Ecosystems (2016) 19: 786–802
DOI: 10.1007/s10021-016-9968-z

ECOSYSTEMS

Synergies Between Forest Biomass Extraction for Bioenergy and Fire Suppression in Mediterranean Ecosystems: Insights from a Storyline-and-Simulation Approach

Adrián Regos,[1]* Nuria Aquilué,[1,2] Ignacio López,[3] Mireia Codina,[3] Javier Retana,[1,4,5] and Lluís Brotons[1,4,6]

[1]CEMFOR-CTFC, InForest Joint Research Unit, CSIC-CTFC-CREAF, 25280 Solsona, Spain; [2]Centre d'étude de la forêt (CEF), CP 8888, succursale Centre-ville, Montreal, Québec, Canada; [3]CTFC- Forest Science Center of Catalonia –Forest Production Timber and Bioenergy, 25280 Solsona, Catalonia, Spain; [4]CREAF, 08193 Cerdanyola del Vallès, Catalonia, Spain; [5]Autonomous University of Barcelona, 08193 Cerdanyola del Vallès, Catalonia, Spain; [6]CSIC, 08193 Cerdanyola del Vallès, Catalonia, Spain

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 simulations indicated 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. Indeed, 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 0.7). However, the leverage (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 0.45) than with treatment designed for energy reasons (lower than 0.15). We conclude that biomass extraction for energy purposes has the potential to induce changes in fire regimes and can therefore be considered a cost-effective landscape-level fuel-reduction treatment. However, our results suggest that large-scale biomass extraction may be needed if significant changes in fire regimes are to be expected.

Key words: fire suppression; forest fires; forest harvesting; MEDFIRE fire-succession model; Mediterranean basin; process-based model; renewable energy; scenarios-based analysis; landscape simulations.

Received 22 July 2015; accepted 1 January 2016;
published online 29 February 2016
Electronic supplementary material: The online version of this article (doi:10.1007/s10021-016-9968-z) contains supplementary material, which is available to authorized users.
Author contributions AR, NU, and LB conceived the study, implemented the model, and read the manuscript written. All authors analyzed the data, contributed to the conceptual development of the model, and commented critically and substantially on the manuscript.
**Corresponding author; e-mail:* adrian.regos@ctfc.es

Introduction

Every year in the Mediterranean basin, thousands of hectares of forest and shrubland are burned by wildfires, causing major ecological and socioeconomic impacts, and often human casualties (Moreira and others 2011; Keeley and others 2012). Climate warming, land-use/land-cover changes, and human actions such as fire-suppression policies or afforestation programs have reshaped the frequency and severity of wildfires in the Mediterranean Basin over the recent 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 the continued expansion of the wildland–urban interface, have induced radical changes in fire regimes in the western Mediterranean region, bringing increased fire risk (Badia and others 2011; Gonzalez-Olabarria and others 2012).

Fire management has induced changes in fire regimes over the last decade, reducing both the numbers of fires and the burned area in Mediterranean region, due to the increasing efficiency in fire-suppression policies (Turco and others 2013; Moreno and others 2014; Fréjaville and Curt 2015). Nevertheless, most of the burned area is caused by a very small number of fires larger than 1000 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 (Piñol and others 2005). At the landscape-scale, fire-regime results from a complex interplay of ignition frequency, climatic seasonality (length of dry and wet seasons), and fuel structure (Moreira and others 2011; Keeley and others 2012). From a fire-management perspective, fuel complex, spatial distribution, 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 frequency of climatic 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 socioeconomic and territorial issues (Stephens and others 2012) that challenge the controlled burn strategy, especially in densely populated 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 1998). Typical fuel-treatment strategy 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 amount of 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 already 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).

Table 1. Description and Equations of the Indices Calculated to Compare Forest Biomass Extraction Strategies

Indices	Description	Equations
Effectiveness	Ratio of the area where fire was effectively suppressed over the burned area expected with no fire suppression according to the historical fire data (1975–1999 period). It is a measure of the degree to which fire-suppression objectives are achieved without reference to costs/efforts. For example, suppressing completely a fire that is initially expected to burn 6 hectares (ha) (i.e. effectiveness = 1) represents a higher effectiveness than suppressing only 3 ha of that fire (i.e. effectiveness = 0.5)	[Area suppressed (ha)]/[area potential to be burned (ha)]
Leverage	Ratio of the area where fire was effectively suppressed over the area treated. Leverage is the idea that a single hectare of fuel reduction can protect additional hectares (Loehle 2004; Price and others 2012). For example, in a coniferous forest of northern Catalonia, the extraction of 3-4 ha of forest biomass could be required to reduce subsequent wildfire by 1 ha (i.e. leverage = 0.25-0.33), whereas in sclerophyll forests of south-eastern Catalonia, this ratio could be closer to 1 (i.e. exact replacement of wildfire by forest biomass extraction treatment) or even higher if 1 ha of area managed implies 2 ha of area suppressed (i.e. leverage = 2)	[Area suppressed (ha)]/ [area treated (ha)]
Number of fires	Changes in the mean number of fires is calculated from the difference between the mean number of simulated fires and the mean number of fires expected to occur according to historical fire data for each scenario	[Number of simulated fires] − [potential number of fires expected to be burned]

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 two central attributes of fire regime—burned area and number of fires. Specifically, we assess how (i) different levels of fire suppression, and (ii) the intensity and (iii) the spatial allocation of forest biomass extraction could affect (a) the effectiveness (which, here, refers to area suppressed in relation to the potential expected area to be burned) of this fuel-reduction strategy to mitigate large forest fires; and (b) the leverage (which, here, refers to area suppressed in relation to the area managed in which biomass has been extracted) of each treatment (see wider definitions in Table 1). This evaluation was conducted for each bioclimatic subregion identified in the study area to account for the role of landscape context and climatic gradients. Finally, we discuss the advantages and disadvantages of forest biomass-extraction strategies in shaping current fire regimes in the Mediterranean region, and introduce key socioeconomic and ecological issues that should be addressed in future research to facilitate its potential implementation.

Materials and Methods

Study Area

The study was conducted on Catalonia, a Mediterranean region located in the northeastern Iberian Peninsula (Figure 1A). This region is cur-

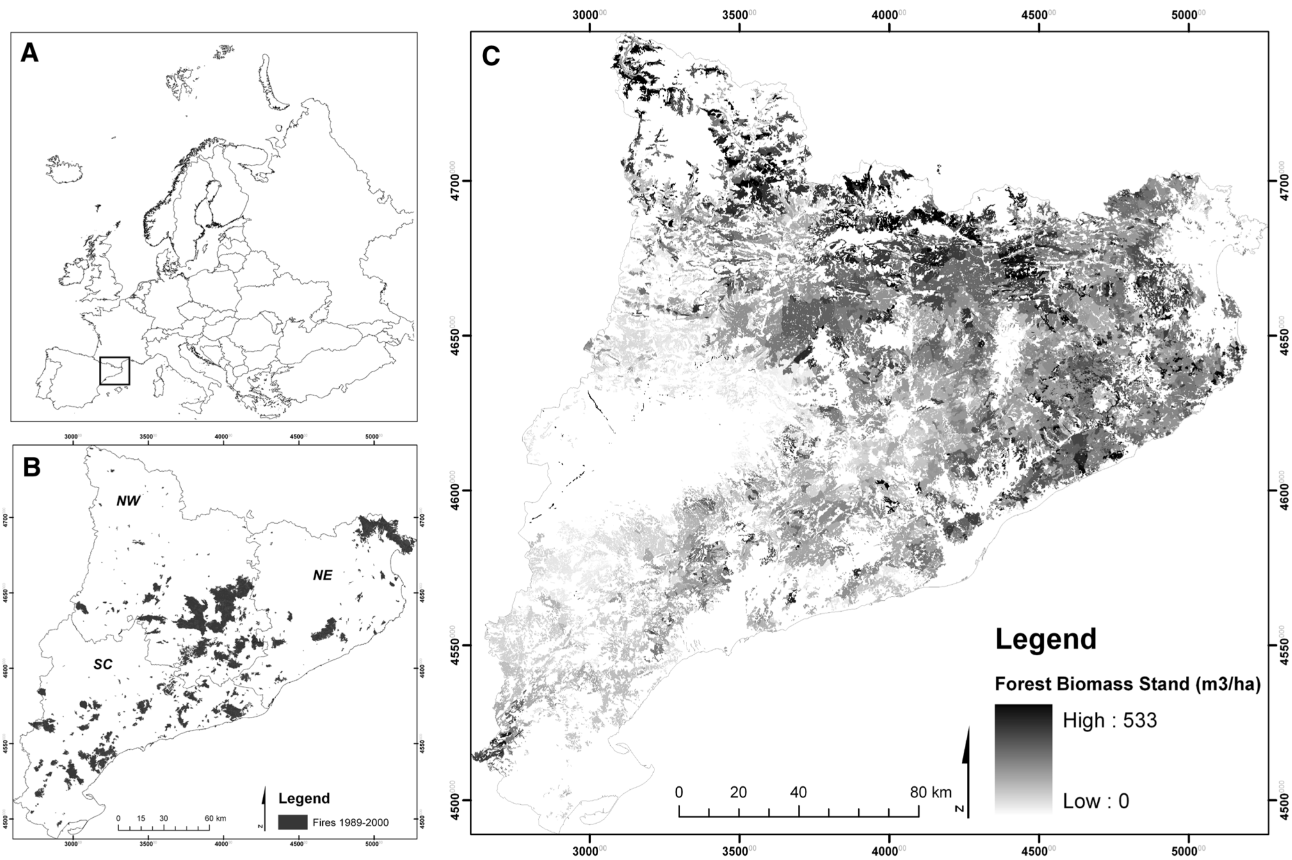

Figure 1. Location of the study area (**A**), wildfires occurred in the study area between 1989 and 2000 (**B**), and growing stock (expressed in $m^3\ ha^{-1}$) (**C**). Following Vallecillo and others (2009), Catalonia was divided in three bioclimatic regions: North-West (NW), North-East (NE), and South-Central (SC).

rently extensively covered by forest (39.6%) and shrubland (16.8%) (CREAF 2009; Ibañez and Burriel 2010). Coniferous forests (mainly *Pinus sylvestris*, *P. halepensis* and *P. nigra*) occupy 58.4% of the total forested area, the broad-leaved species (*Quercus ilex* and *Q. 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 $m^3\ y^{-1}$ (Figure 1C). The annual increment averaged for Catalonia is 3.16 $m^3\ ha^{-1}\ y^{-1}$. Moreover, between the IFN-2 and IFN-3, the amount of standing dead trees increased 11-fold. Higher mortality rates were related to dryness, and growth was reduced with the increasing dryness and temperature, leading to a mismatch in the forest turnover. Sustainable forest biomass extraction could enhance structural diversity within denser stands reducing the vulnerability of forest to drought events (Vila-Cabrera and others 2011). According to government data, average forest-resource exploitation between 2000 and 2010 was 155,000 $m^3\ y^{-1}$ of firewood and 550,900 $m^3\ y^{-1}$ for industrial use, which gives a total (705,900 m^3) that comes to just 20% of forest growth (GENCAT 2014a). Therefore, current forest-harvesting levels could be increased fourfold and idem for the yearly harvested surface.

In Catalonia, wildfires are extensive in pine forests and shrublands, whereas deciduous forest rarely burn (Figure 1B). Focusing in the 1975–98 period, conifer forest was the land cover most affected by fire (43% of total burned area), followed by shrubland (31%), broad-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. To account for the role of landscape context and climatic gradients on fire regimes, we adopted the bioclimatic subregions identified by Vallecillo and others (2009): North-West (NW), North-East (NE), and South-Central (SC) (Figure 1B). SC subregion is characterized by stronger fire impacts due to warmer Mediterranean and continental climates than NE subregion with a stronger wind impact. 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 11–15°C (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 timescales 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 climates 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 and others 2013).

Biomass extraction in the MEDFIRE model is applied as an annual target area to be managed (ha y^{-1}). We assume a constant annual biomass extraction rate (equals to the inter-annual increment, expressed in m^3 ha^{-1} y^{-1}), so the annual target area to manage only depends on a predetermined harvesting intensity (m^3 ha^{-1}) and the total area available for biomass extraction (ha) (see more details in Table 2; 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 (for example, 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 burned 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 2014a). 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^{-1}) and (2) low-intensity level (34.7 m^3 ha^{-1}) (Table 2; Appendix S2). The high-intensity level corresponds to treatments wherein all available biomass yearly (crown fuels, dead, and live) 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, double the area of the 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 (1 year), fires are simulated until the potential annual area to be burned is reached. Potential annual area refers to the area that is expected to burn according to historical fire data (1975–1999 period). The model also mimics the ability of firefighters to take advantage of opportunities in areas where forest biomass has been reduced (that is, fires or biomass extraction treatments). The fire-suppression opportunities derived from these fuel-reduction processes are therefore able to constrain final fire sizes, making fire-size distribution an emergent 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

Table 2. Description of the Variables, Labels, and Values Used in the MEDFIRE Scenarios Characterization

Variable	Value	Label	Description
Biomass extraction rate	3.16 m^3 ha^{-1} y^{-1}		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^{-1}	High-Int	High-intensity extraction was estimated from the available forest biomass feedstock per year (2,714,100 m^3 y^{-1}), considering a rotation period of 22 years and a technically available surface (859.000 ha) (more details in Appendix S2)
	34.7 m^3 ha^{-1}	Low-Int	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 y^{-1}	High-Int + Opt	Target areas to manage (hectares/year) were calculated according to the equation: ([Area for
	78,086 ha y^{-1}	Low-Int + Opt	biomass extraction (ha)] * [biomass extraction
	11,105 ha y^{-1}	High-Int + FireRisk	rate (m^3 ha^{-1} y^{-1})])/[intensity (m^3/year)] (see
	22,211 ha y^{-1}	Low-Int + FireRisk	more details in Appendix S1)
	62,849 ha y^{-1}	High-Int + SubOpt	
	125,698 ha y^{-1}	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
	40%	Medium-FS	relation between biomass extraction and fire-suppression opportunities as well as the possible variability related with firefighting skills and the
	10%	Low-FS	amount of funding or resources invested in fire suppression

ha = hectares; 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.

time since last extraction at the cell level is below a prespecified 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 thereby significantly reducing fuel load in a given area (as illustrated in Figure 2A, B; Appendix S2). This treatment effectively redistributes fire-suppression opportunities at the landscape level by altering fire behavior in two different ways: changing fire-spreading rates and reducing the likelihood of crowning behavior (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 (Figure 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 de-

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

rived from a management action (that is, 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 we assumed the time window for using harvested areas as fire-fighting opportunities will be 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 (that is, favorable site conditions avoiding steep slopes and with small extraction distances) thereby assuming a cost-effective forestry biomass harvesting.

(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 2014b). 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

Table 3. List of MEDFIRE Scenarios Describing Parameters Used to Reproduce Fire Suppression and Biomass Extraction

ID	Target area to manage (ha y^{-1})	Intensity of extraction (m^3 ha^{-1})	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

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.

additional forest biomass extraction also from suboptimal 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.

Scenario Implementation

We designed and implemented 18 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 2, 3). 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 2). All scenarios were characterized by a biomass extraction rate equal to the annual increment averaged for Catalonia (3.16 m^3 ha^{-1} y^{-1}), thereby 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).

The eighteen scenarios resulted from the combination of different values for the three scenario parameters (Tables 2 and 3):

- 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% of opportunities).
- Three treatments dealing with the biomass extraction allocation were designed, each determining where harvesting activities are restricted according to storyline (Figure 3). In the *Renew* storyline, extraction took place in areas where slope was less than 30% and distance to roads was less than 400 m, and was excluded in protected areas like national and natural parks (total extent of about 859,000 ha) (Figure 3A). In the *RenewSub* storyline, we relaxed the biomass extraction constraints to also allow

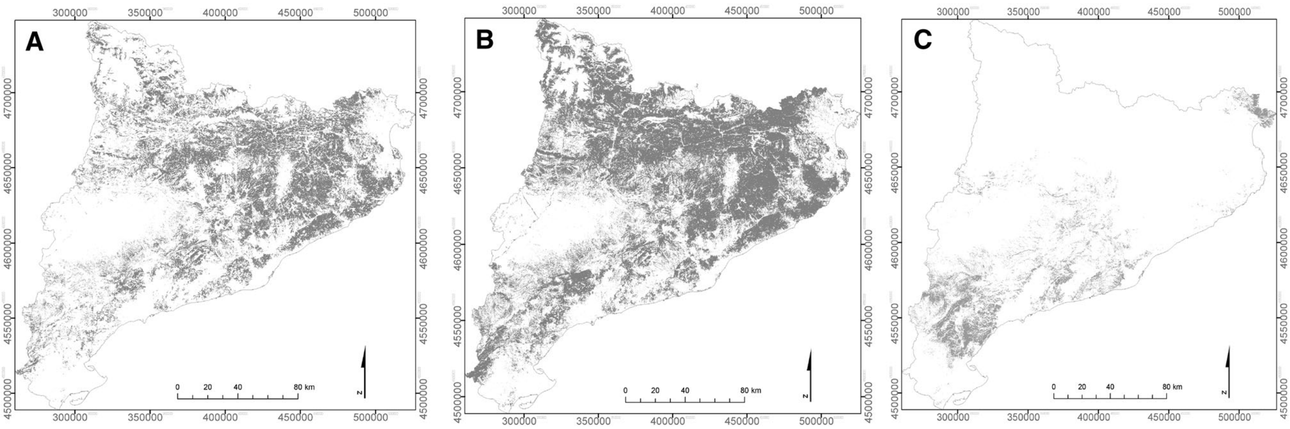

Figure 3. Areas where biomass extraction takes place according to the three storylines: optimal area fitting that slope is less than 30% and distance to roads is less than 400 m, whereas protected areas are also excluded (**A**). Suboptimal areas (areas with slope greater than 30% and distance to roads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

actions in areas with slope above 30, distance to roads greater than 400 m, and within protected areas (total extent of about 1,385,000 ha) (Figure 3B). In the *FireP* storyline, biomass extraction is limited exclusively to high-fire-risk areas (total extent of 244,800 ha) (Figure 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^{-1}), 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^{-1}) involved shorter rotation periods and a larger area. Therefore, under the *Renew* storylines, and considering a sustainable biomass extraction rate (3.16 m^3 ha^{-1} y^{-1}), we needed to manage 39,043 ha every year (annual target area to manage) with high-intensity extraction, whereas for low-intensity treatments 78,086 ha y^{-1} 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.

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 burned obtained if each fire would have burned 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 leverage) (Table 1). Both indices were calculated for the whole set of the simulated fires and for three fire-size classes: large fires (>500 ha), medium fires (500–100 ha), and small fires (<100 ha), and for each bioclimatic subregion identified in the study area: North-West (NW), North-East (NE), and South-Central (SC) (Figure 1B). In addition, we also analyzed how the different treatments affect fire-size distribution. To do so, we predicted the mean numbers of large fires, medium fires, and small fires for each scenario. The increase or decrease in the number of fires was estimated from the difference between the mean number of simulated fires for each class (2000–2050 period) and the mean number of fires expected to occur according to historical fire data (1975–1999 period, without forest biomass extraction).

The effects of the spatial allocation, intensity of extraction, and fire-suppression level were estimated for each index (effectiveness, leverage, and number of fires) using generalized linear models (GLMs) with a Gaussian error distribution and 'identity' link function (McCullagh and Nelder 1989). The effects were considered as significant at $P < 0.05$. R-based packages were used to fit the GLMs, to analyze MEDFIRE outputs (packages

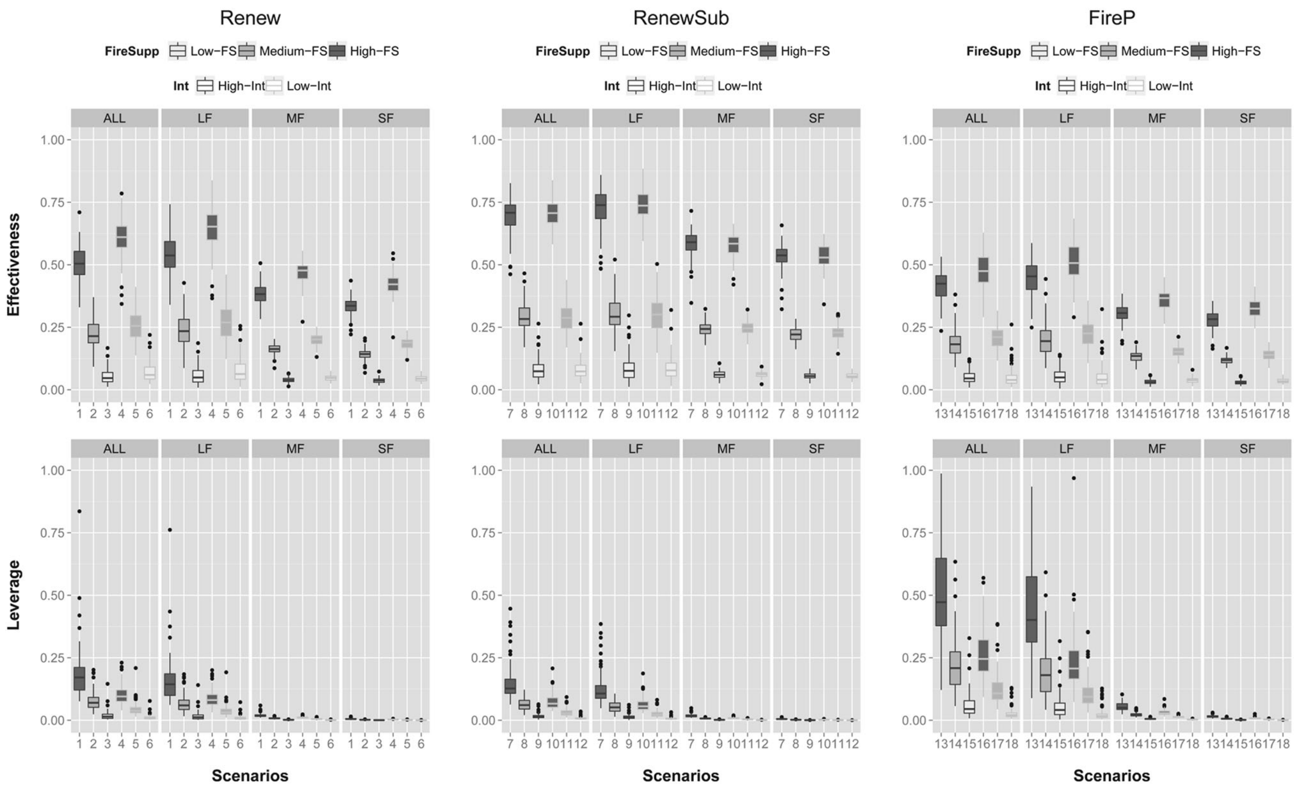

Figure 4. Effectiveness (area suppressed in relation to the potential area to be burned) and leverage (area suppressed in relation to the area managed) for each biomass extraction scenario under the three storylines: (Renew) biomass extraction takes in optimal areas, (RenewSub) suboptimal areas, and (FireP) optimal areas where fire risk is high. Results are presented for the whole set of the simulated fires and for three fire-size classes: large fires (LF), medium fires (MF), and small fires (SF). Scenarios characterized by high (*High-FS*), moderate (*Medium-FS*), and low fire suppressions (*Low-FS*), are represented in *dark gray*, *light gray* and *white* box-plots, respectively. *Black-outline boxes* represent high-intensity biomass extraction scenarios (*High-Int*) whereas *light gray-outline boxes* refer to low-intensity treatments (*Low-Int*). For all boxplots, *lower* and *upper whiskers* encompass the 95% interval, *lower* and *upper hinges* indicate the first and third quartiles, and the *central black line* indicates the median value.

'stats' and 'medfire', version 3.0.2), and to plot the results (package 'ggplot2') (R Core Team 2014).

Results

The reduction in area burned by wildfires depended on fire-suppression levels, intensity, and spatial placement of the biomass extraction (Figure 4). The reduction in area burned by large fires due to opportunities derived from biomass extraction was higher than by medium or small fires (compare all scenarios for each fire-size class in Figure 4). Moreover, leverage was clearly higher for the biomass extraction scenarios that aimed to reduce fuel accumulation in high-risk areas (Figure 4), especially in North-West (NW) and South-Central (SC) subregions (comparison across all scenarios for each subregion in Figure 5). Our simulations also showed that the numbers of large and medium fires strongly decrease, whereas the number of small fires is predicted to increase with biomass-extraction treatments (Figure 6).

Effects of Fire-Suppression Levels

Fire-suppression levels considered for each scenario had a major impact on the effectiveness of biomass extraction at suppressing wildfires ($P < 0.001$). Indeed, the median effectiveness under low fire-suppression levels ranged between 0.04 and 0.07 (see scenarios with white box-plots in Figures 4, 5). Under moderate fire-suppression levels, median effectiveness increased up to 0.18–0.28 (see scenarios with light gray box-plots in Figures 4, 5), whereas in scenarios with high fire-suppression levels, median effectiveness achieved values close to 0.7 (see scenarios with dark gray box-plots in Figures 4, 5). The number of large fires was predicted

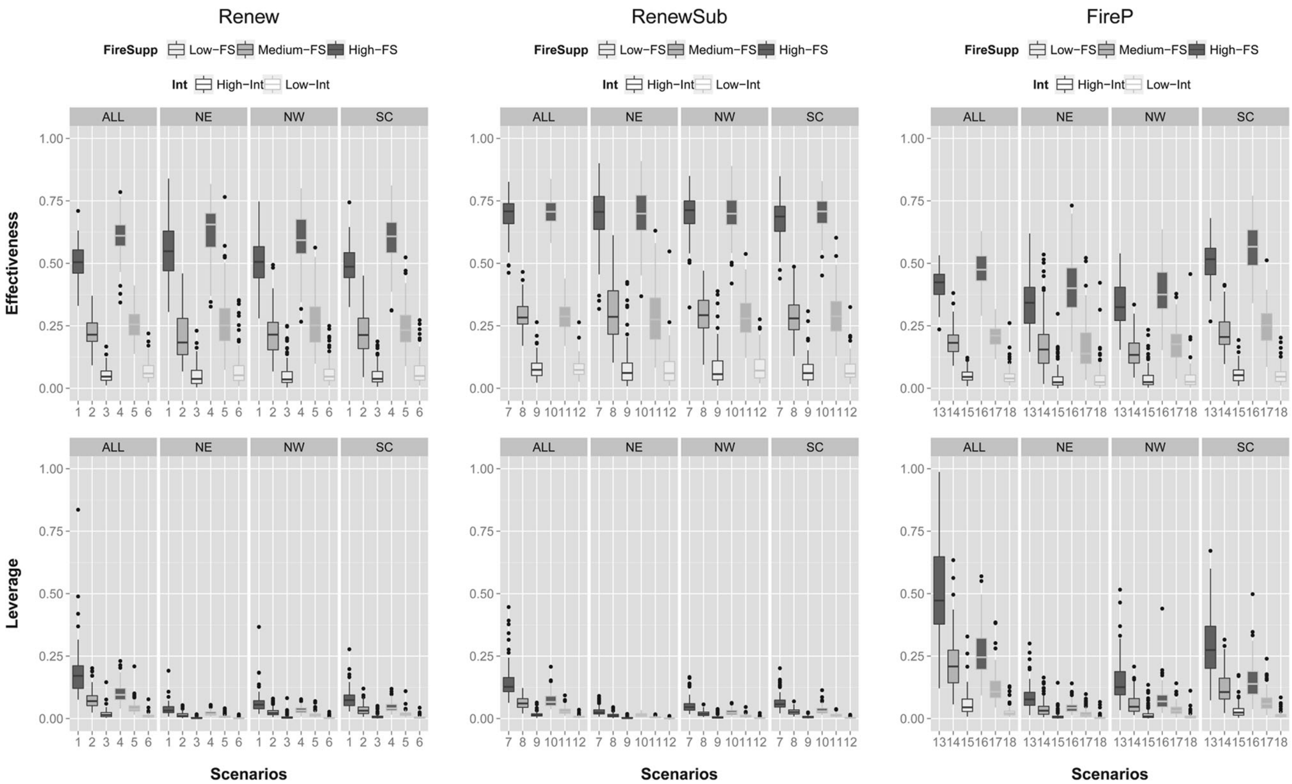

Figure 5. Effectiveness (area suppressed in relation to the potential area to be burned) and leverage (area suppressed in relation to the area managed) for each biomass extraction scenario under the three storylines: (Renew) biomass extraction takes in optimal areas, (RenewSub) suboptimal areas, and (FireP) optimal areas where fire risk is high. Results are presented for the whole study area (ALL) and for the three bioclimatic subregions: North-East (NE), North-West (NW), and South-Central (SC). Box-plot characteristics are as in Figure 4.

to decrease stronger with high than with low fire-suppression levels ($P < 0.001$) (Figure 6).

Effects of Spatial Placement of Biomass Extraction

The scenarios from the *Renew* storyline, in which biomass extraction took place in optimal areas, showed median effectiveness values of about 0.5–0.61 (scenarios 1 and 4, respectively, in Figures 4, 5).

Looking at the *RenewSub* storyline, where biomass extraction included suboptimal areas, the effectiveness reached up to 0.7 (scenarios 7 and 10 in Figures 4, 5). 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, that is, scenarios from the *FireP* storyline, the effectiveness was considerably less, at about 0.42–0.47 (scenarios 13 and 16, respectively, in Figures 4, 5). 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 ($P < 0.01$), especially at suppressing large fires in North-West (NW) and South-Central (SC) subregions (compare scenarios from the *FireP* storyline with those from the *Renew* storylines in Figures 4, 5). The number of large fires was predicted to be smaller under those treatments aimed at obtaining the maximum revenues from biomass extraction (*RenewSub* storyline in Figure 6).

Effects of Intensity of Biomass Extraction

In general, scenarios with low-intensity extraction (34.7 m^3 ha^{-1}) showed slightly higher effectiveness values than those characterized by high-intensity extraction (69.5 m^3 ha^{-1}) (compare scenarios tagged *High-Int* and *Low-Int* in Figures 4, 5), except for scenarios under the *RenewSub* storyline which showed similar figures (see scenarios 7–12 in Figures 4, 5). Thereby, in the scenarios derived from the *Renew* storyline, the suppressed area slightly increased from 0.04–0.5 in scenarios with

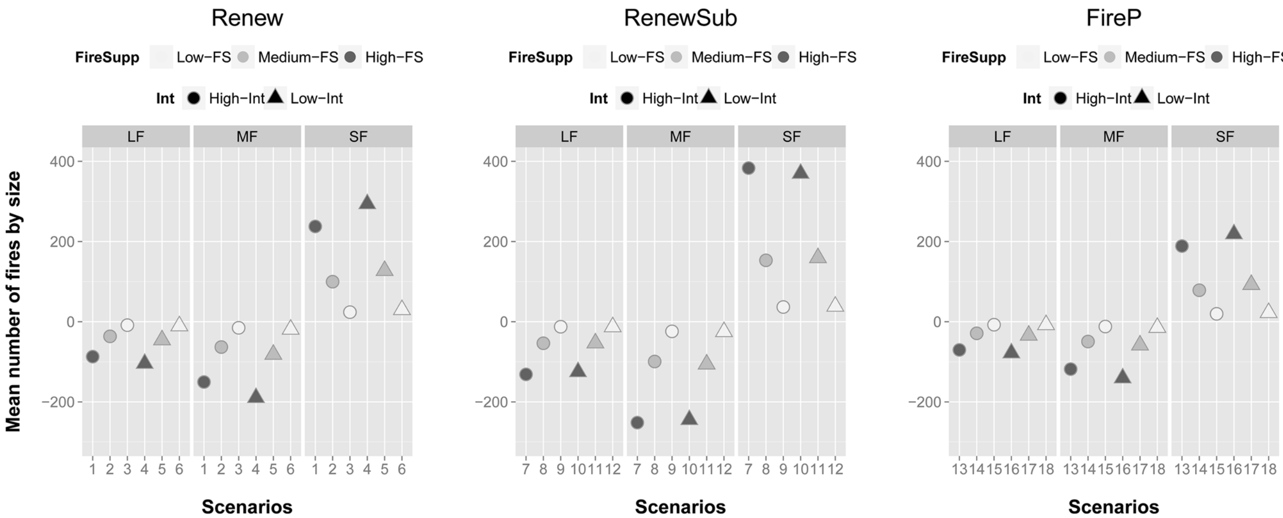

Figure 6. Changes in the mean numbers of fires (difference between the mean number of simulated fires and the mean number of fires expected to occur according to historical fire data) for each biomass extraction scenario under the three storylines: (Renew) biomass extraction takes in optimal areas, (RenewSub) suboptimal areas, and (FireP) optimal areas where fire risk is high. Results are presented for three fire-size classes: large fires (LF), medium fires (MF), and small fires (SF). Scenarios characterized by high (*High-FS*), moderate (*Medium-FS*), and low fire suppression (*Low-FS*) are represented in *dark gray*, *light gray*, and *white*, respectively. *Dots* represent high-intensity biomass extraction scenarios (*High-Int*), whereas *triangles* refer to low-intensity treatments (*Low-Int*).

high-intensity extraction (scenarios 1–3 in Figures 4, 5) to 0.05–0.61 in scenarios with low-intensity extraction (scenarios 4–6 in Figures 4, 5).

For scenarios from the *RenewSub* storyline in which the area to be managed is considerably higher than that in the *Renew* storyline, extraction intensity did not have any effect on suppressed area ($P = 0.285$; see scenarios 7–12 in Figures 4, 5).

Finally, for scenarios derived from the *FireP* storyline with high-intensity treatments (scenarios 13–15 in Figures 4, 5), the suppressed area was 0.04–0.42 whereas under lower-intensity treatments suppressed area was 0.04–0.47 (scenarios 16–18 in Figures 4, 5). Therefore, in this case, although suppressed area increased by 0.05 under high fire-suppression levels, it remained unchanged under lower fire-suppression levels.

Discussion

Our findings suggest that biomass extraction has the potential to substantially contribute to reshape fire regime towards a more desirable scenario by decreasing the number of large fires and, in turn, the amount of burned area. Nonetheless, the *effectiveness* of this fuel-reduction strategy is strongly determined by the spatial allocation of the extraction and how firefighters can use the opportunities created by biomass extraction as fire-suppression strategy and, to a lesser extent, by the intensity of extraction. Moreover, the leverage 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 (Figure 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 gray box-plots in Figure 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 to effectively reduce the impacts of large fires (Fernandes and Botelho 2003; Agee and Skinner 2005; Houtman and others 2013; Regos and others 2014).

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 burned) 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 Figure 4). 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 (Figure 4), especially in North-West (NW) and South-Central (SC) subregions where a stronger fire impact is expected due to warmer Mediterranean and continental climates (Figure 5). Finally, according to our simulation outcomes, the scenarios wherein biomass extraction for energy use also exploits suboptimal areas achieved the highest suppressed area, at values close to 0.7 under high fire-suppression levels (scenarios included in the *RenewSub* storyline in Figure 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 suboptimal areas where its implementation would be very costly as unsuitably placed.

Therefore, our findings reveal that the leverage 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 (that is, 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 under the fire-propagation conditions, and that treatments aimed to create fire-resistant 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 loads 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-resistant stands in Catalonia, because 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 (Figure 2). However, according to our results, the effectiveness of forest biomass extraction at reducing wildfires also depends on extraction intensity. Indeed, the suppressed area is slightly higher with lower harvesting intensities, especially under high fire-suppression capabilities (see scenarios 1 and 4 in Figure 4) and strategies designed to prevent large fires (see scenarios 13 and 16 in Figure 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 fire-suppression opportunities caused by higher amount of remaining fuels (and stand flammability) after low-intensity extractions. However, the leverage of this strategy is higher with high felling intensities as the area treated is considerably smaller than in low-intensity treatments (Figure 5).

Socioeconomic and Ecological Considerations: Scope for Further Research

Applying biomass extraction practices at large spatial extent introduces multiple socioeconomic and ecological challenges, as well as likely tradeoffs with other ecosystem services. From a socioeconomic perspective, enhancing biomass use as a way to reduce wildfire effects hinges on first weighing up the costs and benefits of different investment options. 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 fire-fighting 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, thereby 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 considerations should be taken into account before its implementation. Extracting biomass vulnerable to fires can be an ecological and socioeconomic opportunity to reduce the risk of greenhouse gas generation from wildfire (Verón and others 2012). However, the replacement of *in situ* biomass burning with harvesting, removal, and ex situ combustion could alter the nutrient cycles and lead to net nutrient losses and deterioration of soil fertility (Ouro and others 2001). Besides, changes in forest structure, composition, and dynamics inevitably lead to changes in the biodiversity of forest-dwelling species (Paillet and others 2010). Although forest specialists are expected to benefit from a reduction in the impacts of wildfires in forested areas, open-habitat dwelling species can be negatively affected by applying such a strategy at large scales (De Cáceres and others 2013; Regos and others 2015, 2016). Taking into account some of the considerations mentioned above, we stress the need for a comprehensive evaluation of socioeconomic and ecological impacts potentially induced by a large-scale development of this forest-management policy.

In addition, some limitations of the MEDFIRE model, inherent to any spatial modeling 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-flammable forest fuel model into a very flammable in few years. This highlights the need of combining biomass harvesting with other fuel-reduction treatments aimed at reducing surface fuels (for example, mastication or prescribed burning) to manage fire more effectively (Reiner and others 2009). 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 the 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 should take into account the interacting effects of the main driving forces to adequately 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 socioeconomic and energy policies. In light of our results, a large fraction of the landscape should be effectively managed to achieve an appreciable reduction of area burned; however, the leverage 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-resistant stands in Mediterranean regions, but the effectiveness of this strategy at reducing wildfires also depends on intensity of extraction and fire-suppression effectiveness. 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 sociopolitical 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.

ACKNOWLEDGMENTS

This work received financial support under the research Projects, FORESTCAST (CGL2014-59742) and BIONOVEL (CGL2011-29539/BOS), funded by the Spanish Ministry of Education and Science, and it is a contribution to the FORESTERRA-ERANET Project INFORMED. Lluís Brotons, Núria Aquilué, and Adrián Regos benefited from the NEW-FORESTS project (PIRSES-GA-2013-612645). Ignacio Lopez and Mireia Codina were supported by the strategic project of the MED programme PROFORBIOMED (1S-MED10-009) co-funded by the European Regional Development Fund. We thank the two anonymous referees for their valuable comments and constructive suggestions on the manuscript.

REFERENCES

Abbas D, Current D, Ryans M, Taff S, Hoganson H, Brooks KN. 2011. Harvesting forest biomass for energy—an alternative to conventional fuel treatments: trials in the Superior National Forest, USA. Biomass Bioenergy 35:4557–64.

Agee JK, Skinner CN. 2005. Basic principles of forest fuel reduction treatments. For Ecol Manag 211:83–96.

Alcamo J, Kreileman GJJ, Bollen JC, Van den Born G, Gerlagh R, Krol MS, Toet AM, de Vries HJ. 1996. Baseline scenarios of global environmental change. Glob Environ Change 6:261–303.

Alvarez A, Gracia M, Vayreda J, Retana J. 2012. Patterns of fuel types and crown fire potential in *Pinus halepensis* forests in the Western Mediterranean Basin. For Ecol Manag 270:282–90.

Badia A, Serra P, Modugno S. 2011. Identifying dynamics of fire ignition probabilities in two representative Mediterranean wildland-urban interface areas. Appl Geogr 31:930–40.

Becker DR, Larson D, Lowell EC. 2009. Financial considerations of policy options to enhance biomass utilization for reducing wildfire hazards. For Policy Econ 11:628–35.

Bradstock RA, Cary GJ, Davies I, Lindenmayer DB, Price OF, Williams RJ. 2012. Wildfires, fuel treatment and risk mitigation in Australian eucalypt forests: insights from landscape-scale simulation. J Environ Manag 105:66–75.

Broncano MJ, Retana J, Rodrigo A. 2005. Predicting the recovery of *Pinus halepensis* and *Quercus ilex* forests after a large wildfire in Northeastern Spain. Plant Ecol 180:47–56.

Brotons L, Aquilué N, de Cáceres M, Fortin M-J, Fall A. 2013. How fire history, fire suppression practices and climate change affect wildfire regimes in Mediterranean landscapes. PLoS One 8:e62392.

Brunson MW, Shindler BA. 2010. Geographic variation in social acceptability of wildland fuels management in the Western United States. Soc Nat Resour 17:661–78.

Castedo-Dorado F, Gómez-Vázquez I, Fernandes PM, Crecente-Campo F. 2012. Shrub fuel characteristics estimated from overstory variables in NW Spain pine stands. For Ecol Manag 275:130–41.

Cochrane MAA, Moran CJA, Wimberly MCA, Baer ADA. 2012. Estimation of wildfire size and risk changes due to fuels treatments. Int J Wildl Fire 21:357–67.

CORINE. 2006. Land-use land-cover database 1:250000. Copenhagen, Denmark: European Environment Agency.

CREAF. 2009. Land cover map of Catalonia, 3rd edn. http://www.creaf.uab.cat/mcsc/usa/index.htm http://www.creaf.uab.cat/mcsc/usa/index.htm.

De Cáceres M, Brotons L, Aquilué N, Fortin M-J. 2013. The combined effects of land-use legacies and novel fire regimes on bird distributions in the Mediterranean. J Biogeogr 40:1535–47.

de Chazal J, Rounsevell MDA. 2009. Land-use and climate change within assessments of biodiversity change: a review. Glob Environ Change 19:306–15.

Díaz-Delgado R, Lloret F, Pons X. 2004. Spatial patterns of fire occurrence in Catalonia, NE, Spain. Landsc Ecol 19:731–45.

Espelta JM, Riba M, Retana J. 1995. Patterns of seedling recruitment in West-Mediterranean *Quercus ilex* forests influenced by canopy development. J Veg Sci 6:465–72.

Evans AM, Finkral AJ. 2009. From renewable energy to fire risk reduction: a synthesis of biomass harvesting and utilization case studies in US forests. GCB Bioenergy 1:211–19.

Fernandes PM, Botelho HS. 2003. A review of prescribed burning effectiveness in fire hazard reduction. Int J Wildl Fire 12:117.

Finney MA. 2003. Calculation of fire spread rates across random landscapes. Int J Wildl Fire 12:167–74.

Finney MA, Seli RC, McHugh CW, Ager AA, Bahro B, Agee JK. 2007. Simulation of long-term landscape-level fuel treatment effects on large wildfires. Int J Wildl Fire 16:712.

Fréjaville T, Curt T. 2015. Spatiotemporal patterns of changes in fire regime and climate: defining the pyroclimates of south-eastern France (Mediterranean Basin). Clim Change 129:239–51.

GENCAT. 2014a. Estadístiques forestals. Produccions forestals i incendis. http://agricultura.gencat.cat/ca/departament/dar_estadistiques_observatoris/dar_estructura_produccio/dar_estadistiques_forestals/dar_produccions_forestals_incendis/. Accessed 21/10/2013.

GENCAT. 2014b. Estratègia per promoure l'aprofitament energètic de la biomassa forestal i agrícola. Departament d'Agricultura, Ramaderia, Pesca i Alimentació. Generalitat de Catalunya.

Gonzalez-Olabarria JR, Brotons L, Gritten D, Tudela A, Teres JA. 2012. Identifying location and causality of fire ignition hotspots in a Mediterranean region. Int J Wildl Fire 21:905–14.

Graham R, Harvey A, Jain T, Tonn J. 1999. Effects of thinning and similar stand treatments on fire behavior in western forests. USDA Forest Service, Pacific Northwest Research Station, General Technical Report PNW-GTR-463.

Houtman RM, Montgomery CA, Gagnon AR, Calkin DE, Dietterich TG, Mcgregor S. 2013. Allowing a wildfire to burn: estimating the effect on future fire suppression costs. Int J Wildl Fire 22:871–82. doi:10.1071/WF12157.

Ibañez JJ, Burriel JA. 2010. Mapa de cubiertas del suelo de Cataluña: características de la tercera edición y relación con SIOSE. In: Actas del XIV Congreso Nacional de Tecnologías de la Información Geográfica, Sevilla.

James PMA, Fortin M-J, Sturtevant BR, Fall A, Kneeshaw D. 2010. Modelling spatial interactions among fire, spruce budworm, and logging in the Boreal forest. Ecosystems 14:60–75.

Keeley J, Bond W, Bradstock R, Pausas J, Rundel P. 2012. Fire in mediterranean ecosystems: ecology, evolution and management. Cambridge: Cambridge University Press.

Levers C, Verkerk PJ, Müller D, Verburg PH, Butsic V, Leitão PJ, Lindner M, Kuemmerle T. 2014. Drivers of forest harvesting intensity patterns in Europe. For Ecol Manag 315:160–72.

Loehle C. 2004. Applying landscape principles to fire hazard reduction. For Ecol Manag 198:261–7.

Mason CL, Lippke BR, Zobrist KW, Bloxton TD Jr, Ceder KR, Comnick JM, Mccarter JB, Rogers HK. 2006. Investments in fuel removals to avoid forest fires result in substantial benefits. J For 104:27–31.

McCullagh P, Nelder JA. 1989. Generalized linear models. London: Chapman and Hall.

McIver J, Erickson K, Youngblood A. 2012. Principal short-term findings of the National Fire and Fire Surrogate study. Gen. Tech. Rep. PNW-GTR-860. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

McRae DJ, Duchesne LC, Freedman B, Lynham TJ, Woodley S. 2001. Comparisons between wildfire and forest harvesting and their implications in forest management. Environ Rev 9:223–60.

MINECO. 2013. The Spanish renewable energy plan 2011–2020. Ministry of Industry, Energy and Tourism. http://www.minetur.gob.es/energia/en-us/novedades/paginas/per2011-2020voli.aspx. Accessed 12/06/2013.

Minnich RA, Chou Y. 1997. Wildland fire patch dynamics in the chaparral of Southern California and Northern Baja California. Int J Wildl Fire 7:221–48.

Moreira F, Viedma O, Arianoutsou M, Curt T, Koutsias N, Rigolot E, Barbati A, Corona P, Vaz P, Xanthopoulos G, Mouillot F, Bilgili E. 2011. Landscape–wildfire interactions in southern Europe: implications for landscape management. J Environ Manag 92:2389–402.

Moreno MV, Conedera M, Chuvieco E, Pezzatti GB. 2014. Fire regime changes and major driving forces in Spain from 1968 to 2010. Environ Sci Policy 37:11–22.

Nechodom M, Becker D, Haynes R. 2008. Evolving interdependencies of community and forest health. In: Donoghue E, Sturtevant V, Eds. Forest and community connections. Washington, DC: Resources for the Future. p 91–108.

Ouro G, Pérez-Batallón P, Merino A. 2001. Effects of silvicultural practices on nutrient status in a *Pinus radiata plantation*: nutrient export by tree removal and nutrient dynamics in decomposing logging residues. Ann For Sci 58:411–22.

Paillet Y, Bergès L, Hjältén J, Ódor P, Avon C, Bernhardt-römermann M, Bijlsma R, De Bruyn L, Fuhr M, Grandin U, Kanka R, Lundin L, Luque S, Magura T, Matesanz S, Mészáros I, Sebastià M, Schmidt W, Standovár T, Tóthmérész B, Uotila A, Valladares F, Vellak K, Virtanen R. 2010. Biodiversity differences between managed and unmanaged forests: meta-analysis of species richness in Europe. Conserv Biol 24:101–12.

Parisien M-A, Junor DR, Kafka VG. 2007. Comparing landscape-based decision rules for placement of fuel treatments in the boreal mixedwood of western Canada. Int J Wildl Fire 16:664.

Pausas JG, Paula S. 2012. Fuel shapes the fire-climate relationship: evidence from Mediterranean ecosystems. Glob Ecol Biogeogr 21:1074–82.

Pausas JG, Llovet J, Rodrigo A, Vallejo R. 2008. Are wildfires a disaster in the Mediterranean basin? A review. Int J Wildl Fire 17:713.

Perpiñá C, Alfonso D, Pérez-Navarro A, Peñalvo E, Vargas C, Cárdenas R. 2009. Methodology based on geographic information systems for biomass logistics and transport optimisation. Renew Energy 34:555–65.

Piñol J, Terradas J, Lloret F. 1998. Climate warming, wildfire hazard, and wildfire occurrence in coastal eastern Spain. Clim Change 38:345–57.

Piñol J, Beven K, Viegas DX. 2005. Modelling the effect of fire-exclusion and prescribed fire on wildfire size in Mediterranean ecosystems. Ecol Model 183:397–409.

Piñol J, Castellnou M, Beven KJ. 2007. Conditioning uncertainty in ecological models: assessing the impact of fire management strategies. Ecol Model 207:34–44.

Price OF, Bradstock RA, Keeley JE, Syphard AD. 2012. The impact of antecedent fire area on burned area in southern California coastal ecosystems. J Environ Manag 113:301–7.

R Core Team. 2014. A language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing. http://www.r-project.org/.

Regos A, Aquilué N, Retana J, De Cáceres M, Brotons L. 2014. Using unplanned fires to help suppressing future large fires in Mediterranean forests. PLoS One 9:e94906.

Regos A, D'Amen M, Herrando S, Guisan A, Brotons L. 2015. 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). J Ornithol 156:275–86.

Regos A, D'Amen M, Titeux N, Herrando S, Guisan A, Brotons L. 2016. Predicting the future effectiveness of protected areas for bird conservation in Mediterranean ecosystems under climate change and novel fire regime scenarios. Divers Distrib 22:83–96.

Reiner AL, Vaillant NM, Fites-Kaufman J, Dailey SN. 2009. Mastication and prescribed fire impacts on fuels in a 25-year old ponderosa pine plantation, southern Sierra Nevada. For Ecol Manag 258:2365–72.

Reinhardt ED, Keane RE, Calkin DE, Cohen JD. 2008. Objectives and considerations for wildland fuel treatment in forested ecosystems of the interior western United States. For Ecol Manag 256:1997–2006. http://linkinghub.elsevier.com/retrieve/pii/S0378112708006944.

Rounsevell MDA, Reginster I, Araújo MB, Carter TR, Dendoncker N, Ewert F, House JI, Kankaanpää S, Leemans R, Metzger MJ, Schmit C, Smith P, Tuck G. 2006. A coherent set of future land use change scenarios for Europe. Agric Ecosyst Environ 114:57–68.

Stellmes M, Röder A, Udelhoven T, Hill J. 2013. Mapping syndromes of land change in Spain with remote sensing time series, demographic and climatic data. Land Use Policy 30:685–702.

Stephens SL. 1998. Evaluation of the effects of silvicultural and fuels treatments on potential fire behaviour in Sierra Nevada mixed-conifer forests. For Ecol Manag 105:21–35.

Stephens SL, Moghaddas JJ, Edminster C, Fiedler CE, Haase S, Harrington M, Keeley JE, Knapp EE, McIver JD, Metlen K, Skinner CN, Youngblood A. 2009. Fire treatment effects on vegetation structure, fuels, and potential fire severity in western U.S. forests. Ecol Appl 19:305–20.

Stephens SL, James D, Boerner J, Fettig J, Joseph B, Kennedy L, Schwilk DW. 2012. The effects of forest fuel-reduction treatments in the United States. Bioscience 62:549–60.

Sturtevant BR, Miranda BR, Yang J, He HS, Gustafson EJ, Scheller RM. 2009. Studying fire mitigation strategies in multi-ownership landscapes: balancing the management of fire-dependent ecosystems and fire risk. Ecosystems 12:445–61.

Turco M, Llasat MC, Tudela A, Castro X, Provenzale A. 2013. Brief communication decreasing fires in a mediterranean region (1970-2010, NE Spain). Nat Hazards Earth Syst Sci 13:649–52.

Vallecillo S, Brotons L, Thuiller W. 2009. Dangers of predicting bird species distributions in response to land-cover changes. Ecol Appl 19:538–49.

Van Wagtendonk JW. 1996. Use of a deterministic fire growth model to test fuel treatments. In: Sierra Nevada Ecosystem Project: final report to congress, Vol. II. Final report to congress. Davis: Centers for Water and Wildland Resources. University of California, pp 1155–66.

Verón SR, Jobbágy EG, Di Bella CM, Paruelo JM, Jackson RB. 2012. Assessing the potential of wildfires as a sustainable bioenergy opportunity. GCB Bioenergy 4:634–41.

Vila-Cabrera A, Martinez-Vilalta J, Vayreda J, Retana J. 2011. Structural and climatic determinants of demographic rates of Scots pine forests across the Iberian Peninsula. Ecol Appl 21:1162–72.

Villaescusa R, Díaz R. 1998. Segundo Inventario Forestal Nacional (1986–1996). Madrid: España. Ministerio de Medio Ambiente, ICONA.

Villanueva JA. 2005. Tercer Inventario Forestal Nacional (1997–2007). Madrid: España. Ministerio de Medio Ambiente, ICONA.

Wendland KJ, Lewis DJ, Alix-Garcia J, Ozdogan M, Baumann M, Radeloff VC. 2011. Regional- and district-level drivers of timber harvesting in European Russia after the collapse of the Soviet Union. Glob Environ Change 21:1290–300.

Winter GJ, Vogt C, Fried JS. 2002. Fuel treatments at the wildland-urban interface: common concerns in diverse regions. J For 100:15–21.