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ORIGINAL ARTICLE

Mediterranean forests, land use and climate change: a social-ecological perspective

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Abstract Mediterranean forests are found in the Mediterranean basin, California, the South African Cape Province, South and southwestern Australia and parts of Central Chile. They represent 1.8 % of the world forest areas of which the vast majority is found in the Mediterranean basin, where historical and paleogeographic episodes, long-term human influence and geographical and climatic contrasts have created ecosystemic diversity and heterogeneity. Even if evergreen is dominant, deciduous trees are also represented, with different forest types including dense stands with a closed canopy (forests sensu stricto) and pre-forestal or pre-steppic structures with lower trees density and height. The Mediterranean basin is also a hot spot of forest species and genetic diversity, with 290 woody species versus only 135 for non-Mediterranean Europe. However, the characteristics of the Mediterranean area (long-standing anthropogenic pressure, significant current human activity and broad biodiversity) make it one of the

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world's regions most threatened by current changes. Four examples of Mediterranean forest types, present in south and north of the Mediterranean basin and more or less threatened, are developed in order to show that linking "hard sciences" and humanities and social sciences is necessary to understand these complex ecosystems. We show also that these forests, in spite of specific climatic constraints, can also be healthy and productive and play a major ecological and social role. Furthermore, even if the current human activity and global change constitute a risk for these exceptional ecosystems, Mediterranean forests represent a great asset and opportunities for the future of the Mediterranean basin.

Keywords Mediterranean basin · Forest · *Quercus* · *Pinus* · *Juniperus* · Biodiversity · Functioning · Sustainability · Socio-ecological systems

Mediterranean forests, unique ecosystems?

The founding paradigm of a specific "Mediterranean forest" appeared in forest science at the turn of the nineteenth and twentieth century with two main objectives:

- The scientific recognition of Mediterranean environmental specificity (soils, climate, vegetation) in northern-oriented forest science;
- The legitimation of state intervention and mobilization of scientific knowledge for a "better" management of forest lands, commonly considered as heavily "degraded" by "anarchic and irrational" local agro-sylvo-pastoral practices (Auclair and Michon 2009).

The expansion of this founding paradigm (and of related forest laws and management models) was ensured in Europe by the establishment of "Silva Mediterranea" association in 1920, which allowed professionals from northern Mediterranean to promote their own models and references on the southern shore (Algeria, Tunisia, Morocco) by the French colonization and the transfer of European forest regimes on Maghreb woodlands.

How can we then define a Mediterranean forest? The easiest way is to consider it as a forest that grows under Mediterranean climate, marked by a strong deficit of rainfall during the warm season, causing stress for the vegetation submitted to a dry summer period (Gauquelin 2011). We will restrict here to the forests of the Mediterranean basin which cover more than 48.2 million ha of which 35 million are in South Europe, 8.8 in Middle East and 4.4 in North Africa (adapted from Quézel and Médail 2003; Fady and Médail 2004).

It is however interesting to note that the European Environment Agency (EEA 2006) does not consider an entity "Mediterranean forest" in his classification of European forests. Mediterranean forests can be found in three categories: thermophilous deciduous forests, broad-leaved evergreen forests and coniferous forests.

Climate and soils

The seasonality in air temperature and precipitation, which is the most distinctive feature of the Mediterranean-type climates, has important implications on vegetation functioning, as it limits the active growing season to the humid period between fall and spring (Blondel and Aronson 1999). The length of this period ranges from 5 to 10 months according to distinct climatic subtypes.

In the Mediterranean basin, different parent rocks have given rise to very distinct soils and fertility levels, with siliceous rocks (part of Iberian Peninsula, Corsica, part of Provence), leading to strongly leached nutrient-poor soils in contrast to calcareous rocks leading to moderately leached and shallow high pH soils (Joffre and Rambal 2002; Joffre et al. 2008).

We can also notice the:

- Importance of erosion linked to the general sparse cover of soil by Mediterranean canopies and the high impact of human activity on soils and land use,
- Low rate of organic matter in soils, mainly in arid environments,
- Importance of rubification (or reddening) leading to the red colour of some Mediterranean soils,
- Discontinuous functioning, mainly concerning litter decomposition and the organisms (e.g. fauna and microorganisms) involved in this key process, due to drought season.

Structure and biological types

As reported by EEA (2006), evergreen and sclerophyllous plants are mostly represented but not exclusively as deciduous forests are particularly present in humid and per-humid bioclimates, showing the complexity of forests in the Mediterranean basin (Quézel and Médail 2003).

In the Mediterranean region, the term "forest" not always referring to high, dense stands of trees with a closed canopy, three main forest types are distinguished (Quézel and Médail 2003) according to tree density and height but also presence of specific flora or soil type:

- Forests sensu stricto, with a specific sylvatic flora, growing on deep soils, mainly in areas less impacted by Human action and under the most favourable (sub-humid, humid or more rarely semi-arid) bioclimates.

These are cedar forests, deciduous or evergreen oak forests and sometimes *Tetraclinis* forests.
- Pre-forestal structures, with lower trees density and height, found either in highly degraded areas, or in areas with less favourable climate (semi-arid or arid bioclimates), sometimes called matorrals.
- Pre-steppic structures with very low tree density and perennial steppic species in the understory. The climate is too cold or too dry to allow the development of a dense forest. High mountains forests like *Juniperus thurifera* stands (Gauquelin et al. 1999) or arid or pre-saharian stands with *Vachellia tortilis* subsp. *raddiana* belong to this group. If we adopt FAO's definition (a forest should have more than 10 % tree cover and trees higher than 7 m), FAO 2010 many of these pre-steppic formations can be considered as forests.

Biodiversity

Regarding biodiversity, the Mediterranean basin (sensu lato: 2 % of the Earth's surface) is one of 34 identified biodiversity hot spots based on the multitude of plant and animal species and the presence of a large number of endemic species (Médail and Quézel 1997; Benabid 2000). For instance, the region includes 25,000 flowering plants and ferns species (20 % of the world) which 50 % are endemics, with, among others, *Tetraclinis articulata*, *Argania spinosa*, *Juniperus thurifera, Quercus suber* or fir species as *Abies pinsapo, Abies marocana*, *Abies nebrodensis,* specific to each mountain of the Mediterranean (Blondel et al. 2010).

The high plant diversity in the Mediterranean basin is primarily a result of a noteworthy diversity of habitats. For instance, in the Habitat Directive 92/43 of the European community, 117 out of the 199 habitats of community importance are occurring in this region and 93 of them are exclusively found there.

The present Mediterranean flora is a complex mixture of taxa with very different biogeographic origins (Blondel et al. 2010):

- Afro tropical components, such as *Chamaerops or Argania*,
- Holartic components, such as *Corylus*,
- Irano Turanian components such as *Pistacia*,
- Saharo Arabian components such as *Peganum*,
- Indigenous and endemics.

Concerning woody trees, the Mediterranean basin includes 290 woody species versus only 135 for non-Mediterranean Europe. Fady (2005) showed that Mediterranean conifer species show higher diversity than other conifers worldwide. The diversity is structured along a longitudinal gradient where eastern populations show higher diversity than western populations, possibly as a result of increasing climate severity from east to west during the Last Glacial Maximum, as well as re-colonization routes preferentially originating from eastern refugia (Fady and Conord 2010). This trend is specific of the Mediterranean, whereas latitudinal spatial structures are more often found in Europe (Petit et al. 2003) and is also observed across the tree of life, particularly in insects (Conord et al. 2012). Other noticeable genetic diversity patterns in the Mediterranean concern altitudinal clines, where low-elevation species (particularly trees again) display less diversity than mid- and high-elevation species (Conord et al. 2012). Finally, areas characterized as refugia and containing high levels of genetic originality (private alleles, higher than average differentiation) are often found within regional hot spots of plant diversity and endemism (Médail and Diadema 2009). And concerning birds, 343 breeding species are present over an area three times lower than Europe (Blondel et al. 2010).

Soil mesofauna and microfauna, with numerous species and individuals occupying a wide range of ecological niches, are other interesting representatives of biodiversity (De Nicola et al. 2014). In spite of the great interest of these organisms, this compartment of biodiversity is still poorly understood in the Mediterranean forests.

Functioning

The specificity of Mediterranean forest ecosystems' functioning (phenology, primary and secondary plant metabolism, carbon storage, productivity, water cycle, redistribution of nutrients and microorganisms activity) is linked to the important drought period, with high discontinuity in functioning related to alternating dry and wet periods.

In optimal conditions, the photosynthetic performance of Mediterranean species does not differ particularly from that of species from other biomes. Nevertheless, their leaves have to tolerate high irradiance, and they have to cope with excess intercepted solar radiation when carbon assimilation is limited either by stomatal closure or a decrease of photosynthetic capacity due to water stress and high temperatures or low temperatures (Joffre et al. 2008). In these conditions phanerophytic evergreen and sclerophyllous species dominate, but these features are however not specific to the Mediterranean climate as there are well represented, for example, in mountain or subalpine areas or sea dunes. In any case, evergreen forests and coniferous forests are not exclusive, and deciduous forests, mainly oak forests, are also well represented, particularly in humid and per-humid bioclimates, showing the complexity of Mediterranean forests (Quézel and Médail 2003)

More, Mediterranean plant species produce numerous plant secondary metabolites (PSMs), most of which are terpenoids (volatiles) and phenolics (non-volatiles). PSMs, together with morphological traits (sclerophylly), allow these species to cope with climatic stress (Chaves and Escudero 1999). Their physiological role is still under investigation, but numerous studies suggest their antioxidant role since they protect plants against UV as well as heat and oxidative damage caused by episodes of pollution or drought (Yazaki 2006).

Plant investment in PSMs affects numerous processes in ecosystems functioning and biodiversity. For example, leaf quality has direct effects on litter decomposition. These PSMs mediate also chemical interactions, via allelopathic processes:

- Between plants since chemicals present phytotoxic effects irrespective of their functional group (Bonanomi et al. 2006; Fernandez et al. 2013a, b),
- Between plants and microorganisms because PSMs inhibit soil microorganisms involved in nitrogen cycling and forest regeneration (Pellissier et al. 2002; Jonsson et al. 2006; Chomel et al. 2014).

PSMs are major determinants of community structure and ecosystem processes. For example, *Pinus halepensis* is rich in secondary metabolites (Pasqua et al. 2002; Macchioni et al. 2003; Fernandez et al. 2009) particularly terpenoids but also phenolics that are thought to play a role in plant–plant and plant–microorganisms interactions through allelopathic processes (Fernandez et al. 2006, 2008, 2009, 2013a, b; Chomel et al. 2014). *P. halepensis* allelochemicals might drive plant biodiversity in Mediterranean, but their role in the variability of biodiversity has received little attention so far, particularly in stressful environments. Working on variations on *P. halepensis* PSMs (as functional leaf traits) along a stress gradient (drought) could enable us to understand biodiversity and biotic interactions in Mediterranean ecosystems but also the success of restoration operations.

Litter decomposition and water stress

Decomposition of organic matter, a key process for forest functioning, is controlled by biotic factors (e.g. decomposers: bacteria, fungi, invertebrates), the biochemical composition of the plant litter (i.e. plant diversity; Santonja et al. 2015a) and the environmental conditions, particularly soil water content under Mediterranean climate. In summer, high temperature and low moisture, leading to persistent drought, can drastically limit microbial growth and activity (Criquet et al. 2004; Fioretto et al. 2005), whereas the milder and wetter spring and autumn seasons induce higher metabolic rates of microbes temporarily enhancing the litter decomposition rates (Coûteaux et al. 1995). These markedly dry summer periods lead to a discontinuous decomposition process closely linked to water availability (Chomel et al. 2014).

Mycorrhiza and water stress

As stated earlier, Mediterranean forest ecosystems have a marked floristic diversity with an endemism level reaching 50 %. In this context, the question of the Mediterranean basin fungal diversity seems particularly relevant. Among fungi, diversity of mycorrhizal fungi present in these ecosystems is crucial as these symbiotic fungi are known as belowground linkers between plants, through hyphal networks, facilitating the access of their host plants to soil nutrients (Barto et al. 2012). Additionally, mycorrhizal fungi considerably enhance their access to soil water compartment. Two main types of mycorrhizal fungi (ectomycorrhizal fungi or ECM, for woody plants and arbuscular mycorrhizal ones or AM, for most plant species) are represented. The recent emergence of new generation sequencing approaches permits to have a snapshot of soil fungal diversity in multiple and contrasted ecosystems all around the globe, including Mediterranean ones. This was the aim of a recent study by Tedersoo et al. (2014). These authors showed that all ecosystems host the main phylogenetic and functional groups of fungi, Agaricomycetes (non-mycorrhizal fungi) being the dominant one in all situations. Regarding Mediterranean biomes, their closer biomes in terms of ECM fungal diversities were grasslands and shrublands and, to a less extent, tropical montane forests and tropical moist ones. One of their observations was that relative ECM host plant density had a strong influence on ECM fungal richness, the highest ECM richness coinciding with geographical distribution and dominance of *Pinaceae*, in the northern temperate biomes. Regarding Glomeromycota (AM fungi), they have the lowest average geographical range, probably due to their relatively big spores, not easily dispersed by the air.

As regards to global change, it is generally considered that ectomycorrhizal and AM communities respond similarly to CO_2 enrichment (Johnson et al. 2013). In both type of symbioses, CO_2 enrichment has been shown to accelerate decomposition of soil organic matter, a phenomenon generally known as priming effect (Phillips et al. 2012).

Spatial heterogeneity in Mediterranean forests

We can evenly notice the influence of often wide spaced trees on biogeochemical cycles, soil characteristics and biodiversity (Joffre and Rambal 1988; Gauquelin et al. 1992), leading to the very marked spatial heterogeneity, mainly in pre-forestal and pre-steppic stands. In peculiar man-made ecosystems characterized by a savannah-like physiognomy as dehesas and montados of the Iberian Peninsula, scattered trees imposed a marked spatial heterogeneity of ecosystem functioning. At the local scale, strong soil structural differences and functional differences in water budget and patterns of water use are observed under and outside the tree canopy. Using the concept of ecosystem mimicry, the two coexistent components of these agroforestry systems can be compared to two distant stages of a secondary succession, characterized by very different behaviours. At regional scale, evidence of relationships between tree density and mean annual precipitation suggests that the structure of these man-made agro-ecosystems dominated by evergreen oaks has adjusted over the long term and corresponds to an optimal functional equilibrium based on the hydrological equilibrium hypothesis (Joffre and Rambal 1993; Joffre et al. 1999).

Dynamics

Ecosystem dynamics are quite different on the southern and northern shores of the Mediterranean basin (Gauquelin 2011). The northern shore is characterized by coastal urbanization and an abandonment of agricultural and pastoral lands, leading to a spectacular forest re-colonization; for example, in the French Mediterranean area, forest (more than 1.4 million ha) increased between 0.5 and 2 % by year between 1980 and 2011 (IF 2013; FAO 2013) which corresponds approximately to 16,000 ha by year. On the southern shore, degradation is still intense and leads to fragmentation or disappearance of habitats including forest, with for example, an annually decrease rate of 0.5 % of the Algerian forest area from 1990 to 2010 (FAO 2013).

But the situation can be contrasted. In Lebanon, as a result of unsustainable forest practices and neglect of forested lands and as a result of the decline of controlled grazing in forest understory, oak and pine forests have become highly susceptible to fire events. *Juniperus* forests, a major element of the mountainous conifer forests in the eastern Mediterranean basin (Barbero et al. 1994), are negatively affected by the land exploitation. Continuous losses of the oldest individuals and a lack of regeneration could lead to a severe, genetically deleterious effect of fragmentation on local population diversity (Douaihy et al. 2011).

In contrast, cedar forests have received national, regional and international attention due to their historic, symbolic and biological value (Sattout et al. 2005), even if they just constitute 1.58 % of the total forest cover (MOA/FAO 2005). Massive reforestation programmes are taking place in Lebanon today, taking advantage of the population genetic studies conducted on these emblematic species (Bou Dagher-Kharrat et al. 2007).

Mediterranean forests: a long history of agro-sylvo-pastoral management by rural populations as well as of interactions between local societies and the state

Most of the forests in the Mediterranean region are the result of a long history of agro-sylvo-pastoral management by rural populations as well as of interactions between local societies and the state (mainly through the public forest administration) (Blondel 2006; Aubert 2013). In spite of this strong influence of local management practices and socio-political relationship on the *production* of Mediterranean forests, most scientific studies insist on the *negative impact* that local societies have had on "natural forests" and on their biodiversity (deforestation, forest degradation and desertification). Contrasting with these studies, Michon et al. (2007) have proposed to analyse the *coevolution* between forest ecosystems and their related human populations in terms of *domestication* (of trees, ecosystems and landscapes) and to consider the resulting forests (*domestic forests* or *rural forests*; Genin et al. 2013) as biocultural or socio-ecological products for the agro-forestry systems such as the ones of the Iberian Peninsula (Joffre et al. 1987, 1999).

Mediterranean forests have been in the past and still are in certain region, intensively used for sustaining rural livelihoods. They provide a diversity of resources such as human food, medicines, ritual material, firewood, material wood and forage for livestock. These forests are characterized by different levels of formal and non-formal appropriation by rural communities and shaped by specific, refined knowledge and practices. They are also characterized by particular structures and functioning.

Four major characteristics emerged from analyses in different contexts and form the identity of these domestic or rural forests (Genin et al. 2013):

- Specific forest structures and levels of integration in agricultural matrices linked historically to overall agro-ecosystem structures and social practices (Genin and Simenel 2011),
- A multiscale approach to domestication from individual trees up to landscape level, involving a continuity between "nature" (natural processes) and "culture" (human techniques of control and transformation), (Wiersum 1997; Michon 2015),
- Multiple uses of plants which vary in relation to the commercial or non-commercial status of their products and a reversible nature of these use patterns accordingly (Bahuguna 2000),
- Imbrications of different levels of access and control rules (between state and customary levels, between individual and collective levels), requiring specific

formal and informal arrangements (Sandberg 2007). Rural forests are therefore social-ecological systems that contribute to ecosystem and landscapes configuration, definition of rural territories and sustainability of local livelihoods.

The counterproductive impact of public policies and forest science must be also pointed out (Michon et al. 2013). Most forestlands (and more particularly in the South) are state property and subject to forest laws. In the early twentieth century in northern Mediterranean, and until recently in the southern shore, issues related to the management of these state forests were specified in general terms, relying on representations developed in France in the late nineteenth century that have always considered rural forests as "degraded forests" instead of specific systems of integrated rural forest management. For example, professional foresters seeing stands of highly pollarded trees frequently conclude to a generalized degradation of forests due to human action, totally overlooking a specific management strategy aimed at enhancing forage production for livestock or pole production for roof construction. In order to "regenerate" these "degraded" forests, professional foresters largely rely on two strategies: 1/clear cuts and enclosures of "regenerating" stands in which all human activity is banished and 2/reforestation schemes with exotic tree species. Forests derived from such practices (stands of coppiced trees or exotic forests) are of poor interest for local people, who therefore often do not respect enclosures.

Recently, processes related to patrimonial construction at various scales in Mediterranean forests have emerged (such as the gazetting of the Moroccan argan forest as a biosphere reserve, or of the cedar forest as national parks). These processes must be questioned: the ongoing patrimonial qualification of forests at national and international levels for biological conservation or as elements of the world biocultural heritage could slowly erasing local (rural) forest patrimonies and therefore endangering the reproduction of these forests (Michon et al. 2012).

Mediterranean forests and climate change

Climate models have predicted increases in both temperature and drought conditions in the Mediterranean (Giorgi and Lionello 2008; Somot et al. 2008). These changes are expected to result in increased frequency, intensity and duration of drought, especially during the warm season (Sheffield and Wood 2008; Polade et al. 2014). The response of Mediterranean forests to such extreme climatic events is poorly understood, because controlled field experiments to mimic such conditions are costly and difficult to operate on a large scale without introducing environmental modifications. Different *in natura* platforms have been implemented in different forest types in France, with rain exclusion devices allowing to apply a precipitation scenario close to what models predict for the end of the twenty-first century. Holm oak at Puechabon (Limousin et al. 2008, 2009, 2012), Aleppo pine at Font Blanche (Gea-Izquierdo et al. 2015) and downy oak at O_3HP (Santonja et al. 2015b) are concerned. Results show that changing rainfall pattern will affect (1) directly litter production and decomposition, and (2) volatile organic compounds emissions (Staudt et al. 2002, 2003; Genard et al. 2015). The idea is to develop around the Mediterranean basin a network of experimental stations with simpler and less expensive devices to monitor the effects of climate change in other important forest ecosystems and so under other bioclimates.

Concerning changes in forest vegetation over the last few decades, recent studies in northwestern Africa reported recurrent drought events from the second half of the twentieth century (Touchan et al. 2010; Linares et al. 2011; Kherchouche et al. 2012, 2013; Slimani 2014). Touchan et al. (2008) showed that the 1999–2002 severe drought appears to be the worst in northwestern Africa since the middle of the fifteenth century. This suggests climate conditions more limiting to tree growth and drought-sensitive species geographical distribution, especially for those at the edge of their range. This event triggered substantial mortality in *Cedrus atlantica* forests where, in some areas, stands disappeared completely (Zine El Abidine 2003; Linares et al. 2011; Kherchouche et al. 2012, 2013; Slimani et al. 2014), and even in other tree species reputed for their drought hardiness, including *Pinus halepensis*, *Quercus ilex*, *Quercus suber and Juniperus thurifera* (Allen et al. 2010).

Four contrasting examples of relationships between functioning, structure and global change in Mediterranean forests

Four examples illustrate relationships between human impacts, structure, dynamics and functioning of Mediterranean forests: *Quercus pubescens* (downy oak) forest, *Quercus suber* (cork oak) forest, *Pinus halepensis* (Aleppo pine) forest or *Juniperus thurifera* (thuriferous juniper) forest. They have a very different distribution (see maps in Quézel and Médail 2003), and they are, respectively, representative of the three tree functional types of the Mediterranean region: deciduous species malacophylles (specifically marcescent for downy oak) and evergreen sclerophyllous leaved and coniferous species (for cork oak, Aleppo pine and thuriferous juniper) (Table 1). They also have contrasting strategies to cope with drought and also

Table 1 Comparative data on biological type, bioclimatic stage, distribution area and dynamics, main uses, ecosystems services, human pressure and threats for the four studied species Sources of data: Pons and Quézel (1998), Quézel and Médail (2003), Fernandez et al. (2013a, b), Gauquelin et al. (1999)

Species	Biological type	Bioclimatic stage	Distribution area dynamics	Main uses	Ecosystems services	Human pressure/ Threats
Quercus pubescens Downy Oak	Deciduous, marcescent	Submediterraaneaan and mediterranean (mesomediterranean and supramediterranean)	Widely distributed >2 million ha extension	Wood for fuel and charcoal	Regulation provisioning habitat cultural	Low/Climate change
Quercus suber Cork Oak	Evergreen	Western part of the Mediterranean (thermomediterranean and mesomediterranean) and atlantic	Widely distributed 1.7–2.7 million ha regression	Cork, acorns, grazing, food for livestock, Wood for lumber and fuel	Regulation provisioning habitat cultural	High in north and south/ Deforestation climate change
Pinus halepensis Aleppo pine	Evergreen	Strictly mediterranean (thermomediterranean and mesomediterranean)	Widely distributed 3.5 million ha extension	Wood for paper pulp and fuel	Regulation provisioning habitat cultural	Low/Pioneer species spreading on abandoned lands
Juniperus thurifera Thuriferous Juniper	Evergreen	Western part of the Mediterranean (supramediterranean, mountain and oromediterranean)	Restricted area ±200,000 ha regression in south stability in north	Wood for lumber and fuel food for livestock, extraction of oil	Regulation provisioning habitat cultural	High/ Overharvesting climate change

very different dynamics according to past and current human impact, corresponding to different geographical trajectories (Table 1):

- France where abandonment of forest uses is the main feature and human pressure is very low (Southern Alps for juniper, Eastern Pyrenees for cork oak),
- Spain where relictual uses and managements are still observed and human pressure is moderate to average (Northern Spain for thuriferous juniper, Andalusian dehesa for cork oak),
- Morocco, Algeria or Lebanon where forests are an important component for maintaining rural livelihoods and where human pressure is high, but with different modalities of governance in forest management; Agdal management system, a collectively-built management including seasonal rests and highly refined rules concerning multifunctional product extraction, for example (Auclair and Alifriqui 2012) (High Atlas for thuriferous juniper, and Mamora forest for cork oak).

These comparative analyses are possible thanks to a long expertise of scientists who have been involved for many years in in-depth studies of local situations, with contrasted temporalities and organization in term of forest uses.

Forests of downy oak (*Quercus pubescens*): Which future for deciduous or marcescent oaks in the Mediterranean basin?

Quercus pubescens Willd. (downy oak) is a deciduous native oak widespread in southern Europe and southwest Asia, from northern Spain (Pyrenees) east to the Crimea and the Caucasus. It is also found in France (more than 1,000,000 ha) and parts of central Europe (Ganatsas and Tsakaldimi 2013). Moreover, the downy oak, often occurring in the transition of several climatic influences, seems to be especially responsive to climate change. The dramatic reduction of territories where marcescent oaks like downy oaks dominate, expected in the context of climate change in the near future in Spain (Sanchez de Dios et al. 2009), underlines the need of studies concerning this species, providing typical landscapes in the south of France. Forests generally result from coppicing practiced for centuries for charcoal production and are also used as rangeland for livestock. This species does not exist in North Africa but is replaced by other related deciduous oak species.

The past, present and future place of deciduous oaks in the Mediterranean area (Pons and Quézel 1998) is questioned, and the studies about impact of climate change on the functioning of these ecosystems must be developed.

Forest of cork oak (*Quercus suber*): Which future for cork oak forests in relation to their economic value?

The cork oak forests, which cover between 1.7 and 2.7 million ha in western Mediterranean, distributed unevenly among Portugal, Spain, France, Italy, Morocco, Tunisia and Algeria, have been exploited by humans for the past 3000 years, with an exploitation system combining ranching, agriculture and forestry. Cork oak ecosystems span from open savannas to closed forests. Bark is periodically harvested and represents the second most important marketable non-timber forest product in western Mediterranean. The cork oak ecosystems are also recognized for their remarkable ecological value, providing habitat for several threatened species and being protected by international legislation. But cork oak forests are threatened by wildfires, aging tree populations, abandonment in southwestern Europe and overuse in northwestern Africa where low regeneration rates are observed. Another threat is the recent decline of cork prices, due to the growing utilization of cork stopper substitutes. Cork oaks forests appear to be a good model to investigate about "Payment for Ecosystem Services" and economic incentives that promote ecological and economic viability of cork oak forests. It is also a good model to illustrate differences between Southern and Northern woodlands concerning threats and dynamics.

Forest of Aleppo pine (*Pinus halepensis*): Which future in the frame of global change?

The Aleppo pine is the most widespread pine in the Mediterranean basin (more than 3.5 million ha), mostly in the western Mediterranean. Since the early nineteenth century, the northern margins of the Mediterranean basin have undergone strong rural depopulation (Barbero et al. 1990; Debussche and Lepart 1992). Abandoned agricultural lands are soon to be naturally colonized by pioneer plant species through processes of secondary succession, with forest cover increasing fivefold over the last 150 years (Fernandez et al. 2013a). Among these pioneer species, *Pinus halepensis* Miller is considered as an expansionist species (Barbero and Quézel 1990) that presently dominates forests in this area (Acherar et al. 1984; Debussche and Lepart 1992; Maestre and Cortina 2004), thereby threatening the existing mosaic of forests, shrublands and pastures of high patrimonial value (Quézel and Médail 2003). The different stages of successional dynamics in these Mediterranean forest ecosystems dominated by *Pinus halepensis* are well described (Lepart and Escarré 1983; Quézel and Médail 2003), but the functional mechanisms determining these successional dynamics remain poorly understood. In the southern margins, where the main populations exist, dynamic and biodiversity of Aleppo pine forests are less known and should be compared to the northern populations.

Forest of thuriferous juniper (*Juniperus thurifera*): Which dynamic north and south of the Mediterranean basin?

Thuriferous juniper is only found in isolated parts of western Mediterranean: France (Alps, Pyrenees and Corsican highlands), Spain, Algeria and Morocco with a total area more than 200,000 ha (Gauquelin et al. 2012; Gauquelin and Dutoit 2013). These semi-arid mountain stands, where *thuriferous juniper* trees grow in low-density open woodland, are seriously endangered;

- In the Atlas mountains, *thuriferous juniper* stands are heavily degraded as a result of intensive wood collection and livestock grazing (Gauquelin et al. 1999). This situation is in most parts and could become irreversible by producing an impoverishment of soils and by leading to hillside instability. However, some still operating traditional practices concerning thuriferous juniper forests can mitigate this degradation and promote some equilibrium between forest functioning and local population livelihoods (Hammi et al. 2010; Genin et al. 2012). In Spain, although livestock ranching and cultivation have strongly reduced areas occupied by *Juniperus thurifera*, stands are still numerous and, in some regions, show a good regeneration due to conservation measures;
- In France, the decline in human and livestock activities over recent decades has led to a re-colonization of some of the juniper stands by pines or oaks.

A forest management system that enables these original stands to survive and regenerate must be urgently undertaken. The dynamics of evolution of these stands is quite different north and south of the Mediterranean. In both cases, conservation measures (including positive protection measures designed locally by agro-sylvo-pastoral societies) are urgently required to protect or rehabilitate the original stands with floristic, ecological and socio-economic interest. The idea is to better connect these different models, and that are studied independently south and north of the Mediterranean and to strengthen partnerships concerning Mediterranean forests researches. The comparison with the stands of *Juniperus excelsa*, a close species of thuriferous juniper developing in Lebanon, where human pressure is also strong, is very interesting.

Emphasis will be put, on the one hand, on the relationships between tree forms and architecture, and the functioning of the ecosystem, and, on the other hand, on the regeneration ability of tree stands submitted to diverse human impact degrees and management types. Hence, some traditional knowledge and local initiatives have led to construct other forms of forest management systems which have to be considered with new eyes by scholars. In the High Atlas for example, the agdal system, a collective management enterprise which always includes a period of rest in order to allow trees to recover from aerial exploitation (Hammi et al. 2010; Auclair and Alifriqui 2012), leads to differentially exploit forest patches and creates a diversity of tree ports and forms whose functions participate, both to secure livelihoods by providing differentiated resources (tree foliage, poles, beams) (Genin and Simenel 2011) and to diversified landscape biodiversity. Such resource use systems, far from being exclusively depredators for vegetation cover, could give interesting insights for renewing visions for socially and ecologically sound forest management approaches.

Examples found in these four forest models (e.g. dehesas, agdals, downy oak regeneration practices) give evidence that locally adapted forest management have long been developed by local societies in order to keep the capacity of forests to regenerate while providing goods and services on the long term. However, most of these practices are vanishing due to deep socio-economical, political and livelihood transformations. This erosion of knowledge is as alarming as the loss of biodiversity in Mediterranean forest, since it can be holder of innovative proposals for renewing our visions of what can make “a good forest management for the future”.

Conservation and sustainability use of Mediterranean forests

Significant efforts are needed to globally understand, conserve and sustainably use these remarkable ecosystems.

Forest landscape restoration renews the provision of goods and services to landscapes. The ecological context determines whether it is feasible to attempt to restore the original forest ecosystem or to just reforest the land again.

In many countries, considerable research efforts are made to foster more reliable and precise reforestation when the natural regeneration is not sufficient or not possible, as the cost of reforestation is rising rapidly. Not only are labour, machines and tree seed and seedling costs going up steeply, but also difficulty in having access to credit has also increased. The ultimate target is to accomplish reforestation based on detailed physiological, ecological and meteorological knowledge, inexpensively, quickly and reliably and to ensure that trees grow rapidly after plantation.

One example concerns the resort to exotic trees, often been recommended in the past as a management option to enhance the productivity and biodiversity of Mediterranean disturbed ecosystems. Tree species such as *Pinus* spp., *Eucalyptus* spp. and *Acacia* spp. have been largely exported outside their natural range over the eighteenth and nineteenth centuries. Although these species are recommended to restore degraded ecosystems, it is now well established that they could threaten the structure and composition of plant cover and the vegetation dynamics (succession and dominance) and interact with the soil microbial community and modify mutualistic interactions within the native vegetation. Alteration of mycorrhizal community is of particular importance because it is considered as a key component of the sustainable soil–plant system (Hafidi et al. 2015). Performance of introduced species will be examined in relation to modifications of environmental factors (light availability, soil moisture and microclimatic conditions). Interactions between introduced seedlings, understorey and overstorey must be particularly studied to detect in which conditions competition or facilitation occurs according to vegetation, species and site conditions (Duponnois et al. 2011).

Mediterranean forest ecosystems will have also to face significant disruptions of their functioning due to extreme climatic events, such as longer and more severe drought periods, increasing forest fire frequency and intensity and pest outbreaks (Moriondo et al. 2006; Lindner et al. 2010). These disturbances will put at risk a number of important ecosystems services (Schroter et al. 2005). In this context, new methods increasing the resistance and resilience of Mediterranean forests have to be developed, including those that harness the full potential of Mediterranean forest genetic resources (Lefèvre et al. 2014). For example, *Pinus halepensis* is particularly sensitive to current and future risks as this species is extremely flammable and can favour the spread of large forest fires (Pausas et al. 2008). This species can regenerate after a fire, thanks to a canopy-stored seed bank (Fernandes et al. 2011). But this strategy does not operate when fire intervals are shorter than the maturity age (Daskalakou and Thanos, 1996; Ne’eman et al. 2004). In addition, Aleppo pine forms mostly monospecific stands that are highly sensitive to insect attacks (Maestre and Cortina 2004). Mixed stands, e.g. combining pine and hardwood species, are expected to be less sensitive to pest outbreaks and herbivory (Jactel et al. 2006; Jactel and Brockerhoff 2007), to host a higher biodiversity and to be more resilient to disturbances and changing environmental conditions for a number of ecosystem processes (Yachi and Loreau 1999). Favouring mixed pine-hardwood species stands is therefore a strategy increasingly put forward in order to enhance forest resilience (Pausas et al. 2004).

The impact of different vegetation conditions (including different canopy covers, presence or not of shrubby vegetation) on the response of introduced hardwood of various species differing in various ecological traits (ability to withstand shade and water stress in particular) must be tested in different contrasted Mediterranean regions. To ensure generalization of the results obtained from different sites, modelling of the interactions between the different strata (regeneration/understorey/overstorey) in relation to the use of the main resources (water, light) must be proposed.

Conclusion: conciliating particular ecological functioning, biocultural heritage and threats

A linkage between different elements allows proposing an integrative and original outlook of Mediterranean forests:

- Linking fundamental and applied research: all scientific results should allow implementing a successful strategy for the preservation and development of Mediterranean forests. Knowledge of the different biodiversity levels could help preserve Mediterranean forests. At the species level, the genetic diversity studies and the adaptive potential of the species could help understand its reactions to environment change. At the community level, understanding interactions between different species could have drastic changes on reforestation practices. For instance, identifying the mycorrhizal community of some trees used in reforestation programmes and the nurse effect of some shrub species on these trees could bring high hope for large scale reforestation programmes, reducing watering cost and rising success rate of these plantations. On the other hand, climate modelling applied to species distribution and genetic exploration of marginal populations can also help predict species range shifts and lighten conservation actions.
- Linking "hard sciences" and humanities and social sciences: in the Mediterranean forests, the understanding of these ecosystems and their future must first integrate 1) the secular human–forest interactions which have shaped functional cultural landscapes and 2) the ecosystem services provided by these forests for securing both overall diverse ecosystems and livelihoods.
- Linking academic knowledge and traditional knowledge: we have seen that some localized practices, such as the Agdal system for example, give attention to both forest protection and exploitation for local livelihood improvement. There is therefore an urgent need to better survey and understand the ways local population perceive and manage their forest resources, in order to facilitate hybridization of knowledge for integrated proposals that make sense to both parts and could effectively be applied and respected.
- Linking forestry, agricultural and social approaches and objectives: forests and human populations living in and from these forests have to be protected in a global, comprehensive approach taking into account biological and cultural diversity, which requires truly participative methods (i.e. not forcing local population to participate in projects designed by foresters or biologists who aim at preserving forests per se, but developing negotiation processes in which all stakeholders have to be heard).
- Linking north and south of the Mediterranean: forest structure, dynamics and threats are very different on the two shores of the Mediterranean, and confrontation between these different situations is essential to understand the global evolution of Mediterranean forests. For example, are Aleppo pine, cork oak or thuriferous juniper forests the same south or north according to their structure, functioning, utilization, biodiversity or vulnerability? Which relationships between Aleppo pine and the two oaks in the north? Which place for deciduous oaks (close to *Q. pubescens*) in the Maghreb?
- Linking biodiversity, evolution, dynamics and functioning in these forests in order to put in evidence the need to preserve this biodiversity.
- Linking "nature" and productive systems: this aspect, and particularly in the Mediterranean basin, shows a continuum between "wild" and highly anthropized ecosystems, which has to be better understood in order to detect forms of uses enable to guarantee both sustainability of these sensitive forest ecosystems and local livelihoods.

Mentioning the necessity of these linkages may appear incantatory as it barely refers to actually occurring dynamics. It is also difficult to report true "success stories" in developing productive "biocultural" approaches, i.e. in combining ecological and cultural approaches for a better understanding and management of Mediterranean forests, as these two approaches are generally badly connected. However, some examples of what should not occur and some ideas of what could be achieved can be derived from researches conducted by various disciplines on the argan forest of Morocco. Biologists consider this forest as a unique forest (with the endemic argan tree and associated forest flora, and ecological services it provides). They also consider this forest as highly threatened by local agro-sylvo-pastoral practices hampering the regeneration of the argan tree and reducing floristic diversity (Michon et al. 2016). Social sciences consider the argan forest as a unique example of socio-ecological system linking biological and cultural diversity for the management and reproduction of both a fragile forest ecosystem in arid conditions and a productive agroforestry system (M'Hirit et al. 1998). Combined ecological and cultural approaches highlight the ambiguity of "degradation narratives" in the argan forest (El Wahidi et al. 2014). In areas where human out-migration is occurring (the Anti-Atlas mountains), dense forest vegetation is quickly developing. But as terraces are abandoned, soil erosion is accelerating (which, in the context or increasing extreme rainfall episodes, can become a problem), and bushy undergrowth vegetation is developing, which increases risks of forest fires. Moreover, the argan socio-ecological system is degrading, with the erosion of local knowledge and practices. The "biological forest" is regenerating; the "cultural forest" is vanishing. Foresters, biologists, local populations and social scientists could join their efforts in order to define what is a desirable "state of conservation" for this rural forest, taking into account flora, fauna, ecological services as well as local knowledge, practices and productions. Practical measures to reach, monitor and maintain this state have to be invented mobilizing scientific as well as local indicators of "degradation", regeneration practices, protection measures (for example combining the protective enclosure methods of foresters and the agdal practices of local populations). This can be done only if local populations are integrated from the very beginning in the definition of conservation management objectives. The same global model can be mentioned for the cork oak forest, a formerly "cultural forest" in the northern part of the Mediterranean basin, "naturalized" since local practices of cork oak management have been abandoned and presently heavily impacted by fires. Conservation of the cork oak forest may go through reactivating the interest of local farmers into global ecosystem management for combined cork, pastoral and agricultural productions. Such management models still exist in Spain and south of the Mediterranean basin that could inspire the rehabilitation of abandoned cork oak forests in the north.

This synthesis should highlight both the risks of Mediterranean forest ecosystems and their potential, as well as the opportunities they represent for sustainable development integrating the "man" and its activities. The idea is to project in 2100 by integrating global change (including climate change, land use change and socio-economic) and make proposals in this direction. Dialogue and meeting between the actors of this project will be the main tool to succeed in this challenge.

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