



Managing Mediterranean Forests for Multiple Ecosystem Services: Research Progress and Knowledge Gaps

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Abstract

Purpose of Review Forests provide multiple ecosystem services (ES) to society, and the demand for ES is growing at the global level. However, how to manage forests for the provision of multiple and sometimes conflicting services is a complex and still unresolved issue. In this study, we reviewed the scientific literature for the period 2010–2020 dealing with forest management and multiple ES in Mediterranean forests, with the aim of (1) outlining the progress in research, (2) identifying knowledge gaps and research needs, and (3) discussing management approaches considering multiple ES. The selected literature was analyzed considering different aspects of multiple ES (e.g., drivers of changes, modeling approaches, trade-offs, and synergies).

Recent Findings Our results show that wood production is still one of the main management objectives, with an increasing attention toward non wood forest products. Carbon sequestration and biodiversity were the most investigated regulating functions, but also specific aspects are gaining attention (e.g., lichens for microclimate regulation). Changes in stand structure and density, the impact of coppice vs. high forest, and the effect of management practices vs. abandonment were considered as drivers of change at the stand/management unit scale, while the impact of climate changes and disturbances were considered at the landscape/regional scale using modeling.

Summary Despite the progress made in the last decade, our review highlights that further research is needed to fill the gaps in the scientific literature regarding how forest management influences the provision of multiple ES in the Mediterranean region. From a conceptual point of view, there is the need for a shift to a new paradigm based on an adaptable, flexible management, and planning approach to sustain self-organization, adaptive capacity, and overall resilience of Mediterranean forests, overcoming the ecosystem “service” approach; operatively, research should move toward a transdisciplinary approach, which considers problems from a diversity of points of view and involves extended peer communities not only in the dissemination of research results, but also in the research process itself.

Keywords Forest functions · MFRA · Multi-functional forests · Multi-objective forest management · Multifunctionality · Trade-offs · Synergies

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Introduction

The current demand for multiple goods and benefits from forests, collectively termed “ecosystem services” (ES) [1], is growing rapidly at the global level, but uncertainty remains as to how to manage ecosystems for the provision of multiple, and sometimes conflicting, services [2]. According to Manning et al. [3], multifunctionality has been defined only broadly as “the simultaneous provision of multiple functions” [4] and “the potential of landscapes to supply multiple benefits to society” [5], but underlying these seemingly simple definitions are complex and unresolved issues regarding the conceptualization and

measurement of multifunctionality [4–7, 8•], and the fact that many scientists start from the simplified assumption that ES do not have significant and variable relationships with one another [9].

Although the importance of the multiple functions and the related ES that forests provide is being increasingly recognized [10], forests continue to be managed in many cases through conventional means with single or few objectives, which often fail to address the multiple functions of forests, and are therefore unable to adapt to the challenges increasingly faced by forests. Managing a forest to maximize provision of a service (or set of services) may lead to a less resilient and more vulnerable system, not only from the ecological but also from a socio-economic and governance perspective [11, 12].

This is also the case in the Mediterranean region, where despite the marked multifunctionality of forests in providing valuable goods and services to society, silviculture and forest planning approaches, with few exceptions, have been wood-based [13].

In 2000, Scarascia-Mugnozza et al. [14] identified forest multifunctionality and its scaling aspects as important knowledge gaps on the way to sustainable management of Mediterranean forests. A decade later, the Mediterranean Forest Research Agenda [15], based on a consultation process that involved a large number of institutions in 15 Mediterranean countries and representing a common vision on the challenges of Mediterranean forests for the 2010–2020 decade, pointed out the importance of identifying forest management options for ensuring the sustainable production of multiple goods and services in a changing environment. Specifically, the 2010–2020 Mediterranean Forest Research Agenda identified, among others, the following key challenges: (a) develop tools and methods to predict the effects of forest management on multiple forest goods and services, and related resources; (b) design new forest management models that address the multifunctionality of Mediterranean forests in an integrated stand-to-landscape scale; and (c) develop user-friendly forest landscape decision support systems to capture the preferences of key stakeholders regarding forest goods and services, and be able to optimize forest management to ensure the provision of these goods and services. Expected outputs of research efforts for the decade were new silviculture models and planning models for addressing multiple objectives and tools for optimizing multi-objective forest management and analyzing the trade-offs between various forest functions and conflicting goals.

In this paper, we review the scientific literature of the last decade specifically dealing with forest management and multiple ES in Mediterranean forests, with the aim of (1) outlining the progress in research, (2) identifying knowledge gaps and research needs, and (3) discussing management approaches considering multiple ES.

After a synopsis of the multifunctional role of Mediterranean forests (“[The multifunctional role of Mediterranean forests](#)” section) and a methodological section reporting how the literature survey was carried out (“[Materials and methods](#)” section), we present the results of the literature analysis considering different aspect of multiple ES (e.g., ES indicators, drivers of change, modeling approaches, forest types, trade-offs and synergies; “[Research progress in managing Mediterranean forests for multiple ecosystem services](#)” section), and finally discuss the results and point out the knowledge gaps in the light of recent developments in forest management approaches in Mediterranean forests (“[Discussion](#)” section).

The Multifunctional Role of Mediterranean Forests

Mediterranean forests are part of a landscape mosaic that reflects interactions between variable climatic and geomorphological conditions, regional landforms and human influence [14, 16, 17]. The very long history of human-induced changes has caused a strong reduction of forest area in the Mediterranean region [18], and it has been estimated that by mid-twentieth century, less than 15% of the “potential” Mediterranean forest vegetation remained [19]. This trend has changed in the last decades, and according to the Global Forest Resources Assessment the total forest area estimated in 2015 in Mediterranean countries (88 million ha, [20]) has been increasing since 1990, largely the result of natural forest expansion, and, to a minor degree, reforestation, with deforestation remaining at a low level of 0.05 percent/year [20]. In 2015, forests occupied 10% of the total area of Mediterranean countries, but this proportion varies greatly between the different countries (e.g., 6% in Israel, 37% in Spain, 61% in Slovenia). However, it is worth noting that part of the forest expansion reported for Mediterranean countries has actually taken place outside the Mediterranean region, such as the Euro-Siberian ecoregions of northern Spain or France.

Natural forest expansion is taking place mostly on abandoned agricultural land: land abandonment is increasing in the Mediterranean Basin, mainly in its northern rim respect to North African countries [21–23], especially in mountain areas [24], often altering the century long dynamic equilibrium of Mediterranean landscapes [25].

Forests in the Mediterranean countries have been providing multiple goods and benefits, which are crucial for the socio-economic development of rural areas, as well as for the well-being of the urban populations of the region [13].

Mediterranean forests provide provisioning, regulating, and cultural ES, all of them facilitated by supporting services ensuring the vital ecosystem functions and processes

(Fig. 1), as classified according to the Millennium Ecosystem Assessment [1]. Among the provisioning services, wood forest products, such as timber and firewood, have been and are still important, but non-wood forest products such as resins can sometimes be more important. Particularly food products, like mushrooms, game, nuts, and herbs, are actively collected from many Mediterranean forests, and often represent an economic value larger than the harvested wood products [26, 27•]. It is therefore necessary to optimize management while considering trade-offs between wood production and, e.g., mushrooms [28•]. But perhaps most important of all are the public services and externalities provided by Mediterranean forests [29]. For regulating services, these forests play a fundamental role in soil protection, watershed management, climate change mitigation, and microclimate amelioration [13]. Finally, they also have a large importance in providing cultural ES. In addition to their increasing recreational value, Mediterranean forests are often cultural landscapes full of legacies of former human land use and land management practices [30]. These heritage values merit particular management attention because of their unique historical and archeological importance [31, 32].

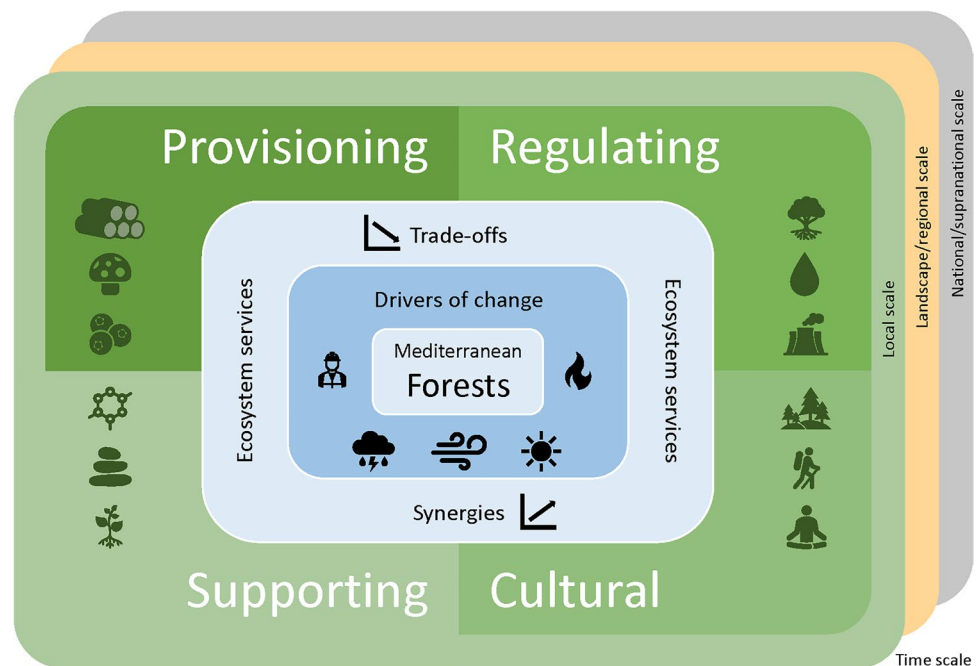
The millennia long process of deforestation in the Mediterranean region has caused and is still causing problems for *soil conservation* and *forest hydrology*. The destruction of the forest cover started in prehistoric times with the transformation of forests into agricultural land and the intensive use of forests for grazing or various systems of shifting cultivation. The role of Mediterranean forests in soil conservation and watershed protection, mainly through canopy

cover, rooting, and organic matter build-up, has long been acknowledged: as early as the fifteenth–sixteenth centuries, forest management in countries such as Catalonia and the Republic of Venice aimed primarily at protecting rural welfare and conserving soil and water, and only secondarily at timber production [13, 29]. Using the total economic value framework, Croitoru [29] estimated that in many countries in the Mediterranean region, the single most valuable forest benefit is that deriving from watershed protection, accounting for more than 50% of total economic value (e.g., in Syria, Greece and Italy).

In the fragile Mediterranean environment, *water conservation* is particularly important. The Mediterranean region is recurrently confronted with water scarcity due to both climatic factors (limited and irregular rainfall, which is expected to further decrease with climate change), and social factors (e.g., changes in land use with the expansion of irrigated agriculture; unsustainable water consumption especially in growing urban areas) [33, 34]. Dryland forests have prominent features like increased water infiltration contributing to water conservation [35]. On the other hand, increasing forest cover may also increase evapotranspiration and decrease water discharge to rivers, which offers options for more water use efficient forest management [33]. It also needs to be emphasized that evapotranspiration by forests is not to be considered as water loss, as this water is recycled into rain elsewhere [36].

Mediterranean forests are a unique world natural heritage in terms of *biological diversity* [15]. The Mediterranean Basin is one of the world’s major centres for plant diversity and one of the richest in endemism [37, 38]; this diversity

Fig. 1 Graphical representation of the relationships between Mediterranean forests, main drivers of change and ecosystem services



is also the consequence of the interaction between environmental conditions and human activity which has produced a great variety of forest types. According to Blondel [18], the apparent resilience of recent Mediterranean ecosystems is the result of the dynamic coexistence of human and natural living systems with positive and negative feedback cycles operating for long periods at local or regional levels. As a consequence of early deforestation, only little old growth or ancient Mediterranean forests remain, which means that biodiversity features related to primary forests are largely lost [39–41]. On the other hand, a large share of Mediterranean forest biodiversity, especially herbaceous species and associated insects, is related to various levels of disturbance, including fire and herbivory by livestock, as, e.g., in Mediterranean heath ecosystems [42, 43], and tends to disappear after dense afforestation or land abandonment. As a consequence, safeguarding the biodiversity of the Mediterranean forest faces a complex challenge of managing both natural and human-induced disturbance regimes [31, 39, 44].

Mediterranean forests contribute to *carbon storage and sequestration* even if the uncertainty related to the assessment in the various countries is high, and this indirect benefit (e.g., regulation of global climate) is not assessed in a systematic way and often remains site-specific [45]. The importance of Mediterranean forests in carbon sequestration is thus quite variable and is affected by the general lower productivity of Mediterranean systems in comparison to northern- or central-European ecosystems [46]. Forests in northern Mediterranean countries sequester about 0.01–1.08 t C/ha annually [29]. Over the past 25 years, growing stock in Mediterranean forests has increased by 137 million m³ per year. The reasons for growing stock accumulation in Mediterranean forests are many and complex, but land abandonment and reduction of harvest levels are the principal ones [47].

Mediterranean forests also contribute to *air quality* regulation, noise reduction, and have a cooling effect [47], all benefits which are particularly important for forests around urban areas [48–51].

Mediterranean forests have a very important role in providing what have been collectively termed “*cultural ecosystem services*”, e.g., opportunities for tourism and recreational activities; appreciation of natural scenery; inspiration for culture, art and design; sense of place and belonging; spiritual and religious inspiration; education; and science [1]. Mediterranean forests contribute to the cultural landscapes that have been shaped by centuries of human–environment interactions [52••]. The co-evolution between forest ecosystems and the related human populations in terms of domestication (of trees, ecosystems and landscapes [53]) have resulted in forests (domestic forests, or rural forests [54]), which can be considered as biocultural, or socio-ecological products of the agroforestry

systems that have been characterizing many Mediterranean areas [52••]. Recreation has always been a significant activity in the Mediterranean region, varying widely across countries; it is very important in the northern Mediterranean and its importance is likely to grow throughout the region [29]. Forest areas are also a fundamental asset for the esthetic appreciation of rural landscapes [55, 56].

Although forests in the Mediterranean area are still expanding, their ability to provide all these goods and services will become increasingly affected by environmental and social changes.

Climate change is emerging as the primary driver of environmental change in the region [47, 57]. The Mediterranean has been identified as one of the most reactive regions to climate change and defined as a major hotspot [58, 59]. The primary projected impacts of climate change on the natural environment and consequently on forests in the Mediterranean are rapid change in the water cycle due to increased evaporation and lower precipitation; a decrease in soil water storage capacity (due to changes in porosity resulting from a change in temperatures, making soils drier) and thus an acceleration of desertification already underway by previous overexploitation and depletion of soils; a northward or altitudinal shift in altitude of terrestrial biodiversity (animals and plants); and extinction of the most climate-sensitive or least mobile species and colonization by new species [47, 57].

It is anticipated that demographic evolution will be another major driver of Mediterranean forest ecosystem change in the near future [47], with most of the population growth occurring in southern and eastern countries, particularly in urban and coastal areas. Increased population numbers may intensify pressure on the resources provided by forests, in terms of resource use, including drinking and irrigation water, and recreational use [47]. A related major change is that of rural exodus and land abandonment, which has accelerated in the northern rim of the Mediterranean since the 1970s, while it has increased since the 2000s in the Eastern Mediterranean, particularly Turkey, and might get triggered in the southern Mediterranean in the decades to come. This large-scale landscape transformation holds opportunities and risks for the Mediterranean forest [60••]. Opportunities in the sense that as the forest area increases, the potential provision of associated ES also increases. It is as well a massive phenomenon of rewilding, where large areas get depopulated, and, e.g., rare larger mammals, like wolves, bears, and others, are able to re-establish. There are also increased opportunities of wood provisioning, e.g., for engineered timber, biorefinery, or bioenergy for local use, which stay so far largely untapped due to mobilization challenges [61], but which should be carefully evaluated in relation to the multiple functions that these new or aging forests can provide. On the other hand, the accumulation

of biomass over large contiguous landscapes can increase the risk of megafires [62••].

Thus, forest management in the Mediterranean faces a substantial challenge if the capacity of forests to provide the multiple and valued ecological goods and services is to be maintained in the future.

Materials and Methods

To identify research progress and knowledge gaps, we searched Scopus and Web of Science databases for all types of documents that were explicitly related to forest management and ES in the Mediterranean area for the period 2010–2020. The literature survey was carried out in December 2020 using the following terms in the combined field of title, abstract, and key words: (“forest management” AND Mediterranean AND service) OR (“forest management” AND Mediterranean AND multi). A total of 107 publications satisfied this conditional search, which were reduced to 97 publications after removing duplicate documents found on both databases. Then, we read in full the documents to assess their relevance for the scope of our review using the following criteria: (1) the research must be related to forests in the Mediterranean basin, (2) the research must be related to the forest management context, and (3) at least one ES and the relationships with forest management must be considered. Documents that considered land use management but did not explicitly use forest management criteria to assess ES were not considered; economic evaluation of ES was out of the scope of our review. In order to get a complete picture of research on forest management and multiple ES in the Mediterranean area in the 2010–2020 period, we then examined the literature referenced in the selected documents, using a snowball approach and the criteria listed above, leading to a final set of 56 documents (Online Resource 1) that were used for analysis.

Selected documents were analyzed to extract the following information:

- Scale/scope of research (stand, landscape, general, etc.);
- Considered ES and indicators;
- Drivers of change in ES provisioning;
- Modeling approaches;
- Forest types;
- Interactions between ES and trade-offs and synergies.

Research Progress in Managing Mediterranean Forests for Multiple Ecosystem Services

In the last decade, there has been a growing research interest towards the impact of forest management on the provision of multiple ES from Mediterranean forests.

The large majority of the selected documents emerging from our literature survey were research papers (82%), followed by literature reviews and general discussions (18%) on various aspects of ES provided by Mediterranean forests. Most of the research papers (91%) come from the north-western countries of the Mediterranean basin (Spain, Italy, Portugal, and France), while only 9% are from the south and south-eastern countries of the Mediterranean basin (Israel, Tunisia, Turkey).

Scale of Application

Research papers considered different scale levels using various approaches. At the stand or management unit level (32% of the selected documents), analyses were based on experimental field data or inventory data [63–66, 67•, 68–70] or retrospective studies based on archives [71]. At larger scale levels, the impact of forest management on the provision of multiple ES was more often analyzed through stakeholder perception [72], expert opinion [73, 74] or modeling, typically at the landscape or regional scale (43% of the selected documents) [75, 76]. For their growing importance, we will examine the methodological aspects of modeling approaches in a separate section ([Modeling Approaches](#)).

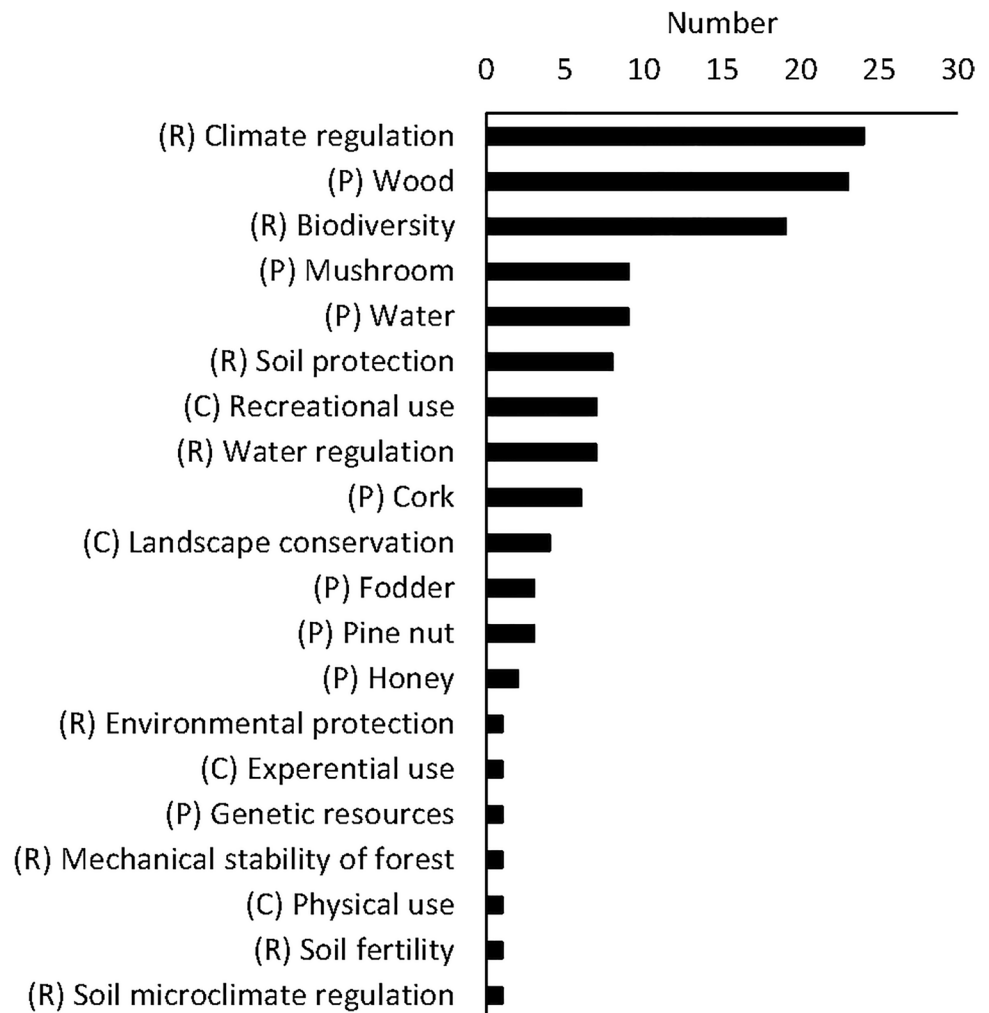
Ecosystem Services and Indicators

Although title, keywords, and/or abstract contained the term “multiple” referred to ES or functions, our results showed that only a relatively limited number of documents actually considered the impact of forest management on more than one ES. Most of the publications (77%) mentioned one, two, or three ES, rarely more than three (23%).

Twenty different ES were considered among provisioning (8 ES), regulating (8 ES), and cultural (4 ES) services (Fig. 2). While wood production is still one of the main management objectives in Mediterranean forests, in the last decade the focus has increasingly shifted towards impact of management on other aspects of forest ecosystems. Our review highlighted an increasing attention towards specific products which have a relevant socio-economic role in the Mediterranean context, such as the production of cork [25, 68, 77], pine nuts [75, 78], fungi (edible [63, 65, 67•, 79]; for biobased innovations [80]), pine honeydew honey [81], and water [25, 64, 68, 82••, 83•]. Interestingly, new terms referring to specific objective/ES oriented silviculture have been coined, such as *mycosilviculture* [80], *hydrology-oriented silviculture* [64], *water-yield silviculture* [64].

Climate regulation (carbon sequestration) and biodiversity (generic), among regulating functions, were the most frequently investigated in relation to other ES, but also specific aspects are gaining attention such as, e.g.,

Fig. 2 Ecosystem services considered in the selected documents and number of times that each service was considered (C=cultural service, P=provisioning service, R=regulating service)



the importance of lichen communities for microclimate regulation in Mediterranean forest and woodland ecosystems [66, 84•].

Cultural services such as recreation, ecotourism, sports, and esthetic values were less investigated [73, 82••].

A great variety of indicators/parameters have been used to quantify forest response in terms of the considered ES (Table 1). As an example, impact on carbon cycle, related to climate regulation, has been measured in terms of carbon stored in above ground biomass [68, 75, 77], in above ground and below ground biomass [76, 82••, 85], annual wood volume increment [69], carbon sequestration rate vs on site carbon stock [78], overall wood production, i.e., considering both carbon stored in the forest compartments and carbon fixed in removed wood [78], biomass growth of trees, and shrubs [83•]. Another example, biodiversity response has been quantified using the number of tree species [69], floristic diversity [69], lichen communities [84•], structural diversity and number of “large” trees [71], habitat diversity and endangered species [25], and tree micro-habitats [70].

Drivers of Change

The majority of the studies considered forest management as the only driver of change in multiple ES provision (72%), while the remaining studies considered no more than three drivers. Regarding the studies based on multiple drivers, forest management was most often combined with climate change (20%) and to a lesser extent with fire (4%); few studies (4%) analyzed the combined effect of climate change and biodiversity with management or socio-economic variables.

At the stand/management unit scale, changes in stand structure and density are the main management features considered as drivers of change in the provision of multiple ES from Mediterranean forests [63, 68, 69, 71, 75, 77].

Other drivers are the impact of coppice vs. high forest [84•, 86] and the effect of traditional management vs. abandonment of traditional practices, including grazing, in agro-silvo-pastoral systems [25, 66, 83•]. The impact of climate (climate change scenarios [75]) and disturbances, such as fire [86], were more often considered at the landscape/regional scale using modeling approaches.

Table 1 Examples of indicators used in the selected documents to assess ecosystem services in the Mediterranean forests

Ecosystem service		Indicator	Units	Method	Reference
Provisioning	Cork	Cork supply	kg kg ha ⁻¹	Model-based	[77, 152]
		Annual increment cork mass	kg ha ⁻¹ year ⁻¹	Model-based	[91, 153]
				Model-based	[68]
	Edible mushroom	Mushroom production in one year	kg ha ⁻¹ year ⁻¹	Model-based	[63, 82••, 88••, 154]
		Mushroom production	kg ha ⁻¹	Field data	[65, 67•]
	Fodder	Annual fodder production	Annual FU	Model-based	[68]
		Forage for goats and forage for cattle	kcal m ⁻²	Literature data	[119]
		Grazing	FU	Model-based	[153]
	Genetic resources	Seed dispersal	ha	Model-based	[155]
	Honey	Annual honey production	kg ha ⁻¹ year ⁻¹	Literature data	[81]
		Index based on flower counts in the plots	Score (0–10)	Model-based	[119]
	Pine nut	Annual cone production	kg ha ⁻¹ year ⁻¹	Model-based	[75, 156]
			kg tree ⁻¹ year ⁻¹	Model-based	[94]
	Water	Water exported yearly by surface runoff or deep drainage into the water table	l m ⁻² year ⁻¹	Model-based	[82••, 88••]
			m ³ ha ⁻¹ year ⁻¹	Model-based	[68, 83•]
			mm year ⁻¹	Model-based	[157, 158]
kg ha ⁻¹ year ⁻¹			Model-based	[159]	
Wood	Wood production per year	t ha ⁻¹ year ⁻¹	Official statistics	[82••]	
		m ³ ha ⁻¹ year ⁻¹	Model-based	[71, 81, 88••, 156]	
	Wood production	m ³ ha ⁻¹	Field data		
			Model-based	[69, 71, 76, 87, 91, 158, 160]	
		t ha ⁻¹	Field data	[70]	
		Capacity of forest type to fulfil different functions in the sampling point	Score (0–10)	Expert opinion	[73]
	Timber yield	m ³	Model-based	[77]	
Annual increment	m ³ ha ⁻¹ year ⁻¹	Model-based	[75]		
Regulation	Biodiversity	Grassland habitat cover	%	Model-based	[86]
		Tree microhabitats	n ha ⁻¹	Field data	[70]
		Habitat for biodiversity (deadwood)	m ³ ha ⁻¹ year ⁻¹	Model-based	[88••]
		Habitat conservation (capacity of forest type to fulfil different functions in the sampling point)	Score (0–10)	Expert opinion	[73]
		Density of geophyte, density of flowers,	n m ⁻²	Model-based	[119]
		Density of fleshy fruits	kcal m ⁻²	Model-based	[119]

Table 1 (continued)

Ecosystem service	Indicator	Units	Method	Reference
Climate regulation	Tree species diversity	–	Shannon index, Field data	[69]
		n	Model-based	[161]
	Floristic diversity	–	Shannon Index, Field data	[69]
	Reptiles	n	Model-based	[155]
	Reptile (species richness)	n	Model-based	[157]
	Bird (species richness)	n	Model-based	[157]
	Bird species (density)	n ha ⁻¹	Model-based	[162]
	Vertebrate (species distribution)	ha	Model-based	[163]
	Photosynthetic performances by forest macrolichens	–	Chlorophyll a fluorescence emission, Field data	[84•]
	Stand structure diversity indices	–	Model-based	[71]
	Ecosystem diversity (pattern analysis)	–	Model-based	[160]
	Carbon in above ground biomass	kg	Model-based	[77, 91]
		kg ha ⁻¹	Model-based	[75, 119, 153]
		Mg ha ⁻¹	Model-based	[68, 86, 152]
	Carbon in above and below ground biomass	t _{CO₂eq} ha ⁻¹ year ⁻¹	Model-based	[157]
	t ha ⁻¹ year ⁻¹	Model-based	[82••, 83•, 88••, 160]	
	kg ha ⁻¹	Model-based	[164]	
Carbon in above ground and below ground biomass, dead organic matter, and soil organic carbon	Mg ha ⁻¹	Model-based	[76, 87]	
Carbon in above and below ground biomass derived from annual increment of tree volume	t _{CO₂eq} ha ⁻¹ year ⁻¹	Field data	[69]	
Gross primary production and soil respiration	kg C·m ⁻² year ⁻¹	Model-based	[165]	
Vegetation carbon and soil organic carbon	kg C·m ⁻²	Model-based	[165]	
Environmental protection	Capacity of forest type to fulfil different functions in the sampling point	Score (0–10)	Expert opinion	[73]
	Riparian forest cover around watercourses considering a buffer zone of 25 m around	%	Map-based	[82••]
Erosion control	Forest cover of areas with a slope higher than 30%	%	Map-based	[82••]

Table 1 (continued)

Ecosystem service	Indicator	Units	Method	Reference	
	Total amount of soil erosion avoided in each plot, compared to the potential soil erosion that could occur in absence of vegetation	t ha ⁻¹	Model-based	[88••]	
	Capacity of forest type to fulfil different functions in the sampling point	Score (0–10)	Expert opinion	[73]	
	Sediment retention	m ³ ha ⁻¹	Model-based	[153]	
	Soil loss per unit of area per unit of time	t ha ⁻¹ year ⁻¹	Model-based	[159]	
Soil fertility	Amount of organic carbon in the soil	t ha ⁻¹	Model-based	[82••]	
Water regulation	Sum of canopy water storage capacity and soil water holding capacity	l m ⁻² year ⁻¹	Model-based	[82••]	
	Water holding capacity by forest macrolichens	mg H ₂ O cm ⁻²	Field and laboratory data	[84•]	
	Deep percolation, evapotranspiration, interception, runoff, soil evaporation, stemflow, transpiration	mm year ⁻¹	Model-based	[165]	
Soil microclimate regulation	Lichens, bryophytes and cyanobacteria living on topsoil (biocrusts)	% soil covered by biocrusts	Field data	[66]	
Mechanical stability of the forest system	Average slenderness ratio of dominant trees	H D ⁻¹	Field data	[69]	
Cultural	Experiential use	Animal species observations introduced on web portal	N° obs. ha ⁻¹ year ⁻¹	Other statistics	[82••]
	Landscape conservation	Surface of protected areas included in the Natura 2000 Network	%	Map-based	[82••]
		Capacity of forest type to fulfil different functions in the sampling point	Score (0–10)	Expert opinion	[73]
	Physical use	Routes recorded and introduced by users using app and web portal	N° tracks ha ⁻¹	Other statistics	[82••]
	Recreational use	Number of beds in rural tourism establishments per municipality	N° places ha ⁻¹	Official statistics	[82••]
		Capacity of forest type to fulfil different functions in the sampling point	Score (0–10)	Expert opinion	[73]

Table 1 (continued)

Ecosystem service	Indicator	Units	Method	Reference
	Monetary quantification of touristic and recreational value	€	Model-based	[160]
	Decrease in annual burned area due to forest fires	ha	Model-based	[161]

Modeling Approaches

Various research papers used modeling approaches for multiple forest ES assessment at the stand, landscape, or regional scale. Most of these studies used forest modeling to assess both forest multifunctionality and the influence of forest management [73, 76, 77, 83•, 87] and other drivers/disturbances (e.g., climate change, fires [75, 82••, 86, 88••]) on ES.

Examples of forest models used to assess the relationships between multiple ES (provisioning, regulation, and cultural services), forest management, and other drivers of change in different forest types in the Mediterranean is reported in Table 2. More information on scenarios and models used to evaluate ES in the Mediterranean can be found in Morán-Ordóñez et al. [89••].

Among the research papers that investigated the influence of forest management on ES, the majority of these studies (70%) used non-spatial indices or growth models that simulate forest dynamics at plot scale, while others (30%) used forest models for mapping ES.

The Index of Importance of Function and the Capability of Function Fulfilment Index (IFF-CFFI) were proposed to assess the forest multifunctionality at the landscape scale, and to calculate the capability of forest management systems to fulfil different forest functions [73]. The model requires the stratification of the forests into forest types and the assessment of multifunctionality on field plots by estimating the capacity of each forest type to fulfil forest functions. A score ranging from 0 (for less important function) to 10 (for the most prevalent function) is used to calculate the Index of Importance of Function for each function. Field plots are aggregated according to management systems and forest types, and then compared with three indicators of multifunctionality: average number of functions fulfilled by each forest type, average value of each function associated to a forest type, and mean total value of all functions referred to each forest type. The Capability of Function Fulfilment Index is calculated as the mean of the product between Index of Importance of Function and capability of the management system to fulfil the function of all plots related to the forest type.

A decision support system (DSS) was developed for large scale applications to assess trade-offs between ecosystem management planning [77]. The DSS SADfLOR integrates the vegetation dynamic model SUBER v. 4.0 [90] with a trade-off analysis functionality between criteria. The trade-off analysis is based on the Pareto Frontier approach [91], which includes multi-objective linear model building functionalities and an interactive decision map building functionality to analyze trade-offs between the different criteria. Economic indicators such as the net present value are also calculated based on prices and operational costs from statistical data.

The hybrid forest patch model PICUS was specifically developed for *Pinus pinea* [92–94]. It allows to assess the influence of forest management scenarios and of climate change projections on stand development and on the related ES. PICUS includes 3D gap model [95], process-based production model, management module, and cone and nut production module. It provides a projection of stand dynamics under simulated management prescriptions and climate conditions, including single tree information such as diameter, height, and volume [75].

The process-based forest model GOTILWA (Growth Of Trees Is Limited by WAter) is a stand level ecophysiological model that models forest growth as a function of climate, soil, and other environmental and management factors [96]. It is parameterized for a range of Mediterranean tree species. In a more recent version called GOTILWA + [97, 98], it developed into a forest management optimization tool by linking the model with a multiple particle swarm algorithm, which allows to find the optimal forest management for several ES simultaneously, taking into account the trade-offs between them. Considered ES are wood production, water use efficiency, fire risk and net present value, and considered management practices are rotation length, age of first thinning, thinning frequency, and thinning intensity.

A model to assess future trade-offs and synergies between multiple ES under climate change scenarios and management options reflecting different EU forest policy scenarios was proposed by [88••]. These authors used the process-based model SORTIE-ND [99, 100] to simulate forest dynamics at plot level under each scenario and

Table 2 Examples of forest models used in the selected documents to assess multiple ecosystem services and their relationships with forest management and other drivers of change in different forest types in the Mediterranean (L = landscape scale, MU = management unit/stand scale; N = national scale, R = regional scale, n.c. = not considered)

Model name	Country	Scenario map	Scale	Time period (years)	Forest type	Ecosystem services		Drivers of change		Trade-offs and synergies	Reference
						Provisioning	Regulating	Cultural	Regulating		
LURE	France	Yes	L	200	Silver fir	Genetic resources	Biodiversity	n.c	Forest management strategies (traditional forest management, genetic forest management)	No	[155]
IIF-CFFI	Italy	No	L	10–30	Oak	Wood production	Biodiversity Environmental protection Erosion control	Landscape conservation Recreational use	Forest management regimes (coppice and high forest)	No	[73]
GOTILWA	Spain	No	MU	200	Pine, Evergreen oak	Wood production	Climate regulation Water use efficiency	Fire risk	Forest management regimes (Rotation length, frequency and intensity of thinning)	Trade-offs analysis	[97]
LANDIS-II	Italy	Yes	L	150	Grassland Oak Pine	n.c	Biodiversity Climate regulation	n.c	Climate Change scenario Soil	No	[86]
PICUS	Spain	No	L	120	Pine	Cone production Wood production	Climate regulation	n.c	Forest management prescriptions (thinning, coppicing, elimination of encroaching vegetation on non-forest areas) Climate change Fire	No	[75]

Table 2 (continued)

Model name	Country	Scenario map	Scale	Time period (years)	Forest type	Ecosystem services		Drivers of change	Trade-offs and synergies	Reference	
						Provisioning	Regulating				Cultural
PINEA2	Spain	No	MU	100	Pine	Cone production Wood production	n.c	n.c	Forest management scenarios (wood production, cone production, wood and cone production)	No	[156]
SUBER	Portugal	No	L	90	Oak	Cork production	Climate regulation	n.c	Forest management regimes (business-as-usual, adaptive management) Climate Change scenario	No	[152]
SADFLOR	Portugal	No	R	50	Oak	Cork production Wood production	Climate regulation	n.c	Forest management prescriptions (planting density, cork extraction periodicity, thinning interval)	Trade-offs analysis	[77]
–	Portugal	Yes	N	40	Different forest types	Water provisioning (water quality)	Erosion control	n.c	Forest management scenarios (as set up by Portuguese regulations)	No	[159]
MIMOSE	Italy	Yes	R	20	Different forest types	Wood production	Climate regulation	n.c	Forest management regimes (coppice, coppice in conversion to high forest, and high forest) Management restrictions (e.g., lengthening rotation periods, reducing harvesting intensity)	Trade-offs analysis	[76, 87]

Table 2 (continued)

Model name	Country	Scenario map	Scale	Time period (years)	Forest type	Ecosystem services		Drivers of change		Trade-offs and synergies	Reference
						Provisioning	Regulating	Regulating	Cultural		
–	Spain	No	R	100	Pine	n.c.	Biodiversity	Decrease in burned area due to forest fires	Forest management (no management, thinning and scrub clearing)	No	[161]
–	Spain	No	L	100	Pine	Water provisioning Wood production	n.c.	n.c.	Forest management regimes (no management, thinning)	No	[158]
–	Spain	No	MU	100	Pine	Wood production	Biodiversity	n.c.	Forest management (from even-aged structure to multi-aged structure)	Trade-offs analysis	[71]
TOOFES	Italy	Yes	MU	50–210	Silver fir	Wood production	Biodiversity Climate regulation	Recreational use	Forest management prescriptions (thinning and final felling)	Trade-offs analysis	[160]
–	Italy	Yes	MU	n.c.	Oak	Cork production Fodder production Water provisioning	Climate regulation	n.c.	Forest management (alternative silvicultural options)	No	[68]
–	Spain	Yes	R	Different time period depending on ESs	Different forest types	Edible mushrooms production Water provisioning Wood production	Climate regulation Erosion control Flood protection Soil fertility Water regulation	Experiential use Landscape conservation Physical use Recreational use	Socioeconomic variables Climatic variables Biodiversity variables	Trade-offs and synergies analysis	[82•••]
–	Spain	No	MU	50	Oak	n.c.	Climate regulation Water regulation	n.c.	Forest management (no management, thinning and scrub clearing)	Trade-offs analysis	[165]
EEFMD	Spain	Yes	R	90	Oak Pine	Water provisioning	Climate regulation	n.c.	Forest management is abandoned or is continued	Trade-offs analysis	[83•]

Table 2 (continued)

Model name	Country	Scenario map	Scale	Time period (years)	Forest type	Ecosystem services			Drivers of change	Trade-offs and synergies	Reference
						Provisioning	Regulating	Cultural			
-	Tunisia	Yes	L	n.c	Oak	Cork production Fodder production	Climate regulation Erosion control	n.c	Forest management (thinning and afforestation of the shrub land)	No	[153]
SORTIE-ND	Spain	No	L	99	Pine	Wood production Edible mushrooms production Water provisioning	Biodiversity Climate regulation Erosion control	n.c	Forest management scenarios (business-as-usual, promotion of wood energy, promotion of carbon storage, reduction of forest vulnerability) Climate change scenarios	Trade-offs and synergies analysis	[88••]

combined the outputs with empirical and process-based models to estimate changes for six different ES. Pearson's correlations were used to evaluate trade-offs and synergies among ES.

More recently, a growing number of simulation models have been used to produce scenario maps that can help to advance the understanding of the influence of drivers of change on ES.

LANDIS-II [101] is a grid-based model which includes variable time steps for ecological processes (e.g., woody biomass and carbon dynamics) and a platform to incorporate drivers of change. LANDIS-II was used at the landscape scale to examine the impacts on grasslands of simulated scenarios including climate change projections, forest management prescriptions, and fire disturbance [86]. The ecosystem process model PnET-II was used to simulate growth and dispersal of tree and shrub species. Fire disturbance was simulated using the base fire extension [102]. The LANDIS-II output maps of the dynamics of the biomass of forest species were compared with the land-cover/land-use map to evaluate the potential impacts on ES (climate regulation and biodiversity).

The Multiscale Mapping of ecoSystem services (MIMOSE) is a spatially explicit multi-scale approach which was developed to model the influence of alternative forest management scenarios on ES and their trade-offs [76, 87]. It combines GIS-based model, scenario model, economic valuation, and the Integrated Valuation of Environmental Services and Tradeoffs (InVEST) model. MIMOSE allows to investigate the effects of forest management regimes on ES provision at the operational level of the forest management unit, and attempt to upscale results at a broader scale (e.g., regional or national). The model requires qualitative (forest types) and quantitative (altitude, slope, forest age, standing volume, biomass) spatial data for each forest unit (polygon). Annual increment of wood volume is used to take into consideration forest growth. The InVEST model [103], partially modified to adapt input data and simulations to the context of Mediterranean forest ecosystems, is used to assess ES provision and their economic value. A trade-off analysis based on the concept of equilibrium [104, 105] is used to investigate the interaction between ES and management scenarios.

An environmental-economic forest management decision (EEFMD) model was developed to estimate spatially distributed effects of forest management scenarios on ES, and to simulate the potential effects of payments of ES, and of trade-offs between ES, on forest management decisions and their environmental consequences [83•]. The EEFMD model integrates detailed forest, hydrological, and economic data, and includes functions to predict forest growth, yield, and structure at the forest management unit level. The management model is combined with an economic decision module

to predict commercial harvesting and forest regeneration investment decisions.

A method to spatially assess both trade-offs and synergies among ES, and their relationships with predictor variables was proposed by Rocés-Díaz et al. [82••]. Such method foresees the use of quantitative indicators of ES, the standardization of ES indicators to a common scale (0–1) using the proximity-to-target methodology, and their aggregation at the municipality level, assuming that all indicators are relevant and similarly important. Pearson correlations are used to investigate the trade-offs and synergies among normalized ES, and to explore their relationships with predictors of ES supply.

Forest Types

The most frequently investigated forest types in the Mediterranean are cork oak woodlands (20% of the selected documents), pine stands (29% of the documents) (*Pinus halepensis*, *Pinus pinaster*, *Pinus pinea*, *Pinus sylvestris*, *Pinus brutia*, and *Pinus nigra* re-laf-forestations), oak forests (11% of the documents) (*Quercus cerris*, *Quercus ilex*, and mixed oak forests), and, at the landscape scale, the presence of both broadleaved and coniferous forests (32% of the documents).

Cork Oak Forests

Cork oak woodlands, a traditional part of Mediterranean landscapes and rural economies, have been traditionally managed so as to provide multiple productions, mainly cork, wood, and fodder for livestock grazing. These traditional productions have been included in the current ES framework, which is increasingly adding other important functions such as water regulation, carbon storage, landscape enhancement, cultural heritage value, which in turn leads to trade-offs and synergies with traditional productions.

Density management is an important tool in these traditional woodlands, with a tangible impact on the relationship between the different ES, with varying outcomes depending also on the scale and methods used in the analysis. High-density management scenarios can provide an increase in cork production and carbon sequestration, and a decrease in fodder and water yield compared to low density scenarios, with a clear trade-off between the considered ES [68], while a large-scale application of SADfLOR DSS ([77], see [Modeling Approaches](#)) using multiple-criteria forest ecosystem management planning scenarios in Alentejo in Southern Portugal, showed that wood production directly competes with carbon stock and cork supply. Both over-use and abandonment of traditional management practices can affect the provision of ES from cork oak savannahs [25]. Overuse causes soil degradation, which together with drought hampers tree regeneration and increases tree mortality, reducing

ecosystem carbon stocks, while abandonment favors shrub encroachment which shifts soil carbon from below- to aboveground plant biomass, increasing the risk of carbon losses through wildfires or other disturbances [25].

An interesting aspect of the relationship between biodiversity and the overall functioning of the cork oak system is the impact of livestock grazing on the biocrust cover (i.e., lichens, bryophytes, and cyanobacteria living on topsoil), which contribute to key ecosystem processes by fixing carbon and nitrogen, protecting soil surface from erosion forces, promoting soil formation and stability, and taking part in hydrological cycles and biotic interactions [66]. According to these authors, changes in topsoil-soil surface microclimate may have a notable effect on cork-oak regeneration processes, which is one of the main concerns in cork oak woodland management. The contribution of biocrusts to ES is thus traded-off by livestock grazing.

Pine Forests

Pines are typical of the Mediterranean area, with different species participating in different ecosystems, from lowland and coastal forests to mountain forests. Silvicultural tools such as thinning and regeneration methods have an impact on the provision of different ES, causing trade-offs and synergies. Wood production and biodiversity are often compared in relation to different management options, e.g., Marchi et al. [69] in *Pinus nigra* plantations and Alonso-Ponce et al. [71] in *Pinus sylvestris* forests. In this second case, ecological features and especially management systems interact to drive the evolution of diversity indices and, where management maintains more than one age class, a synergy between timber production and structural diversity can be obtained. The effect of management and thinning treatments on mushroom yields (*Lactarius deliciosus*) in *Pinus pinaster* forests in Spain is an interesting example of the complex relations that must be considered when targeting research to identify the links between forest management, ES, and the underlying ecological and functional processes [63, 65]. Climate and site quality have been shown to have a greater impact than management on the annual income from wood, nut, and carbon storage in *Pinus pinea* forests in the Spanish Northern Plateau [75], based on a simulation of three forest management regimes—focus on timber, cones, and combined objectives—and five climate scenarios (see [Modeling Approaches](#)). An interesting case of joint production optimization on a modelling basis is presented by de-Miguel et al. [81], who analyzed the relationship between timber production and pine honeydew honey, an economically important non-wood forest product in eastern Mediterranean countries produced by bees harvesting the honeydew caused by a scale insect, *Marchalina hellenica* Genn. in *Pinus brutia* forests. From a strictly economic point of view, the simulations show

that stands growing on good sites should be managed using rather short rotations aiming at timber production, while in medium- and poor-quality sites longer rotations take advantage of the joint production of pine honey and timber.

Oak Forests

Most oak forests in the Mediterranean area have a century-long history of coppicing for firewood production and often characterize traditional rural landscapes. Conversion to high forest is a possible alternative between forest abandonment, largely present in many Mediterranean areas where coppicing is not commercially profitable, and intensification of forest utilization, with larger felled areas, whole tree harvesting, and other methods which have a heavy impact on soil conservation and landscape quality [17]. An important research and operative question in these forests is the impact of coppicing vs. high forest on the trade-offs and synergies between wood production, biodiversity, and other regulating and cultural ES. Coppice management in Mediterranean oak forests can pose a threat to the conservation of important organisms with a regulating role in forest ecosystems, such as *Lobaria pulmonaria*, a macrolichen which can increase the water storage capacity in forest canopies and positively influences their hydrology: retaining unlogged forest-patches in a Mediterranean oak coppice increases the availability of microhabitats in Mediterranean oak forest, thus producing a synergy between regulating services and biodiversity [84]. A trade-off evaluation between biodiversity and wood production using tree microhabitats (TreeMs) as proxy indicators of biodiversity in Mediterranean mixed forests (*Quercus cerris* and other broadleaves) showed that the retention of TreeMs hinders the maximization of the economic revenue during harvesting operations; the identification of TreeMs can help forest managers develop more informed decisions during tree marking operations, so that forest management can actively sustain the conservation of forest biodiversity enhancing the multifunctional role of forests [70]. Evidence from a landscape scale expert evaluation exercise in Southern Italy showed that the high forest management system fulfilled the highest number of functions, thus the conversions from coppice to high forest in the most fertile sites may increase the overall value by incrementing protective, tourism and productive functions [73].

Broadleaved and Coniferous Forests

Mediterranean landscapes are often characterized by the presence of patches of different forest types, which can produce diversified combinations of ES in relation to different management and planning strategies, such as, e.g., favoring productive aspects vs. nature protection, or management vs. abandonment.

In two study cases in Italian landscapes characterized by broadleaved forests (coppices and high forests) and artificial conifer stands ([76, 87], see [Modeling Approaches](#)), management restrictions, longer rotation periods, a reduced harvesting intensity, and a close-to-nature forestry approach increased carbon sequestration and decreased wood production (and associated Total Net Present Value), while the total ecosystem service value did not show substantial differences. Specifically, timber provision and carbon sequestration came out as conflicting services, i.e., biomass removal yielded high timber revenues and low carbon stock at least in the short-term [87].

The impact of active forest management continuation or abandonment on carbon and water related ES was evaluated by Ovando et al. [83•], using the EEFMD model (see [Modeling Approaches](#)) in Andalusia (southern Spain) in a landscape comprising many forest species (*Quercus ilex*, *Quercus suber*, *Pinus pinaster*, *Pinus halepensis*, *Pinus nigra*, *Pinus pinea*, and *Pinus sylvestris*). Active forest management generally implied a reduction in the carbon sequestration potential, whereas abandonment was expected—at least in the medium term—to increase carbon stocks due to shrub encroachment and tree densification. Conversely, forest abandonment was expected to increase biomass stock and consequently evapotranspiration, reducing water flow (total blue water), but Authors caution on the fact that their carbon sequestration estimates for the forest abandonment scenarios consider a simplified model and assumptions which ignore the complex ecological succession dynamics in forest ecosystems.

In Catalonia (North-eastern Spain), an area characterized by a variety of forest ecosystems from coastal to mountain areas with *Pinus* spp., *Quercus* spp., *Fagus sylvatica* L., *Abies alba* Mill., Roces-Díaz et al. [82••] assessed the spatial relationships (trade-offs and synergies) of a set of provisioning, regulating and cultural ES (Table 2). Land-based indicators and forest-based indicators of the selected ES were compared. Biodiversity (particularly woody species richness) had a positive relation with most of the investigated ES (provisioning, regulating and cultural ES), while climatic conditions were the main determinants in the supply of the different ES, with most indicators being positively associated with precipitation and negatively associated with temperature. Positive associations were particularly strong among provisioning and regulating services, with highest values ($r > 0.7$) between water storage and mushroom production or water exported. Forest-based indicators better reflect the intrinsic properties of forests and therefore appear more appropriate than land-based indicators when the aim of the study is to identify the fundamental trade-offs between different ES.

Discussion

Our review shows that process-oriented research on drivers, response type, interactions, synergies, and trade-offs between multiple ES in Mediterranean forests, based on field experiments and research protocols, is still at the beginning. Instead, the growing ability in data processing, coupled with increasing availability of remote sensing data, is promoting substantial progress in research based on spatially explicit data and modeling at different scales, from local to regional/national. This approach, often implicitly, refers to an “ecosystem service bundle” approach, where individual ES can be thought of as different elements of an interrelated whole [106] or, empirically, as sets of ES that repeatedly appear together across space or time. The analysis of spatial patterns of ES can show how services are distributed across the landscape, how the distributions of different services compare, and where trade-offs and synergies among ES might occur [107], but these patterns cannot definitively determine whether or not trade-offs or synergies are occurring over time [108].

The analysis of forest ES and their relationships with drivers of change, including management, is a complex task. Approaches based on one or few ES allow more flexibility in accounting for drivers of change but provide a partial view of the multifunctional role of forest ecosystems. On the other hand, approaches that attempt to consider a wide range of ES for a more complete assessment of forest functions most often rely on heterogeneous data, with differences regarding their sources, calculation methods, spatial scales, and temporal mismatches [82••], making data combination more complex and less robust due to problems of uncertainty assessment [109–112].

Selection of ES indicators is frequently problematic. Some indicators may be somewhat simplistic since they are constrained by data availability, and some potentially important ES indicators are not considered because of the lack of information, especially for regulating and cultural services [82••, 113]. In addition, some indicators that are used to assess a specific ES could be related with more than one ES, e.g., in Mediterranean forests mushroom production can be associated with cultural values or as an indicator of food provision [82••]. Information regarding marketed services of forest ecosystems (e.g., ecological, biospheric, social, amenity, and other services) is still scarce, and large variations persist in monitoring and reporting the value of marketed forest services [114].

Forest management is one of the major drivers of change impacting on ES, and in our review several studies investigated the influence of management on multiple ES supply from Mediterranean forests. To this end, innovative forest modeling techniques have been developed to

enhance decision making in forest management. Especially spatial models have gained attention in the last decade as they provide ES maps that have many potential uses for decision-makers and planners. For example, ES maps provide spatial tools that can help to consider synergies and trade-offs of forest management [82••, 87] and could be overlaid with predicted future land-use and climate changes to understand the influence of drivers of change on ES into a dynamic planning perspective. However, approaches based on forest modeling rely on assumptions that management prescriptions, such as, e.g., thinning intensity and interval, remain constant over the considered time period, which is not likely especially in long-time interval analysis (cfr., e.g., [76]). Thus, modeling complex forest dynamics, e.g., forest growth, changes in species composition, and competition between trees, shrubs, and grasses, is still a challenge for future research [88••, 115, 116].

This reflects a general shortcoming in ES research: according to Bürgi et al. [117], the long-term dynamics are quite relevant and important to estimating future ES because (a) ecosystem properties (structures and processes) change, by natural or human-induced processes (e.g., succession or land use), and (b) demands for ES also change because of factors such as population dynamics, technological innovations, and socioeconomic changes. There are also varied time-lags between the effects of management and service provision: for example, carbon sequestration following a forest plantation will begin within 5–10 years of planting, but landscape, recreation, and biodiversity values may take several decades to emerge [118]. Generally, in natural or semi-natural ecosystems, with complex and long-term dynamics, such as forests, the full consequences of management decisions can be evaluated only over decades [119]. Furthermore, research generally focuses a set of ES that is currently considered important by the stakeholders or the researchers, but it is not certain that this set of ES will remain the same in the future because several factors may contribute to long-term changes in ES, including scientific insights that bring new ES to light, and emerging concerns, such as climate change [117].

One of the main challenges when managing for multiple ES is that they are not independent of each other and the relationships between them may be highly non-linear [120]. Attempts to optimize a single service often lead to reductions or losses of other services—in other words, they are “traded-off” [121]. The interaction among different ES is a fundamental process that influences how the considered ES responds to a driver of change [108]. Synergies arise when multiple services are enhanced simultaneously, while trade-offs occur when the provision of one service is reduced due to increased use of another. Detecting synergies or trade-offs

among the different ES in relation to the considered driver is not an easy task.

In Table 3, we attempted an analysis of the relationships that link forest management, Mediterranean forest ecosystem processes, and the related products and benefits. Our analysis is necessarily a simplification but we believe it can be useful for highlighting the complexity of the connections involved and for highlighting research gaps. The green area in the table shows synergies, the yellow area trade-offs. We separated modelling approaches, experimental trials/field data, and literature reviews.

As can be seen from the table, there is a variety of outcomes, the same driver can produce synergies or tradeoffs, which depend not only on forest type but also on many other factors, starting from the aim of the different papers, which consequently conditions the methods applied and the type of research approach, e.g., field trials usually refer to a limited time and space scale which may capture only a limited picture of the actual interactions [69] while modeling approaches usually consider a larger space and time scale, but are based on standardized parameters which might not grasp the real complexity of the effects.

Interactions among the services themselves can cause changes in one service to alter the provision of another [9]. Thinning is an interesting example of what Bennett et al. [9] have termed a *shared driver* in relation to the provision of multiple ES, causing different types of *responses* and *interactions* among ES. For example, moderate thinning in Mediterranean evergreen oak coppices has been shown to increase water availability by reducing stand evapotranspiration and soil water depletion while at the same time increasing carbon assimilation [122, 123•]. In this case, thinning acts as a shared driver with a similar positive response which is unidirectional (increased water availability for the remaining trees is expected to increase their water status and hence their carbon assimilation) but individual growth does not in turn increase water availability. Similarly, increased edible mushroom production (*Lactarius* spp.) in *Pinus pinaster* stands thinned with low intensity (removal of 10 m² ha⁻¹ irrespective of pre-thinning density) has been attributed to reduced water interception by standing trees and an increased water availability at the soil level [63]. Conversely, thinning can be considered as a shared driver resulting in a synergy but with no interaction among the considered ES, as for example in the case of thinning in conifer afforestations which can increase tree biodiversity by favoring natural regeneration of local broadleaved species and at the same time improve wood quality production [69], but the increase in biodiversity does not affect wood production, nor is the opposite true.

Table 3 shows that wood production is the most frequently investigated ES in relation to other ES, as could be expected, while water provisioning and water holding capacity have been much less investigated in their relation

Table 3 Synergies (Syn) and trade-offs (Trad) between different ecosystem services in Mediterranean forests. Synergies are reported in the green area, trade-offs in the yellow area. References in brackets () indicate that one ecosystem service is not directly investigated as such but appears in the discussion/conclusions as possible trade-off or

synergy. References in blue indicate modelling approaches, in black field data and experimental trials, in red literature reviews. Drivers: * thinning intensity/type/stand density; ** regeneration method; *** evenaged/uneven aged; + traditional management; ++ traditional management abandonment; +++ coppice/high forest; °long rotations

ES Trad ⇓	Syn ⇐	Wood production	Cork production	Pine nuts	Edible mushrooms	Honey	Fresh water (Blue water)	Fodder	Carbon sequestration	Biodiversity	Water holding capacity	Provisioning services generic	Cultural services generic	Regulating services generic
Wood production	-				[(63)]* [88]-				[69]*	[69]* [71]** *** [70]				
Cork production	[77]*	-							[68]*	[25]+				
Pine nuts	[75]			-					[75]					
Edible mushrooms					-						[82]			
Honey	[81]°					-								
Fresh water (Blue water)			[68]*				-							
Fodder			[68]*					-						
Carbon sequestration	[75] [76]+++ [77]* [87]*** +++		[25]++				[83]++		-	[69]* [86]* +++ [88]-				
Biodiversity										-	[84]°			
Water holding capacity											-			
Provisioning services generic												-	[82]	
Cultural services generic												[82]	-	
Regulating services generic												[82]		-

to the provision of other ES, especially wood production. The relationship between wood production, non-wood forest products like edible mushrooms and other ES, has also been scarcely investigated, despite the fact that mushroom gathering, including truffles [124], is a popular practice in many Mediterranean countries. Similarly, cultural ES have been only rarely considered in relation to other ES and to the various drivers. Integrating genetic diversity into adaptive forestry practice may contribute to enhance the capacity of managed forests to respond to climate-driven changes; however, the influence of silvicultural systems on gene flow and pollen dispersal within Mediterranean forest is not fully understood [125, 126]. Since all these functions will increase their importance in the Mediterranean area in the near future, research should focus on them.

Climate change is a growing global threat impacting on ES and human well-being [127], and is likely the main threat to the diversity and survival of Mediterranean forests [128].

Projected impacts of climate warming in the Mediterranean show a general reduction in the provision of regulating services, a general increase in climate-related forest hazards, and reductions in range extent and habitat suitability for the most drought-sensitive forest species [129••]. However, our review shows that only a limited number of studies considered climate change as a driver in multiple ES provision. The potential impact of land abandonment on ES supply due to changing socio-economic factors is still not fully understood [83•, 130••, 131•, 132••]. In addition, the added effects of climate change and land abandonment can increase the risk of fire: due to global warming, fire danger and burned areas are expected to increase in Mediterranean areas and will be further exacerbated by ongoing changes in land use and management that increase fuel loads and continuity [133, 134].

In addition to climate change, one of the biggest threats to Mediterranean ecosystems and their ES provision is

biodiversity loss. The biodiversity crisis of the Mediterranean terrestrial ecosystems is largely underestimated due to a lack of information. Most reported studies lack biodiversity indicators. Studies have considered tree diversity or woody species diversity at most, while these woody species represent only a few percent of the 20,000 plant species in the Mediterranean area. By overlooking effects of land abandonment, afforestation, invasive exotics, eutrophication, ruderalization, forest management, and climate change on herbaceous species and associated invertebrates, a massive extinction is taking place unnoticed [43]. Clever forest management techniques in synergy with water, fire, livestock, bioeconomy management could get a far end in taking biodiversity more actively on board in management [60••]. A major obstacle to evaluate management measures beneficial to biodiversity conservation is the lack of taxonomic expertise and monitoring efforts. The diversity is overwhelming, identification a serious challenge. But new citizen science apps like plant@net and iNaturalist could help a lot to make this more feasible than ever. Foresters taking the ES of plant diversity on board will have an extra asset for management, and will ascertain their role and recognize their ability to manage habitats for Natura 2000 goals.

Because of the variety of experimental approaches and methods, time/space scales, and, above all, of the complex combination of different forest types in landscapes which have a long history of human impact, translating research results in univocal operative guidelines for real life management and planning of Mediterranean forests for the provision of multiple ES is not an easy task.

Nevertheless, some general insights can be identified, some similar to those identified for other forest regions (e.g., temperate forests, boreal forests etc.), others which instead are peculiar to the specific Mediterranean situation. Managing Mediterranean forests is a perfect example of the adagio “think globally, act locally”. Globally, there is the urgency of guaranteeing forest resilience and adaptive capacity in face of an uncertain future both in the environmental and socio-economic conditions, and the need for considering stakeholder perceptions and expectations as inevitable drivers. On the local level, Mediterranean forests face two main constraints: water limitation and fire risk, both of which are increasing due to climate change and socio-economic driven land use changes.

Mediterranean forests will probably undergo substantially stronger water limitations by the end of the twenty-first century [123•]. This points out the need for devising forest management approaches that can promote a synergy between fire prevention and water management both at the stand and landscape scale, especially where land abandonment is favouring a densification of forest stands. This can produce further synergies with biodiversity conservation and the development of circular bioeconomy as

well. Overall, management should promote an increase in heterogeneity and adaptability of simplified and often maladapted forest systems, such as extensive conifer afforestation, in the face of changing conditions [17].

Research shows, e.g., that thinning is potentially beneficial in terms of reducing the risk of fire hazard [135, 136] or increasing the ground water supply [137, 138], but may as well lead to a certain loss of forest microclimate. Defining the optimal density for these combined benefits depends on the site, composition, and structure of each specific situation [123•, 139].

Research must therefore focus on more in-depth knowledge of the ecohydrology of Mediterranean forests and their response to drought to ensure the best application of these management practices [140].

From a general point of view, the growing interest for provision of multiple ES from Mediterranean forests can be considered as a further evolution of the concept of multifunctionality, which has been a concern of forest management for much longer time before the emergence of the ES concept. In the conventional forest management approach, multifunctionality was based, explicitly or implicitly, on the “wake theory”, which states that if forests are efficiently managed for wood production, then all the other forest utilities will follow [141, 142]. In recent times, this approach, based on a reductionist and deterministic paradigm [12], by ignoring dynamics and reactions from other interacting systems, has caused and is still causing conflicts (e.g., between wood production, landscape and nature conservation, recreation and related stakeholders, etc.) [12]. Furthermore, societal preferences and values can change very quickly, significantly altering the social environment for forest management [143, 144].

A shift in the management paradigm is therefore necessary. Mediterranean forests show many of the characteristics of complex adaptive systems [17] and are the result of co-evolutionary processes between cultivation and adaptation at various scales [18, 145]. This makes them perfect examples of complex socio-ecological systems [146] where management must strive to maintain overall resilience not only from an ecological point of view but also taking into account the interacting social systems. In this context, a flexible approach is needed for capturing the information and insights necessary to manage Mediterranean forests not only for their instrumental value, but also for their biocultural [52••] and intrinsic value [12], thus accepting the challenge coming from the development of an ethic of nature which is currently being debated in a historical and evolutionary perspective of forest research [147••]. This also requires abandoning the use of the term “service” when dealing with forest ecosystems, which should not be valued only for the services they provide to humans.

On the operational level, it is still unclear how fast the transition from provisioning to multifunctionality is affecting silvicultural and forest regulation methods applied in everyday practice. Although this question was outside the scope of our review, we believe that further studies are needed to identify progress and trends in silvicultural methods and management approaches actually used in multifunctional forest management in the Mediterranean area, and on ways to introduce some level of management in new Mediterranean forests resulting from land abandonment. It can be expected that Mediterranean forest management will become more often part of overall landscape planning, where the conservation, restoration, or creation of mixed agro-silvo-pastoral landscape mosaics serve multiple goals of resource provisioning, biodiversity conservation, heritage and ecotourism, and crucially, fire resilience [60••], in a context of global change. Therefore, it is necessary to develop flexible management strategies to promote adaptation to future changes [148] and the role of forests in providing important services that can help people adapt to climate variability and change [149].

Finally, research progress in managing Mediterranean forests will also depend on the research potential of the countries facing the Mediterranean, and on the possibility of overcoming the unequal distribution of resources and infrastructures which characterizes them [150]; specifically, forest management research in the Mediterranean area should build on long-term research partnerships and networking involving the use of participatory research and research capacity building [151].

Conclusions

Our review highlights that there are still many gaps in the scientific literature regarding the interactions between ES and drivers of change in Mediterranean forests, providing opportunities for further research on synergies and/or trade-offs between ES in relation to management.

From a conceptual point of view, research on multifunctionality of Mediterranean forests is still mostly conceived following an ES-oriented approach, which is based on a deterministic view and leads to managing forests so as to create the structure and composition that best meet the desired output in terms of benefits for humans. The risk of this approach is that it intrinsically reduces the ability of forest ecosystems to adapt to future, often unexpected changes, while at the same time missing the connection with the complexity and unpredictability of the socio-economic environment.

There is therefore the need for a shift to a new paradigm which considers Mediterranean forests as complex adaptive systems and recognizes also their intrinsic value,

overcoming the ecosystem service approach. This implies an adaptable, flexible management and planning approach that sustains self-organization, adaptive capacity, and overall resilience of Mediterranean forests.

This means promoting functionally diverse forests and landscapes, which can act as insurance for the maintenance of key ecosystem functions such as, e.g., water conservation and regulation, carbon storage, resilience against disturbances (fire, drought), and ecosystem productivity.

Traditional Mediterranean forest landscapes, which are the product of a very long co-evolution of society and nature, should be maintained not only for their cultural and historical importance, but also because they can contribute to keeping more options open for adaptation to future climate and other global changes. Human presence and involvement in Mediterranean forest landscapes is a safeguard against the negative consequences of rural abandonment: both research and policymakers should contribute to finding sustainable solutions for maintaining economically and environmentally viable livelihoods in these precious environments.

Finally, research on managing Mediterranean forests for multiple functions and benefits for the present and the future requires moving toward a transdisciplinary approach, where problems are approached from a diversity of points of view and where extended peer communities are involved not only in dissemination of research results, but also in the research process itself.

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Declarations

Conflict of Interest Susanna Nocentini, Davide Travaglini, and Bart Muys declare that they have no conflict of interest.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

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permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

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- Of major importance

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