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Creating resilient silvopastoral systems: Mediterranean silvopastoralism as a model for agroforestry

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1 Introduction

Spanning approximately 227 million hectares, the forests of the European Continent embody a diverse mosaic of ecosystems, characterised by coniferous, broadleaf, and mixed forests, as outlined in the State of Europe's Forests Report (FOREST EUROPE 2020). However, this distribution is far from uniform across the Continent, with considerable variations in forest cover, types, and management among European nations. Consequently, forest management strategies vary, from timber production-centric approaches in some regions to cultivating non-timber products and services in others. The overall figure does not include Other Wooded Land (OWL): land not classified as forest but which still contains a significant percentage (typically over 10%) of trees, bushes, and

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shrubs). OWL accounts for roughly 27 million hectares, a relatively small overall area. The prevalence of OWL varies across European territories, ranging from 0.6% to 4.7%, except in Southwest Europe where OWL encompasses 14.4% of the land area (FOREST EUROPE 2020).

The dominance of broadleaf trees characterises the forests of southwestern Europe. More than 60% of the forests in this region are broadleaved, 30% are coniferous, and less than 10% are mixed forests (FOREST EUROPE 2020). The Mediterranean climate, marked by prolonged droughts and alternating wet and dry periods, provides conducive conditions for the prevalence of evergreen and sclerophyllous species (adapted to cope with periods of drought) with limited wood productivity compared to their counterparts in Northern and Central Europe. This distinction has historically shaped the utilisation of Mediterranean forests, with a rich tradition of harvesting animal and plant products over millennia (Chebli et al. 2018; Aubert 2013; Blondel 2006; Gómez Sal 2000). Today, it is estimated that silvopastoral systems cover about 6.5 million hectares in the Iberian Peninsula, representing about 30% of the agricultural area (den Herder et al., 2017).

Quezel and Medail (2003) highlighted the ecological significance of oak woodlands in the Mediterranean region (see Fig. 1, *Distribution of the most important oak species of the Iberian Peninsula in the Mediterranean area*). Due to their ecological attributes, the silvopastoral systems of these species provide essential resources such as meat, charcoal, cork, firewood, and timber and offer many ecosystem services. Combining forestry and grazing of domesticated animals on the same land unit has been a cornerstone of rural life on the Iberian Peninsula for centuries, supporting livelihoods and contributing to biodiversity conservation (Mosquera-Losada et al. 2009; Casals et al. 2009; Moreno and Rolo 2019; Castro 2009).

However, over the past century, intensifying agricultural practices to enhance food security and productivity have marginalised traditional agroforestry practices. Guerra et al. (2016) found that, over the past 35 years, cattle-related headage payments have markedly influenced tree cover density and regeneration under agricultural policy in Portugal, notably impacting the Supply of Ecosystem Services. This effect intensified after 1986, aligning with the activation of numerous Common Agricultural Policy tools to enhance farm modernisation and productivity.

This chapter investigates the complex interactions occurring on the Iberian Peninsula between key oak species – holm oak (*Quercus ilex* L.), cork oak (*Quercus suber* L.), and Pyrenean oak (*Quercus pyrenaica* Willd.) – and various livestock species, including ruminants (sheep, goats, and cattle) and monogastric animals (horses and pigs). The chapter aims to show the pivotal role of Mediterranean silvopastoral systems as resilient and sustainable agroforestry models, with a particular focus on their economic,

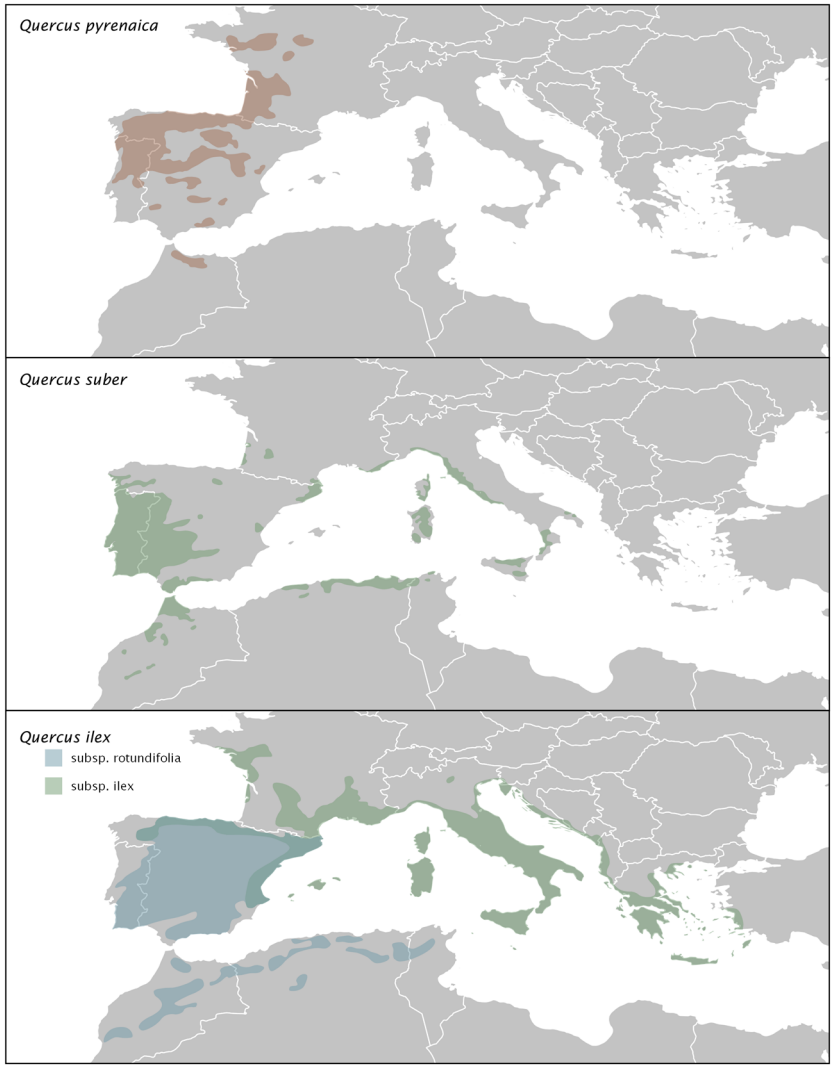

Figure 1 Distribution of the most important oak species of the Iberian Peninsula in the Mediterranean area

ecological, and cultural significance. By examining these systems, the chapter underscores the synergistic interplay between anthropogenic activities and natural ecosystems, highlighting their potential to support sustainable land management practices and biodiversity conservation within Mediterranean landscapes.

2 Functional interactions within silvopastoral systems

Forests and animals have a complex, dynamic relationship crucial for maintaining biodiversity and providing ecosystem services (Velamazán et al. 2020). Grazing domestic and wild animals interact with forest ecosystems in ways that can significantly alter their structure (Gill and Fuller 2007; Ramirez et al. 2018) and function (Beguin et al. 2016). These interactions occur through feeding habits, trampling, rubbing, dung and urine deposition, debarking, and other behaviours that affect seed dispersal, plant community composition, and soil properties (Wachiye et al. 2022; Candel-Pérez et al. 2024). Velamazán et al. (2020) and Tittonell et al. (2021) highlight the dual nature of ungulates (hoofed animals) as both providers of ecosystem services and sources of disservices (Velamazán et al. 2020; Tittonell et al. 2021).

According to Nair's agroforestry typology, silvopastoral systems involve at least two distinct components: trees and pasture/animals, so the balance between services and disservices depends on animal and plant factors (Li et al. 2021; Fan et al. 2019; Nair 1991). The supply of a specific service is rarely independent of others, and both positive (synergies) and negative (trade-offs) pairwise relationships between ecosystem services are common (Roces-Díaz et al. 2021). Sales-Baptista and Ferraz-de-Oliveira (2021) highlight that interactions can lead to different outcomes and influence ecological processes. One of the main conditions of agroforestry is reciprocal benefits between the system entities.

Exploring the connection between ungulates and the ecosystems of Mediterranean forests and scrublands requires an in-depth understanding of the unique interrelations present within these environments. The Mediterranean region, characterised by its biodiversity hotspots and distinct ecosystems, provides an illustrative example of the complex relationships between wild and domestic ungulates and their habitats. Here, pastoralism, a traditional and extensive form of livestock grazing of spontaneous fodder resources in areas commonly called rangelands, plays a crucial role in shaping these landscapes (see Figs. 2 and 3) (Dubeuf et al. 2023). While ungulates provide essential services, their impacts can become detrimental under certain conditions. Overgrazing by domestic livestock, exacerbated by insufficient management, can lead to soil degradation, loss of plant cover, and decreased biodiversity. The challenge is serious in Mediterranean woodlands, where the soil is prone to erosion and desertification.

3 Silvopastoral ecosystem services and disservices in the Mediterranean region

Silvopastoral systems embody many ecosystem services indispensable for environmental sustainability, particularly in the Mediterranean (Quintas-Soriano

Figure 2 *Preta de Montesinho* goats grazing in the oak forest

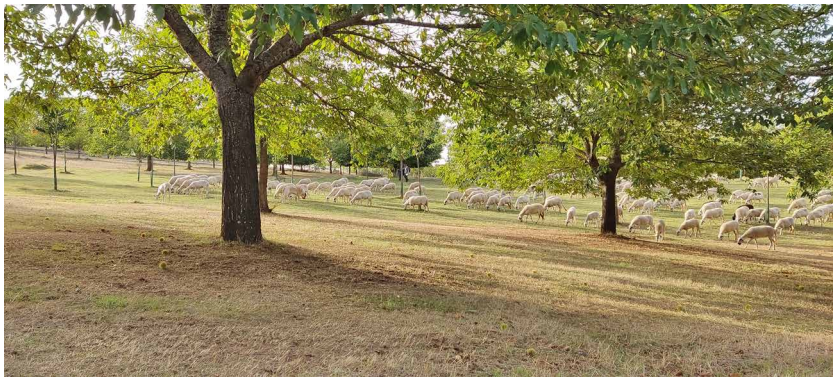

Figure 3 Sheep grazing in chestnut groves

et al. 2022; Bangash et al. 2013; Balzan et al. 2020). These systems, through the strategic integration of domestic ruminants adapted to local landscapes, contribute significantly to biodiversity conservation, soil preservation, carbon sequestration, and the mitigation of fire hazards. Each of these services reflects the sustainable and symbiotic relationship fostered between the land and livestock, showcasing the potential of these practices in enhancing the ecological integrity of agricultural landscapes.

Ungulates, including wild species like deer and boar, are instrumental in forest regeneration. By consuming fruits and traversing varied landscapes,

these animals facilitate the dispersal of seeds to new locations, thereby playing a pivotal role in enhancing plant dispersal and genetic diversity. As highlighted by Janzen (1984) and Malo and Suárez (1995), this process is crucial for sustaining forest resilience and adaptability to changing environmental conditions. Moreover, in Mediterranean ecosystems, the role of ungulates extends beyond simple seed dispersal. Their movement through the woodlands aids in the propagation of numerous plant species, including those essential for maintaining the region's biodiversity, as Gómez (2003) notes. For instance, the ingestion and subsequent dispersal of seeds by these animals can lead to the regeneration of key tree species, such as oaks (*Quercus* spp.), which are pivotal in these ecosystems.

Furthermore, through selective feeding, ungulates significantly influence the composition of plant communities. This activity can enhance habitat heterogeneity and biodiversity, as Olff and Ritchie (1998) discussed. Their grazing behaviour helps control the potential dominance of certain plant species, allowing a more diverse plant community to flourish. This aspect of ungulate behaviour is particularly relevant in maintaining the open landscapes characteristic of the Mediterranean, as outlined by Seligman and Perevolotsky (1994).

Additionally, this grazing pressure aids in preventing the encroachment of shrubs, thus supporting a mosaic of habitats conducive to high biodiversity. Moreover, suppressing fire-prone species through grazing reduces the risk of wildfires, a significant concern in these regions. The movement and trampling activities of ungulates also enhance soil aeration and contribute to nutrient cycling through their manure, thereby boosting soil fertility and promoting plant growth, as detailed by Bardgett and Wardle (2003).

Despite the undeniable benefits provided by ungulates to forest ecosystems, a spectrum of adverse effects accompany their contributions. Research, including studies by Velamazán et al. (2020), has explained ungulates' significant yet complex role in ecosystems, highlighting their positive impacts on biodiversity and wildfire prevention and the negative consequences they can also cause. These include biodiversity loss in vegetation, plant recruitment failure, habitat degradation, decreased plant diversity, soil erosion, and the facilitation of invasive species spread and disease transmission, as evidenced in studies by Milchunas and Lauenroth (1993), Vitousek et al. (1997), and Gortázar et al. (2007). The complex interplay between these beneficial and detrimental effects underscores the need for informed management and conservation strategies that acknowledge and address the ecological intricacies of ungulate-forest interactions.

Mediterranean forests and scrublands serve as prime examples of these nuanced interactions, where the roles of both wild and domestic ungulates in ecological functions and biodiversity are evident yet must be mediated by

careful management to mitigate potential disservices. The ecological services and disservices of silvopastoral systems, underscored by the contributions and challenges associated with ungulates, highlight the critical importance of these agricultural practices in creating resilient and sustainable landscapes (Gill and Fuller 2007; Ramirez et al. 2018).

By fostering a balanced and symbiotic relationship between livestock and their environment, silvopastoral systems also offer pragmatic solutions to contemporary environmental challenges, including climate change and wildfire management, underscoring the need for continued research, informed management, and the adoption of sustainable pastoral practices to preserve these landscapes' unique biodiversity and ecological health (Olea et al. 2006; San Miguel-Ayanz et al. 2010). By embracing sustainable pastoral practices and acknowledging the ecological roles of ungulates, it is possible to preserve the Mediterranean's unique biodiversity while supporting the livelihoods of local communities (Papanastasis et al. 2008; Rogosic et al. 2006).

4 Tree cover, forage productivity, and nutritional value

In the Mediterranean basin, characterised by fluctuating climatic conditions, the role of forest trees in supporting forage production and quality for grazing animals seems crucial (Papachristou 2016; Castro 2004). Forest trees make an essential contribution to the diet of extensive livestock production systems by diversifying the forage resources available to animals throughout the year, increasing the diversity and quality of forage, and providing a range of nutritional benefits to grazing animals, such as anthelmintic components (Torres-Fajardo et al. 2024; Torres-Acosta et al. 2016).

Climatic change is expected to have a major impact in this region due to increased temperature, reduced water availability, and inter-annual variability (IPCC 2014). The increased climatic variability will strongly influence pastoral systems, even though they have developed the capability to cope and adapt to climate uncertainty (Nardone et al. 2010). For instance, del Prado (2021) has stated that the severity of climate change threatens sheep and goat production systems in the Mediterranean area. Apart from their direct impact on animal welfare and performance, there is also an impact on the reduction of feed resources. The warmer and drier conditions forecasted for the Mediterranean region might impact net primary productivity and biomass quality (Martinez et al. 2014). Integrating the multiple contributions of forest trees to improve the production and quality of fodder resources is essential to ensure the sustainability of extensive livestock production systems and a healthy Mediterranean forest.

In silvopastoral systems, pasture yield depends on the light pastures receive and the availability of water and nutrients. The presence of the tree

induces a microenvironment that is generally favourable to forage quality. Tree canopies reduce abiotic stress by moderating air and soil temperatures, reducing plant evapotranspiration, and reducing water stress in lower-lying herbaceous plants (Moreno et al. 2016; Moreno 2008; Mvondo et al. 2022). This shade is particularly beneficial during the hot and dry Mediterranean summers when the risk of drought stress is high (Canteiro et al. 2011).

Although this section describes the effects in general terms, there are significant differences between the effects produced by scattered tree systems – wood pastures – and those of dense forests in wetter mountain areas – forest grazing. This difference is because the canopy's density directly affects the radiation that reaches the lower levels, where the grass grows, and because of the availability of organic materials produced by the trees. For instance, the amount of litterfall accumulated on the soil surface is estimated at 400 in scattered tree systems and 8000 kg ha^{-1} in dense forests (Escudero et al. 1985).

Trees significantly affect the fertility of the soil, primarily by recycling leaf litter and by the turnover of nutrients that are moved through the root systems from deep in the soil (Escudero Berián 1992). This nutrient cycling is crucial for maintaining the productivity of Mediterranean pastures (Etienne 1996). Moreover, trees can facilitate the development of mycorrhizal associations and symbiotic relationships between fungal mycelium and plant roots, which improve plant access to water and soil nutrients. This symbiosis is beneficial for the growth of forage species under the nutrient-poor conditions often found in Mediterranean environments (Smith and Read 2008). In addition, trees modify soil physical properties, increasing soil water-holding capacity, macroporosity, and infiltration rates compared to open areas (Joffre and Rambal 1993), mainly explained by the increase in soil organic matter and the decreased bulk density near the trees enhancing capacity to store water in the soil.

In addition, the tree's presence reduces thermal extremes in its immediate area. Temperatures are never as high as they are beyond the tree, nor are they as low in winter, allowing pasture to grow longer in summer (Moreno et al. 2016). In dense forest systems, similar effects are also reported during the summer: temperature and light levels decrease, whereas the relative air humidity increases from the edge towards the forest interior (Meeussen et al. 2021).

Regarding forage quality, canopy cover has a positive effect on pasture phenology. It controls warming which otherwise shortens the period when plant biomass has optimal nutritional quality, increasing fibre and lignin content, and reducing digestibility (Dumont et al. 2020; Habermann et al. 2019). In addition, a moderate water deficit slows plant maturation, and biomass quality can be maintained or even improved because it delays stem development, reduces lignification, and increases digestibility (Hidalgo-Galvez et al. 2023).

Nevertheless, severe droughts usually reduce net primary productivity and quality.

Previous studies have reported that the net effect of tree canopy on forage production in Mediterranean oak woodlands can be positive, negative, or neutral, depending on inter- and intra-annual rainfall variations (Gea-Izquierdo et al. 2009; Rivest et al. 2013; López-Carrasco et al. 2015; López-Sánchez et al. 2021; Rolo et al. 2015). In addition, other factors such as soil type and fertility, as well as biological factors such as understorey species, oak species, canopy cover, tree age, and plant root architecture, play a crucial role in this variation (Rivest et al. 2011). Over-dense forests can lead to excessive competition for light, water, and nutrients between trees and understory vegetation, potentially reducing forage availability. Therefore, appropriate silvopastoral practices, including selective thinning and the maintenance of tree-pasture balance, are essential for maximising forage production while conserving forest ecosystems (Moreno and Pulido 2008).

The Mediterranean oak forest provides various fodder resources, including herbaceous pasture, acorns, foliage, and shrubs. The annual value of these products varies greatly depending on the location – weather conditions, soil type, tree or shrub species, type of system (scattered trees or dense forests), and stand density of tree or shrub cover – and, in the case of fruit, inter-annual variation. Furthermore, valuing the resource depends on who is valuing it. For instance, Evlagon et al. (2010) states that, in the Mediterranean shrubby range, the nutritional value of pasture for goats is typically more than twice that for sheep or cattle. In addition, there is almost no data on the forage production of forests or woodlands, i.e. considering all their components. However, Lledó et al. (1992) provides a global value of about 2700 kg ha^{-1} for holm oak woods, including the annual production of leaves, fruits, and flowers of trees and shrubs.

The published data for the productivity of shrubby ranges are highly variable. For instance, Ameray et al. (2022) give a value for available biomass of 3126.65 kg DM (dry matter) ha^{-1} for leguminous and cistaceous scrublands in the Mediterranean region of Portugal. However, according to these authors, only 1416.03 kg DM ha^{-1} has potentially consumed biomass, as animals only eat the year's shoots. Papanastasis et al. (1983) found annual DM production of Kermes oak pasture in Greece to vary between 378 and 742 kg DM ha^{-1}. Robles et al. (2009) give a 3264 kg DM ha^{-1} value for 'medium leguminous shrublands' in Andalusia, Spain. Evlagon et al. (2010) found an annual DM production of *Quercus calliprinos* and *Pistacia lentiscus* pasture in Israel between 700 kg and 1100 kg DM ha^{-1}. López-Díaz (2009) gives a value for tree fodder of cork and holm oaks of 350–550 kg DM ha^{-1} in wood pastures. Moreno et al. (2016) report values ranging from 500 kg to 1000 kg DM ha^{-1} obtained by pruning every 3 years.

Due to different situations, data on the productivity of herbaceous plants also vary widely between authors. In the case of Pyrenean oak, at densities between 400 and 1100 stems ha^{-1}, Castro (2004) found an annual herbaceous production of 570–2500 kg DM ha^{-1} $year^{-1}$ in mountainous regions of Portugal. In the case of scattered tree systems, according to Moreno et al. (2016), the leading natural pastures can be functionally divided into three groups:

- Annual production of between 1000 kg and 2700 kg DM ha^{-1} $year^{-1}$ for common annual pastures in the poorer soils;
- 3000 kg DM ha^{-1} $year^{-1}$ for 'majadal' pastures, created by the intense and continuous action of livestock; and
- 1500 and 2500 kg DM ha^{-1} $year^{-1}$; for the remaining type characterised by depressions with a little more water availability.

However, Gea-Izquierdo et al. (2009) reported a value varying between 5777.0 kg and 111.6 kg DM ha^{-1}, with an average annual production of 1901.8 kg DM ha^{-1} for scattered holm oaks wooded pastures in west-central Spain.

Different types of livestock eat the fruit of the oak – acorns – in the Iberian grazed woodlands. The best quality acorns come from holm oak, superior to Portuguese oak (*Quercus faginea* Lam.), cork oak, and Pyrenean oak. Gasmi-Boubaker et al. (2012) found that acorns, as a food source, contain low protein levels (less than 10% DM) and are high in carbohydrates, mainly starch (56.6–59.9% DM), making their composition like cereals. Due to their high carbohydrate content, which can be easily converted into fat, Escribano and Pulido (1998) noted that acorns are commonly fed to pigs during the finishing phase. Pigs are the best consumers of acorns in scattered tree systems, and the Iberian breed of pig can consume them without supplements (Rodriguez-Estévez et al. 2009). Joffre et al. (1999) reported that pigs graze during the seasonal acorn production between October and February, gaining about 60 kg in live weight over 75 days. Ruperez (1957) reported that 9 kg of holm oak acorns produces 1 kg of pork meat. Annual acorn production is highly variable in scattered tree systems, but a typical average value for holm oak is 500 kg ha^{-1}, with values of up to 800 kg ha^{-1} (Moreno et al. 2016).

5 Tree cover and livestock welfare

In the warm and often arduous Mediterranean climate, the welfare of grazing animals such as cattle, sheep, and goats is a significant concern. The challenges posed by the hot, dry summers, and variable precipitation patterns necessitate adaptive strategies to ensure the health and productivity of livestock (Giridhar and Samireddypalle 2015; Gitz 2016). Forest trees play a pivotal role in this

context, offering both refuge and resources that enhance the welfare of these animals (Souza et al. 2019; Vizzotto et al. 2015; Roese et al. 2017; Oliveira et al. 2021; Smith et al. 2022).

Livestock animals seek shelter in various environmental and climatic conditions, such as hot or cold weather, heavy rain, or high insect infestation (Proops et al. 2019). In particular, Mediterranean summer conditions affect animal welfare by causing heat stress (Holinger et al. 2023). Heat stress poses an increasing risk to animal welfare, health, and productivity in pasture-based livestock systems (Arnott et al. 2017; Boyle et al. 2020). Heat stress occurs when environmental conditions, such as air temperature, relative humidity, air movement, and solar radiation, cause body temperature to be above the animal's thermo-neutral zone (Silanikove 2000), a limiting factor to livestock production (Paim et al. 2014). Gonzalez-Rivas et al. (2020) and Knight et al. (2023) associate heat stress with lower animal growth rates, reduced feed intake, poor fertility, inconsistent carcass composition and quality, increased veterinary costs, and animal welfare issues associated with compromised biological functioning.

Studies by Florindo et al. (2020), Maia et al. (2005), and Silanikove (2000) highlight the vital role of shade in reducing heat stress for grazing animals, leading to improved welfare and productivity. Vandenheede et al. (1995) further illustrate forests' protective role against adverse weather, enhancing livestock welfare. Silvopastoral systems, as discussed by Bertogna et al. (2022), Christensen et al. (2022), Leite-Moraes et al. (2023), and Santos Neto et al. (2022), offer a multifaceted solution by providing shade, improving fodder nutritional value, and supplementing diets during scarcity, showcasing their potential in improving animal welfare and productivity.

Finally, Ruiz and Sanz-Sánchez (2020) emphasise the indispensable role of forest ecosystems in water regulation and preserving water sources, a boon for the Mediterranean's water-stressed environments critical for livestock rearing. Trees modulate the hydrological cycle by capturing rainfall and managing water flow, fostering groundwater replenishment, and supporting springs and streams, as Bennett and Barton (2018) and Zema et al. (2021) have documented. This process is crucial for sustaining water supplies for grazing animals, mainly through the sweltering summer months, underscoring the findings of Belsky et al. (1989).

6 The complex interplay between grazing animals and forest trees

The interplay between grazing animals and forest ecosystems is critical in the Mediterranean basin's distinct climate and biodiversity framework. While crucial for landscape management and agricultural yields, grazing presents

notable challenges for forest vitality and diversity. Key issues include tree damage through bark stripping, which impairs tree health and heightens susceptibility to environmental pressures. Soil compaction caused by animal trampling hinders root growth and water absorption, exacerbating tree stress in dry conditions. Moreover, selective grazing on young vegetation can shift forest dynamics, possibly diminishing biodiversity and the forest's natural regeneration processes, as highlighted in studies by Bullock and Gregory (2009), Milchunas and Noy-Meir (2002), and Plieninger et al. (2003).

Grazing's effects on Mediterranean forests vary, affected by factors like forest type, species diversity and grazing intensity, as pointed out by Doblas-Miranda et al. (2017), Stark et al. (2023), and Vaz et al. (2024). These variables pose challenges to the generalisation of results to all forest ecosystems. The aims of forest management and production direction significantly shape perceptions of grazing's effects. The evolution towards specialised forestry over recent centuries complicates the assessment of grazing, often aligning livestock management in contrast to timber production goals, as discussed by Kardell (2016), Nichiforel et al. (2018), Öllerer et al. (2019), and Serrano Alvarez (2014).

The assessment of grazing's effects is complex, influenced by regional disparities, forest types, and diverse forest management approaches. Concerns about grazing's impact on the regeneration of specific species, notably oaks, highlight the intricate dynamics of grazing, which can range from obstructing regeneration to potentially benefiting certain seedlings through altered soil water dynamics, as noted by Dufour-Dror (2007), Guy (2014), and Pinto-Correia and Azeda (2017). This intricate dynamics underscores the importance of distinguishing between the effects of undergrazing and overgrazing, pointing to the necessity of a nuanced comprehension of grazing's ecological functions, as discussed by Hidalgo-Galvez et al. (2023) and Seligman and Perevolotsky (1994).

Comprehensive strategies are vital for enhancing landscape management and mitigating the negative impacts of grazing. These strategies include managed grazing, young tree protection, and the promotion of silvopastoral systems that combine trees, shrubs, and grazing animals. This combination significantly improves biodiversity, soil quality, and carbon capture and storage. Such measures mitigate grazing's immediate adverse effects and reinforce the resilience and sustainability of Mediterranean forest ecosystems. Given grazing's dual nature – harmful and beneficial – it is imperative to implement balanced, sustainable management practices in the Mediterranean. These practices are crucial to preserving biodiversity, boosting ecosystem services, and sustaining agricultural and forest landscapes, as evidenced by Moreno and Pulido (2008) and Ruiz-Mirazo et al. (2011).

7 Silvopastoralism in Iberia: integrating nature, culture, and agriculture

The silvopastoral systems in the Iberian Peninsula, with origins dating back to ancient times, are integrally linked with the region's ecological, cultural, and economic frameworks. This interdependent relationship has been extensively documented, with notable contributions from Díaz-Maroto and Vila-Lameiro (2008), Roces-Díaz et al. (2021), and Santiago-Freijanes et al. (2021). Originally developed to address the challenges of the region's rugged and variable topography, these systems innovatively integrate forestry and livestock grazing. This strategy has enabled agricultural communities to optimise use of challenging landscapes, a concept thoroughly discussed by Glick (2005). The historical integration of domestic ruminants into these ecosystems has significantly shaped land use strategies over thousands of years, as shown by the research of Gómez Sal (2017) and McClure et al. (2006).

During the medieval period, the transhumance system, a seasonal movement of livestock between winter pastures (valley bottoms and southern latitudes) to summer pastures (mountains and northern latitudes), emerged and became a cornerstone of the Iberian agricultural calendar. This practice was fundamental to Iberian agriculture, an enhancement that authors such as López-Sáez et al. (2014) and Blanco-González et al. (2015) extensively documented. This process, involving the seasonal livestock migration, was instrumental in interweaving socio-economic structures and facilitated the exchange of goods, cultural traditions, and knowledge across regions. Specifically, sheep and goats were at the core of this system, serving as significant economic resources by producing various goods and playing a critical role in maintaining ecosystem health, a concept elaborated upon by Gómez Sal (2017).

Over time, researchers and policymakers have increasingly acknowledged the significance of silvopastoral systems in contributing to sustainable land management and biodiversity conservation, leading them to incorporate these systems within various legal frameworks aimed at their protection. Gómez Sal and Lorente (2004) have investigated the establishment of the 'Mesta' in Spain, highlighting it as a notable illustration of these systems' economic and political importance. However, the advent of industrial and agricultural modernisation presented significant challenges, leading to a decline in these traditional practices. Despite these obstacles, specific regions within the Iberian Peninsula continue to practice silvopastoralism, ingeniously integrating these age-old practices with contemporary requirements. This approach addresses modern needs and preserves the area's rich historical and ecological legacy, as documented by Herrera and Pulido (2021).

The revision of agricultural policy in 1992 marked a pivotal transformation in the European agricultural framework, prioritising biodiversity, water quality,

carbon sequestration, and soil conservation. This shift is extensively analysed in the work of Mosquera-Losada et al. (2018), highlighting its significance in the context of agricultural practices. Silvopastoral systems have been identified as a practical paradigm for sustainable agriculture, aligning closely with current conservation goals in response to the pressing challenges imposed by climate change. Researchers recognise these methodologies for their critical role in reducing environmental impacts and promoting sustainability amid a global ecological crisis, a perspective that Mosquera-Losada et al. (2018) strongly support.

8 Vegetative components of Iberian silvopastoral systems

Iberian silvopastoral systems feature an integrated management strategy that synergistically combines woodlands (trees and shrubs) with livestock (ruminants and monogastric animals). This approach involves interaction among components on the same patch and landscape, fostering diverse entities to coexist and thrive. This integrative strategy optimises using environmental conditions and landscape features to achieve sustainable agricultural productivity. Silvopastoral systems are the most common and extended agroforestry systems in the Iberian Peninsula, with multiple management systems, practices, and outcomes combinations. According to Castro (2009), the two most representative are the forest grazing, mainly in mountainous areas, and the wood pastures in the more arid regions known as 'Montado' (Portugal) or the 'Dehesa' (Spain).

The vegetation component exhibits significant heterogeneity, a variation attributable to differences in regional climate, soil properties, and anthropogenic management practices. Commonly, these agroforestry systems incorporate indigenous oak species, beneath which a rich undergrowth comprising grasses, herbs, and shrubs proliferates. Drawing upon the genetic adaptations to the varied landscapes of the Peninsula, both native ruminant and monogastric livestock breeds exhibit robust performance. The domestic ruminants that graze these landscapes have evolved and been selectively bred over centuries to adapt to specific environmental conditions and best use the available resources. The structural diversity of oaks woodlands supports a multifunctional landscape conducive to livestock grazing, fosters wildlife biodiversity, and yields economically valuable non-timber forest products.

The genus *Quercus*, which includes diverse and ecologically-significant species of oak tree, is a pivotal group within the flora of the Northern Hemisphere. Vila-Viçosa et al. (2022) and Vitelli et al. (2017) highlight that these trees play crucial roles in economic and environmental contexts, including as grazing oak woods. Oaks thrive across a remarkable range of environments,

from arid landscapes to the moist conditions of swamp forests and from lowland areas to high altitudes of up to 4500 metres above sea level, with Denk et al. (2023) providing insight into their adaptability.

The Iberian Peninsula is a hub for oak diversity in Eurasia, hosting over nine unique oak species that enrich its forests and woodlands. Castro and Fernandez-Nuñez (2014) and Ruiz de la Torre (1990) underline the area's ecological importance. Notably, the Pyrenean oak (*Quercus pyrenaica* Willd), cork oak (*Quercus suber* L.), and holm oak (*Quercus ilex* L.) are prominent for their extensive distribution, economic benefits, and crucial roles in silvopastoral system development. The Pyrenean woods, favouring the cooler northern climates, contribute to the region's ecological diversity, including fire resilience and habitat for wildlife. Holm oak woods are vital for southern silvopastoral practices, offering wildlife habitats and livestock grazing, while the cork oak's regenerative bark is invaluable to industry.

The extensive coverage of the Pyrenean oak, spanning 660 000 hectares in Spain and 81 700 ha in Portugal, is highlighted by Castaño-Santamaría et al. (2013) and ICNF (2016), highlighting its prevalence at various altitudes and its adaptation to siliceous soils (De Rigo and Caudullo 2016). Despite its adaptability, the species faces challenges from climate change, with vulnerabilities such as limited migration options and susceptibility to pests and diseases, as discussed by Pérez-Luque et al. (2020) and Roces-Díaz et al. (2021). The potential decline in suitable habitats, especially in southern areas like the Sierra Nevada, is a concern raised by Dorado-Liñán et al. (2019) and Pérez Luque (2022), indicating the need for focused conservation efforts.

The resilience of the Pyrenean oak to summer droughts, a characteristic feature of the Mediterranean climate, is underscored by the work of Aranda et al. (1996), Sisó et al. (2001), and Corcuera et al. (2002), emphasising its ecological importance. This species' distribution, confined mainly to the Iberian Peninsula, southwestern France, and northern Morocco, is detailed by Lorite et al. (2008) and Souto-Herrero et al. (2018), with Spain and Portugal accounting for a significant portion of its habitat, as noted by Luis Calabuig et al. (2000).

Cork and holm oaks stand out in the Mediterranean basin for their ecological and economic significance and role in the singular 'Dehesa' and 'Montado' agroforestry systems. The spatial distribution of cork oaks and holm oaks across varying moisture regimes – where cork oaks predominantly occupy coastal regions experiencing oceanic influences, and holm oaks are more prevalent in the arid inland areas – demonstrates the impact of the Mediterranean climate on vegetation patterns. This adaptation is further explored by Aronson et al. (2012) and Eriksson et al. (2017), who note the cork oak's symbolic representation of the Mediterranean's ecological and cultural heritage.

Various studies detail species' distribution, their resilience to climate extremes, and the specific environmental conditions they require, including

Oliveira et al. (1994), Eriksson et al. (2017), and Houston Durrant et al. (2016). The holm oak's adaptability across a wide range of Mediterranean climates, from semi-arid to very humid conditions, and its tolerance to temperature extremes are discussed by De Rigo and Caudullo (2016), with additional insights on its soil preferences and climatic requirements provided by Aronson et al. (2012) and Camponi et al. (2023).

9 Domestic ruminant species in silvopastoral systems

The integration of domesticated breeds into local rangelands exemplifies a remarkable adaptation to the Iberian Peninsula's unique environmental conditions. The extensive variety of indigenous livestock breeds further demonstrates this diversity. According to the national catalogues of Portugal and Spain, it includes 50 breeds of cattle, 48 breeds of sheep, 23 breeds of goats, 11 breeds of pigs, and 22 breeds of horses and donkeys, showcasing the rich biodiversity present within these silvopastoral systems and landscapes.

The co-evolution of livestock and landscape underscores the importance of traditional knowledge and selective breeding in maintaining the sustainability and productivity of these systems. Practices such as rotational grazing, controlled burning, and pruning of trees are employed to maintain the ecosystem's health, ensuring it continues to provide for the needs of the domestic ruminants while preserving biodiversity. The sustainable management of silvopastoral systems requires a nuanced understanding of the dynamic interactions between natural vegetation growth cycles, patterns, and livestock grazing practices. Joffre et al. (1988) highlight the intricate ecological dynamics between livestock and woodland habitats within the 'dehesas' and 'montados' of the Iberian Peninsula, emphasising the role of these practices in maintaining these unique agroforestry systems.

The native domestic ruminants of Iberia have developed remarkable adaptations, enabling them to thrive in challenging environments. Managing their silvopastoral grazing patterns optimises using natural resources and mitigates the impact of grazing on the environment, allowing for vegetation recovery and maintaining landscape diversity. These breeds exemplify the incredible adaptability of livestock to diverse and challenging environments as a testament to centuries of evolution and selective breeding, underlining the importance of these practices in maintaining the ecological and economic sustainability of rural mountain communities.

9.1 Sheep

Adapted across varied ecosystems within the Iberian Peninsula, ovine species significantly contribute to ecological equilibrium. In the mountain areas, sheep foraging behaviour is instrumental in sustaining open wooded landscapes by

consuming understorey shrubs and herbs. Grazing practices in wood pastures are pivotal in enhancing species biodiversity and health. Pinto-Correia and Mascarenhas (1999) have explored the integration of agriculture and nature conservation, particularly in the context of traditional landscapes like the Portuguese 'montado,' underscoring the vital role of these livestock practices in promoting soil health and biodiversity.

Notably, indigenous sheep breeds such as the Merina and Churra, embedded within the transhumance tradition, exhibit remarkable resilience and are adept at exploiting the heterogeneous forage available within silvopastoral ecosystems. Historically, the commerce of Merina wool has been a cornerstone of economic development, emphasising the economic significance of these breeds. Castro et al. (2021) show the versatility of these species in terrain adaptability, including their pivotal role in forest fire prevention and landscape stewardship, mainly through their dietary preferences that curb the proliferation of shrubs, thereby reducing combustible material and lessening the likelihood of forest fires. They underscore the integral role of sheep breeds in the conservation of open woodlands and rangelands, highlighting their contribution to environmental conservation and management.

9.2 Goats

Goats also play an indispensable role, favouring rugged and mountainous woodlands in the Iberian landscapes. These animals thrive by browsing rather than grazing, focused on shrubs and trees. This specific dietary preference is crucial for preventing overgrowth and maintaining landscape diversity. Manzano and Malo (2006) describe how extensive grazing by goats in mountainous regions contributes to balancing biodiversity conservation with livestock production. Their unique browsing habits are instrumental in controlling bush encroachment.

The ecological management of marginal woodlands, often deemed unsuitable for conventional forestry, is markedly improved by the presence of goats (Rosa García et al. 2012). By consuming plant species that other livestock typically find unpalatable, goats help in the health and regeneration of woodlands. This is particularly true for breeds such as the Murciano-Granadina and the Spanish Ibex. Although the latter is not a domestic breed and thus not traditionally managed for commercial purposes, both species share similar habitat preferences and contribute positively to their environments (Delgado et al. 2017; Velamazán et al. 2020). These breeds have superbly adapted to the challenges presented by mountainous terrains, demonstrating an exceptional ability to utilise the sparse vegetation found under forest canopies (Acevedo et al. 2008; El Aich and Waterhouse 1999; Ferreira et al. 2013; Robles et al. 2009; Sanjuán et al. 2018).

The versatility of goats renders them invaluable for managing understorey and significantly reduces the risk of fire, an increasingly important issue in the face of climate change. Sanjuán et al. (2018) and Ferreira et al. (2013) have shed light on the significance of goat grazing as a strategic tool in forest management and bush encroachment control. Their research underscores how goats, through their natural behaviours and dietary preferences, serve as critical agents in the ecological stewardship of the Iberian Peninsula, enhancing biodiversity and mitigating risks associated with dense undergrowth and fire. Castro et al. (2021) provide a comprehensive understanding of how traditional and indigenous livestock breeds, through their unique behaviours and dietary preferences, serve as critical agents in the ecological stewardship of the Iberian Peninsula, enhancing biodiversity and mitigating risks associated with dense undergrowth and fire. Rigueiro-Rodríguez et al. (2009) explore the productive, ecological, and social perspectives of agroforestry systems in Europe, illustrating how these practices integrate livestock like goats into woodland ecosystems, enhancing their utility in landscape and environmental management.

9.3 Cattle

The milder climates and abundant suitable meadows make the open woodlands of the north and centre of the Iberian Peninsula ideal for cattle grazing (Gómez Sal 2001). Each breed exhibits adaptations to the unique landscape features, ranging from the rugged terrains of the Pyrenees and Cantabrian Range to the expansive plains of Castile and León. Certain breeds, such as the Sayaguesa and Maronesa, have evolved with a particular affinity for woodland environments. These breeds graze in the more humid, densely-wooded areas, benefiting from a diet of mixed vegetation. The symbiotic relationship between cattle and these woodland ecosystems is crucial for maintaining open spaces within forests, thereby promoting biodiversity by creating a variety of habitats for different species (Velado-Alonso et al. 2022).

The impact of cattle on the landscape extends beyond mere grazing. Breeds like the Cachena and Rubia Gallega serve to transform diverse vegetation into valuable resources like meat and milk (Sánchez 2005; Caballero et al. 2009). These Iberian domestic ruminants are especially appreciated for their grazing efficiency in lands deemed unsuitable for other forms of agriculture, playing an essential role in preserving open landscapes and preventing forest encroachment. López (2002) discusses the transition from traditional agricultural systems to more industrialised livestock-raising practices, the effects of rural emigration, and the subsequent impact on landscape management and biodiversity. He highlights the importance of maintaining traditional cattle grazing systems and suggests integrating them with modern agricultural practices to preserve these regions' environmental and cultural heritage.

9.4 Pigs

In the southwestern wood pastures, traditional Iberian pig rearing occurs within the 'dehesa' system, a distinctive agroforestry system in the Iberian Peninsula that merges oak woodlands with grazing livestock to enhance biodiversity and ecosystem health. Free-grazing pigs, feeding on acorns, contribute to maintaining this landscape while improving meat quality, producing premium Iberian ham. This practice, known as 'montanera,' showcases a sustainable method combining environmental conservation with economic gain, preserving the unique 'dehesa' ecosystem while ensuring the production of high-quality ham. Rodriguez-Estévez et al. (2012, 2009) emphasise the environmental advantages of integrating livestock grazing with woodland management, highlighting the symbiotic relationship between traditional rearing practices and conservation efforts in supporting the region's unique ham production and ecological balance.

9.5 Donkeys and horses

Donkeys and horses, traditionally employed as working animals, similarly graze in woodland areas, aiding in maintaining these habitats, albeit with less browsing pressure than goats. This lower grazing pressure helps to conserve woodland areas without compromising their ecological integrity. Velado-Alonso et al. (2022) emphasise the importance of native domestic grazers in bolstering the conservation value of semi-natural pastures in the Iberian Peninsula, showcasing how these animals, including donkeys, play a crucial role in the preservation of semi-natural habitats. The study by Segarra et al. (2023) also highlights the importance of donkeys in landscape maintenance in the Iberian Peninsula, particularly in less intensively managed woodland areas, shedding light on these animals' pivotal role in the ecological stewardship and biodiversity conservation of their habitats. Bartolomé et al. (2020) highlight donkeys and goats' differential grazing behaviours in holm oak habitats, emphasising their collective utility in fire prevention. Donkeys primarily target more easily digestible species, while goats consume flammable woody plants, suggesting their symbiotic grazing can enhance fire risk management and species conservation in Iberian ecosystems.

10 Conclusion: challenges facing Iberian silvopastoral systems

Agroforestry, which intertwines woody vegetation with agricultural production, can be seen as a symbiotic paradigm of land management. It an integral part of the agricultural practices of the Iberian Peninsula. Categorised as 'silvopastoral'

systems, these practices serve as quintessential models of sustainable land use, embodying the intricate balance between forestry, agriculture, and grazing (Moreno and Rolo 2019; Santiago-Freijanes et al. 2021). They help create unique agroecosystems across more than 6.5 million hectares across the Iberian landscape (den Herder et al. 2017). These ecosystems are pivotal for their contributions to biodiversity conservation, carbon sequestration, and soil stabilisation, necessitating focused conservation efforts to safeguard these critical habitats (Campos et al. 2020; Laporta et al. 2021; Marta-Pedroso et al. 2018).

Beyond their ecological footprint, silvopastoral systems underpin the socio-economic fabric and cultural heritage of rural communities within the Iberian Peninsula. The production of distinctive, high-quality local products, such as artisanal cheeses and the renowned Jamón Ibérico ham, not only fuels the local economy but also acts as a bastion for traditional practices and breeds, thus reinforcing regional cultural identity and heritage (Haddad et al. 2022; Castro 2009). At the nucleus of these systems lies the institution of family farming, encapsulating a generational legacy of agrarian practice deeply intertwined with the land.

Small-scale, familial enterprises are essential for the preservation and operational efficiency of silvopastoral systems, given their adaptive management capacity and intrinsic understanding of the multifaceted nature of the landscapes in which they live (Mosquera-Losada et al. 2020; Rois-Díaz et al. 2018). Moreover, silvopastoral systems advocate for sustainable consumption models by providing locally-sourced, ecologically-sourced products. This paradigm minimises carbon footprints and fosters a robust linkage between producers and consumers, enhancing societal awareness of food provenance, and the environmental and community impact of consumption behaviours (Pantera et al. 2021).

Contemporary challenges such as climate change, land-use conflicts, and globalisation pressures in agricultural markets actively threaten the sustainability of silvopastoral systems. These threaten the sustainability of these systems and, by extension, the livelihoods they support. Addressing these challenges requires a multifaceted approach, incorporating policy interventions, advancements in sustainable agronomic practices, and the strategic promotion of local products globally to ensure the resilience and sustainability of these agroecological systems (Haddad et al. 2022). This holistic strategy is paramount for safeguarding the legacy and viability of these systems for future generations, thus reinforcing their role as a linchpin in the socio-economic and ecological landscape of the Iberian Peninsula (Campos et al. 2020; Laporta et al. 2021; Marta-Pedroso et al. 2018).

Adopting integrated land use policies is crucial for the sustainable management of Iberian silvopastoral systems (Moreno et al. 2014; Varela et al.

2022). By recognising their multifunctional nature, these policies can enhance biodiversity and ecosystem services (Mastrangelo et al. 2014). Coupled with financial incentives, such as subsidies or payments for ecosystem services, they motivate farmers to adopt sustainable practices (Piñeiro et al. 2020). This dual approach ensures that silvopastoral systems remain economically viable while conserving the environment, thus fostering a balance between agricultural productivity and ecological preservation (Fernández-Núñez and Castro 2016).

The future of Iberian silvopastoral systems hinges on innovation and market integration. Advanced agroforestry techniques, such as drought-resistant species or improved grazing management, can significantly enhance sustainability and productivity. Diversifying value chains and developing niche markets for organic and sustainable products can enhance economic outcomes. Embracing digital technologies to access broader markets also plays a pivotal role, allowing small-scale producers to connect with consumers directly, fostering transparency, and boosting profitability through premium pricing on sustainable products.

Enhancing social cohesion and economic resilience is also vital for the sustained success of silvopastoral systems. Community-led initiatives, education, and participatory management involve stakeholders in sustainable resource management, ensuring knowledge transfer and innovation. Focusing on resilience planning against climate change and market volatilities, these strategies aim to diversify income sources and enhance adaptive capacities. Ultimately, fostering a community-centric approach with robust support mechanisms ensures the longevity and prosperity of silvopastoral practices, securing both ecological and economic benefits for future generations.

Addressing the challenges faced by Iberian silvopastoral systems requires a multifaceted approach that integrates sustainable land management practices, market innovations, and social engagement. Strategic imperatives focused on policy support, innovation, and enhancing community cohesion are crucial for the long-term sustainability and resilience of these systems. By implementing these strategies, it is possible to preserve the ecological, economic, and cultural values of silvopastoral systems in the Iberian Peninsula.

11 Where to look for further information

- Journal of Mountain Research and Development https://www.mrd-journal.org
- Pastoralism, Research, Policy and Practice https://pastoralismjournal.springeropen.com/
- Agroforestry Systems (Springer) https://link.springer.com/journal/10457

- Rangeland Ecology & Management (Elsevier / Society for Range Management) https://www.journals.elsevier.com/rangeland-ecology-and-management
- International Year of Rangelands and Pastoralists (IYRP 2026) https://iyrp.info
- FAO Pastoralist Knowledge Hub https://www.fao.org/pastoralist-knowledge-hub
- L'Association Française de Pastoralisme: L'AFP http://www.pastoralisme.net/

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