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Review

Ecological impacts of atmospheric pollution and interactions with climate change in terrestrial ecosystems of the Mediterranean Basin: Current research and future directions☆

Raúl Ochoa-Hueso [a, *, 1], Silvana Munzi [b, 1], Rocío Alonso [c], María Arróniz-Crespo [d], Anna Avila [e], Victoria Bermejo [c], Roland Bobbink [f], Cristina Branquinho [b], Laura Concostrina-Zubiri [b], Cristina Cruz [b], Ricardo Cruz de Carvalho [b], Alessandra De Marco [g], Teresa Dias [b], David Elustondo [h], Susana Elvira [c], Belén Estébanez [i], Lina Fusaro [j], Giacomo Gerosa [k], Sheila Izquieta-Rojano [h], Mauro Lo Cascio [l], Riccardo Marzuoli [k], Paula Matos [b], Simone Mereu [l], José Merino [m], Lourdes Morillas [l], Alice Nunes [b], Elena Paoletti [n], Luca Paoli [o], Pedro Pinho [b, p], Isabel B. Rogers [q], Arthur Santos [b], Pierre Sicard [r], Carly J. Stevens [q], Mark R. Theobald [c]

[a] Autonomous University of Madrid, Department of Ecology, 2 Darwin Street, Madrid 28049, Spain
[b] cE3c Centre for Ecology, Evolution and Environmental Changes, Faculdade de Ciências, Universidade de Lisboa, Campo Grande, C2, Piso 5, 1749-016 Lisbon, Portugal
[c] Air Pollution Division, CIEMAT, Avda. Complutense 22 (edif. 70), Madrid 28040, Spain
[d] Escuela Técnica Superior de Ingenieros Agrónomos, Universidad Politécnica de Madrid, Ciudad Universitaria, 28040 Madrid, Spain
[e] Center for Ecological Research and Forestry Applications (CREAF), Universitat Autònoma de Barcelona, 08193 Bellaterra, Spain
[f] B-WARE Research Centre, Radboud University, PO Box 9010, 6525 ED Nijmegen, The Netherlands
[g] ENEA, Via Anguillarese 301, 00123 Rome, Italy
[h] LICA, Department of Chemistry and Soil Science, University of Navarre, Irunlarrea, 1-31008 Pamplona, Spain
[i] Departamento de Biología, Unidad de Botánica, Universidad Autónoma de Madrid, C/ Darwin 2, 28049, Madrid, Spain
[j] Dept. of Environmental Biology, Sapienza University of Rome, Piazzale Aldo Moro 5, Rome, Italy
[k] Dept. of Mathematics and Physics, Catholic University of Brescia, Via dei Musei 41, Brescia, Italy
[l] Department of Science for Nature and Natural Resources, University of Sassari, Via Enrico De Nicola 1, 07100 Sassari, Italy
[m] Departamento de Sistemas Físicos, Químicos y Naturales, Universidad Pablo de Olavide, Ctra. de Utrera km. 1, 41013 Sevilla, Spain
[n] IPSP-CNR, Via Madonna del Piano 10, 50019, Sesto Fiorentino, Florence, Italy
[o] Department of Life Sciences, University of Siena, Via Mattioli 4, I-53100 Siena, Italy
[p] CERENA-IST-UL, Centro de Recursos Naturais e Ambiente, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais, 1049-001 Lisboa, Portugal
[q] Lancaster Environment Center, Lancaster University, Lancaster LA1 4YQ, UK
[r] ACRI-ST, 260 route du Pin Montard, BP 234, 06904 Sophia Antipolis Cedex, France

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ABSTRACT

Mediterranean Basin ecosystems, their unique biodiversity, and the key services they provide are currently at risk due to air pollution and climate change, yet only a limited number of isolated and geographically-restricted studies have addressed this topic, often with contrasting results. Particularities of air pollution in this region include high O_3 levels due to high air temperatures and solar radiation, the stability of air masses, and dominance of dry over wet nitrogen deposition. Moreover, the unique abiotic and biotic factors (e.g., climate, vegetation type, relevance of Saharan dust inputs) modulating the response of Mediterranean ecosystems at various spatiotemporal scales make it difficult to understand, and thus predict, the consequences of human activities that cause air pollution in the Mediterranean Basin. Therefore, there is an urgent need to implement coordinated research and experimental platforms along with wider environmental monitoring networks in the region. In particular, a robust deposition monitoring network in conjunction with modelling estimates is crucial, possibly including a set of

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* Corresponding author.
E-mail address: rochoahueso@gmail.com (R. Ochoa-Hueso).

[1] These authors contributed equally to this work.

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Functional diversity
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common biomonitors (ideally cryptogams, an important component of the Mediterranean vegetation), to help refine pollutant deposition maps. Additionally, increased attention must be paid to functional diversity measures in future air pollution and climate change studies to establish the necessary link between biodiversity and the provision of ecosystem services in Mediterranean ecosystems. Through a coordinated effort, the Mediterranean scientific community can fill the above-mentioned gaps and reach a greater understanding of the mechanisms underlying the combined effects of air pollution and climate change in the Mediterranean Basin.

1. Introduction

Human activities and natural processes have shaped each other over ca. eight millennia within Mediterranean Basin ecosystems (Blondel, 2006). This coevolution, together with the heterogeneous orography and geology, the large seasonal and inter-annual climatic variability, the refuge effect during the last glaciations, and the crossroad location between European temperate ecosystems and North African and Asian drylands, has resulted in the high diversification of the flora and fauna that we observe today, making Mediterranean ecosystems a hotspot of biodiversity, but also of vulnerability (Schröter *et al.*, 2005; Blondel, 2006; Phoenix *et al.*, 2006). Moreover, the Mediterranean Basin is one of the world's largest biodiversity hotspots and the only one within Europe, otherwise dominated by temperate natural and semi-natural grasslands, temperate deciduous forests and boreal conifer forests (Myers *et al.*, 2000). Species-rich ecosystems exclusive to the Mediterranean Basin include Spanish *matorrales* and *garrigas*, Portuguese *matos*, Italian *macchias*, Greek *phryganas*, and agro-silvopastoral ecosystems of high natural and economic value such as Spanish *dehesas* and Portuguese *montados* (Cowling *et al.*, 1996; Blondel, 2006). However, the biodiversity and other ecosystem services of this region are currently at risk due to human pressures such as climate change, land degradation and air pollution (Schröter *et al.*, 2005; Scarascia-Mugnozza and Matteucci, 2012). Air pollution in the Mediterranean Basin is primarily in the form of particulate matter, nitrogen (N) deposition and tropospheric ozone (O_3) (Paoletti, 2006; Ferretti *et al.*, 2014; García-Gómez *et al.*, 2014; Fig. 1). Production of pollutants is mainly associated with industrial activities, construction, vehicle emissions and agricultural practices and, within the European context, is characteristically exacerbated by more frequent droughts and the typical stability of air masses in the region, with important consequences for ecosystem and human health (Millán *et al.*, 2002; Vestreng *et al.*, 2008; Izquieta-Rojano *et al.*, 2016a). This also has important social consequences for the Mediterranean region, where approximately 480 million people live, and where more frequent droughts, extreme climatic events and wildfires will only reinforce the current migrant and humanitarian crisis (Werz and Hoffman, 2016).

Environmental pollution causes and interacts synergistically with climate change (Alonso *et al.*, 2001, 2014; Bytnerowicz *et al.*, 2007; Sardans and Peñuelas, 2013). This is particularly true for seasonally dry regions like the Mediterranean Basin (Baron *et al.*, 2014), but the effects of this interaction on the structure and function of Mediterranean ecosystems are not adequately quantified and, therefore, the consequences are poorly understood (Bobbink *et al.*, 2010; Ochoa-Hueso *et al.*, 2011). Projections for 2100 suggest that mean air temperatures in the Mediterranean Basin region will rise from 2.2 °C to 5.1 °C above 1990 levels and that precipitation will decrease between −4 and −27% (Christensen *et al.*, 2007 and Fig. 2). The sea level is also projected to rise, and a greater frequency and intensity of extreme weather events (e.g., drought, heat waves and floods) are expected (EEA, 2005). These changes will exacerbate the already acute water shortage problem in the region, particularly in drylands (Terray and Boé, 2013; Sicard and Dalstein-Richier, 2015), impairing their functionality and ability to deliver the ecosystem services on which society and economy depend (Bakkenes *et al.*, 2002; Lloret *et al.*, 2004). Functions that will be synergistically impaired by air pollution and climate change include reductions in crop yield and carbon sequestration (Maracchi *et al.*, 2005; Mills and Harmens, 2011; Shindell *et al.*, 2012; Ferretti *et al.*, 2014). In addition, a higher fire risk is attributed to higher temperatures and more frequent droughts coupled with an N-driven increase of grass-derived highly-flammable fine fuel (Pausas and Fernández-Muñoz, 2012).

In the last decades, atmospheric concentrations of major anthropogenic air pollutants such as particulate matter and sulphur dioxide (SO_2) have decreased in Southern Europe due to emission control policies and greener technologies (Querol *et al.*, 2014; Barros *et al.*, 2015; Aguillaume *et al.*, 2016; Àvila and Aguillaume, 2017). However, mitigation strategies have not been equally effective with other compounds such as reactive N and tropospheric O_3 (Fig. 1; Paoletti, 2006; García-Gómez *et al.*, 2014; Sicard *et al.*, 2016). For example, recent increases in N deposition, particularly dry deposition of NO_3, have been detected in North-eastern Spain, where N deposition is estimated in the range of 15–30 kg N ha^{-1} yr^{-1} (Avila and Rodà, 2012; Camarero and Catalan, 2012; Aguillaume *et al.*, 2016). This has been attributed to increased nitrogen oxide (NO_x) and ammonia (NH_3) emissions and changes in precipitation patterns (Aguillaume *et al.*, 2016). Background O_3 pollution is typically high in Mediterranean climates due to the meteorological conditions of the area (Paoletti, 2006) and recent reviews have demonstrated that while O_3 in cities has generally increased, no clear trend, or only a slight decrease, has been detected in rural areas (Sicard *et al.*, 2013; Querol *et al.*, 2014); the annual average at rural western Mediterranean sites over the period 2000–2010 was 33 ppb, with a modest trend of −0.22% yr^{-1} (Sicard *et al.*, 2013). The Mediterranean Basin is also exposed to frequent African dust intrusions, which can naturally increase the level of suspended particulate matter and nutrient deposition, changing the chemical composition of the atmosphere (Escudero *et al.*, 2005; Marticorena and Formenti, 2013; Àvila and Aguillaume, 2017). This has profound impacts on the biogeochemical cycles of both aquatic and terrestrial ecosystems (Mona *et al.*, 2006), further exacerbating the negative consequences of air pollution and climate change on ecosystem and human health.

In this review, originated as a result of the 1st CAPER*med* (Committee on Air Pollution Effects Research on Mediterranean Ecosystems; http://capermed.weebly.com/) Conference in Lisbon, Portugal, we (i) summarize the current knowledge about atmospheric pollution trends and effects, and their interactions with climate change, in terrestrial ecosystems of the Mediterranean Basin, (ii) identify research gaps that need to be urgently filled, and (iii) recommend future steps. Due to lack of information for other regions within the Mediterranean Basin, we mainly focused our review on studies carried out in south-western European countries