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Invited research article

Land-use history as a major driver for long-term forest dynamics in the Sierra de Guadarrama National Park (central Spain) during the last millennia: implications for forest conservation and management

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ABSTRACT

In the Mediterranean Basin, long-lasting human activities have largely resulted in forest degradation or destruction. Consequently, conservation efforts aimed at preserving and restoring Mediterranean forests often lack well-defined targets when using current forest composition and structure as a reference. In the Iberian mountains, the still widespread *Pinus sylvestris* and *Quercus pyrenaica* woodlands have been heavily impacted by land-use. To assess future developments and as a baseline for planning, forest managers are interested in understanding the origins of present ecosystems to disclose effects on forest composition that may influence future vegetation trajectories. Quantification of land-use change is particularly interesting to understand vegetation responses. Here we use three well-dated multi-proxy palaeoecological sequences from the Guadarrama Mountains (central Spain) to quantitatively reconstruct changes occurred in *P. sylvestris* forests and the *P. sylvestris-Q. pyrenaica* ecotone at multi-decadal to millennial timescales, and assess the driving factors. Our results show millennial stability of *P. sylvestris* forests under varying fire and climate conditions, with few transient declines caused by the combined effects of fire and grazing. The high value of pine timber in the past would account for long-lasting pine forest preservation and partly for the degradation of native riparian vegetation (mostly composed of *Betula* and *Corylus*). Pine forests further spread after planned forest management started at 1890 CE. In contrast, intensive coppicing and grazing caused *Q. pyrenaica* decline some centuries ago (ca. 1500–1650 CE), with unprecedented grazing during the last decades seriously compromising today's oak regeneration. Thus, land-use history played a major role in determining vegetation changes. Finally, we must highlight that the involvement of forest managers in this work has guaranteed a practical use of palaeoecological data in conservation and management practice.

1. Introduction

Land-use has long been causing important changes in the distribution, structure and composition of forest ecosystems in the Mediterranean realm, often involving their overexploitation, degradation and even destruction (Carrión et al., 2003; Urbieta et al., 2008; Valbuena-Carabaña et al., 2010). Despite this long history of intense land-use, the Mediterranean mountains of south-western Europe still host relatively extensive forested areas that provide not only valuable natural resources such as timber, firewood and pastures, but also ecosystem services like protection against natural hazards, carbon sequestration and biodiversity (Díaz-Pinés et al., 2011; Pardos et al., 2016). All these values justify the need for protecting Mediterranean forested areas. However, the disturbed conditions of most Mediterranean forest ecosystems make it difficult to define precise conservation and restoration goals. Thus, disclosing the effects of past human activities on current forest composition and structure is a major question for Spanish forest managers to assess future vegetation dynamics. In this context, a palaeoecological perspective on ecological processes can provide relevant insights into ecosystem baseline conditions (i.e. prior to relevant ecosystem disruption by human agency), the impact of land-use history on vegetation composition and structure, and the range of disturbance variability, thus guiding ecosystem

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conservation and management (Willis and Birks, 2006; Froyd and Willis, 2008; Morales-Molino et al., 2015). In fact, in northern and central Europe multi-proxy studies of sedimentary and peat sequences have usually informed management and conservation of protected areas (e.g. Lindbladh et al., 2008; Valsecchi et al., 2010; Clear et al., 2013), but to our knowledge these studies are still lacking in the Mediterranean Basin.

In the Mediterranean Spanish mountains *Pinus sylvestris* and *Quercus pyrenaica* stands are widespread ecosystems of high ecological value, listed as priority habitats for preservation within the Spanish National Parks (NPs) network. However, the lack of undisturbed *P. sylvestris*- and *Q. pyrenaica*-dominated stands hindered the declaration of National Parks focusing on their protection until recently, because the Spanish NPs aims at protecting ecosystems mostly free of human activities. One of the major goals of the recently declared Sierra de Guadarrama NP in the Iberian Central Range is preserving the extensive and quite continuous *P. sylvestris* forests and *Q. pyrenaica* woodlands of these mountains. However, documentary sources show that *P. sylvestris* and *Q. pyrenaica* stands within this NP have been intensively exploited for centuries to produce timber (pine), firewood/charcoal (oak) and pasturelands (mostly oak), with very different land-use histories depending on the dominant tree species (Manuel-Valdés, 1997). Although multi-centennial coppicing of *Q. pyrenaica* forests for firewood and charcoal production explains the present abundance of highly degraded coppiced stands (Salomón et al., 2016), many questions about human-induced disturbances affecting oak woodlands and their responses to disturbance variability remain open. Likewise, some authors allege that forest management has promoted the spread of *P. sylvestris* stands at low altitudes, below 1500–1700 m a.s.l., at the expense of *Q. pyrenaica* woodlands because of the high economic value of pine timber (Rivas-Martínez et al., 1999, 2002). Oppositely, other authors consider, on the basis of historical archives, that 'low-altitude' pine stands are natural (Martínez-García and Montero, 2000). This likely human-induced change in forest dominant species is still not fully resolved and, more importantly, little is known about the historical impacts of human activities on these pine stands. Finally, natural riparian vegetation within the *P. sylvestris* forests has been severely disturbed by forest management and overgrazing, with its species composition remaining mostly unknown. In summary, the Sierra de Guadarrama forest ecosystems are far from a pristine condition and, therefore, a good area to test the impact of land-use history on Mediterranean forests, understanding the associated variability in disturbance regimes and detailing their baseline composition using palaeoecology. Despite several palaeoecological records are available in the Sierra de Guadarrama NP, their chronology, resolution and/or location hinder their usefulness to discuss forest ecological processes in detail (summarized in López-Sáez et al., 2014). Therefore, new palaeoecological analyses of well-dated high-resolution sedimentary and peat sequences will provide a detailed quantitative long-term perspective (i.e. multi-decadal to millennial) on these gaps in the knowledge about Mediterranean forest ecology.

These questions about ecosystem management and conservation that involve a long-term (multi-centennial) perspective arose from our collaborative work with the Valsaín forests managers (Sierra de Guadarrama NP protected area). This site-based approach promotes an effective and practical use of palaeoecological data in ecosystem conservation and management (Davies et al., 2014) but it has been barely used so far. In this case, managers' specific questions covered most of the areas in which palaeoecology can guide forest conservation and management (Froyd and Willis, 2008; Lindbladh et al., 2013), i.e. vegetation composition, vegetation responses to disturbances and range of variability of such disturbances. We produced three new multi-proxy (pollen, spores, stomata, microscopic charcoal, plant macrofossils) well-dated palaeoecological records from two small forest hollows in the *P. sylvestris* forest and a small mire at the current *P. sylvestris*-*Q. pyrenaica* ecotone to address the following questions. Firstly, we quantitatively assessed the responses of *P. sylvestris* and *P.sylvestris*-*Q.pyrenaica* forest ecosystems to their different land-use histories as well as climatic variability at a nearly-decadal timescale. We emphasized the last centuries (since ca. 1300–1400 CE), when detailed records of human activities (mostly qualitative documentary archives) and climatic fluctuations are available, and paid particular attention to the range of variability of disturbance regimes (fire, grazing) and their effects on vegetation. And secondly, we drew on our palaeoecological data to inform about the composition of the lost riparian vegetation and the lower altitudinal limit of *P. sylvestris* forests.

2. Regional setting

The Sierra de Guadarrama NP and its Peripheral Protected Zone stretch over around 100,000 ha of the Guadarrama Mountains (central Spain, Fig. 1a), protecting forests and high-mountain ecosystems. Here we focus on the "Valsaín forests" area (north-western slopes of the Guadarrama Mountains, Fig. 1b), where the main forest ecosystems of the National Park are well-represented and historical archives allow tracking land-use changes through time (since the early Modern Period, ca. 1500 CE). The bedrock is siliceous, mostly granite and gneiss, and soils are consequently acidic. The climate is mountain continental Mediterranean. At 1200 m a.s.l. (lower section of the forest), mean annual temperature is 10 °C and the average annual precipitation is 700 mm, with mean temperatures of the coldest ($T_{January}$) and the warmest months (T_{July}) of 3 °C and 19 °C, respectively. At 1900 m a.s.l. (local timberline) mean annual temperature, $T_{January}$ and T_{July} drop to 6 °C, − 1 °C and 16 °C, respectively, with annual precipitation rising to 1300 mm. Summer drought is not particularly severe, lasting around two months at low altitudes and only one month in the summit area.

Five vegetation belts can be distinguished according to altitude. Sclerophyllous oak woodlands (*Quercus ilex* subsp. *ballota*) dominate at the lowest altitudes, until 1000–1200 m a.s.l., under a more pronounced summer drought. They are replaced at higher altitudes, up to 1500–1700 m a.s.l., with less drought-tolerant deciduous oak woodlands (*Q. pyrenaica*). The highest forest belt corresponds to pine forests (*P. sylvestris*) that mostly grow between 1400–1700 and 1900–2100 m a.s.l. but descend until 1200 m a.s.l. along north-facing humid valleys. Finally, *Juniperus communis* subsp. *alpina* and *Cytisus oromediterraneus* shrublands and dry cryophilic *Festuca curvifolia* grasslands dominate above the timberline. The main human activities in the Valsaín forests area (and the Sierra de Guadarrama NP) are extensive cattle ranching, pine logging and recreation activities.

3. Material and methods

We cored three sites in the Valsaín forests (Fig. 1c) with a Russian peat sampler: two small forest hollows located in the lower part of the *P. sylvestris* forest, Arroyo de las Cárcavas (40°50′31″N, 004°01′53″W, 1300 m a.s.l., 30 m diameter) and Arroyo de Navalacarreta (40°51′08″N, 004°01′52″W, 1250 m a.s.l., 25 m diameter), and a small mire lying on an open ridge at the *P. sylvestris*-*Q. pyrenaica* ecotone, Arroyo de Valdeconejos (40°51′44″N, 004°03′35″W, 1380 m a.s.l., 40 m diameter). According to their small size, all the sites have reduced relevant source areas for pollen and charcoal, mostly coming from several hundred metres radii (Sugita, 1994) and thus reflecting nearly stand-scale vegetation changes (Bradshaw, 2013). However, Valdeconejos may receive a certain proportion of pollen and charcoal from a few kilometres distance because sites lying on ridges at higher altitude are more exposed to upward winds (Andrade et al., 1994). At Navalacarreta and Cárcavas we obtained 135-cm and 149-cm long cores, respectively. The Valdeconejos sequence was 203-cm long, but pollen was well-preserved only for the top 147 cm. All cores were stored at 4 °C and into the dark until sub-sampling. The chronology of the peat sequences is mostly based on AMS radiocarbon dating of terrestrial plant macrofossils and peat (Table 1). To account for changes in peat accumulation, we built age-depth models by fitting smoothing splines (Navalacarreta