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Cork oak woodlands and decline: a social-ecological review and future transdisciplinary approaches

Margarida Lopes-Fernandes · Ernesto Martínez-Fernández · Rui Alves · Daniel Boa-Nova · Cristina Branquinho · Miguel N Bugalho · Felipe Campos-Mardones · Agustin Coca-Pérez · Amélia Frazão-Moreira · Marco Marques · Javier Moreno-Ortiz · Octávio Paulo · Adriana Príncipe · Victoria Quintero · Alfredo Sendim · Hernani Sobral · Javier Escalera-Reyes

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Abstract Cork oak woodlands are socio-ecosystems recognized as biodiversity hotspots, a fundamental economic source for companies and local communities as well as an identitarian landscape for residents and visitors. Cork oak woodlands, however, are facing tree mortality and lack of regeneration. Considering the oak decline scenario, we present Iberian cork oak *montado/dehesa* as a socio-ecosystem facing climate change, management transformations, local knowledge crisis and social uncertainty. We review *montados*/*dehesa*s research through time and by different scholar perspectives. We defend that from an interdisciplinary and transdisciplinary perspective, including the experience and evidence observed in terrain, debate should be stimulated, and novel conceptual approaches may contribute to finding

M. Lopes-Fernandes (✉) · E. Martínez-Fernández · D. Boa-Nova · F. Campos-Mardones · A. Frazão-Moreira
Centre for Research in Anthropology (CRIA) / School of Social Sciences and Humanities, New University of Lisbon (NOVA FCSH), Av. de Berna, 26 C, 1069-061 Lisbon, Portugal
e-mail: margaridalopesfernandes@fcsh.unl.pt

E. Martínez-Fernández
e-mail: emarfer2@upo.es

D. Boa-Nova
e-mail: danielboanova@campus.fcsh.unl.pt

F. Campos-Mardones
e-mail: campomar.felipe@gmail.com

A. Frazão-Moreira
e-mail: amoreira@fcsh.unl.pt

M. Lopes-Fernandes
Instituto da Conservação da Natureza e Florestas, Lisbon, Portugal

E. Martínez-Fernández · A. Coca-Pérez · V. Quintero · J. Escalera-Reyes
Social Research and Participatory Action Group (GISAP), Faculty of Social Sciences, Pablo de Olavide University, Edifício 11, 3ª planta, 41013 Seville, Spain
e-mail: acocper@upo.es

V. Quintero
e-mail: vquimor@upo.es

J. Escalera-Reyes
e-mail: fjescrey@upo.es

R. Alves
Departamento Florestal e de Sustentabilidade, Companhia das Lezírias, Largo 25 de Abril, 17, 2135-318 Samora Correia, Portugal
e-mail: rui.alves@cl.pt

C. Branquinho · O. Paulo · A. Príncipe
Centre for Ecology, Evolution and Environmental Changes (cE3c) & Global Change and Sustainability Institute (CHANGE), Faculty of Sciences, University of Lisbon, Campo Grande, Bloco C2, 1749-016 Lisbon, Portugal
e-mail: cmbranquinho@fc.ul.pt

O. Paulo
e-mail: octavio.paulo@fc.ul.pt

A. Príncipe
e-mail: aprsilva@fc.ul.pt

solutions. We argue that the confluence of ecology, genetics, anthropology and local knowledge can be explored to unveil the complexities and the challenges of these socio-ecosystems and contribute to prevent and mitigate threats to it. We propose a methodological approach built together with scientists, managers and workers, that can explore oak translocations, socio-ecological interactions models, knowledge transfer and other ways to overcome Iberian cork oak woodlands socio-environmental crisis.

Keywords *Montado/dehesa* · Cork oak woodlands decline · Local knowledge crisis · Socio ecosystem · Transdisciplinary approach

Introduction

Montado/dehesa is mostly a human made ecosystem particularly rich in biodiversity (Bugalho et al. 2011). These dryland forests and woodlands, dominated by evergreen oaks, namely the tree key species holm oak (*Quercus rotundifolia*), cork oak (*Quercus suber*) and an understory of diverse grassland patches and shrubs, are recognized hotspots of biodiversity (Myers et al. 2000). Open oak woodlands cover in Portugal ca. 1.22 Mha (Godinho et al. 2016) and in Spain 2.3 Mha, where they are denominated as *montados* and *dehesas*, respectively.

M. Bugalho · M. Marques
Centre for Applied Ecology "Prof. Baeta Neves" (CEABN-InBIO), School of Agriculture, University of Lisbon, Tapada da Ajuda, 1349-017 Lisbon, Portugal
e-mail: migbugalho@isa.ulisboa.pt

M. Marques
e-mail: marco.marques@edu.ulisboa.pt

J. Moreno-Ortiz
Association "Pasos, Participation and Sustainability", Avenida Francisco Ayala 79. 18014 Granada, Spain
e-mail: javier@pasos.coop

A. Sendim
Montado Freixo do Meio, 7050-704 Montemor-o-Novo, Portugal
e-mail: alfredosendim@herdadedofreixodomeio.pt

H. Sobral
Gestiflora, Av. Jorge Nunes, N123, 7570-113 Grândola, Portugal
e-mail: hernani.sobral@gmail.com

The Mediterranean region is facing several challenges in a new climate scenario, in particular the *montado/dehesa* socio-ecosystem[1] is undergoing a critical situation. Therefore, this is an important case study for examining the present and future challenges for woodlands socio-ecosystems in the Anthropocene's crisis context. *Montado/dehesa* are a case of development under the system resilience limits in the ecological and social spheres (Pinto-Correia and Azeda 2017). Under climate crises, but within the critical threshold, this socio-ecosystem has the capacity to adapt, return, organize andregenerate itself to a functional balance, maintaining the essential relationships, after a disturbance or stress without changing its shape and function (Folke et al. 2010). The process in *montado/dehesa* can reveal the emergent capacities of systems such as memory and learning, identitarian drives as well as the natural potential for adaptation. Moreover, crisis in Iberian *montados/dehesas* can have a global and multi-scale economic impact due to worldwide cork use and trade.

Montado/dehesa areas are an important source of provisioning services as well as cultural, regulating and supporting services in dryland areas, such as climate and water regulation, fire hazard reduction and biodiversity conservation (Bugalho et al. 2011). They are also a fundamental economic source for land holders, companies, local communities and an identitarian landscape for residents and visitors. In this sense, *montados/dehesa*s have had a symbolic importance for a long time, additionally to their recognized social and environmental value, which is currently transforming into a process of activation as heritage (or patrimonialization see Del Mármol et al. 2015). The system hosts biodiversity values, including endangered species such as *Narcissus* plants, the Iberian lynx (*Lynx pardinus*) and Imperial eagle (*Aquila adalberti*). *Montados/dehesas* are protected under the European Habitats Directive 92/43/EEC. As an European agricultural landscape that sustains high diversity of

[1] We use "socio-ecosystem" as a synonym of "social-ecological system" (SES) as for instance Petrosillo et al. (2015) discuss it but not centralizing the human influence only as a threat to the ecosystem. It will appear throughout the text implying all the complexity of a system with deeply interrelated environmental and human social components.

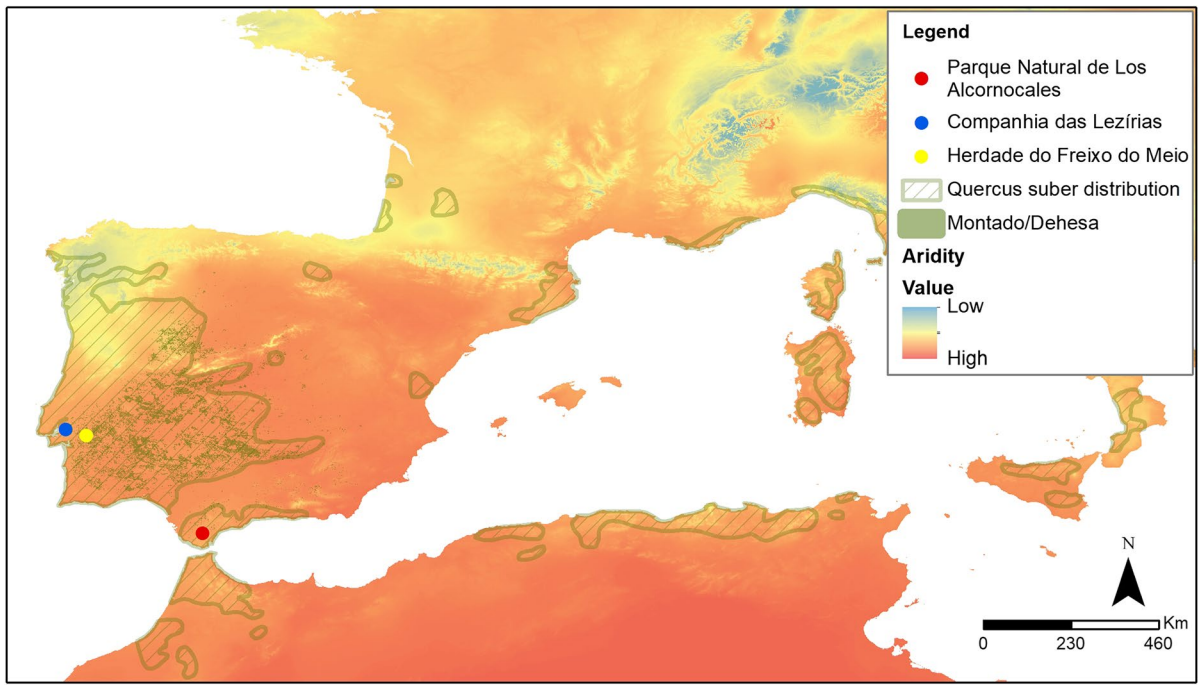

Fig. 1 - Distribution of *Quercus suber* (Caudullo et al. 2017) and *montados/dehesas* in West Mediterranean (CORINE Land Cover, Copernicus Land Monitoring Service), global aridity index (Trabucco and Zomer 2019) and specific illustrative case studies presented along the article

species and habitats, these systems are recognized as a High Nature Value Farmland (Paracchini et al. 2008).

However, in the last decades, under the general effect of climate change, and due to several pressures, tree decline and mortality increased and natural regeneration of holm and cork oak species decreased in most Mediterranean woodlands (Aronson et al. 2009; Fennane and Rejdali 2015). Causes of degradation include pests and diseases (de Sampaio et al. 2013), intense management practices (Arosa et al. 2015), overgrazing in some areas, local unfavorable microclimatic conditions for regeneration (Príncipe et al. 2022), or poor and no management (Sánchez et al. 2000).

We review the scientific knowledge produced by different disciplines around *montados*/*dehesa*s and their decline through time in Iberia, examining their insightful findings, limitations, and then establishing possible unprecedented links. After two intensive workshops and a period of eight months of regular discussions we put data together and analysed the present situation of *montados/dehesas* and their future challenges. We ponder that looking into our different case studies across south of Iberian Peninsula and the geographical variation from clear *montado/dehesa* to closed-canopy cork oak woodland (*sobreiral/alcornocal*) will be illustrative of different contexts, strategies and ecological responses under the common practice of cork extraction (Fig. 1).

Considering that the cross of disciplines and the integration of empirical knowledge are fundamental to fully understand the complexity and problems associated with this socio-ecosystem, we present the need to have Anthropology, Genetics and Ecological research together to address the challenges faced by the system. Our objectives are to understand, from a more complex perspective, the socio-environmental relations established, the possible near futures for the areas where *montados*/*dehesa*s occur, looking at the resilience process; to build socio-ecological indicators and establish transdisciplinary concepts and practices to address challenges faced by these systems and to start regeneration experiments, setting up different conditions to new trees of various origins, and involving different knowledges and local actors. We understand this as a necessary and ongoing task which is by no means exclusive to our disciplines.

Montado/dehesa: genealogies and conceptual nuances

A clear definition of *montado/dehesa* has been described as difficult by several authors. To better understand the emergence of the concept, we review how it has been understood and described by different disciplines. The genealogy of the concept leads us to successive monodisciplinary views, fields that were investigating this subject at different times: from the early 20th century concern of foresters, joined by geographers or economists, through the studies of ecologists since the 1980s and the more recent interest of anthropologists. Subsequently, this section deals with the centrality of biodiversity and conservation as a theme in studies of the *montado/dehesa* and the current approach to the crisis it is undergoing.

Montado referred in Medieval and Modern Portugal to the act of pasturing, in particular, acorn grazing. The lands utilized mainly for this activity (*montar o gado*) were commonly known as *montados,* as well as the tax paid by livestock breeders for grazing in those municipal-owned or manor *montados* (Fonseca 2004). For its part, the Spanish word *dehesa* has also a link with the idea of pasturing. It derives from the Latin word *defensa* (defense, protection), and referred in Medieval Castile to lands delimited for local livestock grazing, and thus "defended" from freely circulating livestock (especially, from transhumant pastoralism) (Mangas 1981). Although grazing was its main use, both *montados* and *dehesas* were at that time a source for local self-supply of charcoal, firewood, game, honey, acorn and also cork (used for seats, troughs, flooring or protection of hives). In the event of risk of famine, municipal and/or communal-owned plots were even delivered to local families for breaking up and growing cereal (Gallego and García 1997; Fonseca 2004).

The open holm and/or cork oak parkland that is characteristic of what is called today *montado/dehesa* was scarce in those lands (Gallego and García 1997). Agrarian historians point to variegated uses and forms of ownership of Medieval and Modern *montados* and *dehesas*, as well as to constant changes depending on particular historical circumstances. In this vein, Martín and Fernández (2006: 25) highlight that, for the 18th century, "oak shrublands, croplands and grasslands with *Retama [spp.]* and groundoaks dominated the landscape" of SW Spanish *dehesas*. In the case of Portugal, towards the end of the 18th century, Sequeira (1789–1815/1991) claimed against the widespread oak thicket in Alentejo and, crucially, in favor of a new stockbreeding based on an oak tree layer to be developed through cultural selection/plantation and further pruning.

Under the influence of 19th century liberalism, two processes converged: changes in land ownership through disentailments, and the consolidation of the corps of forestry engineers Silva Pérez 2010). This conjunction gave rise to the idea of *montado/dehesa* as we know it today. In the less fertile areas of SW Iberia, a specific style of agriculture arose, based on a stratum of oak trees to be developed through cultural selection/planting and subsequent pruning. It was a model dedicated to an integral exploitation of the economic potential of plots with poor soils and therefore unsuitable for intensive crop farming. Those lands adopted an agrosilvopastoral physiognomy, with: 1) diverse oaks species – *Quercus rotundifolia* and *suber* mainly, but also *Q. faginea, Q. pyrenaica, Q. robur and Q. canariensis* – providing acorns, wood, cork or shade, for example; 2) shrubs removed periodically; and 3) an herbaceous understory allowing flexible grazing as well as agricultural crops in flat patches.

In Portugal, it is not clear when the association of the word *montado* with this new landscape took place, although it is already explicit in the Alentejo ethnography by Picão (1983), first published in 1903. In Spain, the use of the word *dehesa* with that new meaning is even more recent. According to Costa Pérez al. (2006), at a time when *dehesa* had become synonymous with large estate (see Teijón 1948), González Vázquez, professor at Madrid's School of Forestry Engineering (1923–1953), rejected the alternative concept 'wooded grassland' (*pasto arbolado*), and coined *dehesa* for it was the word used in the past to designate most of the lands where the new landscape had spread.

Forest engineers defined it as an agrosilvopastoral model, and understood *montado/dehesa* as a cultural and simplified Mediterranean forest, hollowed out for grazing and cropping. González-Vázquez published his main work, *Selvicultura*, between 1937 and 1948, and the Portuguese Vieira de Natividade authored *Subericultura* in 1950, a book on cork oak management. Other disciplines took an interest in it a bit later. Geographers and economists started to explore the associated style of farming, and focused on issues such as profitability, products and production cycle,

workforce management or even energy flow from a systemic perspective (Ribeiro 1945; Martín Galindo 1966; Roux 1975; Campos 1984).

As already presented, *montados*/*dehesa*s exhibit different vegetation spatial structures, from open woodlands in silvopastoral systems to more closed woodlands and dense forests with lower disturbance intensity (Aronson et al. 2009; Pinto-Correia et al. 2011; Acácio et al. 2017). They consist of semi-natural multifunctional systems with a traditional low-intensity agrosilvopastoral management, a relatively sparse tree cover, varying approximately between 40 and 60 trees per hectare, and a diversified understory of shrub and grassland patches. Traditionally, these oak woodlands are multiple use systems that combine livestock raising with cork harvesting, among other activities. Certain management options predict areas without shrub understory but management approaches vary with geographical and socio-economic contexts. Presently many areas of *montado*/*dehesa* have been abandoned and have no active management. In areas usually coincident with more steep slopes, with less use for grazing and higher densities of oak trees, the system is sometimes denominated *sobreiral/monte alcornocal* when cork oak is the dominant tree.

Scientific work on the ecology of *montados*/*dehesa*s started being published around the 1980s, focusing on the biodiversity of *montado*/*dehesa* as its main character (e.g. Escudero et al. 1985). According to the ecological perspective, *montado*/*dehesa* areas are important for biodiversity conservation, also generating a variety of provisioning, regulating, cultural and supporting services (Bugalho et al. 2011). Many ecological aspects of *montados/dehesas* were studied, for instance patterns of plant and bird distribution, and both human activities and biophysical processes were found to be equally important (Joffre et al. 1999). Plants and birds exhibited a similar ecological pattern, although environmental conditions were slightly more important in the case of plants, and human activities were slightly more important in the case of birds (Pereira and Pires da Fonseca 2003). Several disciplinary approaches and institutional actions are currently oriented to the conservation of *montados*/*dehesa*s. According to Habitats Directive, for conservation purposes, *montado*/*dehesa* can be classified as "Habitat 6310 – Dehesas with evergreen Quercus spp." and if considered as a forest (for instance "abandoned" *montados*/*dehesa*s) as "9330 *Quercus suber* forests" or "9340 *Quercus ilex* and *Quercus rotundifolia* forests". This concept is used by EU State Members to report the conservation status of these habitats in each country.

Anthropologists arrived at this topic around the 1990s. They departed from an ecosystem perspective and the previous social-scientific contributions, although focusing on the role of the local human communities. Thus, they intensively explored local knowledge associated with the variegated works that are characteristics of *montado*/*dehesa* management: pruning, clearing, uncorking or plowing, for example (Acosta 2002). Anthropology uses Local Ecological Knowledge (LEK) as the cumulative body of knowledge, practices and beliefs that evolves through adaptive processes and is transmitted through cultural forms from one generation to another about the relationships among living things, including humans, with their environment (Reyes-García 2009). Researchers' interest in local knowledge and the potential of this knowledge was, in some cases, linked to a practical aim, since some authors saw the revitalisation of *montado*/*dehesa* as a sustainable way to overcome the rural crisis in SW Iberia (Ristori 1989; Acosta 2008).

The centrality of the human dimension led anthropologists to question the formula of *montado*/*dehesa* as a Mediterranean forest cleared to promote agrosilvopastoral uses, which was common in ecological and forestry engineering approaches. Instead, from a sound ethno-historiographical background, they highlight the human made character of *montado*/*dehesa*, and the relevance of cork and holm oak plantations in the 19th century onwards to generate newly forested *montados*/*dehesa*s. The role of non-productive uses, like wild species collection, have been also studied, highlighting in the vein of previous ecological studies (see Valladares 2007) the important inter-species coevolutionary associations that result from the anthropic involvement within this ecosystem (Acosta and Guzmán 2022).

Another field of anthropological research has to do with inequality and conflict. Developing the insights from previous social research (Cutileiro 1971; Roux 1975), anthropologists have pointed to starvation wages and exploitative share farming by peasants (*aparcería*) as the main basis for traditional *montado*/*dehesa* economic and ecological viability (Acosta 2002). In this sense, they highlight

that their sustainability and ecological balance was ensured thanks to a landlordism regime of domination, in which the agrarian bourgeoisie controlled not only land, but also local industries and administrative apparatus, thus acting as a shaper of local communities' life and keeping certain patterns of inequality and subordination (Acosta 2008).

Social scientists have also focused on *montado*/*dehesa* from a 'cultural heritage' perspective. Several studies highlighted the landscape values of *montados*/*dehesa*s in their connection with the current relevance of images and historical memories (Hernández and Quintero 2009; Silva 2010). There are multiple patrimonialization processes associated with the conservation of *montados*/*dehesa*s: declarations of biocultural heritage, UNESCO cultural landscape (Silva and Fernández 2015) or intangible cultural heritage. In Portugal, since 2018, the city council of the municipality of Coruche has been articulating the classification of cork stripping as national intangible cultural heritage, based on anthropological advice and with plans to subsequently conduct this same process within the scope of UNESCO. From an ecosystemic services perspective, Bugalho et al. (2017) also present *montado*/*dehesa* as providing so-called cultural and regulating services.

Montado /dehesa: debates and becomings

In this paradigm of conservation and patrimonialization, a debate around the effects of no management and abandonment, naturalization, ecosystem services, sustainability and management arises associated with the profound socio-ecological changes of *dehesa*s/*montado*s. The differences of approach between perspectives based on biodiversity conservation and centrality of human action remain, specifically in cases of abandonment and plant woody encroachment of *montados*/*dehesa*s. Some anthropologists suggest that these woodlands must be understood from a diachronic perspective. Thus they appear as silvopastoral systems that, after the 1950s, underwent transformations induced by specific socioeconomic decisions. The abandonment of most agrarian uses, other than cork harvesting, taken to the extreme, has led to a simplified management.

From the point of view of social scientists, the main reason for the socio-ecosystem's crisis was the end of low salaries due to migration (Roux 1975). The 1950s and 1960s' rural flight amounted to the migration of more than half the population of the rural SW Iberia, mainly workers and peasants, to the appealing, industrializing cities of Spain, Portugal, and other European countries (Barciela and López 2003). The subsequent salary increase undermined the very foundations of the *montado*/*dehesa* economic viability (Acosta 2002). From then on two broad lines of transformation developed. The first one, following a trend of most agricultural systems of technological progress, has led to "intensified *montados*/*dehesa*s". These are farms that underwent a process of labor costs saving and capitalization through the introduction of wire fences and machines, improved cattle breeds and dependence on compound feeds produced off-farm and European Common Agricultural Policy (CAP) subsidies, which are payments provided to farmers to promote or disincentivize particular uses of the land. They would be simplified agroecosystems (Plieninger et al. 2021), with less functional and species diversity, less complementarity and hence worse energetic efficiency (Acosta 2008). The second one is referred to a type characterized by agrarian abandonment, woody encroachment and, often, a focus on game management as a complementary or even main source of income from the system. It would differ from *montado*/*dehesa* in terms of forest cover or uses (forestry and hunting vs. livestock breeding and farming) (Aronson et al. 2009).

Naturalization can be simply interpreted as a natural vegetation succession process that, however slow and complex, occurs during the progressive alleviation of agricultural and other uses (Cramer and Hobbs 2007). This reduction in land-use intensity is happening in many *montados*/*dehesa*s and it results in a gradient including total abandonment at the extreme. There, although provision services diminish, other services, such as regulation and maintenance services of the ecosystem, are meant to be important (Pereira and Navarro 2015). Overall and according to several authors a 'rewilding' process is occurring in some areas of Europe, centred on landscapes reverting from agricultural use to a more natural state (e.g. Pereira and Navarro 2015).

In the case of *montados*/*dehesa*s the abandonment scenario may lead, in many situations, to the loss of the agrosystem and some of its present conservation values (e.g. Bugalho et al 2011). Some authors mention an increased fire hazard that comes with

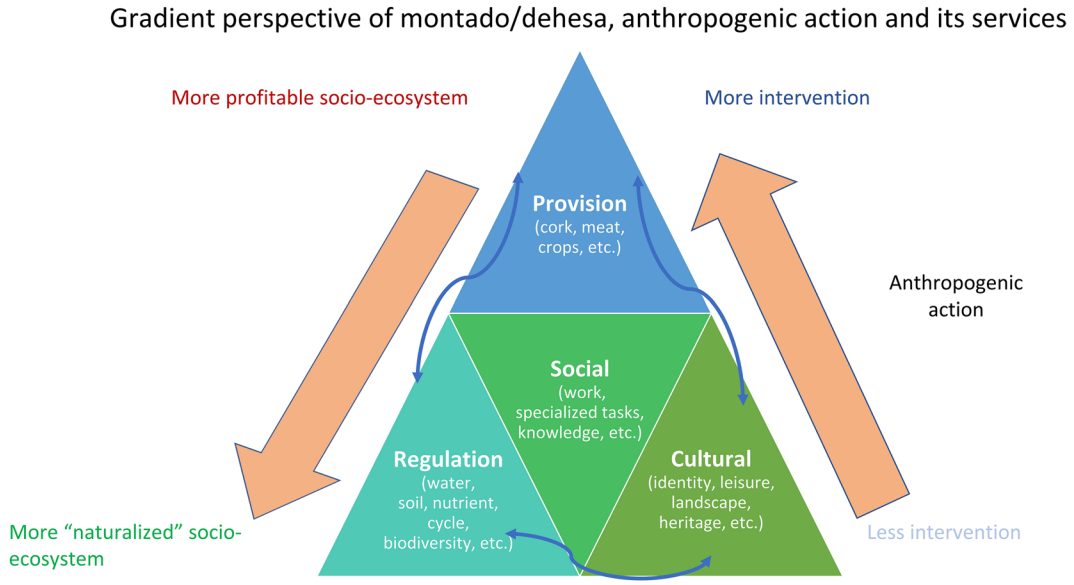

Fig. 2 - *Montado/dehesa* services, anthropic action and relationships. Blue arrows represent a flexible relationship between them, like an elastic thread. Services nomenclature is adapted from bibliography on ecosystem services but can be questioned and developed to a less divided classification

abandonment and shrub encroachment that affects the water balance of the system (Caldeira et al. 2015). Therefore, abandonment might not just be equated to "renaturalization". First, the concept of 'natural' is a social construct and each community socially should negotiate an appropriate mix of human and biophysical components in the local landscape (e.g. Rhoads et al. 1999). Secondly, a *montado/dehesa* characterized by a low intensity human intervention is still a socio-ecosystem favouring biodiversity and providing all ecosystem services: provisioning, regulating, supporting and cultural. If all those services are thought of for *montado/dehesa* we can conceptualise a flexible relationship between them, like an elastic thread, with certain tradeoffs summing up the anthropic action in the system and defining it as a socio-ecosystem that depends on specific local knowledge, unique and valuable, to be intervened (Fig. 2). Thirdly, if *montado/dehesa*, by definition a humanized landscape, is abandoned and totally loses intervention by humans, that is not necessarily a process of immediate naturalization, and has a negative impact on plants and animal species dependent on open areas. Also, fire hazard may increase and water regulation service might be altered (see for instance Bugalho et al. 2011). In fact, not all abandoned *montado*s endure ecological succession towards woodland or forest as they may fall into cases of 'arrested succession' (see Acácio et al. 2017).

Therefore, the concept of 'renaturalization' should be looked upon in detail and questioned in the case of *montado/dehesa*. Areas that are no longer a *montado/dehesa* or an agricultural land might be even considered feral, in the sense of a development of an original habitat constructed by humans now beyond human control, something else by nature (Tsing et al. 2022), eventually a scrubland or woodland in transition that eventually can become or not, in the long-term, a (wild) forest.

The way *montado/dehesa* can be presently conceptualised in a more plural way, integrating all the facets referred above, would benefit scientists, managers, workers and conservationists, and push a political support that accounts for these. That can be a key point for the *montado/dehesa* survival in the future as it is a socio-ecosystem in decline and facing challenges concerning sustainable management options.

Decline and beyond: montado/dehesa crisis

Cork oak *montados/dehesas*' decline and knowledge gaps

Here we revise *montado/dehesa* crisis and oak decline proposing a wider perspective, aiming at the sustainability of these socio-ecosystems. We also propose a deeper approach to decline, including not only tree mortality and loss of vigour, but also incorporating socio-ecosystem sustainability, decline at the social and environmental levels, and its interrelations. We aim to understand the social-ecological resilience process, and ways of long-term sustainability, maintaining the essential characteristics of *montado/dehesa* and promoting social justice.

Montado/dehesas are dryland woodlands which are expected to be particularly affected by climate change. An overall decrease in precipitation, high temperatures, and high frequency of extreme events, increase the aridity levels with a negative impact on vegetation productivity and biodiversity patterns (Vessella et al. 2017). Particularly, the rise in the duration and frequency of extreme events, such as prolonged drought and heatwaves, will be negative for tree cover, by triggering higher tree mortality rates, decreasing the potential for forest natural regeneration and increasing the risk of large-scale forest fires (Zhang et al. 2017; Pausas and Fernández-Muñoz 2012; Bowman et al. 2020). This degradation might occur in gradual terms or in non-linear patterns displaying tipping points after which it is very difficult to reverse the system. Ramos et al. (2015), in a gradient over space, found that below 600 mm annual precipitation there is a tipping point where there is a linear decrease of tree cover of holm oak, measured using NDVI in the website of the Portuguese National Forest Inventory. A prediction of potential habitat of the cork oak for Maamora Forest showed that the total precipitation during the wettest three months of the year was the most important variable for the species distribution model (Laaribya et al. 2021). Additionally, anthropogenic factors such as fast alterations in land-use dynamics, over-exploitation, loss of multifunctionality and poor management, are increasing the degradation levels of dryland forests and their vulnerability to desertification (Acosta 2002).

Forest decline is characterised by premature, progressive loss of tree and stand vigour and health over a given period, which most of the times result from the interaction of a set of factors (Manion 1981; Sinclair and Hudler 1988). Oak decline and mortality have been reported in the Iberian Peninsula since the end of the 19th century (Baeta Neves 1954; Brasier 1996), and in other Mediterranean places, like Morocco (Montoya 1992). Outbreaks and mortality of cork oak trees have been observed long before (e.g. Natividade 1950) in the south of Portugal, but it was during the 1980s that it reached high proportions in the southwest of the Iberian Peninsula. By 2010, more than 50% of Portuguese *montado* areas had some symptoms of decline (Moreira et al. 2017; Sánchez García et al. 2000). Although this problem has been identified for a long time, it persists, as we can see by recent studies and is getting worse (Vallejo et al. 2009).

In the last decades, increasing tree decline, mortality and decreasing natural regeneration of holm and cork oak, due to several causes, have been observed (Aronson et al. 2009; Costa et al. 2009). During the 1990–2006 period, the total area, including both cork and holm oak dominated areas, decreased at a mean rate of 0.14% per year (Godinho et al. 2016). Soares et al. (2018) found a generalised decrease in tree canopy cover of holm oak in the Alentejo region using the Portuguese national forest inventory and which could be due to decrease tree canopy (e.g. branch mortality), tree mortality and low tree performance (causing leaf shedding). Indeed, between 1990 and 2015, canopy cover losses of cork oak and holm oak were much higher than gains (Acácio et al. 2021).

Given the mortality scenario, many studies aimed at identifying isolated causes of decline. There is also the cohort senescence theory, proposed by Mueller-Dombois (1992). It argues that decline could be a process of synchronous senescence, and thus a part of forest dynamics and succession. In any case, pests and diseases can accelerate the onset of oak decline, after the trees become more susceptible to both anthropogenic and abiotic factors (Tiberi et al. 2016). Among pathogen *Phytophtora cinnamomi* in particular has been associated with overall mortality outbreaks (de Sampaio et al. 2013). Drought, a characteristic of the Mediterranean-type of climate, is also responsible for decline episodes of oaks, amplifying the effect of diseases and causing what is also called 'sudden death' (Gentilesca et al. 2017). Oak decline is a multifactorial phenomenon following a spiral of events (Manion 1981; Sinclair and Hudler 1988). These include: i) permanent factors that weaken the trees such as prolonged droughts, late frosts, or tree ageing; ii) factors acting intensively in a short period,

such as severe droughts and attacks from defoliator insects; iii) factors that aggravate the decline process, being associated with dry soils at the end of the summer and sometimes human-induced compaction and iv) the specific vectors that propagate diseases, such as insects (Montoya and Mesón 1993; Muñoz et al. 1996).

Oak regeneration is a key factor that needs to be better studied and related to other variables, namely genetics. Indeed, there is a knowledge gap concerning the genetic component of regeneration, i.e. which genetic characteristics codify for adaptive traits that will be crucial in new climate scenarios. We also need to know more about seed and young plants survival and adult mortality and how these processes will be locally modified by both climate change and management practices.

For the purposes of this paper, aiming at the discussion of socio-ecosystem repercussions of *montado*/*dehesa*s, and considering the diversity of situations, we now restrict the focus to cork oak areas. Although the adaptive response of cork oak has already started to be studied (Vanhove et al. 2021), the role of local practices and management strategies related to genetic diversity has not yet been explored. The genetic diversity of cork oak has been subject to different studies at different geographic scales (c.f. Pina-Martins et al. 2019; Sousa et al. 2022; Vanhove et al. 2021), the main aim was to understand the population structure at the broad scale in the Mediterranean Basin, and identify regions where trees have local adaptations. The results indicate a relative homogeneity across the Iberian Peninsula, with the Catalonian population being the more differentiated one (Vanhove et al. 2021). Sousa et al. (2022) identified potential refugia areas during glaciations, or areas of natural historical persistence before humans drive plantations across Iberia. In terms of future, Pina-Martins et al. (2019) and Vanhove et al. (2021) also identified the population that will be more affected by ongoing climate change and, together with results from Species Distribution Models (Correia et al. 2018; Vessella et al. 2017), provide a wide range perspective on how the *montado*/*dehesa* is going to be affected by current climate change.

We also know that there is intense natural selection during the first stages of tree development (seedlings and young trees establishment) where the vast majority do not survive, due to stochastic events in association with natural selection. Across generations, this will favour certain genotypes at a variable rate according to the intensity of environmental changes. Additionally, long-range pollen dispersal in oaks allows the dispersal of genetic material across hundreds of kilometres, promoting the widespread presence of gene alleles with different origins across the species range, or at least part of it. These widespread gene variants become locally available and, consequently, certain genetic characteristics can be locally selected in seedlings or young trees. In this way, a new generation of local trees may benefit from the standing genetic variation across species and be selected according to the local environmental conditions.

Box 1. Localizing oak decline multiple factors: Los Alcornocales Natural Park (Andalusia)

The Natural Park Los Alcornocales (Southern Andalusia) is worth exploring to understand the variegated ways oak decline develops in particular areas and the relevance of the anthropic dimension. Oak decline is a dramatically growing reality in this natural park, affecting hundreds of hectares every year (Gómez-Aparicio et al. 2012*;* Ibáñez et al. 2017). *As predisposing factors, we find climate change, but also an absentee style of management based exclusively on opportunistic cork extraction and a hunting business of enclosed overpopulations of wild ungulates (Cervus elaphus, Dama dama, Sus scrofa, Capreolus capreolus) which endanger oak regeneration. Overgrazing scenarios can also be observed in other* montados/dehesas *when cattle occurs at very high grazing pressures. Heavy grazing can also compact the soils. Over-use is complemented with a non-management situation by landholders mainly, large estates where regeneration and rejuvenation is neglected* (Sánchez et al. 2000). *In this scenario of fragility, the spreading and action of Phytophthora has been the final factor for cork oak mortality and decline, which was recently aggravated by high incidence of Lymantria dispar, a defoliator.*

The fact that the social and the ecological dimensions are deeply interwoven in the decline of cork oak *montados*/*dehesas* points to the necessity of different disciplines to work together on this theme. While ecological and genetic information about oak decline can be explained by local uses and management practices from human populations, it can also be used to address the oak decline crises. Oak decline is a socio-ecological phenomenon (Fig. 3) which benefits from a holistic approach that analyses the problem in different aspects—such as social, ecology and genetics—by looking how they interact in this new scenario and that has been missing. The new research

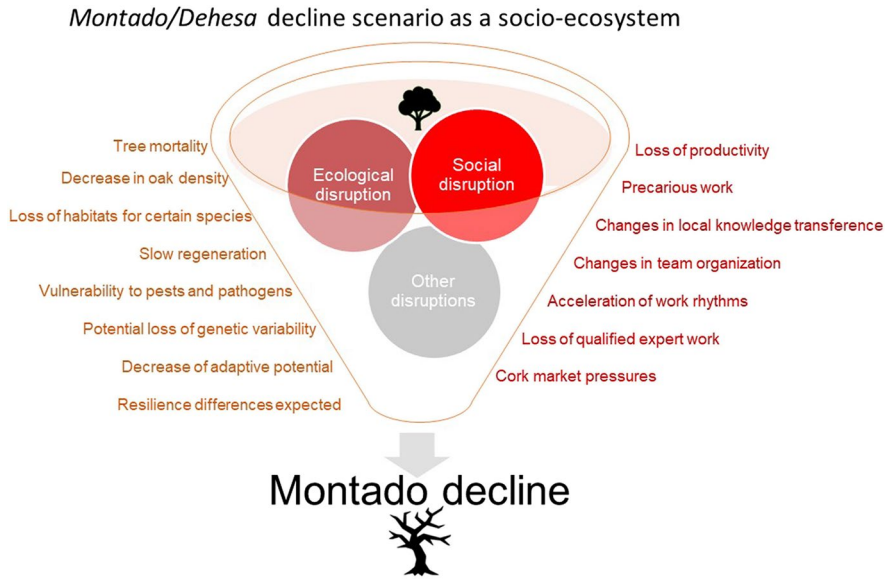

Fig. 3 - Decline as a socio-environmental variable and some of the repercussions associated with social and ecological disruption. Text describes observed dynamics around *montado/dehesa* decline not necessarily factors or causes

questions and recovery actions should relate different variables to obtain a better picture and understanding of the present crisis.

Present situation of socio-environmental change: evidence and data

Recent data shows that the decline of *montado* is ongoing with severity because of the incidence of *Phytophthora* and other diseases. There are also studies indicating that local knowledge associated with work with the cork oak trees is less and less specialized, with a loss of knowledge transfer in the communities.

We have empiric evidence from the terrain and data pointing to ongoing changes which sum up the impacts at social and biological level in cork oak *montado/dehesa*. The situation described in practical cases enlightens the environmental and social character of the oak decline, and points to the necessity of new complementary studies and novel adaptive management practices. We believe that different examples of *montado/dehesa* management, demonstrate a diversity of situations rather than a general extrapolative case. These underline the multifactor causes in cork oak decline and might enlighten future strategies.

It is still unknown, in detail, how climate change and local socio-economics practices are affecting the local diversity and evolutionary potential of *Quercus spp*. genomic prediction, how the species respond to the current and near future climate change is one way to address the current knowledge gap. How to forecast the adaptive tree response of local populations already started for cork oak with preliminary results in Pina-Martins et al. (2019) and Vanhove et al. (2021). These results will benefit from high density sampling and better genomic markers than the ones already used. The role of local practices and management strategies in relation to adaptive diversity has not yet been explored, as well as the critical information at smaller local scales under different microclimatic conditions (Príncipe et al. 2022). Furthermore, a change in the production system causes local changes in practices, which impact the aspects referred before.

We present the cases of some land estates, the experience of managers and their knowledge based on science and empirical observation. From experience of everyday managers of *montado/dehesa*, socio-environmental change is evident and will have important impacts in the further decline of cork oak *montado/dehesa*, and in particular facing aggravated climate conditions. For instance, changes in the global market logics and new circumstantial

work offer are having implications in less specialized workers available for cork oak extraction, just as with other seasonal works in Alentejo (Portugal). The European Union (EU) policy supporting agricultural activities in EU membership countries (CAP), support to cattle must be taken into account too, since these subsidies have promoted a substantial increase in the number and stocking density of breeds often inadequate for *montado/dehesa* in ecological terms (Bugalho et al. 2009). On the other hand, specialized local workers are subjected to new rules of taxes and formal declarations, which makes the job less appealing for some. This situation of non-transference of knowledge and techniques brings a higher risk of damaging trees, due to inexperienced handling of tools, rhythms or observation.

In parallel, the introduction of new machines in cork harvesting changes the work dramatically, and does not necessarily incorporate or preserve all the non-scientific and specialised knowledge on manual cork extraction and respect for trees. This, along with intensification of crops and mobilisation of soil with heavy machinery, namely soil tillage may increase tree vulnerability. During recent years, in certain areas, cork extraction management has been done often by external contract and paid according to weight of cork extracted. That puts additional pressure on the *montado/dehesa*, and might cause extra damage to trees, compromising future yields. In fact, nowadays extraction every nine years is not always adequate for either trees, workers or managers, in terms of survival, production and profitability. There is also evidence that trees might respond differently to climate change and that their genetic legacy influences that.

Recently measures have been tried to mitigate the combined effects of drought. For instance, in forestry, aiming to accelerate the start of cork production and anticipate the first cork harvest, afforestation techniques using fertirrigation were tested and significantly enhanced growth of trees during summer drought (Camilo-Alves et al. 2022). It is not known yet if irrigation will be an economical solution: it requires human management all through the growing of the trees, and it will probably not be possible in many inland areas.

We present specific situations, all integrated in classified areas for conservation, that exemplify the diversity of management options and relationship with *montado/dehesa*s and also the empirical perspective of the managers. They can be considered as different alternatives in a crisis scenario.

Box 2. Case of an organic farm and multiple products strategy at Freixo do Meio (Portugal)

Freixo do Meio, a 600 ha private land estate in central Alentejo, after a long traditional exploitation of montado/dehesa first under a family land estate management, and afterwards a cooperative agricultural organisation, undertook a different direction in the 1990s with establishment of non-interventional biodiversity areas, organic stockbreeding, considered the motor of montado/dehesa but carefully rotated depending on food availability and the introduction of a special cattle breed Barrosã. Tree regeneration with careful protection of young trees is favoured, soil is not mobilised, and neither the usual routine under storage clearances of shrubs, nor pruning. Tree mortality has been very low here, and incidence of pests is practically absent. New or revisited montado products are promoted, such as mushrooms and acorn flour. Micro factories of various food products were established, and certification took place. Cork is just a small part of economic profitability, and extracted every 9 years by local specialised workers. The area is classified as a Private Protected Area, and visitation is important. The extrapolation of the practices of this case study to other montado/dehesa *areas is still a question*

Box 3. Case of a high productivity cork area with research on sustainability—Companhia das Lezírias (Portugal)

Companhia das Lezírias (CL) is a large estate area managed by the State with 6,800 ha of montado/dehesa*. The cork oak woodlands mean 83% of the income of the Company, being located on one of the largest aquifers in Portugal. Despite this, with drought and disease, mortality of trees has been increasing, and its spatial pattern and main cause is difficult to understand, emphasizing the multifactor character of decline. CL had a legacy of overexploitation of the land and nowadays has options of management in search of ecological sustainability, such as: cork extraction every nine years, extensive cattle exploitation (one cows per 2 hectares during 6 months), establishing non grazing plots, intense wire protection of young cork trees under 15 years, control of invasive pine trees to favor regen*eration. *CL offers visiting areas, recreational opportunities for local communities, and 25 outsourced workers, since CL employs only three technicians. It has been investing in research and participatory events for stakeholders to gain knowledge about options and preferences for the future (see* Alves et al. 2020*)*

Epistemology for future study and action in a threatened socioecosystem

Multidisciplinary approaches in a *montado/dehesa* decline scenario

In the Iberian Peninsula, multidisciplinary projects on tree decline are as early as 1999, reuniting forest engineering, ecology and biotechnology in search of techniques for minimizing death of trees (Tuset and Sánchez 2004). During the last decades, a set of projects also addressed the multiple problems of *montado/dehesa*. Examples include projects that tackle the role of *Phytophthora* on the mortality and alternative methods of controlling the disease (INIA 2015–2018); projects for efforts in understanding the effects of forest certification on *montado/dehesa*'s sustainability (CERTFOR 2019–2022) or assess the combined effect of techniques that focused on reforestation success with *Q. suber* in Mediterranean degraded scrubland (Oak Regeneration project) (Muñoz-Rengifo et al. 2020).

Concerning the improvement of production, projects seem also to be now focusing on ferti-irrigation modes, and have been studying the influence of water and nutrients on cork oak radial growth (e.g. Camilo-Alves et al. 2022). Also ongoing, a project on recovery actions on soils, riverine and other habitats experimenting with association of *montado/dehesa* and wine production (*Biomontado*).

Recent projects tend to have a practical interest and future application. For instance, LIFE Biodehesa and LIFE Montado Adapt tried to set up a change in practices, supporting managers and landowners in Alentejo (Portugal), Extremadura and Andalusia (Spain) to face climate change and drought. Pilot areas established strategies to diversify crops associated with *montado/dehesa*. A socio-economic impact evaluation in this project already established indicators such as creation of jobs, business, qualification, and knowledge about *montado/dehesa* as an habitat. However, the focus was more on educating local communities for environmental issues and transference of scientific knowledge to local actors.

Sharing knowledge and deepening the role of local practices was not so much contemplated. However, these projects bring important data, knowledge and experiences. Given the complexity of the crisis scenario, it seems necessary to deepen the interaction of scientific knowledge from different disciplinary bases, and local expertise. To achieve sustainability we need not only knowledge from diverse disciplinary areas, but an approach that integrates it holistically. An approach that integrates scientific knowledge from diverse disciplinary areas, and also local and technical knowledge, provided by people directly engaged in the territory.

A sociocultural gaze is essential to understand the societal transformations which had such an impact in the *montado/dehesa* socio-ecosystems during the 20th century and can be dramatic in the future. On the other hand, the anthropological approach understands nature and culture not as a dichotomy, and also addresses the agency of non-humans (e.g. Latour 2005). Ecology already obtained biophysical variables with better local scale resolution, and so regeneration and mortality studies can now be modelled together with other socio-ecological variables—and with precision. Finally, approaches such as "*omics*" studies about *montado/dehesa* have to take into consideration cork oak local populations and tree diversity, as a product of fundamental processes at different time scales, of natural and anthropogenic selection and other recent processes amplified by contemporaneous climate change.

We trust that Ecology, Genetics, Anthropology and local knowledge can work together to gather essential information to understand cork oak forest in its current challenge to environmental and social change (Fig. 4). The scenario of *montado/dehesa* decline has biological and biophysic causes and consequences, but it also has repercussions at the social level. The social dynamics around *montado/dehesa* has to be characterized and considered in the present and in the future in terms of adapting to new conditions. Our focus is then on socio-environmental changes, and not only on economic or ecological ones.

New perspectives

Given the practical evidence and practical needs on one side, and assuming an interdisciplinary approach and knowledge gaps in different thematic areas together, new research questions arise. The final aim we propose is to look into associations and interconnected variables.

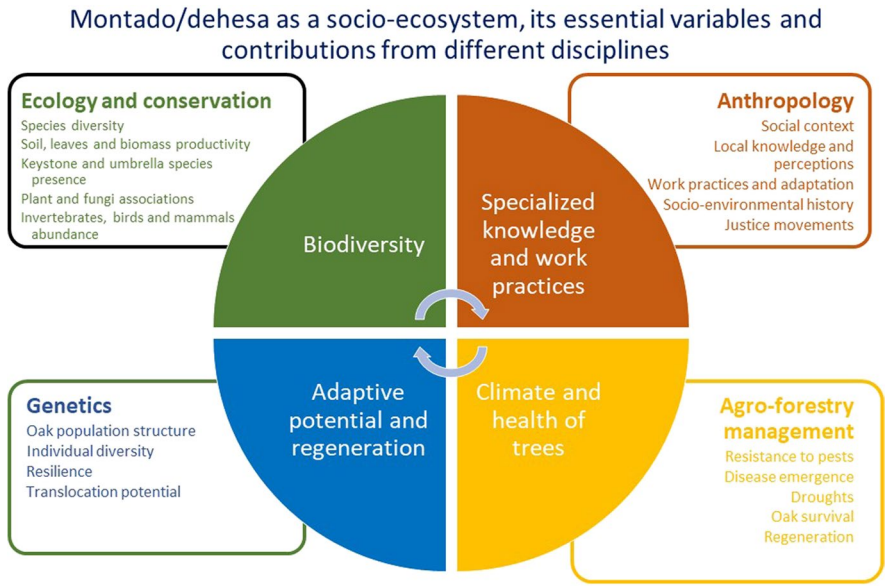

Fig. 4 - *Montado/dehesa* as a socio-ecosystem, its essential variables and study contributions from different disciplines

1. What are the crucial factors in the resilience and sustainability of *montado/dehesa* as a socio-ecosystem?
2. What is the place of the diverse local practices and local knowledge in the resilience and sustainability of *montados/dehesa*s?
3. How are current interactions between local communities, biophysical and genetic components responding to current stress factors?
4. What future scenarios can be foreseen at a local scale and from a socio-ecologically informed perspective?
5. What sets of management practices can be proposed that can contribute to overcome both current socio-ecological decline and be socially just?

These research questions may lead to a better understanding and provide tools to restore or reinvigorate the socio-ecological system in the *montado/dehesa* in an unprecedented way in the future. In practical terms, there is an urgent need for experimental actions and to know what should be done in areas where tree density is expected to be very low due to climate change and/or desertification.

Implied with these questions and in an interdisciplinary and transdisciplinary collaboration is the revision, the discussion and the establishment of base concepts which lay the foundations for a common language. Often it seems that we are talking about the same, namely when referring to ecosystem services, resilience, sustainability or renaturalized processes, but that is not always the case and impedes us from moving forward.

Since there is *montado/dehesa* abandonment we need to understand where are those systems going to, over time, in several dimensions. Although the concept of naturalized or abandoned *montado/dehesa* that makes it into a forest can be criticized and even considered displaced given that *montados/dehesas* are by definition humanized systems, the recent link between *montado/dehesa* and biodiversity conservation is also positive. Furthermore, it can raise important questions on the services *montados/dehesas* provide, namely regulating, sometimes not accounted for.

Furthermore, the development of indicators would be a measurement tool to encompass the complexity of the situation, better diagnose the decline at the social and environmental levels, and its interrelations as a whole. This can guideline future solutions towards resilience and ensuring a socio-ecosystem for future generations.

Concluding considerations: methodological reflections for future trans-disciplinary approaches

We assume both an interdisciplinary and transdisciplinary approach to generate new knowledge. The first is understood as the interaction of scientists from

different disciplines that integrate concepts, methods and results to generate new knowledge. The transdisciplinary approach is a reflexive, integrative, method-driven scientific principle, aiming at the solution or transition of societal problems and concurrently of related scientific problems by differentiating and integrating knowledge from various scientific and societal bodies of knowledge (e.g. Lang et al. 2012).

Specifically, in our study of socio-ecosystem dynamics in the cork oak *montado/dehesa* from a viewpoint of the interrelationship between genetic, ecological and sociocultural factors, we have been applying the interdisciplinary approach to generate a common understanding and theoretical framework between the various scientific disciplines. This would include establishing a common language, revisiting and completing concepts such as sustainability, ecosystem versus socio-ecosystem, *montado/dehesa* and cork oak woodland, productive system, practices and local knowledge, decline as a biologic and genetic event, and also perception about decline.

On the other hand, non-academic knowledge needs to be considered. Presently more than ever we need to include the changes observed in *montado/dehesa*, not only the biological impacts but also the challenges experienced on a daily local basis by workers and managers concerning cork extraction and other interventions. This is the main reason why a transdisciplinary approach integrating a dialogue between different knowledge, directed between different stakeholders, is necessary, in a climate change scenario. It is also a way to involve different stakeholders in the search for and implementation of solutions. To comprehend the current practices and social dynamics around them is fundamental to preview and improve the capacity to adapt and the well-being of local communities.

The proximity afforded by the ethnographic approach, integrating techniques such as participant observation and socio-historical review, facilitates a holistic, ground-level perspective to understand the kinds of transformations occurring around the transfer of knowledge, governance, management practices, and economic drivers that interact at both micro and macroscale levels in the socio-ecosystem configuration of a *montado/dehesa*. On the other hand, integrated methodologies from applied ecology, such as the use of geographic information systems as well as modelling of tree natural regeneration and mortality based on interrelated biophysical variables, allow us to assess the role that anthropogenic management practices are playing and their relationship with climate change variability from a multi-scale perspective, especially at the micro-spatial level.

Genomic prediction, based on high-density sampling methods with the best genomic markers, incorporates macro-spatial and macro-temporal variables that need to be considered to evaluate the adaptive conditions and evolutionary patterns of *Quercus spp*. in relation to other as-yet unexplored variables, such as local socio-economic practices and their effects on adaptive diversity. Finally, local ecological knowledge, based on a practical, embodied, everyday approach to the *montado/dehesa*, can help us identify emerging factors related to the resilience of these socio-ecosystems, as well as empirically test scientific interpretations applied to specific socio-environmental contexts.

Moving beyond parcel-based or mono-disciplinary approaches, under the proposed inter-scientific model can guide us towards more practical objectives. The outcomes can be employed to inform and guide restoration efforts. Results can integrate assessments of actions feasibility within socio-environmental criteria that encompass the complex dynamics at both micro and macro scales. This approach may, for example, support a more suitable selection of acorns to establish or increase oak density in other more suitable areas. We propose translocation experiments and pilot reforestations actions informed by previous knowledge. Regeneration success and mortality must be continuously investigated and monitored in ecological terms and in different geographic contexts. Local knowledge would be integrated and applied to accompany these experiments, empowering local communities in managing, and comparing how that influences growing specimens.

We believe that this approach, study and experiential practices are needed on the current dynamics of the *montado/dehesa* and cork oak woodlands where genetic, ecological and socio-cultural factors contribute and are interrelated.

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Author contributions MNB, MLF and EMF had the idea for the article. All authors contributed to the study conception and design. MLF, EMF, AP and MM performed the literature search and data analysis. The first draft of the manuscript was written by MLF and EMF and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Declarations

Competing interests The authors declare no competing interests. The ideas expressed in this paper do not necessarily reflect the views of the institutions involved.

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