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Title: The use of scenarios and models to evaluate the future of nature values and ecosystem services in Mediterranean forests.

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Abstract

Science and society are increasingly interested in predicting the effects of global change and socio-economic development on natural systems, to ensure maintenance of both ecosystems and human wellbeing. The Intergovernmental Platform on Biodiversity and Ecosystem Services has identified the combination of ecological modelling and scenario forecasting as key to improving our understanding of those effects, by evaluating the relationships and feedbacks between direct and indirect drivers of change, biodiversity and ecosystem services.

Using as a case study the forests of the Mediterranean basin (complex socio-ecological systems of high social and conservation value), we reviewed the literature to assess (1) what are the modelling approaches most commonly used to predict the condition and trends of biodiversity and ecosystem services under future scenarios of global change? (2) what are the drivers of change considered in future scenarios and at what scales? (3) what are the nature and ecosystem services indicators most commonly evaluated?

Our review shows that forecasting studies make relatively little use of modelling approaches accounting for actual ecological processes and feedbacks between different socio-ecological sectors; predictions are generally made on the basis of a single (mainly climate) or a few drivers of change; in general, there is a bias in the set of nature and ecosystem services indicators assessed; in particular, cultural services and human wellbeing are greatly underrepresented in the literature. We argue that these shortfalls hamper our capacity to make the best use of predictive tools to inform decision-making in the context of global change.

Keywords: Ecological forecasting; Future Scenarios; Global Change; Impact Assessment Evaluations; IPBES; Nature Benefits to People; Socio-ecological systems

1. Introduction

Anticipating changes in biodiversity and the services that ecosystems provide to society has been a key goal of the environmental research (Clark et al. 2001), especially since the publication of the Millennium Ecosystem Assessment reports in 2005 (MEA 2005). With rapidly accelerating global changes associated to human activities this task has also become a key challenge for society in general (Vihervaara et al. 2010; Cardinale et al. 2012), motivating the recently published regional assessments on biodiversity and ecosystem services by the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES) (https://www.ipbes.net/assessment-reports). Despite the growing scientific efforts, some of the knowledge gaps identified back in the 2005 MEA reports still exist. For example, we still have little understanding of the interactions and feedbacks between the drivers of ecosystem and biodiversity change and multiple aspects of human well-being, like human health and food security (Pecl and et al 2017; IPBES 2018a). Also, the models used to characterize the relationships between biodiversity and ecosystem services (ES) mostly rely on linear correlations and do not consider non-linear changes, thresholds and tipping points in ecosystems (Ricketts et al. 2016; Lavorel et al. 2017). To address these challenges, the IPBES identifies the use of future scenarios and modelling approaches as fundamental pillars to advance in the understanding of the relationships and feedbacks between direct and indirect drivers of change, biodiversity, ecosystem services (considered through the lens of nature benefit´s to people; Díaz et al. 2015) and aspects conditioning good quality of life (IPBES 2016).

A scenario is a coherent, internally consistent and plausible description of a possible future state of the world (Nakicenovic et al. 2000). Built upon scientific understanding of past and current observed relationships between drivers and environmental trends, scenarios draw upon narratives (storylines) of plausible socio-economic developments or particularly desirable future pathways (visions) under specific policy options and strategies (Alcamo and Ribeiro 2001; Peterson et al. 2003; O´Neill et al. 2015; Bai et al. 2016). One of the main challenges of using scenarios for predicting future impacts of societal development on ecosystems is the translation of scenario narratives into quantitative model input variables (Kok et al. 2015). In this regard, the rapid advances in science and observation of climate change have favored the widespread incorporation of climatic variables as direct drivers in regional-scale scenarios and future projections, especially in impact assessments (Moss et al. 2010). In contrast, substantial research is still needed about the inclusion of other important short-term drivers of biodiversity and ecosystem change such as land use, invasive species and pollution (FRB 2013; Titeux et al. 2016; Sirami et al. 2017; but see for example Malek et al. 2018). Multiple issues hamper the incorporation of those drivers of change in predictive approaches, including mismatching scales between the available data and the modelled process, the short temporal coverage of data, or the actual lack of quantitative data for some drivers (Hauck et al. 2015). Apart from incorporating multiple drivers of change, ecological models should, to the maximum possible extent, represent the complex interdependencies within human and environmental systems (e.g. consider the interactions and feedbacks between multiple economic sectors, e.g. Harrison et al. 2016); this normally requires the use of multiple interlinked models (model coupling or model integration) to account for the various processes operating at different spatial scales (Harfoot et al. 2014; Talluto et al. 2016).

Systems long exposed to human activities are particularly sensitive to this imbalance in the methods and approaches used to predict nature responses to global changes. In these systems, interactions between past land use changes (i.e. land use legacies) and current pressures, as well as the difficulty of untangling multiple causation are likely to require complex, integrated approaches (see Figure 1). Mediterranean forests are a good example of such systems, because they have been subjected to a long history of use and transformation (Nocentini and Coll 2013). They are biodiversity-rich, complex socio-ecological systems that have been continuously adapting to use and exploitation throughout many centuries, while providing important services and goods to society (Myers et al. 2000; Gauquelin et al. 2018). Currently, they cover approximately 25 % of the Mediterranean region (Malek and Verburg 2017). Conservation of these systems must deal with multiple cultural, ecological and economic values, and complex dynamics of social change are likely to be exacerbated by global change (Doblas-Miranda et al. 2015).

In this study, we assess to which extent, the integration of drivers described in Figure 1 is being achieved in predictive exercises of Mediterranean forest systems. These represent a prime case study to evaluate the state of the art and the remaining gaps in the use of models and scenarios to investigate the effects of global change on biodiversity and ecosystem functioning. We review studies using ecological models to predict global change environmental impacts in forest systems in the Mediterranean basin during the last three decades to answer the following questions: (1) What are the modelling approaches most commonly used? We assess whether correlative approaches - those based on statistical relationships among drivers and a response variable – are superseded by more integrative approaches such as process-based models – those explicitly incorporating knowledge of ecological processes – or integrated models – those combining multiple systems, modelling approaches and accounting for feedbacks among different parts of the modelled system. (2) How are specific drivers being included in modelled scenarios (e.g. are models considering multiple drivers and scales)? (3) How holistic is our knowledge about the effects of global change on nature and people? Biodiversity and ecosystem services' indicators are used to assess the condition and trends of earth's systems (through monitoring of species, ecosystem functions, etc.), and represent essential tools for managers and politicians to track the consequences of decisions as well as to measure progress towards sustainable development (e.g. Aichi targets, Sustainable Development Goals; Brooks et al. 2015; Convention on Biological Diversity 2015; Geijzendorffer et al. 2017). Here we evaluate the types of indicators used to predict future condition of Mediterranean forest ecosystems, and whether these cover a wide variety of aspects of forest systems. On the basis of our review, we highlight outstanding knowledge gaps and biases, identify priority areas for research in ecological forecasting (the field of Ecology dedicated to predict how ecosystems will change in the future in response to environmental factors) and discuss a potential way forward.

2. Materials and methods

In June 2016, we conducted a systematic review of studies assessing future changes in forest ecosystems in the Mediterranean basin. We searched the Web of Science database for peer-reviewed articles published between 1990 and 2016 that used modelling or simulation approaches to predict future values/change of nature indicators (e.g. species richness, ecosystem functions, etc.) or ecosystem services (ES) indicators linked to Mediterranean forests. The list of databases, keywords and filters used for the literature selection is detailed in Table 1. This search yielded 2424 articles. We reviewed the abstracts to remove duplicates and articles clearly outside the thematic or spatial scope of this study (2029 articles) (Online Resource 1). Exclusion criteria included: articles focusing on the Mediterranean biome but outside the Mediterranean basin (e.g. California, Australia); articles that used models to make inference about ecological processes (e.g. how does drought affect forest growth?) but did not explicitly use scenarios to make future predictions of the indicator; experimental studies (e.g. the study sets vegetation plots where a species X is subjected to increases of 1, 2 and 3 degrees of temperature or to drought stress, to evaluate the effect of increasing temperatures in species growth, reproduction, etc.); studies focused on exotic species located in Mediterranean countries (e.g. *Eucalyptus* spp.) and articles focusing on non-Mediterranean forests within any of the evaluated countries (on the basis of the dominant species and the geographic location of the study area; e.g. beech forests in Normandy). After reading the full-texts of the remaining 395 articles, we excluded an additional 232 studies following the same criteria listed above, leading to a final set of 163 articles that were retained for analysis (Online Resources 1, 2).

For each article, we extracted information about the geographic location of the study area, the modelling approach, the scenarios used and their origin, the drivers of change considered in each scenario, the spatial scales addressed in each study, and the nature and ES indicators evaluated. We generated a unique record for each scenario-indicator combination within each of the articles read. This led to a total of 2075 entries in the database. We calculated summary statistics (frequencies) regarding the above-mentioned fields in our database. Table 2 provides a complete list of the information extracted, together with the criteria used for classification.

3. Results

3.1. Geographic coverage

The majority of articles selected in our review (133 articles; 82 %) corresponded to national, sub-national or local studies carried out within the North-Western countries of the Mediterranean basin (Portugal, France, Italy and Spain; Figure 2). In addition, our review included twelve global or European-wide studies with detailed results for at least one country within the Mediterranean zone, 14 regional studies (focused on two or more countries of the Mediterranean basin), one study with detailed results for the Afro-Mediterranean domain and three studies based on simulated Mediterranean-type landscapes (Online Resource 3).

3.2. Scenarios and drivers

The majority of studies (74.2%) used two or more scenarios when making future predictions of nature and ES indicators, while only 25.8% of studies used a single scenario (93 % of these are also based on a single driver only, mostly a climatic driver). More than half of the scenarios assessed were based on a single-driver only (56%), with climate the most frequently used driver (31.9% of the scenarios were based on climate only; Figure 3a). The second most used driver was management (e.g. different thinning regimes, levels of biomass extraction, etc.), with 13 % of the scenarios, followed by fire (6.2%) and land-use/land-cover change (LULCC; 4.2%). Less than 1% of the single-driver scenarios used drivers other than the previously mentioned (e.g. invasive species). In total, 62.8% percent of scenarios used climate as a driver (either as solo-driver or in combination with other drivers), whereas the other main drivers found (fire, LULCC and management) were considered in less than 30 % of the scenarios (Figure 3b). When multi-driver scenario combinations were used (Figure 3b), fire was most often combined with either climate and/or LULCC, whereas LULCC was most often combined with climate and/or fire, and management was mostly combined with climate and, to a lesser extent, with fire.

We did not find a particular general pattern regarding the spatial extent of the study area (global/EU wide, regional –Pan-Mediterranean-, national, subnational or local) and the number of drivers considered in the scenarios. The exception was regional (Pan-Mediterranean) studies, in which scenarios were always based on a single driver only (mostly climate). This lack of a clear pattern could also be due to the imbalance in representation of scales across the selected articles. However, there were differences in the types of drivers used: whereas global/EU wide studies mostly focused on climate and land use change as main drivers, sub-national and local scale studies mainly incorporated fire and management/disturbance. Moreover, studies carried out at large scales (national, regional or global) generally made predictions based on available scenarios (e.g. IPCC), whereas user-made scenarios were more common at sub-national or local scales (Online Resource 3).

3.3. Modelling approaches

Correlative and process-based/integrated approaches were almost equally represented when modelling either nature or ecosystem services indicators (Figure 4a); the few studies that evaluate nature and ecosystem indicators (3% of the total) used predominantly process-based or integrated approaches (Figure 4a, b). Studies based on process-based or integrated approaches accounted for two or more drivers of change with higher frequency than studies based on correlative/empirical approaches (Figure 4b).

3.4. Nature and Ecosystem services indicators

We found an unequal use of ES and nature indicators within the set of selected articles: 57 % of the studies evaluated ES indicators only, 40 % evaluated nature indicators-only, whereas the remaining 3% evaluated both types of indicators simultaneously (Figures 4a, 5). Of all studies assessing ES indicators, 60% focused on regulation & maintenance services, almost evenly split between climate change regulation and the maintenance of physical, chemical and biological conditions (Figure 5). Almost all the remaining ES studies (38%) focused on provisioning services, mostly on indicators of plant materials for direct use and processing (e.g. timber, 82.6%; Figure 5). Cultural services, integrative ES indicators and other regulating services were only marginally represented (Figure 5). Fire risk, understood here as a regulating & maintenance service, was evaluated in 25 articles (approx. 15% of the total selected articles). All ES indicators found referred to the supply capacity of forest to provide services and none to the demand side.

Almost 80% of the nature indicators evaluated corresponded to measures of species/population trends, such as changes in species abundance, geographical range, etc. (Figure 5); 10% focused on measures of compositional intactness such as forest cover extent, changes in landscape configuration, etc.; whereas only a few studies focused on measures of ecosystem functioning (e.g. forest traits, regeneration capacity) or extinction risk (e.g. allele diversity, viability of populations).

4. Discussion

Future conservation of biodiversity and of the natural capital will require an integrative, broad evaluation of all the challenges that nature will face under the current context of societal and environmental change. Our review shows that, despite the increasing use of scenarios and models as tools to explore those changes (Online Resource 4), the scientific community is still focusing efforts on a fraction of the overall challenges the future might bring to ecosystems and nature. This is reflected in the relatively low proportion of studies considering multiple-drivers operating at different spatio-temporal scales (44%), as well as the very low representation of studies assessing nature and ES indicators simultaneously (3%). Moreover, process-based or integrated modelling approaches are still far from being the norm (53.7%). In this study we wanted to examine what, how and where the current modelling work in the Mediterranean area is taking place. Further research should be devoted to the implications of the modelling approaches used to inform policy and decision-making, and in particular, to evaluate the trade-offs between model complexity and policy relevance (something we could not gather enough information on).

4.1. Geographic coverage

We found a strong geographic bias in the use of scenarios and models in Mediterranean forestry research, with few studies focusing in southern countries (Figure 2). This may stem in part from economic differences between countries of the two sides of the Mediterranean (Online Resource 5), which reflects in differences in their educational systems (i.e. Southern Mediterranean countries present a much lower ratio of post-graduate *vs.* bachelor students in forestry than northern ones), national research budgets (FAO and Plan Bleu 2013) and availability of experts on the study of biodiversity and ecosystem service-related scenarios (IPBES 2018b). Our results might also reflect the importance (in terms of total coverage) of forest systems within each country (Online Resource 5). This unequal distribution of information across the North-South, West-East axes of the Mediterranean makes it difficult for the scientific community to make robust predictions at the level of the whole Mediterranean basin, especially for its southern part.

4.2. Scenarios and drivers

The literature reviewed showed a strong bias towards the evaluation of impacts of climate change on Mediterranean forest systems, especially in studies addressing questions at broad (national to global) scales (as recently observed in other studies; IPBES 2016, 2018a; Kok et al. 2017; Rosa et al. 2017). This bias might be explained by the fast development and public availability of global circulation models and climate scenarios (Moss et al. 2010) and the widespread use of IPCC climate projections to predict biodiversity patterns (Titeux et al. 2016; Sirami et al. 2017), and by the fact that the Mediterranean basin has been identified as a regional climate change hotspot (EEA 2005; Diffenbaugh and Giorgi 2012). We note that, in the literature selected, climate change impacts were always assessed through the change in long-term average climate conditions, mainly annual mean temperature and total rainfall. However, one of the main climate threats to Mediterranean ecosystems is the increase in the frequency and duration of extreme weather events (length of droughts, heatwaves, short periods of intensive raingall, etc.; Stocker et al. 2013). Extreme conditions can play an important role altering the structure and function of Mediterranean forests in the short term, compromising the services they provide (Peñuelas et al. 2017). For example, prolonged droughts can induce diebacks and favor a shift in species composition or the establishment of invasive species (Resco De Dios et al. 2007; Martínez-Vilalta and Lloret 2016), while the co-occurrence of heat waves and drought conditions can cause large wildfires with devastating consequences for people and the environment (Founda and Giannakopoulos 2009; Fernandes et al. 2016; Ruffault et al. 2018). Ignoring those extreme-weather threats might lead to misleading predictions about the future condition and trends of species and ecosystems (Morán-Ordóñez et al. 2018), and therefore, of their benefits on human-wellbeing.

There is still little integration of key drivers of change other than climate in Mediterranean systems (Figure 1), such as fire, LULCC and management (Keeley et al. 2012), which impact ecosystems locally in the short- and mid-term and might have irreversible consequences in ecosystem health before the worst-case climate change scenario could be realized. For example, although forest fires are a growing environmental and societal issue in Mediterranean systems, integration – in scenarios and models – of fire as a driving force with other mid- and long-term drivers such as climate was only found in a few studies focused on local to sub-National scales or simulated landscapes (Pausas 2006; Pausas and Lloret 2007; Brotons et al. 2013; Pacheco et al. 2015; Gil-Tena et al. 2016; Górriz-Mifsud et al. 2016). Local and sub-national scales are ideal for an integrated analysis of processes operating at multiple scales (e.g. local fires and climate), which in turn is crucial to understand the resilience of ecosystems under global change conditions and thus guide sustainable development policies (Seidl et al. 2011). For this reason, local scales have been proposed as one of the starting points for the generation of a new set of multi-scale nature and ES scenarios frameworks to be developed by the IPBES community (Kok et al. 2017). Developing authoritative, integrated future scenarios of forests and associated land use changes, management practices and fire risks is becoming an urgent need in regions subjected to multiple pressures such as the Mediterranean.

Moreover, since driving forces of environmental problems can take such a wide range of different directions, it is good practice (if possible) to develop and test multiple scenarios that reflect different plausible trends, rather than testing a single scenario only as observed in 25.8% of the selected articles (Alcamo and Ribeiro 2001). Testing several scenarios improves our understanding of how different sources of uncertainty might impact our model/target system (Peterson et al. 2003; Mahmoud et al. 2009). This is particularly relevant for the case of *exploratory* or *prospective* approaches (all approaches used in our selected literature), that investigate upcoming changes that might significantly vary from past trends (McCarthy et al.

2011; Rieb et al. 2017). Despite the management of Mediterranean forests can contribute substantially to the achievement of the sustainability goals to which Mediterranean countries have committed (e.g. Aichi targets, Sustainable Development Goals, EU bioeconomy strategy, climate mitigation actions), none of the studies evaluated used target-seeking scenarios (scenarios that first set a vision of the future and then describe different pathways - e.g. management alternatives, policy options- that might lead to achieve the vision of the desired future). This might be because target-seeking scenarios for biodiversity have mainly been developed for the global to continental scales (e.g. Rio+20 scenarios in the Global Biodiverisity Outlook 4; Convention on Biological Diversity 2014).

4.3. Modelling approaches

Under the current context of environmental change, models integrating social, economic and environmental drivers are more likely to be policy-relevant (Seidl et al. 2011; IPBES 2016). Integration of various drivers at multiple spatio-temporal scales (Figure 1) might generally require process-based/mechanistic or integrated model approaches (Kelly et al. 2013; Harfoot et al. 2014) rather than correlative/empirical ones. Both correlative and process-based/integrated approaches were equally represented in our review, suggesting there is still room for a better integration of drivers across scales in the approaches currently used to evaluate the future of Mediterranean forests.

In a predictive framework, process-based approaches arguably bring advantages over correlative approaches, such as their ability to extrapolate beyond known conditions, which makes them particularly useful for making predictions under global change conditions (Cuddington et al. 2013). Process-based and integrated models also allow better exploration of interactions, feedbacks and trade-offs between different components of the modelled systems (e.g. trade-offs between conservation of natural values and production of provisioning services; Korzukhin et al. 1996), which are key for making well-informed decision making. However, the use of advanced integrative modelling approaches that explicitly combine multiple model types with an unique framework over different spatial scales is still rare (but see some examples at EU and global scales: e.g. Böttcher et al. 2012; Kraxner et al. 2013). This is due to the inherent higher complexity of the former: generally, these are parameter- and data-intensive models, that require disciplinary expertise and prolonged time series of data for calibration and validation (Seidl et al. 2011; Harfoot et al. 2014; Rieb et al. 2017). Wider use of these complex approaches would require stronger collaborations between actors of different disciplines (from social sciences to climatology, agriculture and forestry) and knowledge holders (scientists, policy-makers, managers, citizens), and at different scales (e.g. from plant physiologists to macro-ecologists).

Nevertheless, the selection of modelling framework (decisions regarding the choice of model type, the complexity allowed, the spatio-temporal scales included, variables/drivers considered, etc.) should be ultimately determined by the ecological question addressed and the decision-context (with modelling stategies changing across the policy cycle; IPBES 2016). In most cases, this model selection will be limited by knowledge and data availability. As all models have strengths and weaknesses, a minimum requirement is that they are validated and uncertainty is evaluated (e.g. sensitivity analysis, multi-model ensembles) and communicated.

4.4. Nature and ecosystem services indicators

Most of the studies reviewed evaluated regulating and provisioning services. In the particular case of forests in the Mediterranean basin, this observed trend might respond to its recognized multifunctional character (Palahi et al. 2008): on the one hand, forests are (and have traditionally been) an important source of products for consumption and trade such as timber, fuelwood, truffles, pine nuts and cork for Mediterranean societies (FAO and Plan Bleu 2013). This might explain the interest in knowing what the future provision of these products will be in the coming decades. On the other hand, Mediterranean forests fulfill multiple regulation services of great interest for society, because of their direct influence in either the health of the system itself (through the maintenance of physical, chemical and/or biological conditions) and the wellbeing and socio-economic development of Mediterranean societies (e.g. soil erosion is one of the main environmental problems in European Mediterranean agro-forestry systems; García-Ruiz 2010). One of the regulating services most commonly evaluated in the selected literature was fire and fire risk, a disturbance of increasing concern in fire-prone ecosystems (e.g. Mediterranean ecosystems) since it interferes with the continuous and sustainable provisioning of other ES (e.g. carbon storage; Seidl et al. 2014) and threats human safety (e.g. the dead toll in 2017 Portugal wildfires was of 66 people). The role of Mediterranean forests in global change mitigation through carbon sequestration and storage is also increasingly evaluated, and especially the dependence of this service on forest management practices (Koniak et al. 2011; Pardos et al. 2015; Bottalico et al. 2016).

We only found one study making future predictions of cultural services (Koniak et al. 2011). The small representation of studies evaluating the future of cultural services is a general pattern observed in other ES impact evaluations, with independence of the ecosystem/thematic scope (Martinez-Harms et al. 2015; Boerema et al. 2016; IPBES 2018a). This might be because the change of social values over time is very hard to quantify, model and predict (cultural services are most commonly evaluated through proxies Egoh et al. 2012; IPBES 2016), and it is generally easier to make predictions of indicators that depend on already observed environmental relationships (i.e. mathematical equations) such as forest growth and timber production. Given the difficulty of predicting social values and individual choices, future evaluations of cultural services might need to be indirectly inferred from changes in nature-based indicators. For example, the leisure use of Mediterranean pine forests (for walking, mountain biking, hunting, etc.) will probably be negatively affected by the increasing incidence of pest outbreaks of the processionary pine moth (*Thaumetopoea pityocampa*) favored by warmer winters (Battisti et al. 2005), as this species is responsible of strong allergic reactions in humans (Battisti et al. 2017). Although it is difficult to predict when, where and how these allergic symptoms will occur and how this will impact the leisure value of forest, it is possible to predict the vulnerability of forest to pest outbreaks given some knowledge about the ecology of the moth species and its relationship with environmental conditions, and indirectly infer where there could be potential conflicts with humans (e.g. peri-urban parks, national parks and other popular recreational areas). Therefore, the future prediction of cultural services will require the integration of nature/biodiversity and ecosystem services models and indicators, currently poorly linked (IPBES 2016).

None of the studies selected modelled the demand side of the ecosystem services indicators. This might be explained by the fact that estimating and modelling services demands and flows is harder than estimating services production, since in today´s globalized word, the supply and demand of services often occur across different spatial and temporal scales (Burkhard et al. 2012). Despite some modelling tools already allow to quantify ecosystem services flows (e.g. the Artificial Intelligence for Ecosystem Services modelling tool-ARIES; Bagstad et al. 2013), the challenge remains to predict what the future demands will be using integrated socio-ecological approaches.

Regarding nature indicators, the strong bias observed towards the evaluation of species/populations distribution patterns might respond to the fast development of species distribution and population modelling techniques in the last two decades (Brotons 2014). Our results show that there is still considerable scope for research on other types of indicators that might be more informative about ecosystem function and dynamics (e.g. genetic composition, traits diversity; Pereira et al. 2013) and therefore, of the vulnerability of ecosystems to global change and their capacity to adapt and continue providing multiple ES and contributing to human wellbeing. Despite the increasing debate around the link between nature (biodiversity) indicators and the capacity of ecosystems to provide services (Cardinale et al. 2012; Ricketts et al. 2016), the presence of studies evaluating such relationship in the selected literature was negligible (as also found at the IPBES assessment on models and scenarios; IPBES 2016). This hampers our capacity to identify relationships between ecosystem thresholds and tipping points and their consequences for human well-being. Moreover, we show that the proportion of studies evaluating multiple indicators simultaneously is very low, making it difficult to assess trade-offs between biodiversity and ES indicators or among ES types (see also Boerema et al. 2016).

Further work regarding predictions of biodiversity and ecosystem services indicators should focus on assessing indicator trends as a function of the scenario assessed (drivers included, spatio-temporal scales considered, etc.), as recently presented in the IPBES regional assessments (IPBES 2018b, a). Generally, this remains a challenge due to the lack of consensus on the use of indicators, the way the data is reported in studies (e.g. absolute value vs. % increments) and the difficulty of comparing indicators modelled under different global change assumptions (e.g. at different spatio-temporal scales).

5. Conclusions

Our literature review highlights several gaps in the way we conduct assessments of future changes in nature and ES provision in Mediterranean forests. There are various potential avenues to achieve higher levels of integration and realism when making future predictions of the state and dynamics of Mediterranean ecosystems under global change scenarios. In particular, future nature and ES research should focus future work on: (*i*) integrating multiple processes and driving forces operating at different spatio-temporal scales; (ii) considering the uncertainty around how these drivers will change in the future (by comparison of multiple scenarios), as well as any potential feedbacks between them; (*iii*) advancing on integrative approaches that consider the interdependencies between the different components of the socio-ecological systems (*iv*) developing models to assess a wider set of nature and ES indicators, so that trade-offs could be evaluated. There is no doubt of the important role that ecological models and scenarios play in achieving these goals. However, the art of predicting future condition of ecosystems is of little use if this information cannot be adequately incorporated into the decision-making policy cycle to contribute to sustainability goals. Therefore, and in parallel to the improvements in ecological models proposed above, future efforts should focus on strengthening the science-policy interface (one of the main goals of the IPBES) to allow the end-users of the tools and indicators (decision makers) into the framing of the questions tested by scientists/experts. Although we focused our review on Mediterranean forest systems, our results may be of wider implication for other similar regions and systems, keeping in mind that biases and constraints might be larger in many regions (e.g. regarding data and knowledge availability), and not easily solved by downscaling global change assessments to the region of interest.

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Query	Field	Parameters	Motivation
1	Year	1990-2016	Restricts the time period of the results to the last 25 years. It captures the increasing use of scenarios in Ecology since the publication of the first IPCC assessment report in 1990 (Moss et al. 2010)
2	Topic	(((model* OR project* OR predict* OR simulat*) AND future) OR (scenari* OR forecast* OR foresight* OR storyline*))	Captures modelling studies addressing predictions into the future
3	Topic	(Mediterranean OR Gibraltar OR Portugal OR Spain OR France OR Monaco OR Italy OR Malta OR Slovenia OR Croatia OR Bosnia OR Montenegro OR Albania OR Greece OR Turkey OR Cyprus OR Syria OR Lebanon OR Israel OR Palestine OR Egypt OR Libya OR Tunisia OR Algeria OR Morocco OR Iberia* OR Balkan* OR Anatolia)	Sets the geographic context: the Mediterranean basin and all the countries within it
4	Topic	(forest* OR woodland*)	Identifies studies focusing on forest or woodlands as their subject study system

We use the boolean operator 'AND' to combine the different queries. We refined the results using "Articles' as *Document type*, 'English' as Language' and 'Forestry', 'Plant Sciences', 'Environmental Sciences Ecology' or 'Biodiversity Conservation' as *Web of Science Subject categories*. The databases accessible to us in the Web of Science were CABI, SCIELO, WOS (Web of Science Core Collection) and CCC (Current Contents Connect). We selected the set of queries and keywords shown here after an initial scoping literature search phase in which we also included an additional query (5#) accounting for terms related to biodiversity, ecosystems and ES indicators (e.g. 'biodiversity OR ecosystem* OR "ecosystem* function*" OR "biological diversity" OR species OR "ecosystem service*" OR habitat* OR trait* OR vegetation* OR gene* OR landscape* OR biomass OR timber OR wood OR carbon OR erosion OR *water* OR recreat* OR regulat* OR game* OR 'non-wood forest products' OR 'Mushroom*' OR 'nutrient*' OR '*fire*); however, we observed that by adding this query we were leaving out many articles that were relevant for this review (because of terminological issues, eg many studies evaluate forest productivity using net primary production as indicator instead of wood biomass or timber production) and therefore, we chose to retain only the queries 1-4 that are more general.

Table 1. Search terms used for the literature review. The search was made on June 2016 on the complete range of references available at the Web of Science at that time.

Study area location and original extent of the article	• **Global/EU wide**: studies using models and scenario predictions for the global or Pan-European scales, from which we could extract results for the Mediterranean basin systems. • **Regional** (Pan-Mediterranean): predictions specifically designed for the Mediterranean region including case studies in two or more countries in the Mediterranean basin. • **National** (e.g. France) • **Subnational** (extent equivalent to level 2 of the NUTS 2013 classification of European regions available from the Eurostats web: http://ec.europa.eu/eurostat/web/nuts/; e.g. Provence-Alpes-Côte d'Azur) • **Local** (e.g. catchment A, municipality B)
Modelling approach used	• **Correlative/regression**: models assessing statistical relationships, whether causal or not, between two or more variables • **Mechanistic/Process-based or integrated approaches**: mechanistic models are based on a theoretical understanding of relevant ecological processes that are explicitly incorporated in the model. On the other hand, integrated approaches combine multiple model types, processes and/or components of the system modelled in a unique framework (Kelly et al. 2013)
Scenario type	• **Already published** (e.g. the latest greenhouse concentration scenarios adopted by the fifth IPCC Assessment Report: the representative concentration pathways; van Vuuren et al. 2011) • **User made**: scenarios made in the context of the article (e.g. through stakeholder/expert consultation or as a way of hypothesis testing) • **Mixed**: approaches combining already published scenarios with user made assumptions.
Scenario drivers	• **Number of drivers** (understood as values of environmental/social conditions that change over the time horizon of the projection and that are used to make predictions of models) • **Driver type:** climate, forest management, fire, land-use, water-use, pollution, grazing levels, etc.
Nature and/or ecosystem service indicator	• **Nature indicators** include measures of species/ecosystem distribution extent, species abundances or ecosystem structure/function. • **Ecosystem services** indicators (ES) were classified into 'provisioning', 'regulating & maintenance' or 'cultural' services following the Common International Classification of Ecosystem Services (CICES V4.3; www.cices.eu). We also evaluated fire risk as an ES indicator due to its importance in Mediterranean forests to regulate and maintain other ecosystem functions and processes (therefore included within the category 'regulating and maintenance').

Table 2. Information extracted from the selected articles. The right-hand column lists in detail the different categories into which we classified each study within each information field.

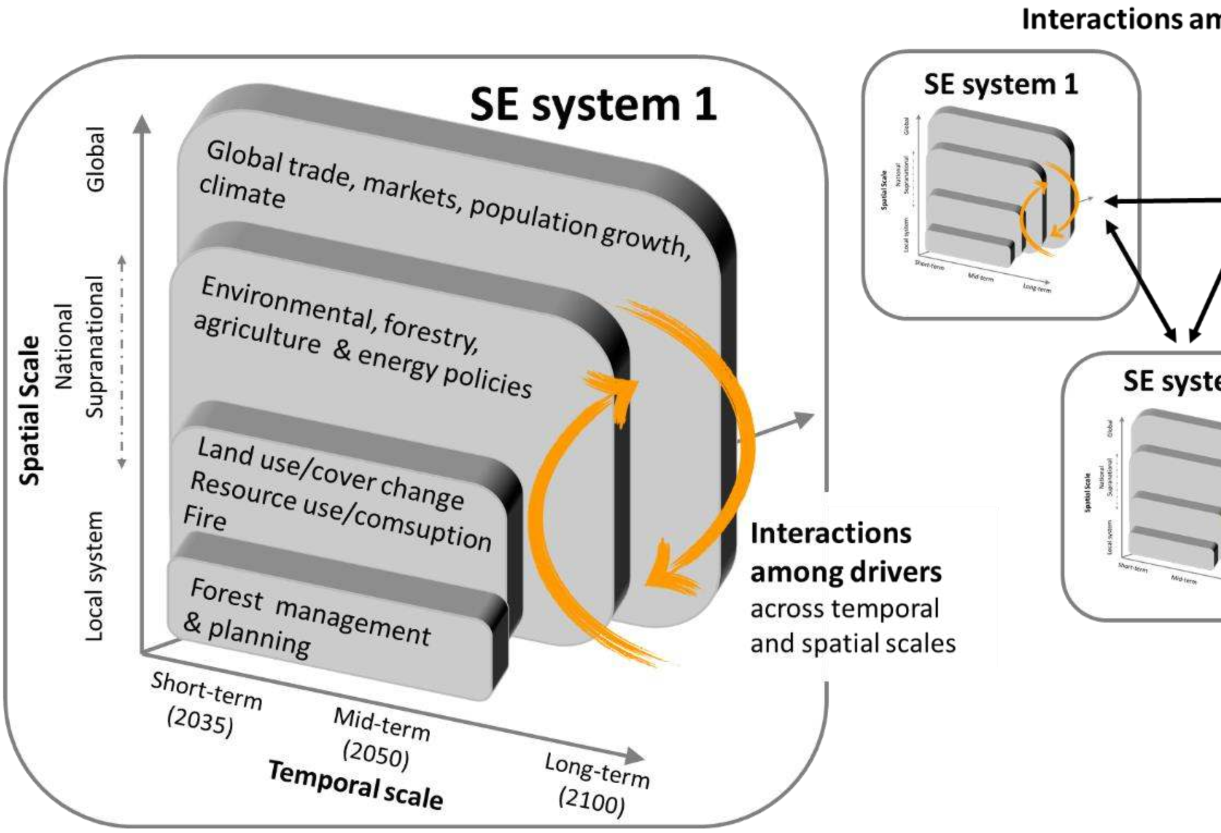


Figure 1. Diagram of potential levels of integration in biodiversity/nature and ecosystem services future impact assessm system (e.g. Mediterranean forests, SE system 1 box on the left side of the figure), scenarios and models should, to the both indirect and direct drivers of global change operating at multiple spatio-temporal scales, as well as for the interacti arrows). Ideally, SE systems should not be evaluated in isolation, but rather considering their interactions with other so also be interpreted as interactions between multiple sectors, such as forestry, agriculture, water management, conservati represented with the interaction between SE systems 1, 2 and 3). In the example of the SE system 1 box, the distributio reflects the temporal scale at which they are expected to exert a stronger impact on ecological processes operating in M implementation of environmental policies generally have an impact in the system at the mid-, long- term, changes in la system in the short-term). On the other hand, the Y-dimension of the rectangles reflects the spatial scale at which drive an influence from global to local environmental conditions, fires or forest management have a more localized impact).

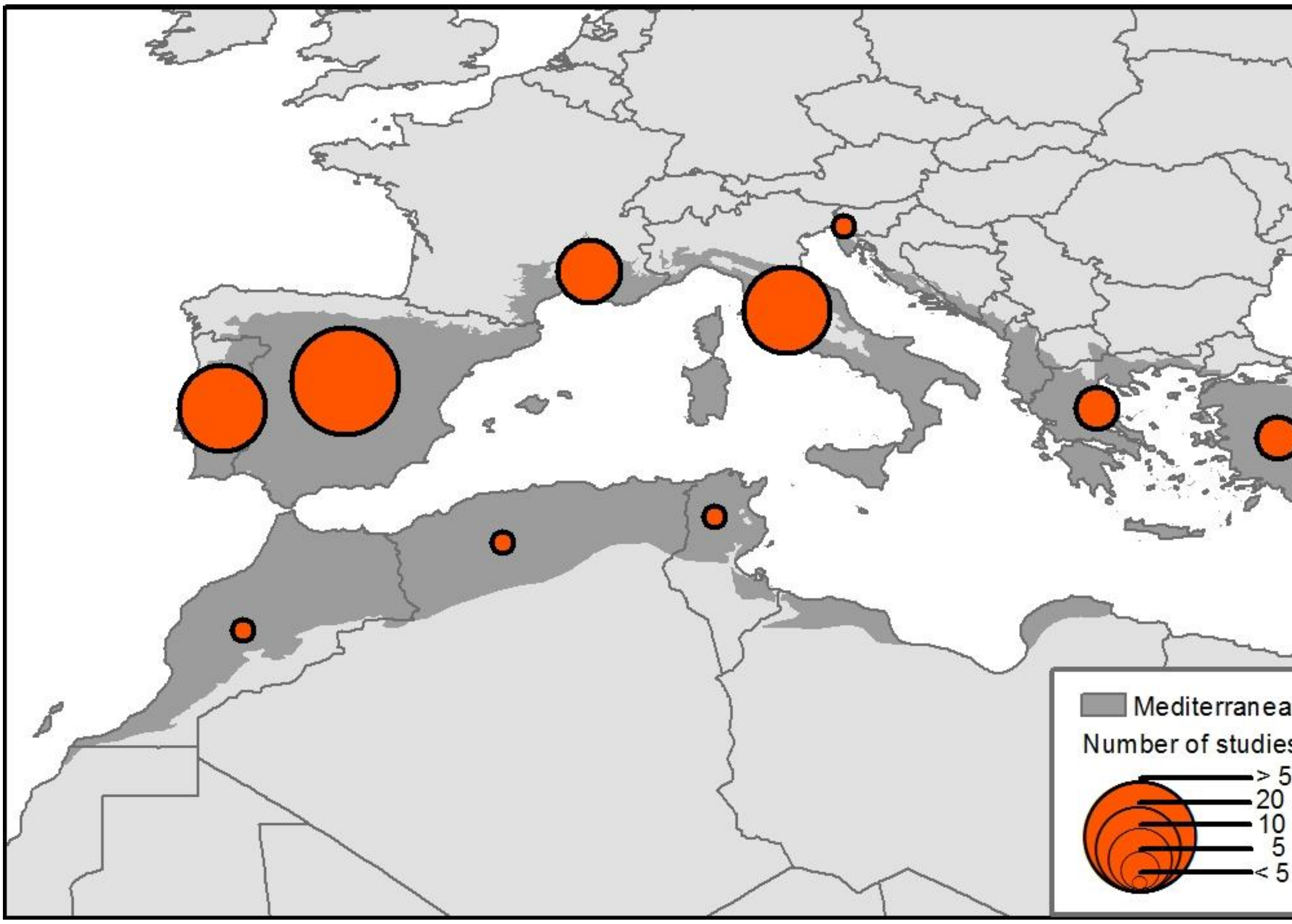


Figure 2. Geographical distribution of 133 national, sub-national and local studies assessed in this review. Note: the cir not the exact location where the study was carried out. The extent of the Mediterranean domain (shaded in dark grey in European Environmental Agency (layer of biogeographical regions: https://www.eea.europa.eu/data-and-maps/data/bio WWF (layer of Terrestial Ecoregions of the World: https://www.worldwildlife.org/publications/terrestrial-ecoregions-o for correlations between the number of studies in each country and different socio-economic indicators.

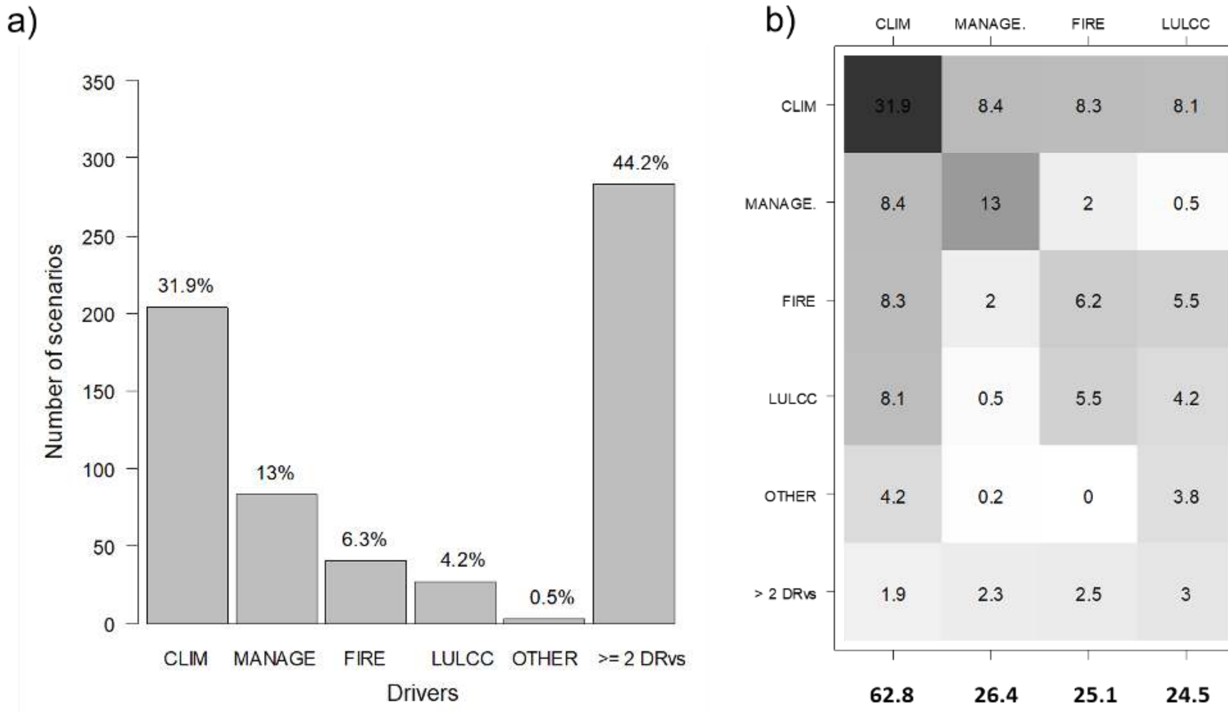
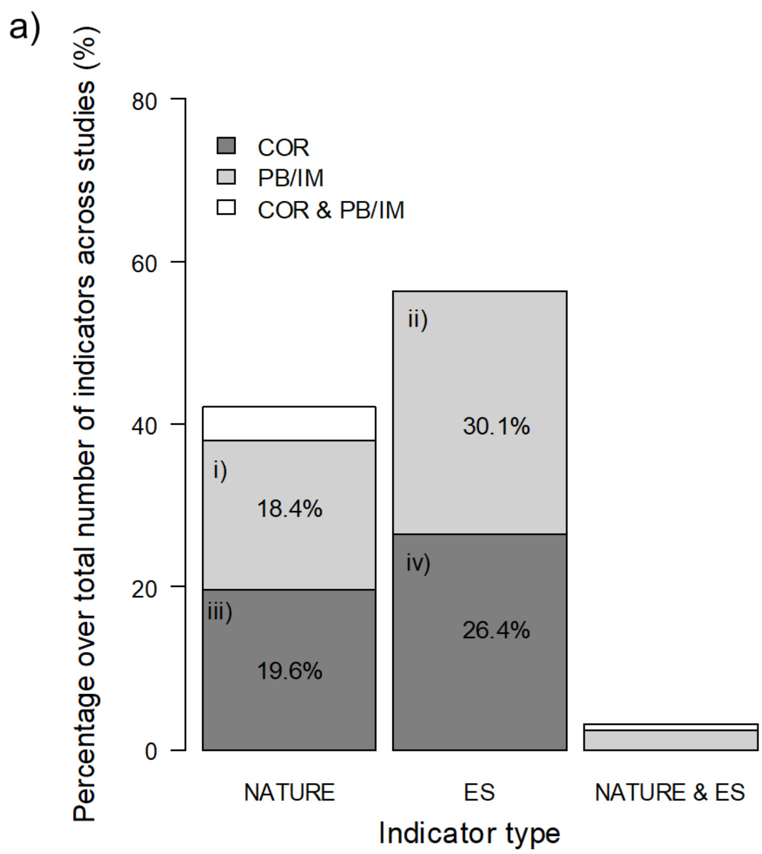


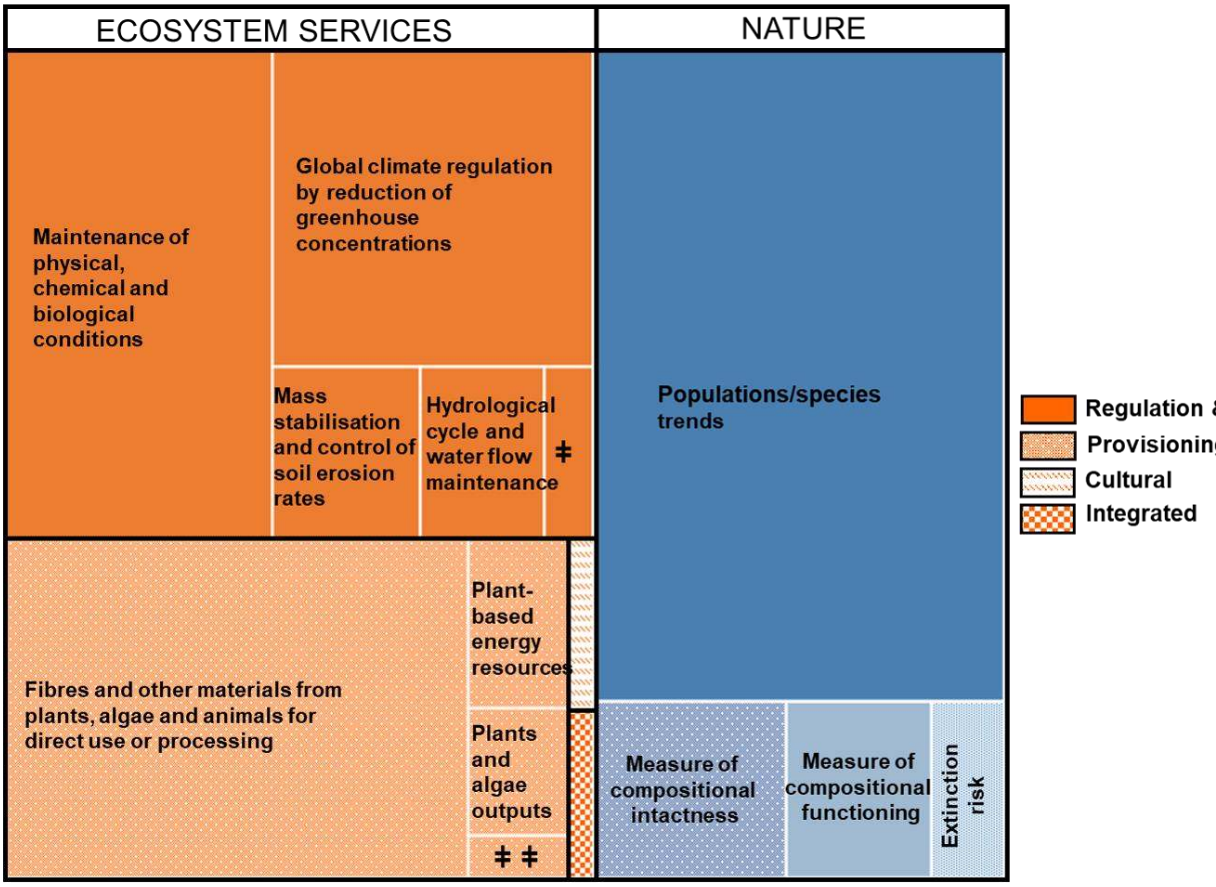
Figure 3. Driver types and driver combinations used in the scenarios found in the literature review. **a)** Each bar represe single driver (X-axis: climate [CLIM], fire, land use land cover change [LULCC], management practices [MANAGE.], species) or two drivers or more jointly (≥ 2 DRvs). The prevalence of the use of each of these drivers within the selecte the top of each bar (e.g. climate bar: 31.9 % of the scenarios used climate as the only driver of system change); **b)** Preva scenarios found in the selected literature. The most frequent combination of drivers is represented by darker gray tones MANAG), whereas lighter squares indicate less frequent driver combinations (e.g. LULCC with MANAGE.). Values v indicate percentages over the total number of scenarios in our database. Values in the diagonal of the heat map represen (same values than in panel a). Values at the bottom of the heat map represent total use of a given driver (read from the t other drivers (read from the left axis) in the scenarios of the selected articles (e.g. CLIM is considered as a driver of for scenarios – 31.9% as solo-driver and 20.9% of the times in combination with other drivers-, whereas FIRE is used only the values are symmetrical at both sides of the diagonal.



b)

	Count	Dri
i) NATURE PB/IM		
	1	73.
	2	16.
	≥3	1(
ii) ES PB/IM		
	1	57.
	2	40.
	≥3	2.(
iii) NATURE COR		
	1	90.
	2	9.4
	≥3	
iv) ES COR		
	1	83.
	2	16.
	≥3	

Figure 4. a) Prevalence in the selected literature of studies assessing ecosystem services indicators (ES), nature indica indicators in the same study (NATURE & ES). Different grey tones indicate different modelling approaches: dark grey approaches (COR), light grey for articles using process-based or integrated modelling approaches (PB/IM) and white fo IM in the same study (COR & PB/IM). **b)** For each of the dominant indicator-modelling approach combinations in plot PB/IM, iii) NATURE-COR and iv) ES-COR– we detail the frequency (from column 'count') of use of single-driver vs frequency of single-indicator vs multiple-indicator evaluations.



‡ Others: flood protection, pollination, etc.

‡ ‡ Materials from plants, animal and algae for agricultural use

Figure 5. Types of indicators found in the literature search and their prevalence in the data set. Orange sections of the service indicators: provisioning, regulating, cultural services or integrative (multi-service indicators). Blue shaded secti indicators that we classified in four main groups: measures of extinction risk (e.g. viability of populations), indicators o expansion/contraction), measures of ecosystem functioning (e.g. trait diversity) and measures of compositional intactne The size of each box indicates the prevalence of each indicator type in the selected literature (ecosystem service classes Classification of Ecosystem Services - CICES V4.3; www.cices.eu).

The use of scenarios and models to evaluate the future of nature values and ecosystem services in Mediterranean forests

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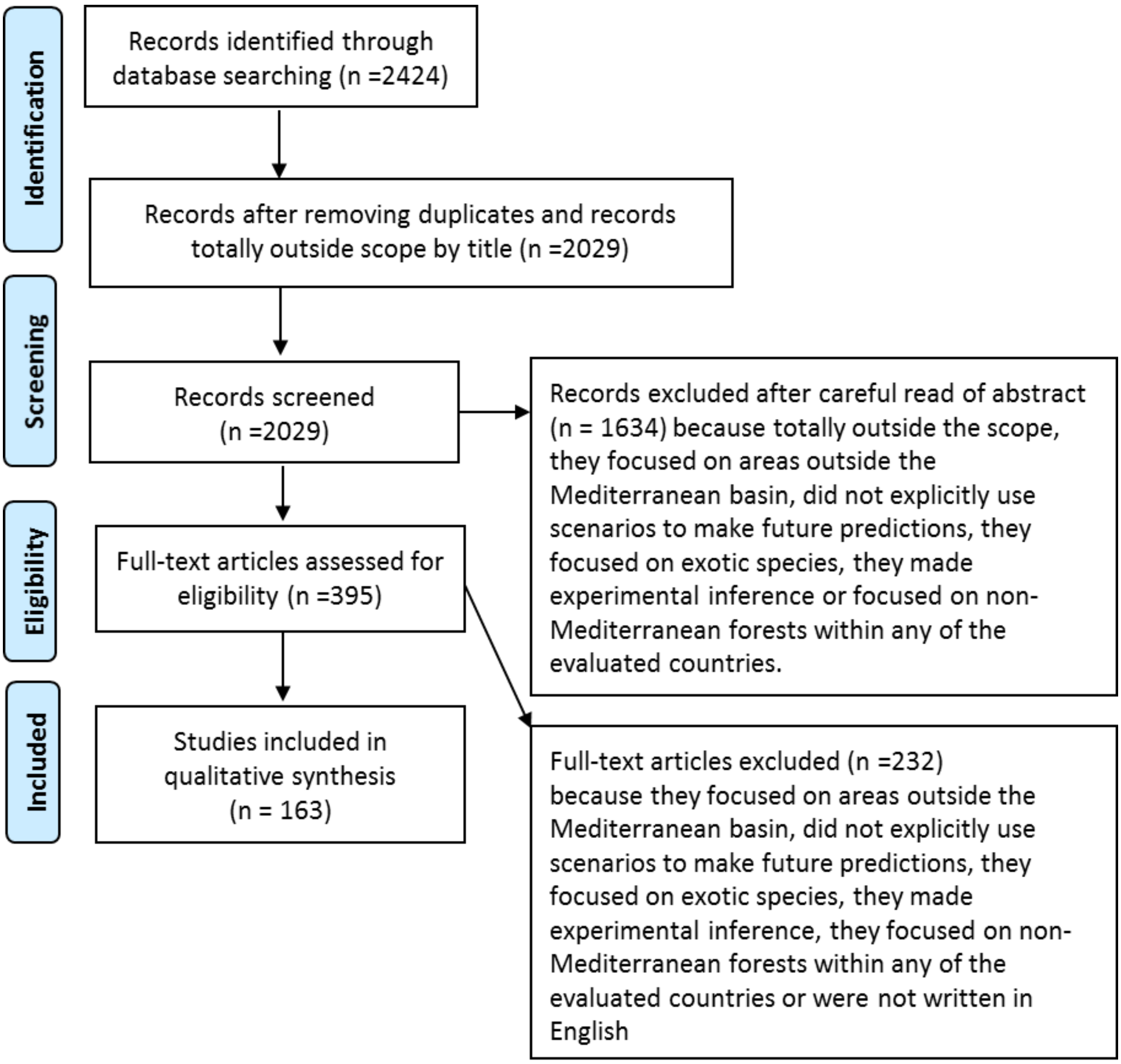
ELECTRONIC SUPPLEMENTARY MATERIAL for Regional Environmental Change

Online resource 1: Details of literature review

Flow chart based on PRISMA protocols (Moher et al. 2009) illustrating how papers were selected or discarded



Moher D, Liberati A, Tetzlaff J, Altman DG, The PG (2009) Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement. PLoS Med 6: e1000097.

Online resource 2: List of publications included in the review.

See summary of the journals included in the review at the end of this list.

1. Ágreda T, Águeda B, Olano JM, Vicente-Serrano SM, Fernández-Toirán M (2015) Increased evapotranspiration demand in a Mediterranean climate might cause a decline in fungal yields under global warming. Glob Change Biol 21: 3499-3510. doi: 10.1111/gcb.12960
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Frequency of journals in the selection of 163 papers

Journal name	Number of papers
Ecological Modelling	9
Climatic Change	7
Biogeosciences	6
Forest Systems	6
Global Change Biology	6
Journal of Biogeography	5
Regional Environmental change	5
Annals of Forest Science	4
Forest Ecology and Management	4
iForest-Biogeosciences	4
Landscape and Urban Planning	4
Landscape Ecology	4
Plant Ecology	4
Plos One	4
Agricultural and Forest Meteorology	3
Applied Vegetation Science	3
Can J Forest Res	3
Global Ecol Biogeogr	3
Journal for Nature Conservation	3
Science of the Total Environment	3
Agriculture, Ecosystems & Environment	2
Catena	2
Climate Research	2
Diversity and Distributions	2
Ecosystem Services	2
Environmental Pollution	2
European Journal of Forest Research	2
Geomorphology	2
International Journal of Wildland Fire	2
Natural Hazards and Earth System Sciences	2
Agricultural Systems	1
Agroforestry systems	1
Artvin Çoruh Üniversitesi Orman Fakültesi Dergisi	1
Aspects of Applied Ecology	1
Atmospheric Environment	1
Biodiversity and Conservation	1
Biological Invasions	1
Biomass and Bioenergy	1
Canadian Journal of Plant Pathology	1
Comptes Rendus Biologies	1
Conservation Biology	1
Croatian Journal of Forest Engineering: Journal for Theory and Application of Forestry Engineering	1

Journal name	Number of papers
Cuadernos de la Sociedad Española de Ciencias Forestales	1
Ecohydrology	1
Ecological Indicators	1
Ecoscience	1
Environmental Modelling & Assessment	1
Environmental Modelling & Software	1
Environmental Reseach	1
Forest Policy and Economics	1
Forestry	1
Forests	1
Frontiers in Ecology and the Environment	1
Hydrology and Earth System Sciences	1
International Journal of Applied Earth Observation and Geoinformation	1
Journal of Applied Ecology	1
Journal of Ecology	1
Journal of Forest Economics	1
Journal of Hydrology	1
Journal of Land Use Science	1
Journal of Mountain Science	1
Journal of Ornithology	1
Journal of the Faculty of Forestry Istanbul University	1
Journal of Vegetation Science	1
Land Degradation & Development	1
Molecular Ecology	1
Nature Climate Change	1
New Forests	1
Phytocoenologia	1
Plant Biosystems	1
Remote Sensing	1
Sains Malaysiana	1
Science	1
Silva Fenn	1
Soil Use and Management	1
Šumarski list	1
Sustainability	1
The Holocene	1
Tree Physiology	1
Turkish Journal of Agriculture and Forestry	1
Water	1
Natural Hazards	1
Environmental Management	1

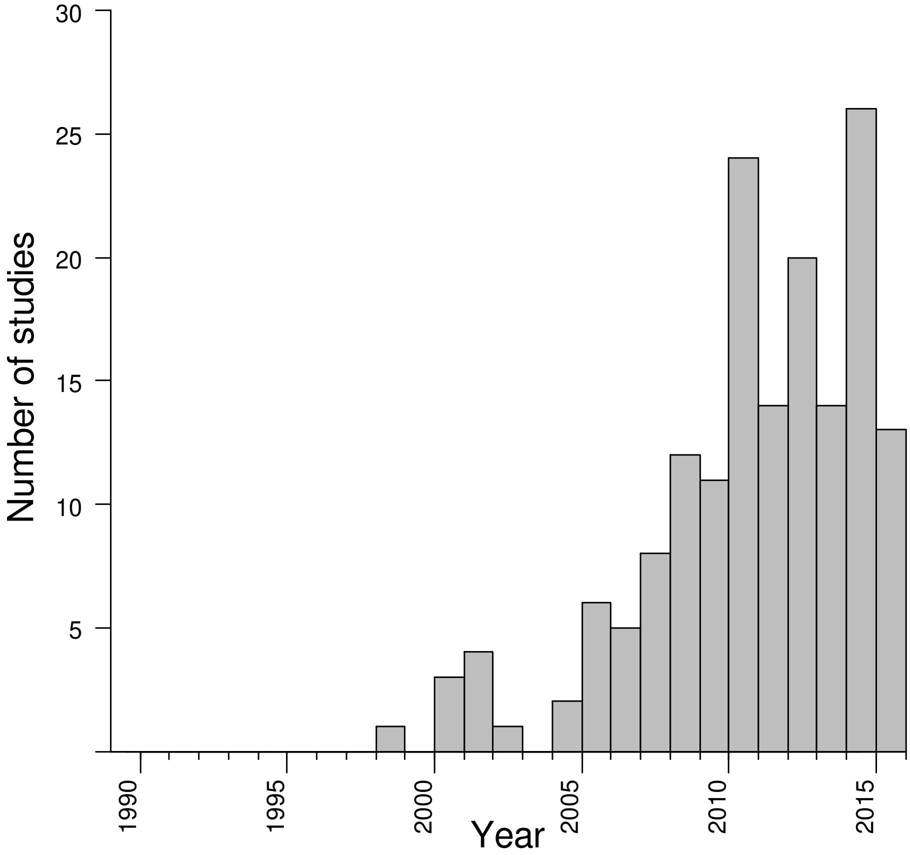
Online resource 3: spatial scales addressed

Number of studies found in the literature review, classified by the original spatial extent/focus of the article and the number of drivers included in the scenarios.

	Number of drivers			
Original extent of the article	**1**	**2**	**3**	**4**
Global	9	3		1
Regional (Pan-Mediterranean)	14			
National	26	10		
SubNational	30	9	1	
Local	37	16	4	
Simulated landscapes (local)	2	1		
Total	163			

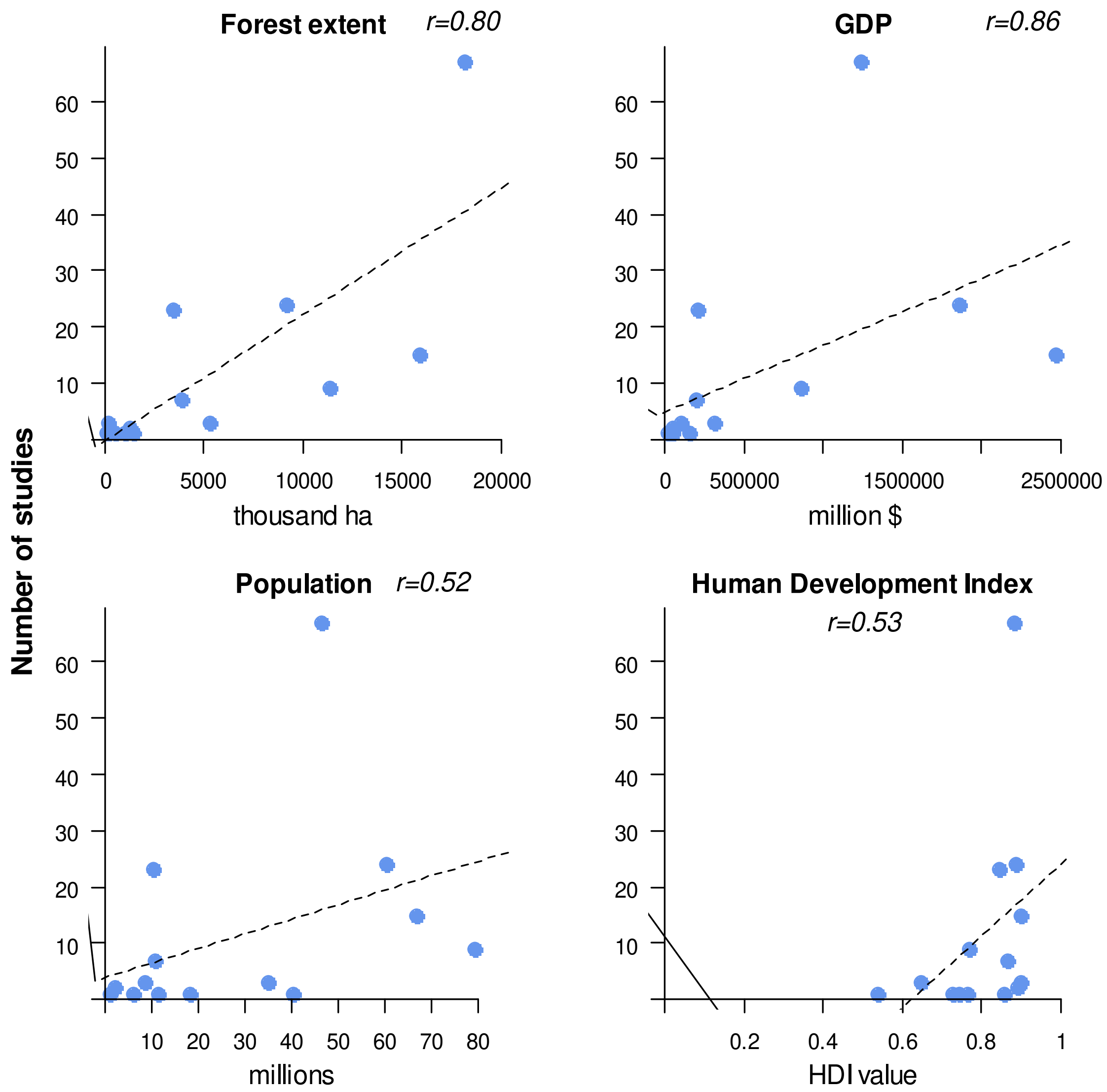
Online resource 4: temporal trend of published literature

Number of published articles that used models and scenarios to forecast nature and/or ecosystem services indicators linked to Mediterranean forests during the period 1990-2016.



Online resource 5: correlations between number of studies and socio-economic indicators.

Number of studies by country in relation to their total forest extent (FAO 2010), Gross Domestic Product (GDP; source: https://data.worldbank.org), population (source: https://data.worldbank.org), and their level of social well-being as measured by the Human Development Index (UNEP 2016). R values indicate Spearman's correlations between each variable and the number of studies by country.



FAO. 2010. Global forest resources assessment 2010. Main report. FAO Forestry Paper No. 163. Rome

UNDP (United Nations Development Programme)–Human Development Report 2016. Human development for Everyone. New York. (also available at http://hdr.undp.org/sites/default/files/2016_human_development_report.pdf)