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

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50

51 ABSTRACT

52

53 Mediterranean forests are found in the Mediterranean Basin, California, the South African Cape Province, South
54 and southwestern Australia, and parts of Central Chile. They represent 1.8% of the world forest areas of which
55 the vast majority is found in the Mediterranean basin, where historical and paleogeographic episodes, long-term
56 human influence and geographical and climatic contrasts have created ecosystemic diversity and heterogeneity.
57 Even if evergreen are dominant, deciduous trees are also represented, with different forest types including dense
58 stands with a closed canopy (forests *sensu stricto*), and pre-forestal or pre-steppic structures with lower trees
59 density and height. The Mediterranean basin is also a hotspot of forest species and genetic diversity, with 290
60 woody species versus only 135 for non-Mediterranean Europe.

61 However, the characteristics of the Mediterranean area (longstanding anthropogenic pressure, significant current
62 human activity and broad biodiversity) make it one of the world's regions most threatened by current changes.
63 Four examples of Mediterranean forest types, present in south and north of the Mediterranean basin and more or
64 less threatened, are developed in order to show that linking "hard sciences" and humanities and social sciences is
65 necessary to understand these complex ecosystems. We show also that these forests, in spite of specific climatic
66 constraints, can also be healthy and productive, and play a major ecological and social role. Furthermore, even if
67 the current human activity and global change constitute a risk for these exceptional ecosystems, Mediterranean
68 forests represent a great asset and opportunities for the future of the Mediterranean basin.

69

70 Keywords: Mediterranean basin, forest, *Quercus*, *Pinus*, *Juniperus*, biodiversity, functioning, sustainability,
71 socio-ecological systems

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74

1. Mediterranean forests, unique ecosystems?

The founding paradigm of a specific “Mediterranean forest” appeared in forest science at the turn of the 19th and 20th century with two main objectives:

1. the scientific recognition of Mediterranean environmental specificity (soils, climate, vegetation) in northern-oriented forest science;
2. 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, broadleaved 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 color of some Mediterranean soils,

114 - discontinuous functioning, mainly concerning litter decomposition and the organisms (e.g. fauna and
115 microorganisms) involved in this key process, due to drought season.

116

117 **Structure and biological types**

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

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

124 - Forests *sensu stricto*, with a specific sylvatic flora, growing on deep soils, mainly in areas less impacted
125 by Human action and under the most favourable (sub-humid, humid, or more rarely semi-arid)
126 bioclimates. These are cedar forests, deciduous or evergreen oak forests, and sometimes *Tetraclinis*
127 forests.

128 - Pre-forestal structures, with lower trees density and height, found either in highly degraded areas, or in
129 areas with less favourable climate (semi-arid or arid bioclimates), sometimes called matorrals.

130 - Pre-steppic structures with very low tree density and perennial steppic species in the understory. The
131 climate is too cold or too dry to allow the development of a dense forest. High mountains forests like
132 *Juniperus thurifera* stands (Gauquelin et al. 1999) or arid or pre-saharian stands with *Vachellia tortilis*
133 subsp. *raddiana*, belong to this group. If we adopt FAO's definition (a forest should have more than
134 10% tree cover and trees higher than 7 m), many of these pre-steppic formations can be considered as
135 forests.

136

137 **Biodiversity**

138 Regarding biodiversity, the Mediterranean basin (*sensu lato*: 2% of the Earth's surface) is one of 34
139 identified biodiversity hot spots based on the multitude of plant and animal species and the presence of a large
140 number of endemic species (Médail and Quézel 1997; Benabid 2000). For instance, the region includes 25.000
141 flowering plants and ferns species (20% of the world) which 50% are endemics, with, among others, *Tetraclinis*
142 *articulata*, *Argania spinosa*, *Juniperus thurifera*, *Quercus suber* or fir species as *Abies pinsapo*, *Abies marocana*,
143 *Abies nebrodensis*, specific to each mountain of the Mediterranean (Blondel et al. 2010).

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

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

149 - Afro tropical components, such *Chamaerops* or *Argania*,

150 - Holartic components, such *Corylus*,

151 - Irano Turanian components such *Pistacia*,

152 - Saharo Arabian components such *Peganum*,

153 - Indigenous and endemics.

154 Concerning woody trees, the Mediterranean basin includes 290 woody species versus only 135 for non-
155 Mediterranean Europe. Fady (2005) showed that Mediterranean conifer species show higher diversity than other
156 conifers worldwide. The diversity is structured along a longitudinal gradient where eastern populations show
157 higher diversity than western populations, possibly as a result of increasing climate severity from east to west
158 during the Last Glacial Maximum, as well as re-colonization routes preferentially originating from eastern
159 refugia (Fady and Conord 2010). This trend is specific of the Mediterranean, whereas latitudinal spatial
160 structures are more often found in Europe (Petit et al. 2003), and is also observed across the tree of life,
161 particularly in insects (Conord et al. 2012). Other noticeable genetic diversity patterns in the Mediterranean
162 concern altitudinal clines, where low elevation species (particularly trees again) display less diversity than mid-
163 and high-elevation species (Conord et al. 2012). Finally, areas characterized as refugia and containing high
164 levels of genetic originality (private alleles, higher than average differentiation) are often found within regional
165 hotspots of plant diversity and endemism (Médail and Diadema 2009). And concerning birds, 343 breeding
166 species are present over an area three times lower than Europe (Blondel et al. 2010).
167 Soil mesofauna and microfauna, with numerous species and individuals occupying a wide range of ecological
168 niches, are other interesting representatives of biodiversity (De Nicola et al. 2014). In spite of the great interest
169 of these organisms, this compartment of biodiversity is still poorly understood in the Mediterranean forests.

170

171 **Functioning**

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

176 In optimal conditions, the photosynthetic performance of Mediterranean species does not differ particularly from
177 that of species from other biomes. Nevertheless, their leaves have to tolerate high irradiance and they have to
178 cope with excess intercepted solar radiation when carbon assimilation is limited either by stomatal closure or a
179 decrease of photosynthetic capacity due to water stress and high temperatures or low temperatures (Joffre et al.
180 2008).

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

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

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

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

201

202 **Litter decomposition and water stress**

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

211

212 **Mycorrhiza and water stress**

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

230 As regards to global change, it is generally considered that ectomycorrhizal and AM communities respond
231 similarly to CO₂ enrichment (Johnson et al. 2013). In both type of symbioses, CO₂ enrichment has been shown

232 to accelerate decomposition of soil organic matter, a phenomenon generally known as priming effect (Phillips et
233 al. 2012).

234

235 **Spatial heterogeneity in Mediterranean forests**

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

248

249 **Dynamics**

250 Ecosystem dynamics are quite different on the southern and northern shores of the Mediterranean basin
251 (Gauquelin 2011). The northern shore is characterized by coastal urbanization and an abandonment of
252 agricultural and pastoral lands, leading to a spectacular forest re-colonization; for example, in the French
253 Mediterranean area, forest (more than 1.4 million ha) increased between 0.5 and 2% by year between 1980 and
254 2011 (IF 2013; FAO 2013) which corresponds approximately to 16.000 ha by year. On the Southern shore,
255 degradation is still intense and leads to fragmentation or disappearance of habitats including forest, with for
256 example, an annually decrease rate of 0.5% of the Algerian forest area from 1990 to 2010 (FAO 2013).

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

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

267

268

269 **2. Mediterranean forests: a long history of agro-sylvo-pastoral management by** 270 **rural populations as well as of interactions between local societies and the State**

271

272 Most of the forests in the Mediterranean region are the result of a long history of agro-sylvo-pastoral
273 management by rural populations as well as of interactions between local societies and the State (mainly through
274 the public Forest Administration) (Blondel 2006, Aubert 2013). In spite of this strong influence of local
275 management practices and socio-political relationship on the *production* of Mediterranean forests, most
276 scientific studies insist on the *negative impact* that local societies have had on “natural forests” and on their
277 biodiversity (deforestation, forest degradation and desertification). Contrasting with these studies, Michon et al.
278 (2007) have proposed to analyze the *co-evolution* between forest ecosystems and their related human populations
279 in terms of *domestication* (of trees, ecosystems and landscapes), and to consider the resulting forests (*domestic*
280 *forests*, or *rural forests*; Genin et al. 2013) as biocultural, or socio-ecological products for the agroforestry
281 systems such as the ones of the Iberian Peninsula (Joffre et al. 1987, 1999).

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

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

- 289 1. specific forest structures and levels of integration in agricultural matrices, linked historically to overall
290 agro-ecosystem structures and social practices (Genin and Simenel 2011),
- 291 2. a multiscale approach to domestication from individual trees up to landscape level, involving a
292 continuity between “nature” (natural processes) and “culture” (human techniques of control and
293 transformation), (Wiersum 1997, Michon 2015),
- 294 3. multiple uses of plants which vary in relation to the commercial or non-commercial status of their
295 products and a reversible nature of these use patterns accordingly (Bahuguna 2000),
- 296 4. imbrications of different levels of access and control rules (between state and customary levels,
297 between individual and collective levels), requiring specific formal and informal arrangements
298 (Sandberg 2007). Rural forests are therefore social-ecological systems that contribute to ecosystem and
299 landscapes configuration, definition of rural territories and sustainability of local livelihoods.

300
301 The counterproductive impact of public policies and forest science must be also pointed out (Michon et al. 2013).
302 Most forestlands (and more particularly in the South) are State property and subject to forest laws. In the early
303 20th century in northern Mediterranean, and until recently in the southern shore, issues related to the management
304 of these State forests were specified in general terms, relying on representations developed in France in the late
305 nineteenth century, that have always considered rural forests as “degraded forests” instead of specific systems of
306 integrated rural forest management. For example, professional foresters seeing stands of highly pollarded trees
307 frequently conclude to a generalized degradation of forests due to Human action, totally overlooking a specific
308 management strategy aimed at enhancing forage production for livestock or pole production for roof
309 construction. In order to “regenerate” these “degraded” forests, professional foresters largely rely on two
310 strategies: 1/clear cuts and enclosures of “regenerating” stands in which all Human activity is banished and 2/

311 reforestation schemes with exotic tree species. Forests derived from such practices (stands of coppiced trees or
312 exotic forests) are of poor interest for local people, who therefore often do not respect enclosures.
313 Recently, processes related to patrimonial construction at various scales in Mediterranean forests, have emerged
314 (such as the gazetting of the Moroccan argan forest as a biosphere reserve, or of the cedar forest as national
315 parks). These processes must be questioned: the ongoing patrimonial qualification of forests at national and
316 international levels for biological conservation or as elements of the world biocultural heritage could slowly
317 erasing local (rural) forest patrimonies and therefore, endangering the reproduction of these forests (Michon et al.
318 2012).

319

320 **3. Mediterranean forests and Climate change**

321

322 Climate models have predicted increases in both temperature and drought conditions in the Mediterranean
323 (Giorgi and Lionello 2008, Somot et al. 2008). These changes are expected to result in increased frequency,
324 intensity and duration of drought, especially during the warm season (Sheffield and Wood 2008; Podale et al.
325 2004). The response of Mediterranean forests to such extreme climatic events is poorly understood, because
326 controlled field experiments to mimic such conditions are costly and difficult to operate on a large scale without
327 introducing environmental modifications. Different *in natura* platforms have been implemented in different
328 forest types in France, with rain exclusion devices allowing to apply a precipitation scenario close to what
329 models predict for the end of the 21th century. Holm oak at Puechabon (Limousin et al. 2008, 2009, 2012),
330 Aleppo pine at Font Blanche (Gea-Izquierdo et al. 2015) and downy oak at O₃HP (Santonja et al. 2015b) are
331 concerned. Results show that changing rainfall pattern will affect i) directly litter production and decomposition,
332 ii) and volatile organic compounds emissions (Staudt et al. 2002, 2003; Genard et al. 2015). The idea is to
333 develop around the Mediterranean basin a network of experimental stations with simpler and less expensive
334 devices to monitor the effects of climate change in other important forest ecosystems and so under other
335 bioclimates.

336 Concerning changes in forest vegetation over the last few decades, recent studies in northwestern Africa
337 reported recurrent drought events from the second half of the 20th century (Touchan et al. 2010; Linares et al.
338 2011; Kherchouche et al. 2012, 2013; Slimani 2014). Touchan et al. (2008) showed that the 1999-2002 severe
339 drought appears to be the worst in northwestern Africa since the middle of the 15th century. This suggests
340 climate conditions more limiting to tree growth and drought-sensitive species geographical distribution,
341 especially for those at the edge of their range. This event triggered substantial mortality in *Cedrus atlantica*
342 forests where, in some areas, stands disappeared completely (Zine El Abidine 2003; Linares et al. 2011;
343 Kherchouche et al. 2012, 2013; Slimani et al. 2014), and even in other tree species reputed for their drought
344 hardiness, including *Pinus halepensis*, *Quercus ilex*, *Quercus suber*, and *Juniperus thurifera* (Allen et al. 2010).

345

346 **4. Four contrasting examples of relationships between functioning, structure and** 347 **global change in Mediterranean forests**

348

349 Four examples illustrate relationships between human impacts, structure, dynamics and functioning of
350 Mediterranean forests: *Quercus pubescens* (downy oak) forest, *Quercus suber* (cork oak) forest, *Pinus*

351 *halepensis* (Aleppo pine) forest or *Juniperus thurifera* (thuriferous juniper) forest. They have a very different
352 distribution (see maps in Quézel and Médail 2003) and they are respectively representative of the three tree
353 functional types of the Mediterranean region: deciduous species malacophylles (specifically marcescent for
354 downy oak) and evergreen sclerophyllous leaved and coniferous species (for cork oak, Aleppo pine and
355 thuriferous juniper) (Table 1). They also have contrasting strategies to cope with drought and also very different
356 dynamics according to past and current human impact, corresponding to different geographical trajectories
357 (Table 1):

- 358 - France where abandonment of forest uses is the main feature and human pressure is very low (Southern
359 Alps for juniper, Eastern Pyrenees for cork oak),
- 360 - Spain where relictual uses and managements are still observed and human pressure is moderate to
361 average (Northern Spain for thuriferous juniper, Andalucian dehesa for cork oak),
- 362 - Morocco, Algeria or Lebanon where forests are an important component for maintaining rural
363 livelihoods and where human pressure is high, but with different modalities of governance in forest
364 management (Agdal management system, a collectively-built management including seasonal rests and
365 highly refined rules concerning multifunctional product extraction, for example, Auclair and Alifriqui,
366 2012), (High Atlas for thuriferous juniper, and Mamora forest for cork oak).

367

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

371

372 **Forests of downy oak (*Quercus pubescens*): Which future for deciduous or marcescent oaks in the** 373 **Mediterranean basin?**

374

375 *Quercus pubescens* Willd. (downy oak) is a deciduous native oak widespread in southern Europe and
376 southwest Asia, from northern Spain (Pyrenees) east to the Crimea and the Caucasus. It is also found in France
377 (more than 1.000.000 ha) and parts of central Europe (Ganatsas et al. 2013). Moreover, the downy oak, often
378 occurring in the transition of several climatic influences, seems to be especially responsive to climate change.
379 The dramatic reduction of territories where marcescent oaks like downy oaks dominate, expected in the context
380 of climate change in the near future in Spain (Sanchez de Dios et al. 2009), underlines the need of studies
381 concerning this species, providing typical landscapes in the South of France. Forests generally result from
382 coppicing practiced for centuries for charcoal production and are also used as rangeland for livestock. This
383 species does not exist in North Africa but is replaced by other related deciduous oak species.

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

387

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

389 The cork oak forests, which cover between 1.7 and 2.7 million ha in Western Mediterranean, distributed
390 unevenly among Portugal, Spain, France, Italy, Morocco, Tunisia and Algeria, have been exploited by Humans

391 for the past 3000 years, with an exploitation system combining ranching, agriculture and forestry. Cork oak
392 ecosystems span from open savannas to closed forests. Bark is periodically harvested and represents the second
393 most important marketable non-timber forest product in western Mediterranean. The cork oak ecosystems are
394 also recognized for their remarkable ecological value, providing habitat for several threatened species and being
395 protected by international legislation. But cork oak forests are threatened by wildfires, aging tree populations,
396 abandonment in southwestern Europe and overuse in northwestern Africa where low regeneration rates are
397 observed. Another threat is the recent decline of cork prices, due to the growing utilization of cork stopper
398 substitutes. Cork oaks forests appear to be a good model to investigate about “Payment for Ecosystem Services”
399 and economic incentives that promote ecological and economic viability of cork oak forests. It is also a good
400 model to illustrate differences between Southern and Northern woodlands concerning threats and dynamics.

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

402 The Aleppo pine is the most widespread pine in the Mediterranean basin (more than 3.5 million ha),
403 mostly in the western Mediterranean. Since the early 19th century, the northern margins of the Mediterranean
404 basin have undergone strong rural depopulation (Barbero et al. 1990; Debussche and Lepar 1992). Abandoned
405 agricultural lands are soon to be naturally colonized by pioneer plant species through processes of secondary
406 succession, with forest cover increasing fivefold over the last 150 years (Fernandez, Bousquet-Melou and
407 Prevosto 2013). Among these pioneer species, *Pinus halepensis* Miller is considered as an expansionist species
408 (Barbero and Quézel 1990) that presently dominates forests in this area (Acherar, Lepar and Debussche 1984;
409 Debussche and Lepar 1992; Maestre and Cortina 2004), thereby, threatening the existing mosaic of forests,
410 shrublands and pastures of high patrimonial value (Quézel and Médail 2003). The different stages of
411 successional dynamics in these Mediterranean forest ecosystems dominated by *Pinus halepensis* are well
412 described (Lepar and Escarré 1983; Quezel and Médail 2003), but the functional mechanisms determining these
413 successional dynamics remain poorly understood. In the southern margins, where the main populations exist,
414 dynamic and biodiversity of Aleppo pine forests are less known and should be compared to the northern
415 populations.

416 417 **Forest of thuriferous Juniper (*Juniperus thurifera*): Which dynamic North and South of the** 418 **Mediterranean basin?**

419
420 Thuriferous juniper is only found in isolated parts of western Mediterranean: France (Alps, Pyrenees
421 and Corsican highlands), Spain, Algeria and Morocco with a total area more than 200.000 ha (Gauquelin et al.
422 2012; Gauquelin and Dutoit, 2013). These semi-arid mountain stands, where *thuriferous juniper* trees grow in
423 low-density open woodland, are seriously endangered;

- 424 i. in the Atlas mountains, *thuriferous juniper* stands are heavily degraded as a result of intensive wood
425 collection and livestock grazing (Gauquelin et al. 1999). This situation is in most parts, and could
426 become irreversible by producing an impoverishment of soils and by leading to hillside instability.
427 However, some still operating traditional practices concerning thuriferous juniper forests, can mitigate
428 this degradation and promote some equilibriums between forest functioning and local population

429 livelihoods (Hammi et al. 2010; Genin et al. 2012). In Spain, although livestock ranching and
430 cultivation have strongly reduced areas occupied by *Juniperus thurifera* stands are still numerous and,
431 in some regions, show a good regeneration due to conservation measures;

432 ii. in France, the decline in human and livestock activities over recent decades has led to a re-colonization
433 of some of the Juniper stands by pines or oaks.

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

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

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

459
460

461 **5. Conservation and sustainability use of Mediterranean forests**

462

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

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

468 In many countries, considerable research efforts are made to foster more reliable and precise reforestation when
469 the natural regeneration is not sufficient or not possible, as the cost of reforestation is rising rapidly. Not only are
470 labor, machines, and tree seed and seedling costs going up steeply, but the cost of borrowing money also has
471 risen sharply in recent years. The ultimate target is to accomplish reforestation based on detailed physiological,
472 ecological, and meteorological knowledge, inexpensively, quickly and reliably, and to ensure that trees grow
473 rapidly after plantation.

474 One example concerns the resort to exotic trees, often been recommended in the past as a management option to
475 enhance the productivity and biodiversity of Mediterranean disturbed ecosystems. Tree species such as *Pinus*
476 spp., *Eucalyptus* spp. and *Acacia* spp. have been largely exported outside their natural range over the 18th and
477 19th centuries. Although these species are recommended to restore degraded ecosystems, it is now well
478 established that they could threaten the structure and composition of plant cover and the vegetation dynamics
479 (succession and dominance) and interact with the soil microbial community and modify mutualistic interactions
480 within the native vegetation. Alteration of mycorrhizal community is of particular importance because it is
481 considered as a key component of the sustainable soil-plant system (Hafidi et al. 2015). Performance of
482 introduced species will be examined in relation to modifications of environmental factors (light availability, soil
483 moisture and microclimatic conditions). Interactions between introduced seedlings, understorey and overstorey
484 must be particularly studied to detect in which conditions competition or facilitation occur according to
485 vegetation, species and site conditions (Duponnois et al. 2011).

486
487 Mediterranean forest ecosystems will have also to face significant disruptions of their functioning due to extreme
488 climatic events, such as longer and more severe drought periods, increasing forest fire frequency and intensity
489 and pest outbreaks (Moriondo et al. 2006; Lindner et al. 2010). These disturbances will put at risk a number of
490 important ecosystems services (Schroter et al. 2005). In this context, new methods increasing the resistance and
491 resilience of Mediterranean forests have to be developed, including those that harness the full potential of
492 Mediterranean forest genetic resources (Lefèvre et al. 2014). For example, *Pinus halepensis* is particularly
493 sensitive to current and future risks as this species is extremely flammable and can favour the spread of large
494 forest fires (Pausas et al. 2008). This species can regenerate after a fire, thanks to a canopy-stored seed bank
495 (Fernandes et al. 2011). But this strategy does not operate when fire intervals are shorter than the maturity age
496 (Daskalaku and Thanos, 1996; Ne'eman et al. 2004). In addition, Aleppo pine forms mostly monospecific
497 stands that are highly sensitive to insect attacks (Maestre and Cortina 2004). Mixed stands, e.g. combining pine
498 and hardwood species, are expected to be less sensitive to pest outbreaks and herbivory (Jactel et al. 2006; Jactel
499 and Brockerhoff 2007), to host a higher biodiversity and to be more resilient to disturbances and changing
500 environmental conditions for a number of ecosystem processes (Yachi and Loreau 1999). Favouring mixed pine-
501 hardwood species stands is therefore a strategy increasingly put forward in order to enhance forest resilience
502 (Pausas et al. 2004).

503 The impact of different vegetation conditions (including different canopy covers, presence or not of shrubby
504 vegetation) on the response of introduced hardwood of various species differing in various ecological traits
505 (ability to withstand shade and water stress in particular), must be tested in different contrasted Mediterranean
506 regions. To ensure generalization of the results obtained from different sites, modelling of the interactions

507 between the different strata (regeneration/understorey/overtstorey) in relation to the use of the main resources
508 (water, light) must be proposed.

509
510

511 **6. Conclusion: conciliating particular ecological functioning, biocultural heritage** 512 **and threats**

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

515 - Linking fundamental and applied research: all scientific results should allow implementing a successful
516 strategy for the preservation and development of Mediterranean forests. Knowledge of the different
517 biodiversity levels could help preserve Mediterranean forests. At the species level, the genetic diversity
518 studies and the adaptive potential of the species could help understand its reactions to environment
519 change. At the community level, understanding interactions between different species could have
520 drastic changes on reforestation practices. For instance, identifying the mycorrhizal community of some
521 trees used in reforestation programs and the nurse effect of some shrub species on these trees could
522 bring high hope for large scale reforestation programs, reducing watering cost and rising success rate of
523 these plantations. On the other hand, climate modelling applied to species distribution and genetic
524 exploration of marginal populations can also help predict species range shifts and lighten conservation
525 actions.

526 - Linking “hard sciences” and humanities and social sciences: in the Mediterranean forests, the
527 understanding of these ecosystems and their future must first integrate 1) the secular human-forest
528 interactions which have shaped functional cultural landscapes, and 2) the ecosystem services provided
529 by these forests for securing both overall diverse ecosystems and livelihoods.

530 - Linking academic knowledge and traditional knowledge: we have seen that some localized practices,
531 such as the Agdal system for example, give attention to both forest protection and exploitation for local
532 livelihood improvement. There is therefore an urgent need to better survey and understand the ways
533 local population perceive and manage their forest resources, in order to facilitate hybridization of
534 knowledge for integrated proposals that make sense to both parts, and could effectively be applied and
535 respected.

536 - Linking forestry, agricultural and social approaches and objectives: forests and human populations
537 living in and from these forests have to be protected in a global, comprehensive approach taking into
538 account biological and cultural diversity, which requires truly participative methods (i.e. not forcing
539 local population to participate in projects designed by foresters or biologists who aim at preserving
540 forests *per se*, but developing negotiation processes in which all stakeholders have to be heard).

541 - Linking North and South of the Mediterranean: forest structure, dynamics and threats are very different
542 on the two shores of the Mediterranean and confrontation between these different situations is essential
543 to understand the global evolution of Mediterranean forests. For example, are Aleppo pine, cork oak or
544 thuriferous Juniper forests the same South or North according to their structure, functioning, utilization,
545 biodiversity or vulnerability? Which relationships between Aleppo pine and the two oaks in the North?

- 546 Which place for deciduous oaks (close to *Q. pubescens*) in the Maghreb?
- 547 - Linking biodiversity, evolution, dynamics and functioning in these forests in order to put in evidence
- 548 the need to preserve this biodiversity.
- 549 - Linking “nature” and productive systems: this aspect, and particularly in the Mediterranean basin,
- 550 shows a continuum between “wild” and highly anthropized ecosystems, which has to be better
- 551 understood in order to detect forms of uses enable to guarantee both sustainability of these sensitive
- 552 forest ecosystems and local livelihoods.

553 Mentioning the necessity of these linkages may appear incantatory as it barely refers to actually occurring

554 dynamics. It is also difficult to report true “success stories” in developing productive “biocultural” approaches,

555 i.e. in combining ecological and cultural approaches for a better understanding and management of

556 Mediterranean forests, as these two approaches are generally badly connected. However, some examples of what

557 should not occur and some ideas of what could be achieved can be derived from researches conducted by various

558 disciplines on the argan forest of Morocco. Biologists consider this forest as a unique forest (with the endemic

559 argan tree and associated forest flora, and ecological services it provides). They also consider this forest as

560 highly threatened by local agro-silvo-pastoral practices hampering the regeneration of the argan tree and

561 reducing floristic diversity (Michon et al. 2016). Social sciences consider the argan forest as a unique example of

562 socio-ecological system linking biological and cultural diversity for the management and reproduction of both a

563 fragile forest ecosystem in arid conditions and a productive agroforestry system (M’Hirit et al. 1998). Combined

564 ecological and cultural approaches highlight the ambiguity of “degradation narratives” in the argan forest (El

565 Wahidi et al. 2014). In areas where human out-migration is occurring (the Anti-Atlas mountains), dense forest

566 vegetation is quickly developing. But as terraces are abandoned, soil erosion is accelerating (which, in the

567 context of increasing extreme rainfall episodes, can become a problem), and bushy undergrowth vegetation is

568 developing, which increases risks of forest fires. Moreover, the argan socio-ecological system is degrading, with

569 the erosion of local knowledge and practices. The “biological forest” is regenerating, the “cultural forest” is

570 vanishing. Foresters, biologists, local populations and social scientists could join their efforts in order to define

571 what is a desirable “state of conservation” for this rural forest, taking into account flora, fauna, ecological

572 services as well as local knowledge, practices and productions. Practical measures to reach, monitor and

573 maintain this state have to be invented mobilizing scientific as well as local indicators of “degradation”,

574 regeneration practices, protection measures (for example combining the protective enclosure methods of

575 foresters and the agdal practices of local populations). This can be done only if local populations are integrated

576 from the very beginning in the definition of conservation management objectives. The same global model can be

577 mentioned for the cork oak forest, a formerly “cultural forest” in the northern part of the Mediterranean basin,

578 “naturalized” since local practices of cork oak management have been abandoned, and presently heavily

579 impacted by fires. Conservation of the cork-oak forest may go through reactivating the interest of local farmers

580 into global ecosystem management for combined cork, pastoral and agricultural productions. Such management

581 models still exist in Spain and south of the Mediterranean basin that could inspire the rehabilitation of

582 abandoned cork oak forests in the North.

583 This synthesis should highlight both the risks of Mediterranean forest ecosystems and their potential, as well as

584 the opportunities they represent for sustainable development integrating the “man” and its activities. The idea is

585 to project in 2100 by integrating global change (including climate change, land use change, socio-economic,
586 etc...) and make proposals in this direction. Dialogue and meeting between the actors of this project will be the
587 main tool to succeed in this challenge.

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881 Table 1: Comparative data on biological type, bioclimatic stage, distribution area and dynamics, main uses, ecosystems
 882 services, human pressure and threats for the four studied species. Sources of data : Pons and Quezel 1998; Quézel and Médail
 883 2003; Fernandez, Bousquet-Melou and Prevosto 2013; Gauquelin et al. 1999.

Species	Biological type	Bioclimatic stage	Distribution area Dynamics	Main uses	Ecosystems services	Human pressure and threats
<i>Quercus pubescens</i> Downy Oak	Deciduous, marcescent	Submediterranean and mediterranean (mesomediterranean and supramediterranean)	Widely distributed > 2 million ha Extension	Wood for fuel and charcoal	Regulation Provisioning Habitat Cultural	Low Climate change
<i>Quercus suber</i> 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
<i>Pinus halepensis</i> 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
<i>Juniperus thurifera</i> 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

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