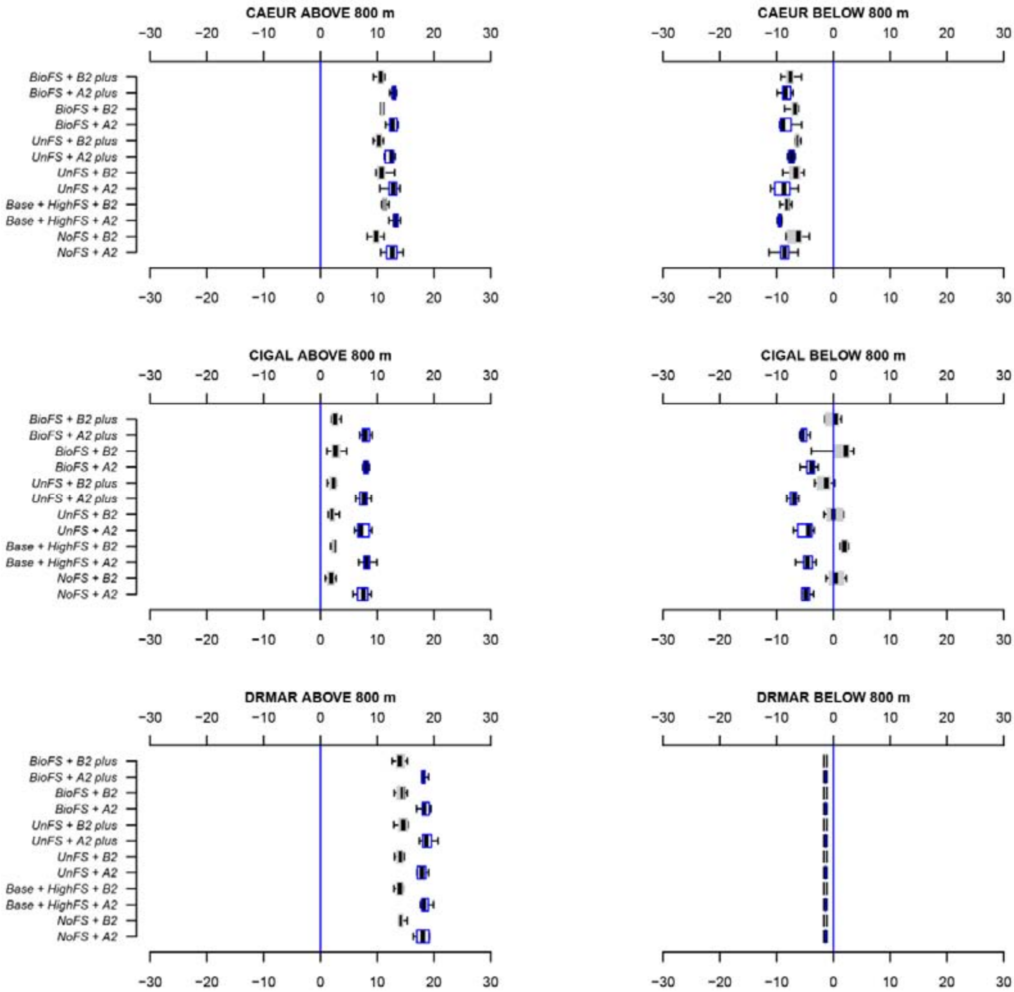
APPENDIX S6: Changes in the effectiveness of N2000 for the conservation each bird species under climate and land cover change scenarios.

This appendix provides detailed information about the increase and decrease in the effectiveness of N2000 to preserve the optimal habitats for the 23 species analyzed in our study between 2000 and 2050 under each scenario of future environmental change above and below an average altitude of 800 meters (Fig. S6). To assess the extent to which N2000 will likely be able to maintain its role to ensure the persistence of key habitats for the target species under climate and land cover change scenarios, we first calculated the percentage of squares with optimal habitats inside N2000 relative to those in the whole study area and we used this percentage as a measure of effectiveness of N2000 in 2000 (Eff_{2000}) and in 2050 (Eff_{2050}). Second, increase or decrease in effectiveness was estimated from the difference between Eff_{2050} and Eff_{2000} for each species under each scenario. Third, we calculated the number of species for which N2000 is expected to increase or decrease in effectiveness by less than 5%, by 5% to 10% and by more than 10% between 2000 and 2050.

In addition to a global analysis of the results over the whole N2000 network, we also explored the geographical variation in the decrease/increase of the number of squares with optimal habitats for the species and in the effectiveness of N2000 along the latitudinal/altitudinal gradient in Catalonia. We split the N2000 sites into two sets of PAs associated with different elevation ranges: (1) above 800 meters (> 800 m) and (2) below 800 meters (< 800 m) (Fig. 1). This elevation threshold was used to distinguish between PAs predominantly located in mountain areas (north of Catalonia) from those in the lowlands (south).

Figure S6. Predicted percentage of change in the effectiveness of N2000 for preserving the optimal habitats for the target species between 2000 and 2050 under each scenario of future environmental changes according to the combined models. The whiskers indicate the 5% and 95% percentiles, the hinges indicate the first and third quartiles (in white and grey for A2 and B2 climate change scenarios, respectively) and the central black line indicates the median value across the different MEDFIRE runs simulating land cover changes. Based on such predicted changes, we counted the number of species for which N2000 is expected to increase or decrease in effectiveness by less than 5%, by 5% to 10% and by more than 10% under climate and land cover changes between 2000 and 2050 (Figure 4). See Tables 1 and 2 for scenario and species acronyms, respectively.

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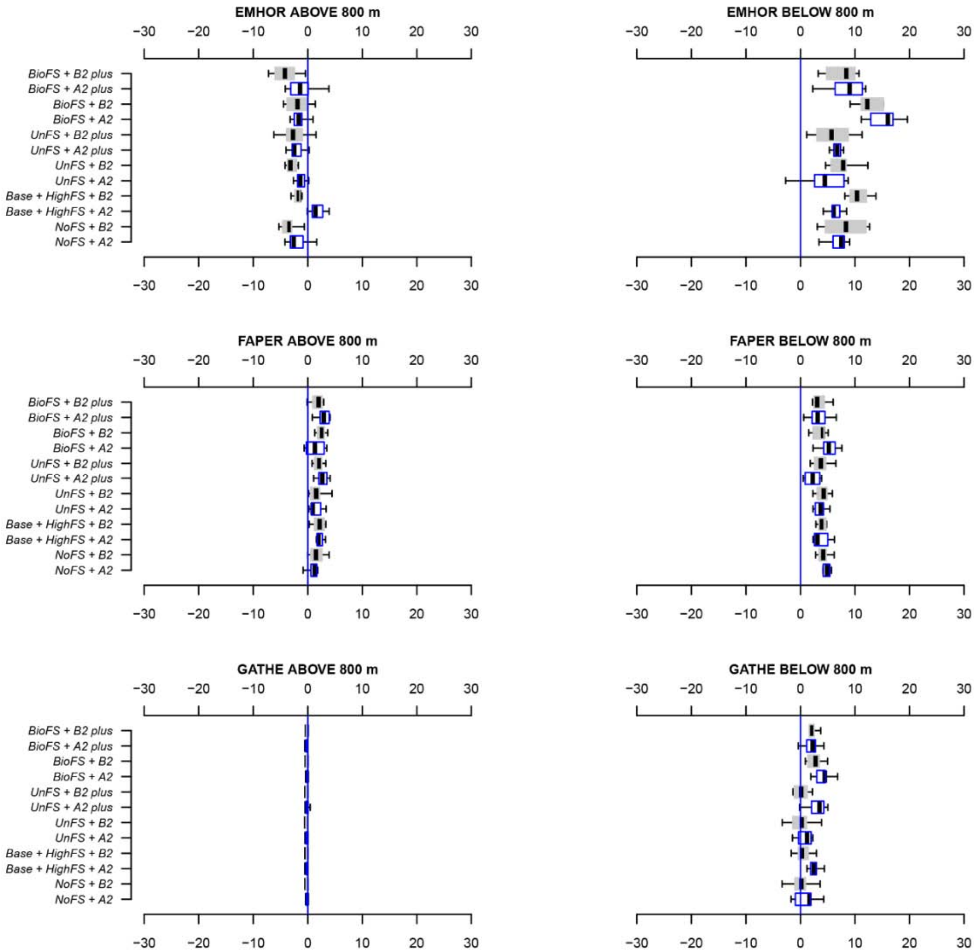
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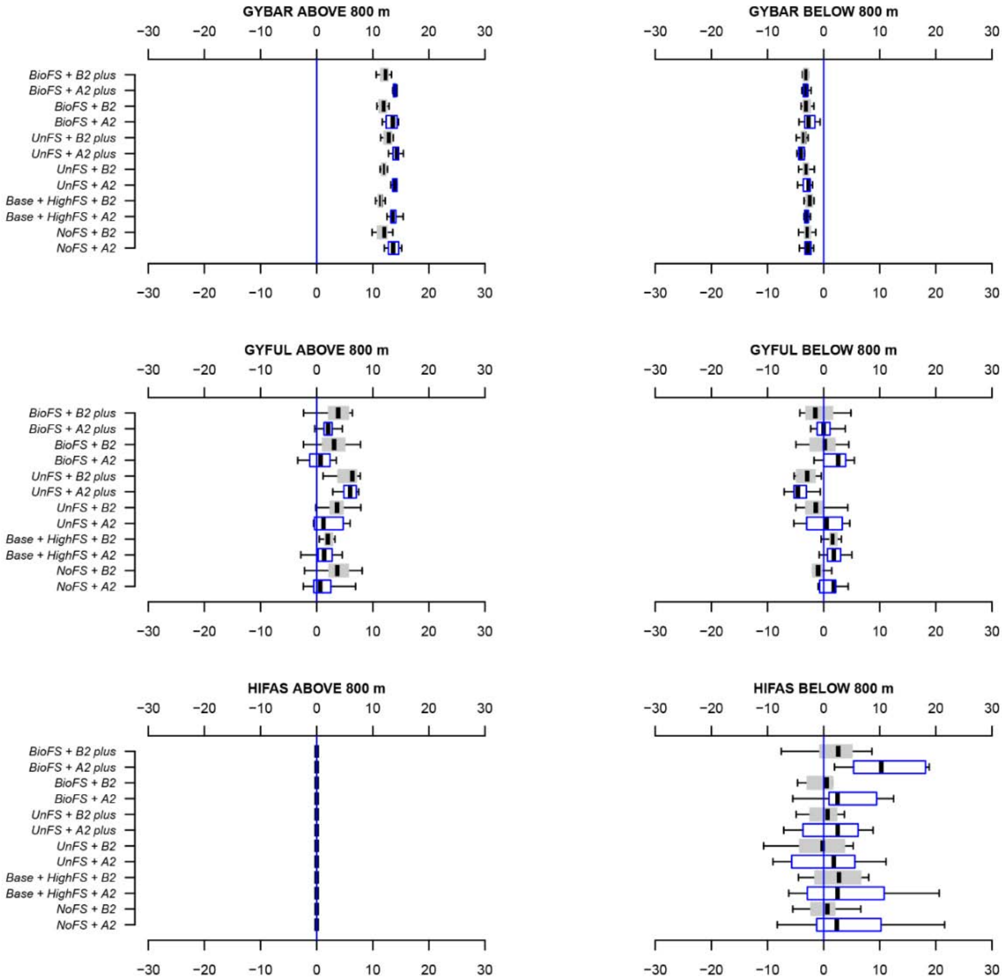
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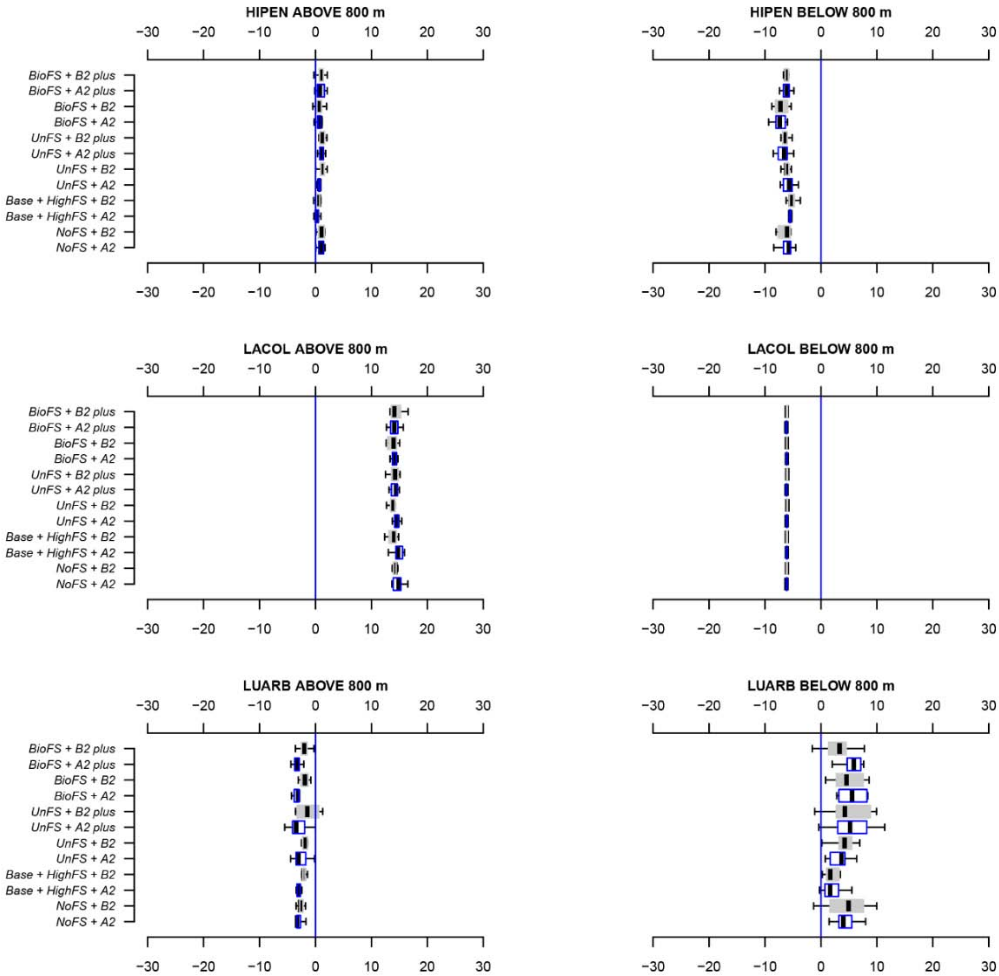
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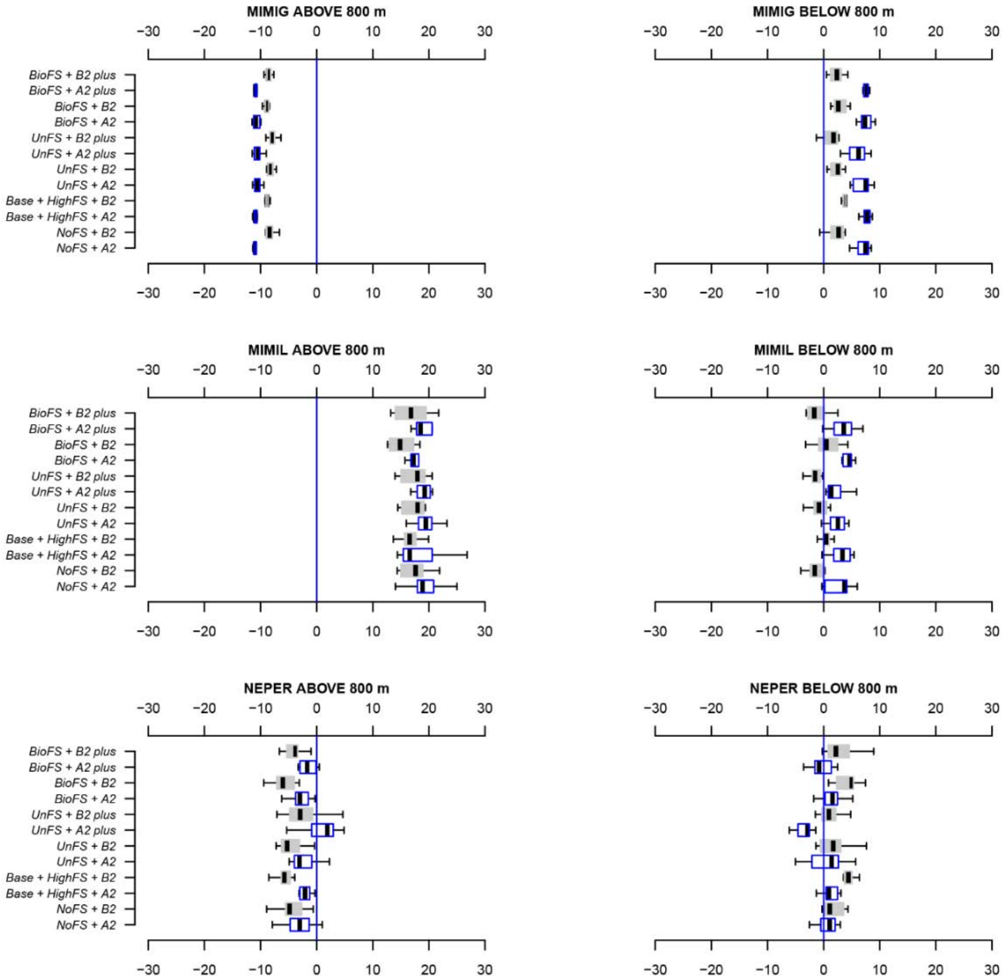
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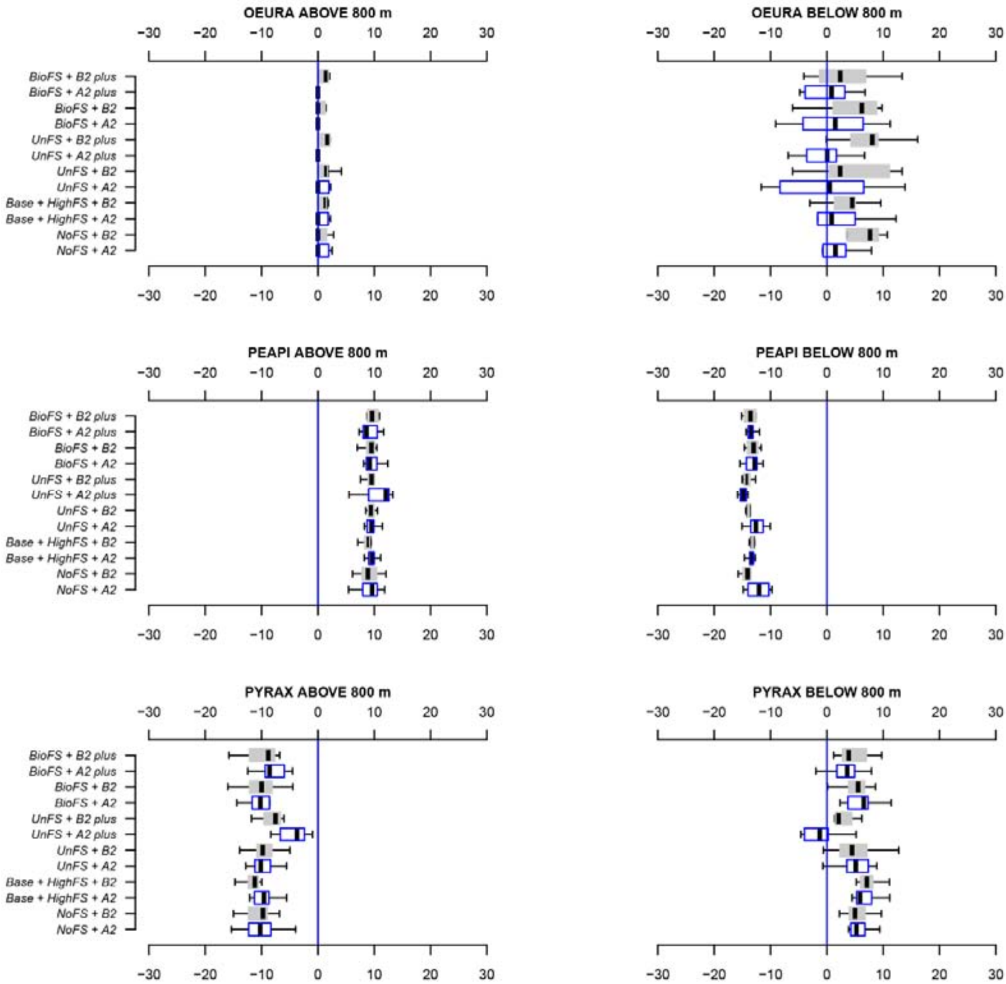
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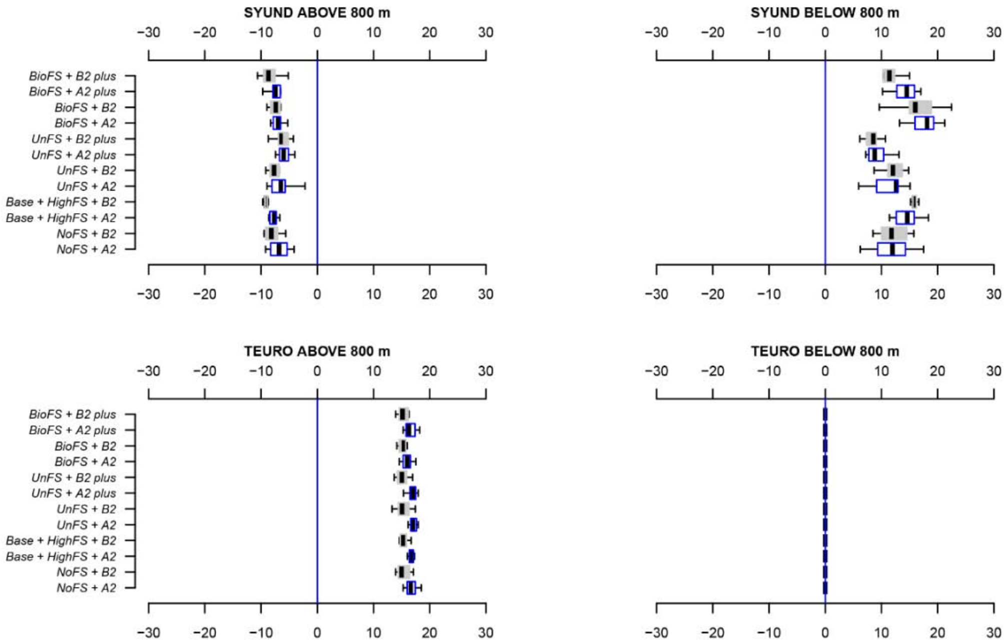
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DISCUSSION

Conservation science needs strategic foresight leading to effectively address the ongoing challenges posed by global change [8]. We have illustrated the role for scenario planning and model simulations in underpinning the strategic foresight processes —using storylines as conceptual scenarios, and simulations as numerical estimates of future environmental changes. Horizon-scanning activities were also essential in identifying and prioritizing future possible pathways in Mediterranean ecosystems. This strategic foresight exercise contributes to opening up new fire management policy options and testing developed current policies in relation to their resilience to unknown, but plausible, new emerging threats posed by global change. This visioning exercise that integrates social, economic and ecological dimension has clearly contributed to bridge the gap between conservation policy and science. In particular, horizon-scanning activities enabled to recognize the main driving forces that are currently shaping Mediterranean landscapes (namely fire disturbance regime, vegetation encroachment, climate change and their interactions) as well as new opportunities for sustainable environmental management and effective biodiversity conservation.

A new debate between politicians, scientific community and fire managers about future fire management, in terms of extinction and prevention was identified. The increasing impact of fire in many regions poses the need of learning to coexist in a more sustainable way with wildfires [36]. A fire suppression paradigm shift is claimed by the different stakeholders of forestry sector and fire-fighting brigades to move away from the "stop all fires" vision to new efficient and cost-effective polices. New opportunities to achieve the stand structure and fuel reduction objectives required to minimize the undesired impact of megafires through alternative fire management strategies were explicitly evaluated in the first part of the thesis (chapter I and II).

In the first chapter, we envisaged a fuel-reduction strategy based on modulating fire suppression efforts in mild weather conditions to create a novel fire regime with a large number of smaller fires but a reduction in area burnt by large, high-intensity fires (hereafter 'letting unplanned fires burn' strategy). This perspective assess the role of using unplanned fires and associated fuel reduction to create opportunities for suppressing large fires in future adverse weather conditions. According to our simulation-based scenario analysis, this fire management strategy has the potential to substantially reshape future fire regimes and decrease the amount of area burnt under undesired, extreme climate conditions [1]. It also increases landscape heterogeneity but do not seem enough to offset the decade-long general trend towards homogenization due to land abandonment and the coalescence of natural vegetation patches [84,110,111]. Moreover, climate change brings warmer and drier summers and increased fire weather risk [112–114]. This climate warming also implies a lower number of mild years and therefore fewer windows for creating opportunities. In this context, exponentially larger areas need to be burnt in mild years to create additional fire suppression opportunities. Our study suggests that to achieve the stand structure and fuel reduction goals required to minimize large fires in extreme fire weather, this strategy should be accompanied by other fuel-reduction treatments such as large-scale forest biomass extraction.

In the second chapter, an alternative fuel-reduction strategy based on forest harvesting for bioenergy purposes was posed. Again, the horizon-scanning activities allowed identifying sectoral policy dialogues on emerging issues [63] such as fire-risk assessment, renewable energies and socioeconomic demands of the society closely related to forestry sector and rural world. In this chapter, a new set of scenarios aimed at mitigating the escalating impact of wildfires was designed. This study provides the first comprehensive estimates that clearly support the view that biomass extraction for bioenergy can be considered by policy makers as a viable strategy to reduce large fires. According to our findings, the effectiveness of this fuel-reduction strategy is strongly determined by the intensity and spatial allocation of the extraction as well as how firefighters are able to use the opportunities created by biomass extraction as fire suppression strategy. However, the efficiency of this forest harvesting effort in suppressing wildfires depends on the allocation of extraction (clearly related to the objectives for which the treatment is designed) and the intensity of such extraction. This valuable information for forest and fire managers will be a keystone for the optimization of this fuel-reduction strategy and its successful implementation in future firefighting programs forced to deal with global change [89,115]. Additional benefits can be generated from forest ownerships, by linking forests to bioenergy production, simultaneously creating sustainable development opportunities for rural communities [116]. Our findings are not restricted to our study region but could extend to multiple spatial, temporal and socio-political scales, since this fuel-reduction strategy presents strong synergies with social and energy-based policies, helping to bridge the gaps between forest policies, fire management and renewable energy strategies [117,118].

This forward-looking perspective has identified two large-scale fire management strategies alternatives to the basic firefighting principle of tackling "all fires" as soon as possible. These novel strategies might potentially bring fire regime back towards a more natural and self-regulated state where fire plays a key role in shaping landscapes while simultaneously reduces fire risk. However, optimal fire management strategy (i.e. the one most likely to maximize biodiversity and minimize fire risk) hinges on the initial state of the system, the cost associated with each strategy, and the time frame over which the managers have set their objectives [49]. Therefore, evaluating the relative value of these fire management practices from a future perspective is key for ecologically sustainable management of fire [47–50]. Consequently, understanding and forecasting how species will respond to these novel fire regimes is essential to maximize biodiversity in fire-prone ecosystems [34,45,46]. Likewise, testing the future effectiveness of protected areas at preserving species targeted by European Directives is essential.

In the second part of this thesis (chapter III and IV), we envisaged a new set of contrasting scenarios wherein the current fire suppression paradigm based on 'stop all fires' (business-as-usual scenarios) was directly confronted to the emerging fire management strategies here posed (chapter I and II). Besides, these new set of scenarios take explicitly into account the direct and indirect effect of climate change on the target species. The multi-scale modelling approach we implemented allowed us to predict the future changes in habitat suitability for conservation-concern bird species as a response to climate change and vegetation dynamics driven by fire-related disturbance regime and land abandonment. Our findings show that, although the future response of the species to global change is species-specific, large decreases in the amount of habitats are expected for most of the species. In addition, our results also indicate that such a decrease in habitat suitability will be driven by both climate and land cover changes, and their combined effect. The response of a high number of species to these changes is predicted to vary substantially depending on the fire management practice that will be implemented in the future.

In particular, the greatest number of species with a decreasing amount of habitats in the future is predicted under the business-as-usual scenario, so the continuation of the *status quo* is not a desirable scenario. Overall, our projections suggest that fire management practices aimed at decreasing fire impact through the creation of new early-succession stages and sparsely vegetated areas by letting unplanned fires burn during mild weather conditions is the best option to help reduce the decline of open-habitat species in a context of land abandonment (chapter III). Simultaneously, such strategy is not predicted to have negative side-effects on forest-specialist species: future habitat suitability for these species is negatively affected by climate change and positively affected by forest expansion under land abandonment (chapter IV) (see also [119]). Thus, two main conservation opportunities were identified: 1) promoting early-succession stages of vegetation for open-habitat dwelling species through fire management; and 2) increasing the resilience of key forest habitats to climate change for forest-dwelling species.

According to our scenario-based analysis, the effectiveness of Nature 2000 network for the protection of the target conservation-interest bird species will likely increase over the next decades as the proportion of optimal habitats within Nature 2000 relative to the whole of Catalonia is predicted to increase (chapter IV). However, this effectiveness may be considerably improved through the implementation of alternative fire management strategies that are not in line with those that have been traditionally applied so far. Our findings highlight the importance of a wider conservation perspective wherein agricultural, forest and fire management policies should be integrated to effectively maintain key habitats for threatened birds in these fire-prone systems.

CONCLUSIONS

This thesis exemplifies how a strategic foresight exercise (combining horizon scanning, scenario planning and simulation-based scenario analysis) might help to support more proactive and integrative conservation policies when faced the inherently uncertainty of the future. This looking-forward perspective increases the resilience of forest management, fire planning and conservation decisions to undesired future situations. In particular, this strategic foresight exercise contributes to opening up two promising fire management policy options alternatives to the basic fire-fighting principle of tackling "all fires" as soon as possible. Such visioning exercise, in which the social, economic and ecological dimensions are integrated, helps at closing the gap between policy and science. From a more methodological perspective, our approach also underlines the need for an explicit consideration of fire dynamics and their interacting effects with climate change when forecasting the future of a fire-prone landscapes and their biodiversity in a context of global change.

More specifically, a fire management policy based on principles of 'letting unplanned fires burn' has the potential to substantially reshape future fire regimes and decrease the impact of large fires under undesired, extreme climate conditions. However, this strategy by alone is not able to counterbalance the synergistic effect of decade-long trend of vegetation encroachment caused by land abandonment, and ongoing climate warming. Beside, forest biomass extraction for energy purposes has proved to be a cost-effective fuel-reduction strategy to help suppressing forest fires. Therefore, both fire management policies could be strategically combined in order to achieve the stand structure and fuel reduction goals required to minimize the increasing impact of large fires under global change. The ecologically sustainability of both fire management policies and the effectiveness of the Nature 2000 network has been explicitly evaluated in a context of future climate change and vegetation encroachment. The continuation of the current fire suppression paradigm of tackling of 'all fires' is not the most desirable scenario. Two main emerging conservation opportunities should be prioritized in order to effectively protect community-interest bird species in the near future: 1) promoting early-succession stages of vegetation for open-habitat dwelling species via 'letting unplanned fires burn' policies; and 2) increasing the resilience of key forest habitats to climate change for forest-dwelling species.

This thesis emphasizes the need for an integrative conservation perspective wherein agricultural, forest and fire management policies should be explicitly considered to effectively preserve key habitats for threatened birds in fire-prone, highly-dynamic systems. This thesis also sheds light about the importance of considering landscape dynamics and the synergies between different driving forces when assessing the long-term effectiveness of fire management at reducing fire risk and safeguarding biodiversity in Mediterranean-type ecosystems.

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