Forest management for adaptation to climate change in the Mediterranean basin: a synthesis of evidence

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Running Head: Forest management in Mediterranean forests

Abstract

As global climate becomes warmer, the maintenance of the structure and function of Mediterranean forests constitutes a key challenge to forest managers. Despite the need for forest adaptation, an overall evaluation of the efficacy of current management strategies is lacking. Here we describe a theoretical framework for classifying management strategies, explicitly recognizing trade-offs with other, untargeted ecosystem components. We then use this framework to provide a quantitative synthesis of the efficacy of management strategies in the Mediterranean basin. Our review show that research has focused on strategies aimed at decreasing risk and promoting resistance in the short-term, rather than enhancing long-term resilience. In addition, management strategies aiming at short-term benefits frequently have unintended consequences on other adaptation objectives and untargeted ecosystem components. Novel empirical studies and experiments focusing both on adaptation objectives and multiple responses and processes at the ecosystem level are needed. Such progress is essential to improve the scientific basis of forest management strategies and support forest adaptation in the Mediterranean basin.

Key-words: climate change, disturbance, forest adaptation, management strategies, Mediterranean ecosystems, resilience, trade-off

1. Introduction

In an era of global environmental change the maintenance of ecosystem functions and the provision of ecosystem services are being compromised (Millennium Ecosystem Assessment, 2005). This is especially true for forest ecosystems in the Mediterranean basin, which have sustained human populations for millennia (Blondel and Aronson, 1999). In particular, increased aridity with climate change and widespread forest expansion due to socioeconomic changes during the last century have resulted in more recurrent and severe wildfires (Pausas and Fernández-Muñoz, 2012) and drought-induced forest decline episodes (Carnicer et al., 2011). At the same time, the vulnerability of forests to biotic attacks is threatening (Sangüesa-Barreda et al., 2015) and the impacts of windstorm events have increased during the last decades (Gardiner et al., 2013). As a consequence, forests of the Mediterranean basin are undergoing changes at accelerated rates, which could have cascading effects for biodiversity and ecosystem functions (Falcucci et al., 2007; Sheffer, 2012; Valladares et al., 2014).

Forests in the Mediterranean basin have a set of particular features. The geographic location and the heterogeneous topography of this territory determine an exceptional variety of forest ecosystems, including elements of Atlantic, sub-Atlantic, and sub-Mediterranean deciduous forests; montane, subalpine, and Mediterranean coniferous forests; and sclerophyllous and evergreen shrublands and forests (Blanco et al., 1997). These forests contain an impressive plant and animal diversity, with high tree species richness relative to forests in Northern latitudes (Scarascia-Mugnozza et al., 2000), and high genetic diversity as the region played as glacial refugia for many taxa (Hampe and Petit, 2005). Consequently, it is obvious that the anticipating global impacts may constitute a key challenge for forest managers, regarding the future service provisioning and maintenance programs to ensure the functional and structural characteristics of Mediterranean forests. (MFRA, 2009).

Management strategies for forest adaptation upon climate change needs to consider the different temporal scales over which ecological mechanisms and rapid environmental changes act. Therefore, the use of such strategies should not be only addressed towards attaining short-term objectives such as decreasing the immediate risk of a particular disturbance, but also towards the promotion of resilience as a key objective for long-term adaptation. Resilience is quantified using a broad range of metrics, which makes comparisons across systems difficult and precludes applicability in forest management. Acknowledging the ongoing debate around resilience, here we consider ‘resistance’ and ‘recovery’ as complementary and measurable components that together represent resilience (Hodgson et al., 2015; Millar et al., 2007).

At the same time, forest managers must recognize the existence of trade-offs among ecosystem responses when planning and implementing any management action. There is increasing evidence that the implementation of a given management practice may be beneficial for reaching a specific objective but, at the same time, it can impair the consecution of other objectives or induce negative impacts on untargeted ecosystem components (Bradford and D’Amato, 2012). In a Mediterranean context, for instance, managers may seek forest resistance to droughts by releasing competition after thinning (Calev et al., 2016), but such treatments can reduce the benefits for carbon storage (Ameztegui et al., 2017; Ruiz-Peinado et al., 2013) or modify the habitat conditions needed for some forest-dwelling species (De La Montaña et al., 2006).

The use of appropriate management strategies to enhance the adaptive capacity of Mediterranean forests to climate change has been increasingly argued by scientists (Bravo-Oviedo et al., 2014; Doblas-Miranda et al., 2015; Fernandes et al., 2013; Keenan, 2015; Kolström et al., 2011; Resco de Dios et al., 2007; Scarascia-Mugnozza et al., 2000). The efficiency of some of these strategies have been empirically assessed in individual case studies, such as forest thinning to increase resistance to drought stress (Cotillas et al., 2009) or to promote forest recovery after a wildfire (de las Heras et al., 2013). Yet a general evaluation of the efficacy of management strategies and the associated trade-offs is lacking. Here, our goals are to (1) describe a theoretical framework for classifying and assessing management strategies for forest adaptation, explicitly recognizing the potential for trade-offs; (2) provide a quantitative synthesis on the evidence of the efficacy of management strategies achieving adaptation objectives ; and (3) assess evidence of potential trade-offs of management strategies with other, untargeted ecosystem components.

2. Material and methods

2.1 Theoretical framework

Our framework for the implementation of forest management strategies regarding the adaptation in the Mediterranean basin includes four components: disturbances, management strategies, objectives for adaptation, and indirect effects on other ecosystem components and the need for trade-offs (Fig. 1). The framework aims at synthetizing the potential effects of a management action in a given forest system. As a generic example, we can imagine that the initial state of a given forest has been altered or it is expected to change due to a disturbance. Managers seek to accommodate the altered (or potentially altered) forest ecosystem to the new or expected environmental conditions, so they define a given management strategy to attain specific adaptation objectives. However, the implementation of a management practice could cause unexpected forest responses through indirect effects on other ecosystem components. Trade-offs may arise between the targeted objective for adaptation and other ecosystem aspects, including untargeted adaptation objectives and ecosystem responses affecting forest functions or biodiversity.

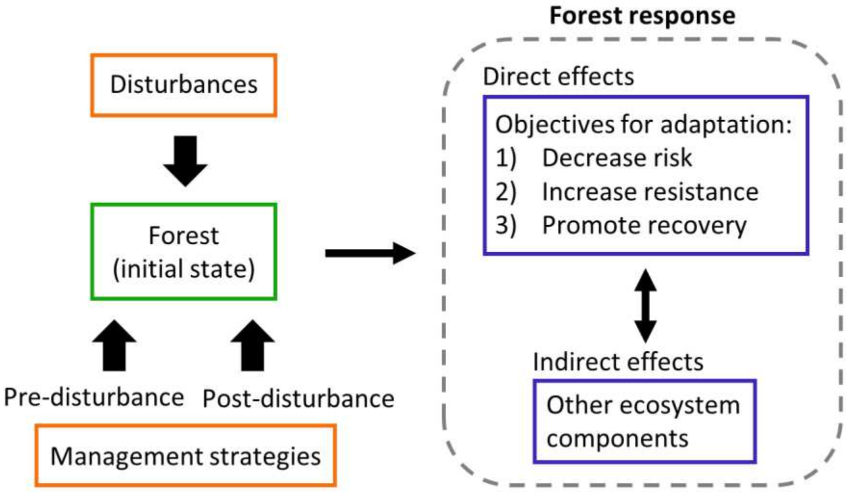


Figure 1. Theoretical framework for assessing adaptive forest management. For the description of each component and the interpretation of the framework see the main text.

The different components of the framework (disturbances, management strategies, objectives for adaptation, and indirect effects–trade-offs) are described below:

(i) Disturbances

We consider the four most threatening forest disturbances in the Mediterranean basin: fires, droughts, pests, and windstorms. These disturbances are becoming more frequent and severe (see *Introduction*) and are already causing important structural and compositional changes in Mediterranean forest ecosystems (Carnicer et al., 2013; Vayreda et al., 2016, 2012).

(ii) Management strategies

We consider five different management strategies - four at the stand level and one at the landscape level. Each management strategy is expected to induce short/mid-term effects (see below strategies 1, 2 and 5) or long-term effects (see below strategies 3, 4 and 5), and it can be implemented before disturbance (e.g. to improve resistance to drought) or after disturbance (e.g. to improve forest recovery after fire). We define these management strategies according to forest management manuals (Alonso et al., 2013), as well as expert knowledge (see examples below).

1) *Reduction of stand density*. Thinning treatments aiming at achieving forest structures characterized by low adult tree densities. This management strategy has a strong scientific and technical basis. Thinning typically reduces fire risk and the associated carbon losses (Hurteau et al., 2008), and stimulates resistance to drought (D'Amato et al., 2013) and pests (Waring and O'Hara, 2005).

2) *Management of the understory*. Treatments aimed at reducing the understory cover towards breaking vertical and horizontal fuel continuity. These actions can include both mechanical treatments and prescribed burning and are considered efficient tools to reduce fire risk (Adams, 2013).

3) *Promoting mixed forests*. Strategies aimed at promoting mixed forests at the species or genotype levels, or actions focused towards the promotion of forest structural diversity (i.e. uneven-aged forests). There is growing interest towards managing for forest diversification given that mixed forests may exhibit greater resistance and

recovery capacity as a consequence of niche partitioning and differential response to stressors (de-Dios-García et al., 2015; del Río et al., 2017; Sánchez-Pinillos et al., 2016). Uneven-aged forests are also expected to show higher stability to disturbances (Martín-Alcón et al., 2010).

4) *Changing species or genetic composition*. Strategies aiming at promoting changes in forest composition towards species or genotypes better adapted to the conditions forecasted under future climates. These strategies can include actions in-situ by using extant species or ex-situ by using assisted-migration (Martín-Alcón et al., 2016; Mason and Connolly, 2014).

5) *Promoting spatial heterogeneity at the landscape-scale*. Strategies at the landscape scale aiming at promoting spatial heterogeneity for disturbance prevention and control, as well as enhancing connectivity in order to assist gene flow and species migration. For example, fuel treatment patches have been suggested as effective measures to control fire behaviour (Regos et al., 2016), while the conservation of key areas within landscapes might increase not only the spatial heterogeneity but also the potential for adaptation through the conservation of genetic sources, favouring ecological connectivity and dispersal processes (Lindenmayer et al., 2012).

(iii) Objectives for adaptation

As a main goal, management strategies seek to elicit forest responses to attain specific objectives for adaptation. In terms of forest adaptation to global change, we consider three main objectives for adaptation: decrease disturbance risk, increase resistance against disturbances and fostering recovery after disturbance.

(iv) Indirect effects – trade-offs

Indirect effects leading to potential negative impacts and reduction of ecosystem benefits have to be recognized when implementing a given management strategy. The attainment of a specific objective may trade-off with other forest responses associated to other objectives for adaptation or other ecosystem components. For example, a reduction of stand density to release tree-to-tree competition may enhance immediate drought resilience (Aldea et al., 2017) but, as the remaining trees become larger, detrimental impacts to future disturbances can be expected due to increased vulnerability to drought and insect attacks (Bennett et al., 2015). Furthermore, key ecosystem functions such as litter decomposition rates can be negatively affected (Bravo-Oviedo et al., 2017). Trade-offs are expected to increase as the number of involved objectives and ecosystem components increase the complexity of the management system.

2.2 Literature review and classification of case studies

We conducted a literature search in the *Web Of Science* in June 2015 to assess the empirical evidence addressing the different components of our theoretical framework. We searched for articles containing the topic words ‘forest* AND Mediterranean’ in the abstract, plus multiple different combinations of topic words related to the management strategies studied (see Appendix A). To be included in the final database studies had to: 1) be published in SCI journals, 2) be carried out in the Mediterranean basin, and 3) test the effects of at least one management strategy, including experimental as well as modelling approaches. The final list of 90 articles (see Appendix B for the list of included articles) was broken down into records (termed case studies, $N = 239$) according to the four components of our theoretical framework (Figure 1). Case studies were defined as unique combinations of study, disturbance, management strategy, objective for adaptation, and type of effect being assessed (direct vs. indirect). The latter indicated whether the case studies examined the *direct* effect of the management strategy on a given objective for adaptation, or the *indirect* effect on other ecosystem components, giving rise to potential trade-offs. Additionally, we also recorded the following information for each case study: a) when the strategy was intended to be implemented (pre or post disturbance); b) the different experimental cases assessed, such as contrasted environmental conditions, sites or species; and c) the approach used (i.e. experimental or model). Finally, the effects of management strategies on the forest responses assessed in each case study were recorded as *positive* (if the effect favoured the targeted adaptation objective or was considered beneficial for biodiversity or ecosystem functioning), *negative* (if the opposite happened) or *neutral* (if the effects were not significant or unclear).

A more detailed analysis of benefits and associated trade-offs was conducted focusing on the two most widely assessed strategies, i.e. reduction of stand density and management of the understory, and the two most common disturbances, i.e. drought and fire (see *Results* section). The conditional classification tree approach (Hothorn et al., 2006) was used as an heuristic tool to identify which components of the framework were more likely associated to the outcomes of forest responses, using the function “ctree” from the R package “Party” (Hothorn et al., 2006). Our response variable was ‘response’ (positive, neutral or negative) and the predictors were disturbance (drought, fire), adaptation objective (risk, resistance, recovery) and type of effect (direct, indirect).

3. Results

The scientific output on forest management for adaptation in the Mediterranean basin increased steadily during the last 15 years, from only 1 paper published by 2000 to a total of 90 papers until 2015 (Fig. 2). All case studies were located in the northern rim of the Mediterranean basin and 90% of them in the western part of the region. Most of the case studies addressed management strategies to cope with fire and drought impacts, while only three case studies addressed strategies to face pests or windstorms (Fig. 3a). In the case of fire, 44% of case studies focused on post-disturbance management strategies (Fig. 3a).

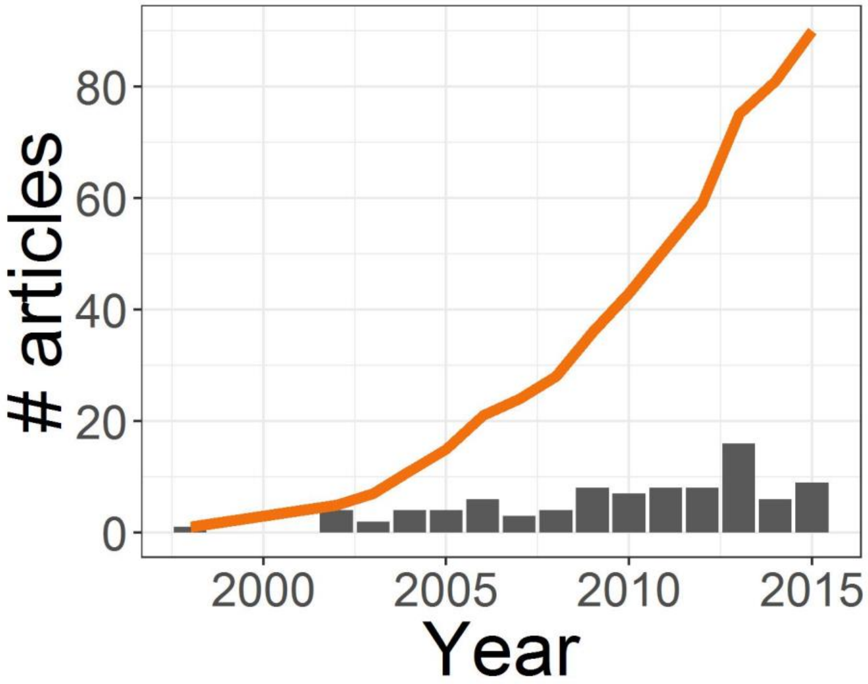


Figure 2. Cumulative number of articles per year (line) and number of articles per year (bars) addressing forest management strategies in the Mediterranean basin (see Web Text 1 for specific search criteria).

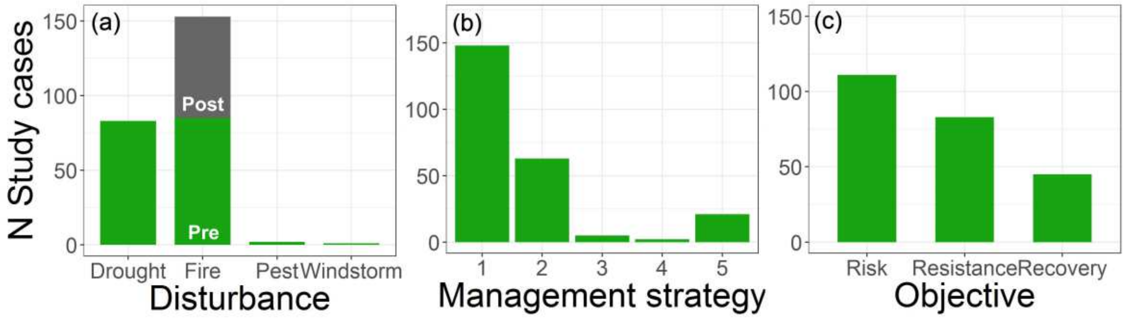


Figure 3. Number of case studies as a function of (a) disturbance type, (b) management strategies and (c) objectives for adaptation. Management strategies: 1) reduction of stand density; 2) management of the understory; 3) promoting mixed forests; 4) changing species or genetic composition; 5) promoting spatial heterogeneity at the landscape-scale.

Most case studies (88%) assessed management strategies that expected to have short- or mid-term effects on forest responses, i.e. reduction of stand density and management of the understory; whereas 9% tested for strategies at the landscape scale and only 3% addressed strategies that may enhance forest adaptation in the long-term, i.e. promoting mixed forests and changing species or genetic composition (Fig. 3b). Almost half of the case studies (46%) addressed management strategies aiming at risk reduction, while 35% and 19% focused on benefits for resistance and recovery, respectively (Fig. 3c).

More than half of the case studies (56%) quantified the direct effects of a management strategy for a specific adaptation objective, while the remaining 44% quantified indirect effects of the management strategy on untargeted forest responses, providing evidence of potential trade-offs. Indirect effects were assessed more frequently in studies focusing on risk reduction (Fig. 4). Of all suggested indirect effects, 33% concerned untargeted objectives for adaptation and 67% other ecosystem components. Overall, negative effects were much more frequent when assessing indirect effects (51 out of 105 case studies) than when assessing direct effects on the targeted adaptation objective (4 out of 134 case studies) (Fig. 4). We did not have enough empirical evidence to draw conclusions about the efficacy of management strategies at the landscape-scale or that might provide long-term benefits for adaptation. In the case of management at the landscape scale, 71% of responses were positive, while negative and neutral responses represented 10% and 19%, respectively. In general, these case studies used modelling approaches to evaluate short- or mid-term effects of fire risk reduction. Only 7 study cases tested for the promotion of mixed forests or for changes in species or genetic composition by using a modelling approach, and the outcomes of the responses were positive (4 case studies) or neutral (3 case studies).

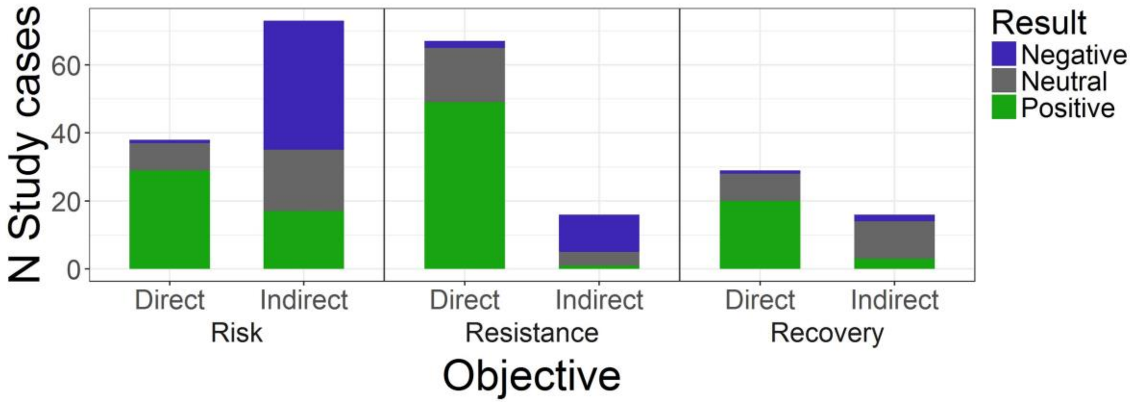
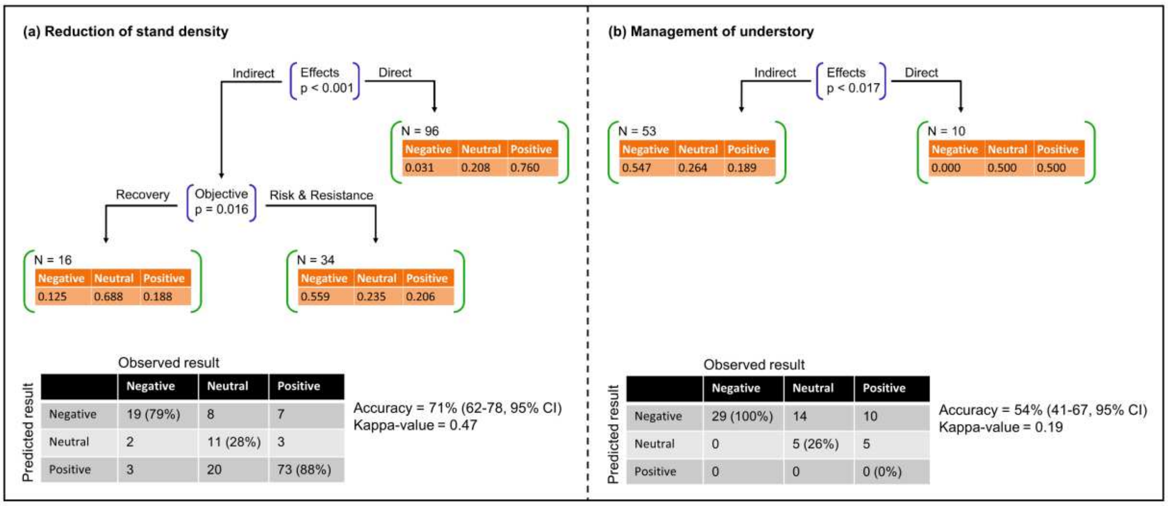


Figure 4. Number of study cases as a function of the objectives for adaptation, the type of effects being assessed (direct vs indirect) and the outcomes of the treatments. All study cases are included.

The predictive power of the resulting tree classification models was higher for reduction of stand density than for management of the understory (see Fig. 5 for details). The outcomes of forest responses to reductions of stand density and management of the understory were conditional to the assessment of direct vs. indirect effects (Fig. 5). When direct effects on the objectives for adaptation were assessed, the probability of observing a positive response (favouring the corresponding objective) was higher. On the contrary, when indirect effects were assessed the probability of observing a negative or neutral response was higher, suggesting trade-offs between targeted objectives for adaptation and other ecosystem components. In the model for reduction of stand density, the probability of observing a negative result when indirect effects were assessed was higher when the targeted objectives of the management action were promoting resistance and reducing risk, while neutral results were more likely when the targeted objective was recovery (Fig. 5a).



(a)

	Negative	Neutral	Positive
Negative	19 (79%)	8	7
Neutral	2	11 (28%)	3
Positive	3	20	73 (88%)

Accuracy = 71% (62-78, 95% CI)
Kappa-value = 0.47

(b)

	Negative	Neutral	Positive
Negative	29 (100%)	14	10
Neutral	0	5 (26%)	5
Positive	0	0	0 (0%)

Accuracy = 54% (41-67, 95% CI)
Kappa-value = 0.19

Figure 5. Results of the conditional classification trees for (a) reduction of stand density, and (b) management of the understory. The tables show the fraction of positive, neutral and negative responses for terminal nodes as a function of the type of effects being assessed (direct vs indirect, significant in the two trees) and the adaptation objective (significant only in the reduction of stand density tree). Model accuracy is summarized using confusion matrices. The confusion matrix shows the number of correctly classified and misclassified cases, which is used to calculate the classification error and percent correctly classified (model *Accuracy*). In addition, weighted Cohen's

Kappa coefficients (*Kappa-value*) were used to quantify the level of agreement between multiple ratings of categorical variables. Weighted Cohen's Kappa is the proportion of agreement corrected for chance, ranging from -1 to +1. A coefficient of 1.0 indicates maximum possible agreement, zero indicates exactly chance agreement, and a negative kappa coefficient indicates worse agreement than expected by chance.

4. Discussion

4.1 Short-term benefits of management do not efficiently meet long-term adaptation

Our results show that research on forest management in the Mediterranean basin is biased towards those management strategies seeking short-term benefits for forest ecosystems such as reducing risk and promoting short-term resistance. The benefits of thinning at reducing drought and fire vulnerability or at enhancing post-fire recovery during the immediate years after the application of treatments have been broadly demonstrated. For example, thinning experiments have been shown to reduce tree-to-tree competition for resources and to enhance tree growth, survival or fruit production (Olivar et al., 2014; Rodríguez-Calcerrada et al., 2011; Sánchez-Humanes and Espelta, 2011), the physiological performance of individuals (Di Matteo et al., 2010), and forest functions such as C sequestration (de las Heras et al., 2013), as well as the reduction of drought vulnerability and fire risk (Garcia-Prats et al., 2015). The positive effect of understory treatments such as prescribed burning on fire risk reduction is also well documented (reviewed in Fernandes *et al.* 2013), as well as that of mechanical treatments on the understory to improve post-fire recovery (De Las Heras et al., 2002).

There is, however, a lack of experimental approaches addressing management strategies to promote long-term adaptation (i.e. promoting mixed forests or changes in species or genetic composition) (but see Benito-Garzón and Fernández-Manjarrés 2015 for a modelling approach). This is surprising given the broad range of empirical evidence and predictions of drought and fire impacts on forests and potential changes in species composition in the Mediterranean basin (reviewed in Doblas-Miranda *et al.* 2017). Mixed forests are expected to provide important benefits for climate change adaptation and the maintenance of ecosystem services (del Río et al., 2017; Gamfeldt et al., 2013; Jactel et al., 2017). For instance, altering forest composition towards a greater representation of species with drought- or fire-tolerant traits or with post-disturbance regeneration mechanisms can benefit the future resilience of ecosystems (Elkin et al., 2015; Granados et al., 2016; Henne et al., 2015). At the same time, the promotion of diversity and thus species interactions can benefit key ecosystem functions such as productivity (Liang et al., 2016). At the intraspecific level, modifying the functional and genetic diversity can improve the adaptive capacity of populations to future environmental stress (Bussotti et al., 2015). Innovative experimental approaches testing the potential for long-term adaptation are needed and addressing how to scale-up these strategies at the landscape level (e.g. Regos *et al.* 2016), should be primary goals for research on forest management during upcoming years.

4.2 Recognizing trade-offs

Our results show that management strategies are reasonably good at achieving the adaptation objectives for which they are intended. However, management objectives seeking short-term benefits frequently generate trade-offs between the targeted objective for adaptation and other components in the ecosystem. These trade-offs can arise at two different levels: 1) between objectives for adaptation, i.e. targeted vs. untargeted objective; and 2) between objectives for adaptation and other forest responses, including ecosystem function and biodiversity components.

Trade-offs between objectives for adaptation can be illustrated by two examples. The first one is related to potential reductions of the structural diversity of a stand after thinning (Ruiz-Mirazo and Gonzalez-Rebollar, 2013). This may result, for instance, in a trade-off between the short-term resistance and the long-term resilience to drought, as the beneficial effect of thinning at reducing drought vulnerability can reverse as the stands mature due to greater physiological constraints associated with larger trees (D'Amato et al., 2013). The second example focuses on the reported negative impacts of prescribed burning on the subsequent survival, growth and physiological performance of trees (Fernandes et al., 2012; Lavoir et al., 2013; Valor et al., 2015). Such empirical evidence suggest a potential trade-off between immediate reductions of fire-risk and resilience of surviving individuals to droughts and pests. Other evidence, however, show that these negative effects can also reverse in the short-term (Battipaglia *et al.* 2014; Valor *et al.* 2015).

At a second level, our results suggest that trade-offs may also arise between the specific objective for adaptation and untargeted forest responses related to ecosystem function and biodiversity components. For example, thinning experiments reported negative treatment effect (depending on the intensity) on forest biomass growth and nutrient dynamics (Ameztegui et al., 2017; Blanco et al., 2006; Roig et al., 2005; Ruiz-Peinado et al., 2013). This illustrates a trade-off between the short-term benefits for resistance to drought or fire-risk reduction and important ecosystem functions such as carbon sequestration and nutrient regulation. The effects on the soil are likely to be a key element regulating the long-term impact of management strategies. Neutral and even beneficial effects of thinning treatments have been observed on the soil C pools, understory productivity and nutrient dynamics (Bravo-Oviedo et al., 2015; López-Serrano et al., 2005; Navarro et al., 2010; Ruiz-Peinado et al., 2013; Wic Baena et al., 2013), but trade-offs have also been observed for understory treatments (Fernández et al., 2012). Finally, negative effects of thinning or understory treatments on biodiversity at different trophic levels can be expected , although the mixture of negative, positive and neutral effects found across and within studies suggest high uncertainty on biodiversity dynamics under such management strategies (Azul et al., 2011; De La Montaña et al., 2006; Jiménez et al., 2015; Mangas and Rodríguez-Estival, 2010).

4.3. Improving the scientific basis of forest adaptation strategies

Despite the broadly recognized need for adaptation of forest ecosystems in the Mediterranean basin, research on forest management has focused disproportionally on decreasing risk and increasing resistance in the short-term, rather than adapting to long-term change. In addition, the synthesized outcomes of empirical evidence suggest that the short-term benefits of management strategies are trading-off with other ecosystem components. The lack of experimental (and modelling) assessments of the long-term effects of adaptation strategies on a representative range of forest responses greatly limits our capacity to plan and implement sound forest management strategies and support forest adaptation as global climate becomes warmer.

New field experiments with appropriate treatments are needed, that focus not only on immediate adaptation objectives but also on multiple responses and processes at the ecosystem level. For example, forest structural diversity has been associated with the promotion of disturbance-tolerant species in the understory, the diversity of wildlife forage and insect-pollinated species, and the abundance and richness of species able to maintain key ecosystem functions such as N-fixation (Ares et al., 2010; Neill and Puettmann, 2013). At the same time, specific protocols on how to scale treatment effects in time (short vs. long-term) and in space (local vs. regional) are essential. Regional field-data assessments (Coudel et al., 2016) and the use of modelling and remote sensing techniques (Bottalico et al., 2017, 2016) can improve our understanding of landscape and long-term impacts of management practices on the structure and function of forest ecosystems. We advocate for combining experimental, remote-sensing and modelling approaches within a clear conceptual framework (e.g., Figure 1) and encompassing:

(i) a diversity of treatments reflecting different management strategies, disturbances and adaptation objectives. The explicit recognition of resilience as a long-term goal and a clear, quantitative definition of its components facilitate treatment comparisons and proximity-to-target assessments;

(ii) a wide range of ecosystem responses, including intended and unintended effects and their interactions. A context-dependent, ecosystem services approach can be useful in identifying key ecosystem functions and in prioritizing between actions with conflicting effects on different ecosystem components;

(iii) short as well as long term effects, and the interactions between treatment effects on different ecosystem components over time. This temporal scaling should explicitly consider climate change projections and (whenever possible) socioeconomic scenarios; and

(iv) multiple spatial scales. Specific protocols are needed to scale the impacts of management strategies from the plot to the landscape.

Designing, assessing and implementing these management strategies is a prerequisite to maintain the delivery of forest ecosystem services in a warmer future in the Mediterranean basin and will only be achievable through a close cooperation between scientists, forest managers and policymakers.

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