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1 **Reassessing global change research priorities in Mediterranean terrestrial ecosystems:**
2 **how far have we come and where do we go from here?**

3

4 E Doblas-Miranda^{1*}, J Martínez-Vilalta^{1,2}, F Lloret^{1,2}, A Álvarez¹, A Ávila¹, F J Bonet³, L
5 Brotons^{1,4}, J Castro⁵, J Curiel Yuste⁶, M Díaz⁶, P Ferrandis⁷, E García-Hurtado⁸, J M Iriondo⁹,
6 T F Keenan¹⁰, J Latron¹¹, J Llusà^{1,12}, L Loepfe¹³, M Mayol¹, G Moré¹, D Moya⁷, J
7 Peñuelas^{1,12}, X Pons², R Poyatos¹, J Sardans^{1,12}, O Sus¹, V R Vallejo⁸, J Vayreda¹, J Retana^{1,2}

8

9 Email addresses in the same authors order: e.doblas@creaf.uab.es, Jordi.Martinez.Vilalta@uab.es,
10 a.alvarez@creaf.uab.es, Anna.Avila@uab.es, fjbonet@ugr.es, lluis.brotons@ctfc.es, jorge@ugr.es,
11 curielyuste@gmail.com, mario.diaz@ccma.csic.es, Pablo.Ferrandis@uclm.es, elisa@ceam.es,
12 jose.iriondo@urjc.es, trevor.keenan@mq.edu.au, jerome.latron@idaea.csic.es, Francisco.Lloret@uab.es,
13 j.llusia@creaf.uab.es, lasse.loepfe@gmx.net, Maria.Mayol@uab.es, g.more@creaf.uab.es,
14 daniel.moya@uclm.es, josep.penuelas@uab.cat, xavier.pons@uab.cat, r.poyatos@creaf.uab.es,
15 j.sardans@creaf.uab.es, o.sus@creaf.uab.es, ramonv@ceam.es, j.vayreda@creaf.uab.es, javier.retana@uab.es

16

17 1 CREAM, Cerdanyola del Vallès 08193, Spain.

18 2 Univ Autònoma de Barcelona, Cerdanyola del Vallès 08193, Spain.

19 3 Univ Granada, iEcoLab Lab Ecol, Instituto Interuniversitario Sistema Tierra, Granada 18006, Spain.

20 4 CTFC (Forestry Technology Centre of Catalonia), St. Llorenç de Morunys km 2, 25280 Solsona, Spain.

21 5 Department of Ecology, University of Granada, E-18071 Granada, Spain.

22 6 Department of Biogeography and Global Change, Museo Nacl Ciencias Nat, CSIC (BGC-MNCN-CSIC), E-
23 28006 Madrid, Spain.

24 7 Technical School of Agricultural and Forestry Engineering, University of Castilla-La Mancha, Campus
25 Universitario s/n, 02071 Albacete, Spain.

26 8 Fundación Centro de Estudios Ambientales del Mediterráneo (CEAM), Paterna, Valencia, Spain.

27 9 Univ Rey Juan Carlos, Dept Biol & Geol, Area Biodiversidad & Conservac, Mostoles, Madrid, Spain.

28 10 Department of Biological Sciences, Macquarie University, North Ryde NSW, Australia

29 11 CSIC, Institut de Diagnosi Ambiental i Estudis de l'Aigua IDAEA, ES-08034 Barcelona, Spain.

30 12 CSIC, Global Ecology Unit CREAF-CEAB-UAB, Cerdanyola del Vallès 08193, Spain.

31 13 Grupo Interdisciplinar de Sistemas Complejos (GISC), Departamento de Matemáticas, Universidad Carlos III
32 de Madrid, 28911 Leganés, Spain.

33

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37

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40 **Corresponding author:** Enrique Doblas-Miranda

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42

43 **Abstract**

44 Aim: Mediterranean terrestrial ecosystems serve as reference laboratories for investigating of
45 global change because of their transitional climate, the high spatiotemporal variability of their
46 environmental conditions, a rich and unique biodiversity and a wide range of socio-economic
47 conditions. As scientific development and environmental pressures increase, it is increasingly
48 necessary to evaluate recent progress and to challenge research priorities in the face of global
49 change.

50 Location: Mediterranean terrestrial ecosystems.

51 Methods: This article revisits the research priorities proposed in a 1998 assessment.

52 Results: A new set of research priorities is proposed: 1) To establish the role of the landscape
53 mosaic on fire-spread; 2) To further research the combined effect of different drivers on pest
54 expansion; 3) To address the interaction between global change drivers and recent forest
55 management practices; 4) To obtain more realistic information of global change impacts and
56 ecosystem services; 5) To assess forest mortality events associated with climatic extremes; 6)
57 To focus global change research on identifying and managing vulnerable areas; 7) To use the
58 functional traits concept to study resilience after disturbance; 8) To study the relationship
59 between genotypic and phenotypic diversity as a source of forest resilience; 9) To understand
60 the balance between C storage and water resources; 10) To analyse the interplay between
61 landscape-scale processes and biodiversity conservation; 11) To refine models by including
62 interactions between drivers and socio-economic contexts; 12) To understand forest-
63 atmosphere feedbacks; 13) To represent key mechanisms linking plant hydraulics with
64 landscape hydrology.

65 Main conclusions: (1) The interactive nature of different global change drivers remains poorly
66 understood; (2) there is a critical need for rapidly developing regional and global scale models

67 to be more tightly connected with large-scale experiments, data networks and management
68 practice; (3) more attention should be directed at drought-related forest decline and the current
69 relevance of historical land use.

70

71 **INTRODUCTION**

72 The earth system is changing, threatening the ecosystem services upon which we depend
73 (Steffen *et al.*, 2004). Greenhouse gas emissions are causing climate change, characterized by
74 warmer temperatures and more frequent and intense droughts (Giorgi & Lionello, 2008),
75 which, in turn, imply an increase in climatic fire risk (Pausas, 2004). Other anthropogenic
76 changes include major changes in land use, increasing nitrogen deposition, and tropospheric
77 ozone accumulation (Steffen *et al.*, 2004).

78 Mediterranean Terrestrial Ecosystems (MTEs), including forests, shrublands and pastures,
79 serve as exemplary natural laboratories in which to study global change, because they are
80 highly sensitive to several drivers of such change and to the interactions among these drivers
81 (Sala *et al.*, 2000). Climate in MTEs shows high sensitivity to global atmospheric changes
82 due to the transitional nature between arid and temperate regions in these ecosystems (Giorgi,
83 2006). Increased aridity is expected in most existing MTEs (Sillmann *et al.*, 2013). The
84 combination of extreme climate events, a long history of land-use changes, and the particular
85 geology of these ecosystems have resulted in more frequent and intense fires, water scarcity,
86 and land degradation (soil and productivity loss), among other impacts (Conacher, 1998;
87 Keeley *et al.*, 2012). MTEs show high levels of heterogeneity at different scales due to these
88 disturbances and large seasonal and inter-annual climatic variability (Rundel, 1998). This
89 distinctive spatiotemporal variability of environmental factors has resulted in a singular and
90 diverse biota, with elevated vulnerability to global change-induced extinction (Malcolm *et al.*,
91 2006). Given that socioeconomic trends are projected to have a greater effect than climatic
92 drivers on land use (Schröter *et al.*, 2005), it is important to be able to study global change in
93 different social and economic contexts and across different policy regimes. Among the
94 world's MTEs, the Mediterranean Basin serves as a particularly valuable global change

95 laboratory because of its wide range of socio-economic conditions and government policies
96 (Brauch, 2003).

97 A consistent evaluation of principal research gaps within MTEs, with special consideration
98 given to the Mediterranean Basin, has the potential to provide valuable information on how to
99 advance in handling the future impacts of global change on a global scale. A previous study
100 by the International Geosphere-Biosphere Programme (Lavorel *et al.*, 1998; hereafter La98)
101 provided the first roadmap for conducting global change research in Mediterranean Basin
102 ecosystems and recommended that specific actions be carried out in the region. Now, after 15
103 years of increasing research efforts devoted to global change impacts, it is time to evaluate the
104 current state of the art with regard to these targets and to propose a new set of priorities for
105 the coming decades—including priorities relevant to the MTEs outside of the Mediterranean
106 Basin.

107 To do so, we revisit the priorities recommended by La98, following their original order, and
108 we provide an update of their current state and relevance. We then suggest a new set of
109 priorities for the upcoming years. Our specific objectives are (1) to evaluate the progress of
110 the research carried out in MTEs, (2) to assess the accomplishment of previous priorities, and
111 (3) to update the list of priorities with emerging topics and challenges.

112

113 **EVALUATION OF THE ACCOMPLISHMENT OF LA98 RESEARCH PRIORITIES**

114 **1. To understand future fire regimes and their effects.**

115 *1.1. Prediction of future fire regimes, involving interaction with global changes*

116 **Land use change** may modify fire regime by altering fuel load and distribution or ignition
117 patterns. In MTEs of Europe, massive abandonment of agricultural land has increased
118 landscape homogeneity and crown fire potential, which in turn facilitates fire spread (Lloret *et*
119 *al.*, 2002; Mitsopoulos & Dimitrakopoulos, 2007). In contrast, central Chile has experienced

120 an overall trend of deforestation and loss of shrubland but no clear trend in burned area
121 (Montenegro *et al.*, 2004). In California, urban development is the major driver of land
122 transformation, increasing ignitions in the wildland-urban interface (Syphard *et al.*, 2007).
123 In the Mediterranean Basin, fire-suppression policies may reduce fire size in the short term
124 but promote megafires at larger temporal scales (Piñol *et al.*, 2007; Brotons *et al.*, 2013). In
125 contrast, fuel reduction policies are regularly implemented with prescribed fires in several
126 MTEs in order to reduce hazard in populated areas and to reproduce a fire regime that
127 supports biodiversity in a fine-grain mosaic of vegetation (Price & Bradstock, 2010).
128 Prescribed burning, however, remains controversial (Boer *et al.*, 2009; Fernandes *et al.*,
129 2011). Under extreme weather conditions, fuel quantity no longer serves as a control on fire
130 regime and large fires may occur even with relatively low fuel loads (Keeley & Zedler, 2009;
131 San-Miguel-Ayanz *et al.*, 2013). Site idiosyncrasy is also important affecting pre-fire patch
132 grain and distribution (Syphard *et al.* 2007). Fire-induced landscape homogenization (by large
133 or frequent fires,) as opposed to heterogeneization (by scattered fires through space and time),
134 appears highly dependent on fire regime (Lloret *et al.*, 2002).

135 **Climate change** is expected to increase dryness in MTEs due to warmer temperature and
136 reduced precipitation, particularly during summers (Giorgi & Lionello, 2008; Sillman *et al.*,
137 2013). Overall, this tendency will lead to increasing climatic fire risk (Liu *et al.*, 2010), as
138 already apparent from historical records (Kraaij *et al.*, 2013). However, this trend is also
139 influenced by fuel availability, determined by both fuel quantity and climate-driven fuel
140 moisture (Westerling *et al.*, 2006; Batllori *et al.*, 2013). Although lower air humidity and fuel
141 water content are positively related to fire ignition and propagation, drier climate eventually
142 leads to a decrease of fuel load, due to lower productivity (Lenihan *et al.*, 2003; Batllori *et al.*,
143 2013).

144 **CO₂ fertilization** could affect fuel accumulation and thus fire regimes. Recent projections at
145 the regional level reveal that the net effect of CO₂ fertilization combined with drought stress
146 remains uncertain (Keenan *et al.*, 2011). However, water appears to be more important than
147 CO₂ as a driver of growth in water-limited MTEs (Fatichi *et al.*, 2013). In addition, the
148 combination of increased fire frequency and drought stress could enhance shrub
149 encroachment (Mouillot *et al.*, 2002; Pausas, 1999) and thus reduce carbon storage.

150

151 *1.2 Fire impacts*

152 **On landscape patterns.** One main goal of extensively develop spatially explicit landscape
153 models for MTEs is to assess forest vulnerability to fire due to soil degradation or vegetation
154 shifts (Franklin *et al.*, 2005; Millington *et al.*, 2009). Most of these models, therefore, include
155 forest management and environmental factors within specific landscape configurations
156 (Loepfe *et al.*, 2011; Moreira *et al.*, 2012). However, models are still incomplete, in the sense
157 that anthropogenic factors are usually not included to generate landscape projections and thus
158 to predict future fire impacts (Syphard *et al.*, 2007; LePage *et al.*, 2010).

159 **On vegetation.** Simulation models of fire and vegetation dynamics, including the interaction
160 between these variables, have been developed, considering different spatial scales, vegetation
161 levels, successional approaches and explicit or implicit simulation of fire spread (Keane *et al.*,
162 2004; Millington *et al.*, 2009). Analysis of species and population regenerative traits remains
163 a key approach to assess sensitivity of plant species to predicted fire regimes and to model
164 changes in species distribution and community composition (Lloret *et al.*, 2005; Syphard &
165 Franklin, 2010). Several studies have assessed short-term responses of MTEs vegetation
166 (Keeley *et al.*, 2012; Moreira *et al.*, 2012) but more attention should be paid to longer time
167 frames.

168 **Combined with other factors.** The consequences of the combined effects of fire and drought
169 in the form of plant-regeneration decline and land degradation have been the object of intense
170 study (e.g. Mouillot *et al.*, 2002; Montenegro *et al.*, 2004). More recently, the role of fire in
171 facilitating the spread of biological invasions in MTE has also attracted attention (Rouget *et*
172 *al.*, 2001; Pino *et al.*, 2013) and research in this area is revealing the vulnerability associated
173 with fire regime properties such as fire frequency (Keeley & Brennan, 2012) and intensity
174 (Franklin, 2010).

175

176 *1.3 Fire control and mitigation*

177 **Prevention.** Since La98, many studies have been conducted to characterize the relationship
178 between different fire spread characteristics using diverse approaches. These include fire
179 behaviour models coupling suppression policies and vegetation dynamics, forest inventories,
180 wildfire databases, and fire severity studies (e.g., Boer *et al.*, 2009; Price & Bradstock, 2010).
181 Such studies have provided quantitative information about the best way to manage forest fuels
182 to obtain (1) more favourable fire characteristics (behaviour, frequency, size) aiding future
183 fire suppression (Crecente-Campo *et al.*, 2009) or unplanned fire extent (Boer *et al.*, 2009),
184 and (2) landscape configurations that are more efficient at reducing megafires (Millington *et*
185 *al.*, 2009; Loepfe *et al.*, 2011). Several studies have also reported positive feedback between
186 flammable vegetation types and fire frequency (Vilà *et al.*, 2001; Grigulis *et al.*, 2005).

187 **Restoration.** The last decade has seen substantial advances in key aspects of post-fire forest
188 restoration, such as the analysis of vegetation recovery (Díaz-Delgado & Pons, 2001; Díaz-
189 Delgado *et al.*, 2002). A new field of study deals with the identification of previous land-use
190 changes as drivers of post-fire regeneration (Clavero *et al.*, 2011; Puerta-Piñero *et al.*, 2012).
191 Additional breakthroughs have been made in the study of facilitative interactions and the use
192 of shrubs as potential nurse plants (Gómez-Aparicio, 2009), underscoring the role of early and

193 mid-successional shrubs for forest regeneration in burnt areas (Gómez-Aparicio *et al.*, 2004;
194 Siles *et al.*, 2010). In addition, a novel focus has recently appeared in relation to the use of
195 coarse woody debris to foster restoration success, as this debris may act as a nurse structure,
196 improving microclimatic conditions for seedling establishment, increasing soil nutrient
197 content, and improving other physical and chemical soil properties (Marañón-Jiménez &
198 Castro, 2013; Marzano *et al.*, 2013). Burnt trees are also a biological legacy crucial for the
199 recovery of communities and for the structure and function of regenerating Mediterranean-
200 type ecosystems by increasing plant and animal diversity (Castro *et al.*, 2012; Lee *et al.*,
201 2013; Marzano *et al.*, 2013), reducing invasion by exotic species (Moreira *et al.*, 2013),
202 promoting soil microbial activity (Marañón-Jiménez & Castro, 2013), and carbon
203 sequestration (Serrano-Ortiz *et al.*, 2011).

204

205 **2. To study the effects of land use on biosphere-atmosphere interactions**

206 *2.1. Feedbacks of land-use changes on the climate system*

207 While a great deal of uncertainty persists concerning the impacts of land-use changes on
208 regional climate models (Bonan, 2008), modelling results for the Mediterranean suggest that
209 changes in land use significantly affect climate (Lionello *et al.*, 2006). Changes in
210 evapotranspiration rates and surface albedo due to deforestation in the Mediterranean Basin
211 could provoke cooler and moister springs but warmer and drier summers (Heck *et al.*, 2001),
212 or instead cooling during summer (Zampieri & Lionello, 2011). In Southwest Australia,
213 deforestation may lead to long term reductions in rain fall patterns (Pitman *et al.*, 2004). In
214 summary, available models indicate that the climate of the MTEs is sensitive to changes in
215 vegetation cover, especially in summer. However, the induced climate anomalies can be
216 associated with fine-grained, complex and non-local mechanisms and their relative weights in
217 driving local effects are still uncertain (Seneviratne *et al.*, 2010).

218

219 *2.2 Ecosystem physiology feedbacks on the climate system*

220 **CO₂-driven feedbacks on temperature** through physiological responses of vegetation are
221 negligible, as current evidence suggests (Keenan *et al.*, 2011; Cheaib *et al.*, 2012).

222 **Climate change effects on soil respiration and the emission of other biogenic gases** are
223 still a major concern. Increases of drought intensity in the Mediterranean Basin have been
224 associated to tree mortality episodes during recent decades (Martínez-Vilalta *et al.*, 2012;
225 Sánchez-Salguero *et al.*, 2012). A recent study shows that, although current tree mortality is
226 not affecting the carbon balance of Mediterranean forests, (1) increased warming and drought
227 are likely to alter the capacity of these forests to absorb CO₂ and (2) forest management may
228 be a key factor determining the response of forest C balance to changing climate (Vayreda *et*
229 *al.*, 2012).

230 Some studies have reported an increase in soil organic carbon (SOC) and other nutrient
231 fractions under drought due to rising quantities of litterfall and dead roots (Talmon *et al.*,
232 2011), and to decreased soil decomposition and respiration (e.g., Curiel Yuste *et al.*, 2007;
233 Ryals & Silver, 2013). However, observational studies suggest that drought should decrease
234 SOC in the long term by reducing plant cover, which implies a decrease in litterfall, soil
235 protection and permeability (Boix-Fayos *et al.*, 1998). Furthermore, in MTEs there is an
236 overall reduction in soil biological activity due to soil moisture reduction (Brown *et al.*,
237 1996), and this results in a decrease in soil nutrient availability and soil CO₂ emissions
238 (Sardans *et al.*, 2008; Emmett *et al.*, 2004). An increasing body of research is also starting to
239 reveal the key role of microbial communities in ecosystem processes under climate-change
240 scenarios, particularly in soil carbon dynamics (Balser & Wixon, 2009; Asensio *et al.*, 2012;
241 Curiel Yuste *et al.*, 2012).

242 Biogenic volatile organic compounds were not previously considered but are also crucial to
243 understanding both biological consequences and feedbacks on atmospheric chemistry and
244 climate itself (Monson *et al.*, 2007; Peñuelas *et al.*, 2013). The emission rates of BVOCs
245 increase with rising global temperature, but changes in species and community structure, land
246 use and resource availability can also lead to major changes in Mediterranean regional BVOC
247 fluxes (Peñuelas & Staudt, 2010).

248

249 *2.3 Contribution of fire related emissions of carbon, nitrous oxides and other trace gases to* 250 *the atmosphere and their potential effects on climate*

251 Fire emissions cause significant perturbations of the chemical composition of the atmosphere
252 and in the earth climate system, as several field campaigns, as well as laboratory experiments
253 and prescribed burnings in MTEs have shown (Ciccioli *et al.*, 2001; Phuleria *et al.*, 2005;
254 Wain *et al.*, 2008; Garcia-Hurtado *et al.*, 2013). These gases include principally carbon
255 dioxide (CO₂), carbon monoxide (CO) and methane (CH₄), but also nitrogen oxides (NO_x and
256 N₂O), ammonia (NH₃), sulfur dioxide (SO₂), light hydrocarbons, volatile and semi-volatile
257 organic compounds, and particulate matter (10 to 2.5 μm), which could affect climate change
258 and human health (Ciccioli *et al.*, 2001; Bell & Adams, 2008).

259 Studies have been conducted to characterize biomarkers from woodstove combustions and
260 wildfires (Muhle *et al.*, 2007; Gonçalves *et al.*, 2011), but the challenge of identifying the
261 main tracer compounds emitted by forest fires in MTEs continues.

262 EMEP/CORINAIR emission inventories and satellite observations, including those using
263 Moderate Resolution Imaging Spectroradiometer (MODIS), have been used to feed several
264 emission and air quality models (Lazaridis *et al.*, 2005; Paton-Walsh *et al.*, 2012).

265

266 *2.4 Coupled biosphere-atmosphere models for the Mediterranean Basin*

267 Large-scale generalized simulations of the effects of climate and land-use changes on MTEs
268 exist (Zaehle *et al.*, 2007), but regional applications to key ecosystems (including cropland
269 phenology and management to account for associated albedo feedbacks; Sus *et al.*, 2010) are
270 scarce. During the past decade, development of non-fully-coupled models simulating
271 Mediterranean terrestrial biosphere-atmosphere interactions has focused on the integration of
272 information on ecosystem physiology and land-cover dynamics (e.g. Gritti *et al.*, 2006). Only
273 in recent years, however, have fire models begun to be incorporated into land-surface models
274 (e.g., Prentice *et al.*, 2011). Early efforts identified model deficiencies in reproducing the
275 response of leaf gas exchange to drought events (Reichstein *et al.*, 2003), leading to
276 subsequent model development (Garbulsky *et al.*, 2008; Keenan *et al.*, 2010). Despite this,
277 models continue to perform poorly in conditions of water stress (Vargas *et al.*, 2013). Many
278 ecosystem disturbances, processes and physiological responses remain poorly understood, and
279 are not explicitly accounted for in models, such as, for example, competitive interactions,
280 carbohydrate reserve depletion and stress-induced plant decline and mortality (e.g., Carnicer
281 *et al.*, 2011; Misson *et al.*, 2011).

282

283 **3. To study landscape effects on water availability and quality**

284 *3.1 Research at the patch scale*

285 **Leaf area index (LAI) & hydrological response.** Land use changes, hydro-climatic
286 conditions and fires are the main drivers of vegetation cover changes in MTEs and, therefore,
287 exert great influence on these ecosystems' hydrological responses. Fires, for instance,
288 influence understory regrowth and, hence, may contribute to maintaining ecosystem
289 evapotranspiration fluxes (Macfarlane *et al.*, 2010). Land use history also modulates the
290 hydrological behaviour through changes in soil properties such as soil water repellency and
291 infiltrability (Llovet *et al.*, 2009).

292 Drought-induced vegetation dieback episodes may result in different ecohydrological effects
293 compared to canopy cover changes (Adams *et al.*, 2012). For example, generalised drought-
294 induced defoliation across southern European forests (Carnicer *et al.*, 2011) may gradually
295 reduce stand transpiration (e.g. Limousin *et al.*, 2009). Drought severity and/or duration
296 together with local factors such as soil water-holding capacity (Peterman *et al.* 2012) and
297 species-specific drought-tolerance traits (Jacobsen *et al.*, 2007; Matías *et al.*, 2012) will
298 ultimately determine plant survival and, hence, the impact of episodic drought on
299 hydrological processes.

300 **Temporal variability.** In general, evapotranspiration in MTEs is strongly depressed during
301 summer (Baldocchi *et al.*, 2010; Raz-Yaseef *et al.*, 2012). However, Mediterranean plant
302 species in MTEs show a variety of responses to cope with drought, from complete summer
303 senescence observed in some grasslands (Baldocchi *et al.*, 2004) to various degrees of
304 stomatal control of transpiration (e.g. Quero *et al.*, 2011). In general, increased atmospheric
305 CO₂ concentrations will induce stomatal closure and improve plant water status, enhancing
306 water use efficiency and potentially reducing the effects of increases in evaporative demand.
307 However, the impact of increased CO₂ on ecosystem water use will vary with vegetation type,
308 species and stand development (Li *et al.*, 2003). Regardless of all these functional responses
309 to water deficits, water (and carbon) fluxes in MTEs are strongly reduced during extreme
310 drought events (Granier *et al.*, 2007).

311 **Hydrological equilibrium and simulation models.** In MTEs, maximum LAI is constrained
312 by vegetation type, local climate, and soil conditions, leading to the notion that there is an
313 ‘equilibrium LAI’ that maximises carbon assimilation (Hoff & Rambal, 2003). This
314 hypothesis was framed by La98 within Eagleson’s (1982) broader concept of hydrological
315 equilibrium, but the optimality hypotheses associated with Eagleson’s ecohydrological model

316 have now been questioned in the context of water-limited environments (Kerkhoff *et al.*,
317 2004).

318

319 *3.2 Research at the landscape scale*

320 **Mapping and emergent properties.** The availability of earth observational data for
321 ecological studies has increased due to the launch of several multispectral high/medium
322 spatial resolution platforms and it will increase further in the coming years with Landsat-8
323 and ESA's Sentinel missions. These developments will give continuity to the wide use of
324 remote sensing in previous MTE studies (Shoshany, 2000). Lidar technology is becoming an
325 operative application for acquiring information about forest and shrubland structures in many
326 regions (Estornell *et al.*, 2010; García *et al.*, 2010). In contrast, radar information, a promising
327 data source in the past, has not provided the expected results (Lu, 2006). MTEs have been
328 increasingly studied using remote sensing from different perspectives, including land
329 use/cover changes, drought, carbon budget, and foliar biochemical concentration and canopy
330 structure (e.g. Serrano *et al.*, 2001; Berberoglu & Akin, 2009). Unmanned Aerial Systems
331 (UAV) provide another increasingly popular platform for ecological studies (Dunford *et al.*,
332 2009; Hernández-Clemente *et al.*, 2012). Another area of interest is the use of
333 spectroradiometers as an augmentation to remote sensing for validating or training models
334 (Xu & Baldocchi, 2004; Glenn *et al.*, 2011).

335 **Landscape change.** Different studies at the operational catchment scale in several MTEs
336 have evidenced decreasing trends in the flow records (e.g., Delgado *et al.*, 2010; Zhao *et al.*,
337 2010; see also Lespinas *et al.*, 2010 for contrasting results) and modifications of the flow
338 regime (e.g., López-Moreno *et al.*, 2011; Morán-Tejeda *et al.*, 2011), partly (but not
339 exclusively) attributable to forest expansion. Climate change effects on surface water quality
340 and ecology are attracting growing attention in Mediterranean areas (e.g., Munné & Prat,

341 2011; Otero *et al.*, 2011). Investigations on post-fire flows of soil, water, and nutrients,
342 however, have not been so common, mainly because pre-fire data are frequently unavailable
343 (Shakesby, 2011) and effects of prescribed fires do not directly mimic natural wildfire
344 influences (Seibert *et al.*, 2010).

345 **Simulation models.** Numerous complex hydrological models (often spatially distributed,
346 physically-based) have been used to assess global change effects on water resources, soil
347 erosion and vegetation productivity (e.g., D'Agostino *et al.*, 2010; Senatore *et al.*, 2011).
348 However, there is a growing concern about the current modelling approaches (Ewen *et al.*,
349 2006; Beven, 2011), because of cumulative uncertainties in regional model projections,
350 including uncertainties in downscaling procedures, land-use and land-cover changes, and
351 hydrological model choices.

352

353 **4. To investigate the effects of climate change on ecological diversity**

354 *4.1 Genetic diversity*

355 La98 suggested increasing attention to studies linking genetic diversity with relevant
356 ecosystem functions. However, there is still little knowledge of the adaptive variability
357 present in the different MTEs. The technical difficulty of some measurements, the time-
358 consuming nature of the relevant experiments and the large sample sizes required to
359 determine heritability or selection on functional traits have limited the implementation of
360 reciprocal transplants and/or common garden studies, particularly for long-lived species
361 (Ackerly, 2006). Exceptions include economically important species for which provenance
362 trials have allowed the estimation of ecotypic variation in growth and functional traits (e.g.,
363 Ramírez-Valiente *et al.*, 2009; Kurt *et al.*, 2012).

364 Significant advances have been made in the last decade in understanding the range dynamics
365 of Mediterranean species in response to past climatic changes to validate predictions on

366 ecological and evolutionary consequences of current climate change (e.g., Petit *et al.*, 2005;
367 Petit *et al.*, 2008). In addition, there has been mounting evidence showing that maintaining
368 genetic diversity within natural populations can maximize their potential to withstand and
369 adapt to biotic and abiotic disturbances (Jump *et al.*, 2008).

370

371 *4.2 Species and functional diversity*

372 Since La98 noted the effects of diversity on ecosystem functioning (DEF), those effects have
373 continued to be intensely discussed in MTEs, although the relative importance of DEF in
374 relation to global change still needs to be further assessed (Larsen *et al.*, 2005;
375 Dimitrakopoulos, 2010; Maestre *et al.*, 2012). Further, the role of biodiversity in maintaining
376 man-made systems that provide high value ecosystem services is becoming a key issue in
377 shaping environmental and land use policies (Díaz *et al.*, 2013).

378 In the Mediterranean Basin, higher diversity has been associated with more rapid recovery
379 after fire (Lavorel, 1999). Fire effects also interact with species richness, increasing biomass
380 production in rich communities (Dimitrakopoulos *et al.*, 2006). In most MTEs, restoration of
381 degraded environments due to human alteration could be facilitated by vegetation and soil
382 microbial functional diversity (García-Palacios *et al.*, 2011; Viers *et al.*, 2012). Recent work
383 also emphasizes the role of diversity in the face of invasive species (Prieur-Richard &
384 Lavorel, 2000; Selmants *et al.*, 2012; see also Prieur-Richard *et al.*, 2002 for contrasting
385 results). Also, the effect of invasion-induced species impoverishment on ecosystem
386 functioning is a contested issue (Vilà *et al.*, 2006; Ruwanza *et al.*, 2013).

387 Above-belowground trophic interactions are of potential importance in the functioning of
388 MTEs (e.g., Doblas-Miranda *et al.*, 2009; Janion *et al.*, 2011). Several experiments in the
389 Mediterranean region have related soil respiration and functioning to climate and land-use
390 change (Emmett *et al.*, 2004; Garnier *et al.*, 2007; Lau & Lennon, 2012).

391 The expected increase in aridity in most MTEs may impact plant community dynamics and
392 composition (Lloret *et al.*, 2009; Matías *et al.*, 2012). However, the heterogeneity of
393 Mediterranean landscapes and the variety of responses at different scales give rise to a variety
394 of stabilizing mechanisms promoting community resilience (Lloret *et al.*, 2012) and make
395 predictions difficult (Maestre *et al.*, 2005). Climate change could also affect the biodiversity
396 of important and influential faunal communities (Botes *et al.*, 2006; Gil-Tena *et al.*, 2009).
397 Another promising line of research is to disentangle the combined effects of different factors
398 of change on species and functional diversity (Gil-Tena *et al.*, 2009; Pasquini & Vourlitis,
399 2010).

400

401 *4.3 Landscape diversity*

402 Increasing availability of geospatial information at increasing spatial and temporal resolution
403 has facilitated the study of landscape patterns. Projects in the Mediterranean Basin, in
404 California's Mediterranean landscapes and South Africa boost the development of studies
405 addressing how global change drivers might influence diversity and key ecosystem functions
406 at broad spatial scales (e.g., Santos *et al.*, 2006; Aparicio *et al.*, 2008; García *et al.*, 2011).
407 Current research is demonstrating that landscape structure modulates conservation efforts at
408 local scales due to non-linear effects of landscape diversity on local diversity (Concepción *et al.*,
409 2012). Conservation at local scales would be effective only at intermediate levels of
410 landscape complexity, whereas landscape initiatives would be more effective in the simpler
411 and more complex landscapes (Brotos *et al.*, 2004; Concepción *et al.*, 2008). Landscape-
412 scale management is crucial to preserve both biodiversity and the ecosystem services it
413 provides (Díaz *et al.*, 2013).
414 Landscape heterogeneity effects also have a strong temporal dimension. Due to the long
415 history of land use changes in the Mediterranean Basin, there is increasing evidence of long-

416 term impacts of past land uses on the current state of ecosystems (Puerta-Piñero *et al.*, 2012;
417 Navarro-González *et al.*, 2013). In this way, several projects aim to disentangle the role of
418 past land uses at different scales and in different ecosystems (Bonet *et al.*, 2010; Ortega *et al.*,
419 2010).

420

421 **UPDATE OF PRIORITIES AND NEW CHALLENGES**

422 **1. Advancement of research effort in MTEs**

423 In general, the study of global change in Mediterranean ecosystems has increased since 1998.
424 The proportion of global change studies on MTEs remains relatively low, but is now closer to
425 the proportion of global change studies devoted to other ecosystems, which have diminished
426 (boreal, tropical) or remained approximately constant (temperate) (Fig. 1). There has been an
427 increase in studies in all four lines of research proposed by La98, especially from the mid
428 2000s, and particularly in the last few years (Fig. 2). This increase is quite similar for fire
429 regimes, water availability and quality, and ecological diversity, and somewhat lower for
430 biosphere-atmosphere interactions. Studies about the effects of global change in
431 Mediterranean ecosystems have been mostly carried out in the Mediterranean Basin (88.4%
432 of the total studies), while studies within this region outside European countries (i.e., the
433 Basin's southern rim) constitute just a small fraction (7.8% of the Mediterranean Basin
434 studies).

435

436 **2. New research priorities**

437 Since 1998, great advances have been made in research techniques and knowledge. Most of
438 the research priorities identified by La98 have been addressed (Table 1), but some remain and
439 new MTE research topics and priorities have also emerged. Our evaluation has identified (i)
440 topics listed in La98 which have been only partially addressed, (ii) new approaches to

441 questions already suggested by La98, and (iii) a new set of emerging issues (Table 2). We
442 suggest a new classification of these priorities based on a framework describing how
443 Mediterranean ecosystems will respond to human-induced global change, including
444 ecosystem services derived from ecosystem functioning, and incorporating mechanisms of
445 monitoring, studying and seeking to modify these responses (Figure 3).

446 In our proposed scheme, the first step in organizing future research efforts on global change in
447 MTEs (and other ecosystem types) is to understand the effect of global change drivers on
448 ecosystem functioning. Second, these processes must be monitored, and data must be
449 appropriately analysed to produce useful research outputs. Third, this information should be
450 used to guide ecosystem management aiming at modifying the observed or expected effects.
451 Fourth, the link between ecosystem functioning and ecosystem services should be made
452 explicit, in order to fully realize the opportunities offered by ecosystem management in a
453 global change context. Finally, all the previous steps will depend on spatial and temporal
454 scales of functioning, observation and management, which should be analyzed by means of
455 ecosystem modelling approaches and well-designed, critical experiments.

456

457 *2.1. Effects of the interactions between global change drivers on ecosystem functioning*

458 **1) To establish the role of the landscape mosaic on fire-spread.** A major challenge remains
459 to establish how direct and indirect fire suppression policies influence fire regimes. These
460 policies operate in spatially explicit landscapes that are determined by fuel load and
461 continuity, which in turn determine fire regime. Specifically, we need to better understand the
462 fraction and distribution of agricultural land needed to prevent the spread of megafires, and
463 the role of the critical wildland-urban interface, as well as the associated modification of
464 landscape structure, in preventing the massive crown fires that can cause megafires (Loepfe *et*
465 *al.*, 2012; Keeley *et al.* 2012). In addition, the disruption of the landscape-fire interaction by

466 extreme climatic episodes should be included in these analyses, and increasing vulnerability
467 to fires should be addressed in areas where climate is becoming similar to that of the existing
468 Mediterranean regions.

469 **2) To further research the combined effect of different drivers on biological invasions**

470 **and pest expansion.** Since La98 did not address the impact of fire in combination with

471 factors other than climate change and land use, it did not include biological invasions. The

472 effect of biological invasions in combination with different climatic events (e.g., droughts),

473 disturbance (e.g., fires), and landscape structure (e.g., the wild-land and urban interface) on

474 biodiversity and ecosystem functioning stands as a priority for future research efforts. For

475 example, the impact of the combination of fire and invading biota may be especially

476 important in Mediterranean regions where the spread of invasive species is altering fire

477 regimes. In addition, it is important to assess the influence of climate change combined with

478 land use change in the expansion of certain pest species (native or not) in previously non-

479 accessible habitats like mountains. This new focus will complement the more classical, but

480 still much-needed, analyses on how responses of keystone species or communities to global

481 change may ameliorate or amplify direct effects on forest structure and function (e.g.

482 Valladares *et al.*, 2013).

483 **3) To address the interaction between global change drivers and recent forest**

484 **management practices.** Human influences have shaped the current structure and composition

485 of MTEs and their woodlands. In some regions these impacts have built up over the last

486 decades as a result of changes in forest management and land use practices. In the

487 Mediterranean basin, for instance, there is a widespread process of forest densification owing

488 to widespread abandonment of intensive forest management. This process has critical

489 implications in a global change context, as it affects fire spread and recovery after fire (e.g.,

490 Puerta Piñero *et al.*, 2012), and increases the competition for water and therefore the

491 likelihood of drought-induced forest die-off (Martínez-Vilalta *et al.*, 2012). Although the
492 demographic implications of the interaction between changes in climate and competition are
493 starting to be addressed (Vilà-Cabrera *et al.*, 2011; Ruiz-Benito *et al.*, 2013) there is an urgent
494 need to expand these studies in order to disentangle the contribution of different drivers (and
495 their interaction) to current stand dynamics and to translate this information into credible
496 models of future forest dynamics.

497

498 *2.2. Monitoring and data assessment of ecosystem response to global change*

499 **4) To obtain more realistic information, at larger temporal and spatial scales, of global**
500 **change impacts and ecosystem services to be used in models.** La98 already advised that, in
501 order to disentangle the effects of landscape change on hydrological properties, research on
502 larger spatial scales is necessary. In fact, other ecosystem services such as carbon storage are
503 also better defined and studied at larger spatial and longer temporal scales (e.g., Vayreda *et*
504 *al.*, 2012). Similar reasoning can be applied to the factors that alter these services. For
505 example, there is a need for reliable information on the efficiency of different fire and fuel
506 management alternatives at reasonably large spatiotemporal scales. Long-term manipulative
507 experiments show that ecosystem responses to disturbance frequently change over time (e.g.,
508 Barbeta *et al.*, 2013). Thus, the data inputs for model calibration and validation should
509 include, to the extent possible, long time series of observational data as well as long-term
510 ecosystem manipulation experiments (ecotron) focusing on key drivers (cf., Beier *et al.*,
511 2012).

512 **5) To assess forest mortality events associated with climatic extremes (particularly**
513 **drought).** The drought-induced forest decline detected during recent decades remains
514 insufficiently understood, as it is not yet known which biological mechanisms are involved
515 and which factors other than drought have played causal roles. In MTEs, elevation, substrate,

516 plant composition, stand structure, and soil biota all appear to contribute to the forest die-off
517 (e.g., Martínez-Vilalta *et al.*, 2012). Forest history and, particularly, management, appear to
518 be key drivers, for instance, by determining current forest structure and composition. Strategic
519 actions include long term monitoring at regional scale, with implementation of common
520 protocols, and rapid identification of new events (using for example remote sensing or
521 UAVs), which would make it possible to study the process while it is happening. These
522 actions would benefit critically from the involvement of forest owners and governmental
523 agencies.

524

525 *2.3. Managing ecosystems to enhance resilience*

526 **6) To focus global change research on identifying and managing vulnerable areas.** Future
527 research efforts should aim at identifying areas that might suffer from the combination of
528 multiple climate change drivers. For instance, mountains and sub-Mediterranean zones may
529 be particularly susceptible to the likely increase of climatic fire risk, because these are
530 landscapes that have not previously faced high fire risks they therefore may have low
531 vegetation resilience (Lloret *et al.*, 2005). Other susceptible areas include those where land
532 use transformation has led to high fuel load and, thus, high risk of massive crown fires.
533 Similarly, the recent increase in temperature is likely to favour insect expansion, and
534 unprecedented insect outbreaks can arise in areas with high tree density and landscape
535 connectivity. The resulting management agenda should include the adaptation of MTEs to
536 more arid conditions, for instance by species selection, or by management of stand and
537 landscape structure and water use. Here, one major challenge is to determine how the
538 suppression of wildfires and other management actions could eventually induce non-
539 reversible state transitions of vegetation types and structure, resulting in service-impoverished
540 states.

541 **7) To use the functional and life-history traits concepts to study resilience and**
542 **community assembly after disturbance.** Although the possibility of threshold-type
543 responses in ecosystems is real and should be taken into account, ecosystem resilience to
544 climate change is frequently substantial, and deserves further study (cf. Lloret *et al.*, 2012).
545 Given the variability of species responses to different disturbance types (e.g., plant responses
546 to fire regimes: Pérez *et al.*, 2003; Rey Benayas *et al.*, 2007) and the complexity of the factors
547 shaping community dynamics, there is an urgent need to find synthetic, yet powerful
548 approaches to predict the ecosystem-level effects of environmental changes. In that respect,
549 the functional trait concept has strong conceptual appeal (Lavorel & Garnier, 2002), although
550 its empirical applicability remains to be properly established.

551 **8) To promote cross-disciplinary research to study the relationship between genotypic**
552 **and phenotypic diversity as a source of forest resilience.** Given the complexities
553 underlying evolutionary processes, there is a clear need to intensify cross-disciplinary
554 research among different disciplines such as genetics, genomics, demography, functional
555 ecophysiology, and animal-plant interactions in order to investigate the effects of climate
556 change on genetic diversity. Reciprocal transplants and common garden experiments, linked
557 to next generation sequencing approaches, have yet to be fully applied in Mediterranean
558 contexts. To understand how Mediterranean species will respond to global change in the long
559 term and what the genetic basis of this response will be, it is essential to identify genes under
560 natural selection, as well as to ascertain the relationship between naturally occurring
561 genotypic and phenotypic diversity.

562

563 *2.4. Embracing the link between ecosystem functions and services*

564 **9) To understand how forest management affects the balance between C storage and**
565 **water resources at large spatial and temporal scales.** It has been recently suggested that

566 management could increase the C storage capacity of forests (Vayreda *et al.*, 2012), although
567 the detailed mechanisms are yet to be properly characterized. Indeed, when assessing the C
568 absorption capacity of MTE forests, it is necessary to consider the importance of the water
569 balance; tree density and species should be managed cautiously since high transpiration rates
570 also imply high water losses in the system. The search for management practices favouring C
571 storage should take into account the risk of forest decline due to water scarcity.

572 **10) To analyse the interplay between landscape-scale processes and biodiversity**
573 **conservation along wide gradients of landscape complexity.** Overall, large-scale
574 collaborative efforts among teams in different regions should be promoted and prioritised in
575 order to fully understand how and why landscape processes influence the responses of MTEs
576 to global change. Biodiversity will likely be crucial in modulating such responses, so effective
577 conservation strategies over wide gradients of landscape complexity need to be designed and
578 effectively implemented. In addition, research on the social and economic role of biodiversity
579 in the maintenance of land use systems is urgently needed (Campos *et al.*, 2013) in order to
580 establish how and why biodiversity is contributing to the ecological and economic
581 sustainability of Mediterranean low-intensity management systems of high natural value.

582

583 *2.5. Scaling ecosystem dynamics in space and time under different scenarios*

584 **11) To refine predictive models by including interactions between global change drivers**
585 **and socio-economic contexts.** More attention should be given to anthropogenic factors when
586 generating landscape projections (Serra *et al.*, 2008), to understand not only future fire
587 impacts (Brotons *et al.*, 2013), but also other components of global change such as biological
588 invasions and land use changes, taking into account interactions between these major drivers
589 and the impacts on associated ecosystem services (Campos *et al.*, 2013). Among these factors,
590 further research needs to focus on the integration of already available socioeconomic

591 scenarios into predictive models of land-use driven climatic change (Verburg *et al.*, 2010; Li
592 *et al.*, 2011). The development of reference scenarios of land use and forest change that can
593 be used consistently together with available climate change scenarios remains a gap in current
594 global change science. Furthermore, even if the present review is focussed on forests,
595 shrublands and pastures, to simulate biosphere-atmosphere interactions in other key
596 ecosystems such as croplands and urban environments should be considered.

597 **12) To use manipulative, interdisciplinary and multi-scale experiments to understand**
598 **forest-atmosphere feedbacks.** La98 were already conscious that manipulative experiments at
599 large scales are needed to fully understand the feedbacks between terrestrial ecosystems and
600 the atmosphere, in addition to a wider use of historical data. We have learned from a first
601 generation of manipulative field experiments and we are now in a position to use new designs
602 that are larger in scope and make full use of research networks working with standardised
603 protocols (e.g., see the review by Beier *et al.*, 2012, for precipitation manipulation
604 experiments). Multifactorial (e.g., CO₂ x Warming x Drought) and interdisciplinary
605 experiments combining different experimental approaches (field and microcosm experiments)
606 with the use of innovative techniques (e.g., genome pyrosequencing, solid-state nuclear
607 magnetic resonance) will facilitate the identification of key mechanisms and their integration
608 into predictive models. Emerging issues, such as altered BVOC emissions, nutrient
609 imbalances, and soil microbial processes, deserve special attention.

610 **13) To improve the representation of key mechanisms linking plant hydraulics with**
611 **landscape hydrology.** There is a need for improved representations of soil and plant
612 hydraulics in process models of water and carbon fluxes, both in general and for
613 Mediterranean vegetation in particular (e.g. Hernández-Santana *et al.*, 2009). Mechanisms
614 leading to drought-induced vegetation die-off are poorly understood and their representation
615 in models is frequently inadequate (McDowell *et al.*, 2013), which limits our capacity to

616 predict vegetation shifts and corresponding ecosystem-level implications (Anderegg *et al.*,
617 2013). In addition, hydrological predictions are complicated by the difficulty in properly
618 accounting for ‘natural’ successional dynamics and predicting stochastic events like insect
619 outbreaks and fire occurrence.

620

621 **3. Broad recommendations**

622 From the full list of priorities offered in Table 2, three broad recommendations serve as a
623 conclusion:

624 1) The interactive nature of different global change drivers remains poorly understood.

625 Different global change factors and their interactions, as well as socio-economic constraints,
626 must be included in the forecasts and modelling of future ecosystem changes.

627 2) There is a critical need for rapidly developing regional and global scale models. Better
628 networking of research data, as well as manipulative experiments, covering different abiotic
629 and biotic factors and different temporal and spatial scales, is needed to calibrate and validate
630 these ecological models.

631 3) More attention should be directed at emerging issues especially related to MTEs in the face
632 of global change, including recent drought-related forest decline and the current consequences
633 of historical land uses.

634 Although the MTEs are the focus on our evaluation and they are the direct targets of our
635 recommendations, we believe that these ecosystems serve as good reference laboratories for
636 global change research more broadly and that our broad recommendations can be applied to
637 other ecosystem types. Global change research in MTEs, and especially in the Mediterranean
638 Basin, is mature enough to move a step forward and launch into an integrative phase. In this
639 phase, research on global issues should become more inclusive and allow the development of
640 joint projections on how ecosystems and the services they provide are expected to react to

641 different scenarios of future change. This is the information that societies are likely to need in
642 order to adapt to the new, uncertain changes to come.

643

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650

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- 1239
- 1240 **BIOSKETCH**

1241 E D-M is the research coordinator of the MONTES-Consolider project
1242 (<http://www.creaf.uab.es/MONTES/>), which aims to examine the relationship of
1243 Mediterranean woodlands with the components of global change, and to identify opportunities
1244 to modify these components through appropriate woodland management. The present paper
1245 synthesizes most of the work carried out preparing the background of that project and
1246 analysing its outputs. E D-M, J R, J M-V and P L conceived the ideas and principal scheme of
1247 the manuscript. E D-M led the writing, with all authors contributing their different areas of
1248 expertise.

1 Table 1. Overview of the degree of accomplishment of La98 priorities by the scientific community. It should be
 2 noted that, while practical for abstracting purposes, categorical “yes” or “no” are never applied to science. We
 3 recommend therefore consider “yes” as “great effort invested in this particular subject” and “no” as “although
 4 some attempts have been made to study the subject, it still needs further development”.

Previous priorities		Accomplishment quick view	
1. Understand future fire regimes	1.1 Prediction	<i>Effects of land use</i>	Partially
		<i>Effects of climate</i>	Yes
		<i>Effects of atmospheric composition</i>	No
	1.2 Impacts	<i>On landscape</i>	Yes
		<i>On vegetation</i>	Partially
		<i>Combined with climate change</i>	Yes
		<i>On ecosystem processes</i>	Partially
	1.3 Control	<i>Prevention</i>	Yes
<i>Restoration</i>		Partially	
2. Study biosphere-atmosphere interactions	2.1 Land use and climate		Partially
	2.2 Physiology and climate	<i>CO₂ & temperature</i>	Partially
		<i>Temperature & biogenic emissions</i>	Partially
	2.3 Fire emissions		Yes
	2.4 Coupled models		Partially
3. Landscape effects on water	3.1 Patch scale	<i>LAI & hydrological response</i>	Yes
		<i>Hydrological equilibrium</i>	Partially
		<i>Temporal variability</i>	Partially
		<i>Simulation models</i>	No
	3.2 Landscape scale	<i>Mapping</i>	Yes
		<i>Scales and emergent properties</i>	Yes
		<i>Landscape change</i>	Yes
		<i>Simulation models</i>	Partially
4. Changes in ecological diversity	4.1 Genetic		Partially
	4.2 Species and functional		Partially
	4.3 Landscape		Partially

5

6

- 1 Table 2. Proposed research priorities for Mediterranean terrestrial ecosystems in the face of
 2 global change.

New Priorities
Effects of the interactions between global change drivers on ecosystem functioning
1 To establish the role of the landscape mosaic on fire-spread
2 To further research the combined effect of different drivers on biological invasions and pest expansion
3 To address the interaction between global change drivers and recent forest management practices
Monitoring and data assessment of ecosystem response to global change
4 To obtain more realistic information, at larger temporal and spatial scales, of global change impacts and ecosystem services to be used in models
5 To assess forest mortality events associated with climatic extremes (particularly drought)
Managing ecosystems to enhance resilience
6 To focus global change research on identifying and managing vulnerable areas
7 To use the functional and life-history traits concepts to study resilience and community assembly after disturbance
8 To promote cross-disciplinary research to study the relationship between genotypic and phenotypic diversity as a source of forest resilience
Embracing the link between ecosystem functions and services
9 To understand how forest management affects the balance between C storage and water resources at large spatial and temporal scales
10 To analyse the interplay between landscape-scale processes and biodiversity conservation along wide gradients of landscape complexity
Scaling ecosystem dynamics in space and time under different scenarios
11 To refine predictive models by including interactions between global change drivers and socio-economic contexts
12 To use manipulative, interdisciplinary and multi-scale experiments to understand forest-atmosphere feedbacks
13 To improve the representation of key mechanisms linking plant hydraulics with landscape hydrology

3

4

1 Figure 1. Trends in published research articles (excluding reviews and meeting abstracts)
2 related to global change and Mediterranean forests in the scientific literature, for the years
3 1998–2012, based on ISI Web of Science search. The term forest, but not shrublands or
4 pastures, has been used for comparative purposes. Plotted lines show the percentage of
5 references retrieved using the topic words “(forest change) AND (fire or atmospher* or "land
6 use" or water or diversity) NOT (marine sea)” plus a regional definition (Mediterranean,
7 Boreal, Tropical or Temperate), relative to all references obtained without the regional
8 specification.

9

10 Figure 2. Trends in published research articles (excluding reviews and meeting abstracts)
11 related to global change and forests in the scientific literature, for the years 1998–2012, based
12 on ISI Web of Science search. The term forest, but not shrublands or pastures, has been used
13 for comparative purposes. Plotted lines show the total of references, after a one by one
14 selective review to avoid articles not really related with the subject, using the following topic
15 words:

16 For fire regimes: (*Mediterranean forest fire change*) AND (*predict* OR model OR simulation OR impact OR*
17 *effect OR consequence OR control OR prevention OR restoration*) AND (*"land use" OR "land cover" OR*
18 *landscape OR climate OR temperature OR humidity OR moisture OR atmospher* OR plant OR vegetation OR*
19 *"ecosystem processes"*) NOT (*marine sea*)

20 For biosphere-atmosphere interactions: (*Mediterranean forest atmospher* change*) AND (*feedback OR model*
21 *OR soil OR physiology OR biogenic OR volatile OR emissions OR monitoring OR carbon OR "trace gases" OR*
22 *"nitro* oxides" OR ammonia OR sulphur OR ozone OR transpiration OR eddy-covariance*) AND (*"land use" OR*
23 *"land cover" OR landscape OR climate OR temperature OR humidity OR water OR energy OR moisture OR fire*
24 *OR plant OR tree OR vegetation OR "ecosystem processes"*) NOT (*marine sea*)

25 For water availability and quality: (*Mediterranean forest water change*) AND (*availability OR quality OR model*
26 *OR simulation OR flow OR flux OR "patch scale" OR "landscape scale" OR "leaf area" OR hydrological OR*
27 *"temporal variability" OR trend OR mapping OR "remote sensing" OR catchment*) AND (*"land use" OR "land*
28 *cover" OR landscape OR climate OR temperature OR humidity OR moisture OR atmospher* OR fire OR plant*
29 *OR vegetation OR "ecosystem processes"*) NOT (*marine sea*)

30 For ecological diversity: (*Mediterranean forest diversity change*) AND (*bioindicator OR conservation OR*
31 *restoration OR heterogeneity OR trait OR genotyp* OR phenotyp* OR model OR simulation OR impact OR*

1 *effect OR trophic OR genetic OR species OR functional Or ecological OR biological) AND ("land use" OR "land*
2 *cover" OR landscape OR climate OR temperature OR humidity OR moisture OR fire OR invasi* OR atmospher**
3 *OR soil OR "ecosystem processes" OR "ecosystem function*") NOT (marine sea)*

4

5 Figure 3. Framework for global change research priorities in Mediterranean terrestrial

6 ecosystems. The framework is structured according to different causal and observational

7 pathways, as follows: 1) Effects of the interactions between global change drivers on

8 ecosystem functioning. 2) Monitoring and data assessment of ecosystem response to global

9 change. 3) Managing ecosystems to enhance resilience. 4) Embracing the link between

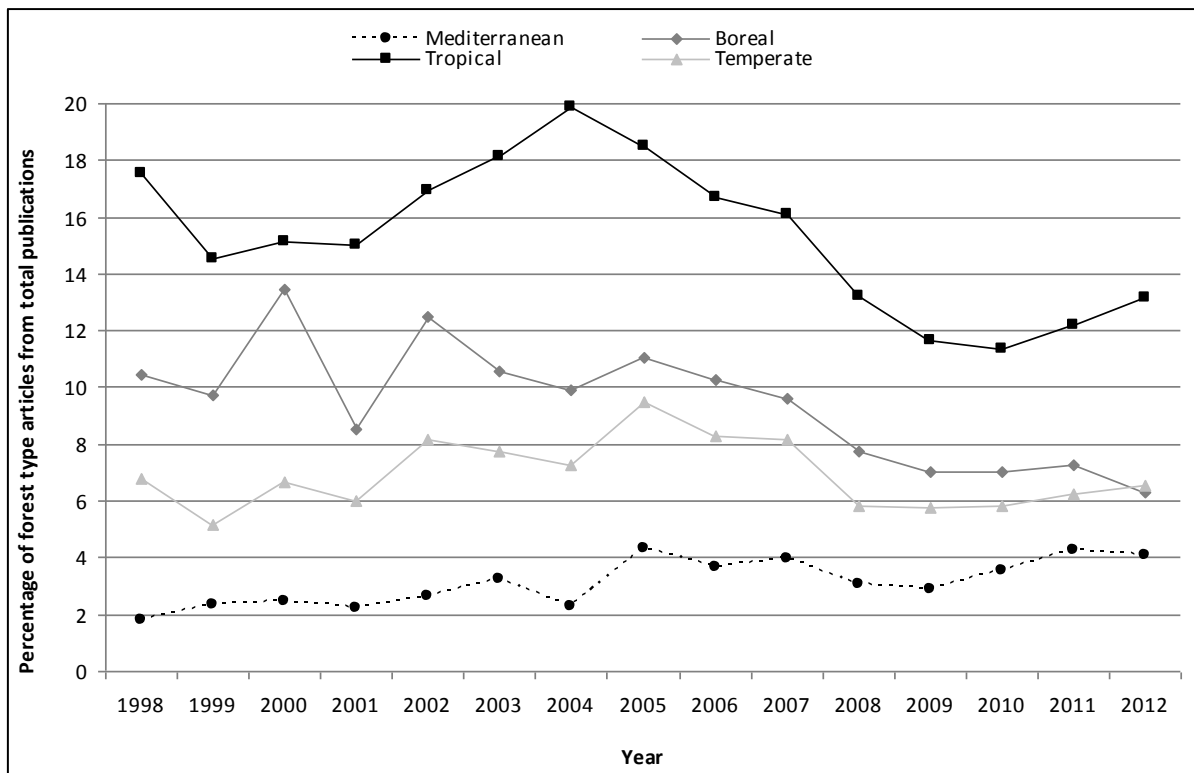
10 ecosystem functions and services. 5) Scaling ecosystem dynamics in space and time under

11 different scenarios.

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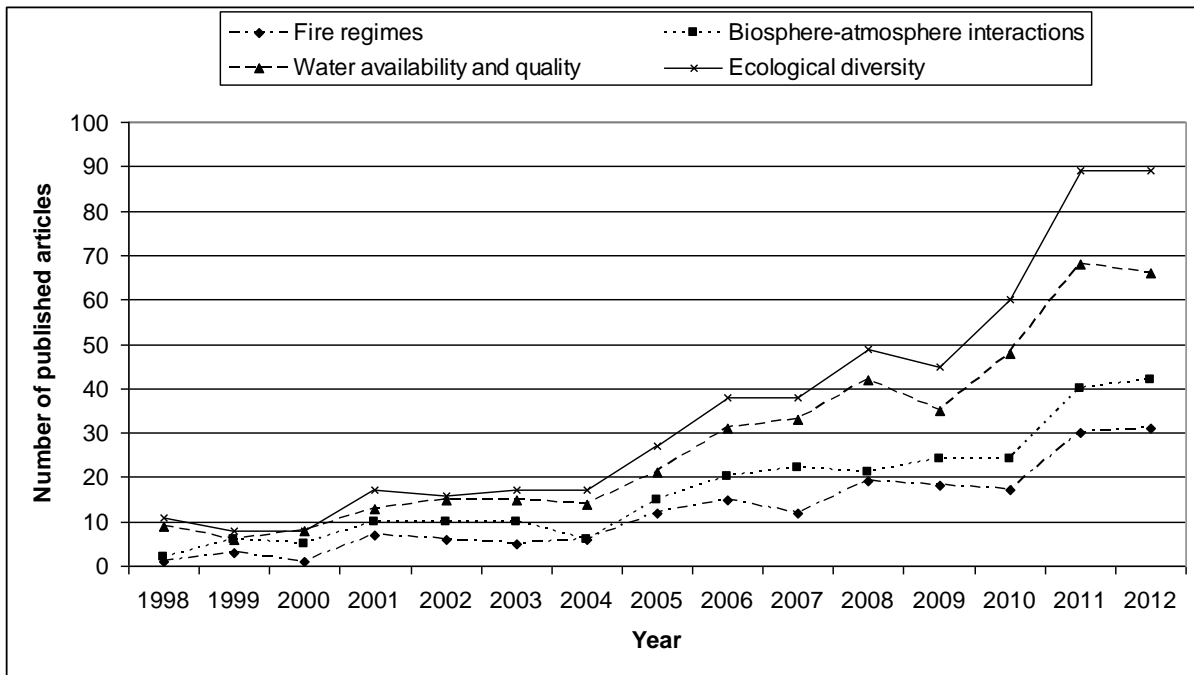
1 Figure 1



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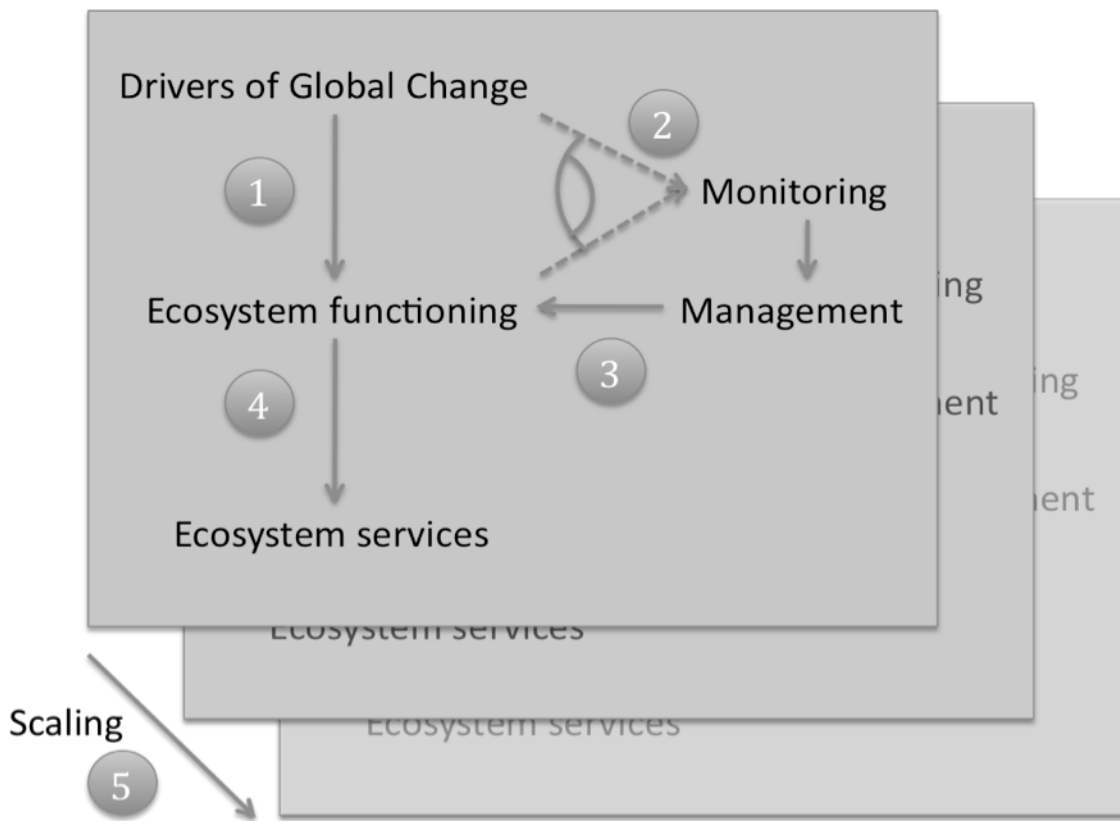
1 Figure 2



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1 Figure 3



2