Agroforest Syst (2025) 99:58
https://doi.org/10.1007/s10457-024-01110-7

The impact of goats grazing on understory vegetation of cork oak woodlands

Júlio Henrique Germano de Souza · **Maria Rosa Mosquera-Losada** · **Marina Castro**

Received: 1 July 2024 / Accepted: 18 November 2024 / Published online: 4 March 2025

Abstract The aim of this study is to evaluate the effects of high grazing pressure for short, intermittent periods (1–2 h per day) on fuel load management in cork oak (*Quercus suber* L.) forests in the north-eastern region of Portugal. This evaluation aims to understand the effectiveness of targeted grazing as a forest management tool, specifically in reducing fuel load accumulation and thereby potentially reducing wildfire risk. In addition, this study extends its analysis to examine the time required for vegetation recovery in the absence of grazing, with the aim of determining the optimal grazing interval. Changes in herbaceous and shrub cover, herbaceous biomass and phytovolume were compared between grazed and ungrazed plots over a period of thirty-four months. Using a stocking rate of 400 goats per hectare for 21 cumulative hours over 12 days resulted in a 93.43% reduction in shrub phytovolume and a 76.2% reduction in shrub cover. Herbaceous biomass also decreased from 53.80 ± 7.82 g m^{-2} to 17.76 ± 6.29 g m^{-2} in the grazed areas. Twenty-two months after cessation of grazing, no significant differences in plant and shrub cover or herbaceous biomass were observed. The results highlight the effectiveness of targeted grazing in managing fuel loads in cork oak woodlands, with pronounced short-term benefits. However, the rapid recovery of vegetation in the absence of grazing highlights the need for a strategic and continuous management approach to maintain the benefits of fuel reduction.

Keywords Targeted grazing · Fuel load management · Vegetation recovery · Cork oak forests

Introduction

In European Mediterranean countries, the incidence of fires has increased dramatically, with the average total area burned per year quadrupling since the 1960s (San-Miguel-Ayanz et al. 2012, cited by Tonini et al. 2018). Today, Southern Europe experiences about 47,000 fires per year, burning an average of 400,000 ha of forest and scrubland (1980–2019 period average) (San Miguel-Ayanz et al. 2021; European Commission 2022). Fire regime has changed as a result of human changes in fuel load management and climatic change (Tonini et al. 2018). In terms of human factors, societal changes affecting the occurrence of wildfires are

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10457-024-01110-7.

J. H. G. de Souza · M. R. Mosquera-Losada
Department of Crop Production and Engineering Projects, High Polytechnic School, University of Santiago de Compostela, 27002 Lugo, Spain

J. H. G. de Souza · M. Castro (✉)
CIMO, LA SusTEC, Instituto Politécnico de Bragança, Campus de Santa Apolónia, 5300-253 Bragança, Portugal
e-mail: marina.castro@ipb.pt

those associated with the massive depopulation of European rural areas after the Second World War. The abandonment of rural areas has led to the expansion of scrublands and forests, while pastures and cropland have declined, resulting in an increase in the accumulation of combustible biomass (Mantero et al. 2020). This change in land use increases the risk of fire, especially when the understorey phytovolume exceeds 2500 m^3 ha^{-1}, a threshold associated with high fire risk (Oliveira 2020).

In addition, climate change has made wildfires more dangerous than ever before, increasing in size and severity of these new types of fires, known as megafires (Alló and Loureiro 2020). Data suggests that climate change will intensify in the future, with uneven impacts in different regions of the world (IPCC 2022). Situated on the western side of the Iberian Peninsula, Portugal is particularly vulnerable to these changes. Projections point to significant increases in temperature and decreases in precipitation (Cardoso et al. 2019; Lionello et al. 2014; Soares et al. 2017; Turco et al. 2015), as well as the associated increase and severity of droughts (Hoerling et al. 2012; Spinoni et al. 2017). As a direct consequence, fires will become increasingly dangerous, with a sharp increase in their magnitude and severity (Chowdhury et al. 2022).

The FAO Voluntary Guidelines on Fire Management state that: "Fire prevention may be the most cost-effective and efficient mitigation programme than an agency or community can implement". Preventing unwanted, damaging fires is always less expensive than fighting them (FAO 2006). It is now widely recognised that prevention is the most effective approach to dealing with wildland fires (Mauri et al. 2023). According to the same authors, prevention should focus on "sustainable forest management" and "sustainable rural areas management" to limit the risk of wildfires in the Mediterranean, especially in the context of climate change. Agroforestry, as the deliberate integration of woody vegetation (trees and/or shrubs) and any combination of livestock, pasture or agricultural crops (Mosquera-Losada et al. 2018), represents a potential strategy to effectively control fuel accumulation at both plot and landscape scales (Rodríguez-Rigueiro et al. 2021). Agroforestry is therefore in line with the strategies proposed above.

On the other hand, at the plot scale, grazing is recognised as an ecological approach to create fuel discontinuities, especially within the shrub layer, thus preventing fuel accumulation. Therefore, it has been adopted as a fire prevention tool in different countries, including Spain, Italy, France, Greece and United States (Lovreglio et al 2014; Moinardeau et al. 2019; Paut et al. 2021; Varela et al. 2018). However, in many rural areas of the Mediterranean, grazing pressure is below the level required for fuel management through traditional grazing (Castro et al. 2020). Consequently, targeted grazing has emerged as a viable alternative to fill this gap.

Targeted grazing is used strategically to achieve specific vegetation management objectives, such as reducing the presence of invasive plants and reducing fuel loads to minimise fire risk (Launchbaugh et al. 2006). The scientific literature highlights the importance of grazing activities characterised by optimal density and seasonal timing (DiTomaso et al. 2008; Rathfon et al. 2014; Bailey et al. 2019; Fuhlendorf et al. 2009). A targeted approach can reduce fuel loads, connectivity and the frequency of fire events (Davies et al. 2017; Schmelzer et al. 2014).

The main objective of this study was to evaluate the impact of high intensity grazing by goats for short periods of time, i.e. targeted grazing, on the reduction of fuel loads within *Q. suber* forests in the Northeast region of Portugal. To achieve this, the study examined changes in herbaceous and shrub cover, herbaceous biomass, and phytovolume in grazed cork oak plots compared to ungrazed plots.

Specific research questions include: (1) whether targeted goat grazing is an effective way of removing phytovolume from oak woodlands; (2) how long it takes for vegetation to recover after grazing.

Material and methods

Study area

The research was carried out in the north-eastern region of Portugal (41°48′ N and 6°45′W), Fig. 1, at an altitude of 755 m above sea level, in a 30-years-old *Q. suber* plantation.

The climate is Mediterranean, with an average annual temperature of 12.5ºC and total annual rainfall of 607.2 mm (data for 1981–2010, IPMA). During the

Fig. 1 Location of the experimental area

study period, annual rainfall varied between 789 mm (2020) and 563.6 mm (2021), thus highlighting the strong inter-annual variability typical of Mediterranean climates (see climate graphs in the supplementary material).

The Afforestation was carried out under the Common Agricultural Policy (CAP) initiative in 1992, in accordance with the provisions of the "set-aside" legislation. During the first two decades after planting, the understorey was mechanically cleared at regular intervals of three to five years. After this period, which coincides with the end of the program contract, understory clearance ceased (2016).

The density of the cork oak stand is 666 trees per hectare, with a spatial arrangement defined by a 5×3 m grid. The understorey consisted of a dense layer of shrubs, mainly of *Cistus ladanifer* L., *Cytisus scoparius* (L.) Link., and *Lavandula stoechas* L. and a sparse layer of herbs, mainly annual grasses. The experimental area consisted of two fenced plots of 2500 m^2 each, one grazed and the other ungrazed. A private herd of 100 Serrana goats (approximately two-thirds pregnant and one-third non-pregnant) extensively reared for meat production, was used. The goats weighed between 45 and 50 kg. The stocking rate was therefore 400 animals per hectare, used sporadically and at short intervals from October 2020 to July 2021. The animals stayed on the plot for only 1–1.5 h per day, over 12 non-consecutive days, for a total of 21 h of grazing activity. During the grazing period, the herd received 20 kg of high energy concentrate in the form of pellets per day (approximately 200 g per goat). This was distributed among the tallest and densest bushes, which not only facilitated consumption but also disturbed the vegetation as the goats jumped in search of the supplementary feed.

Field sampling, and data collection

Data collection took place from July 2020 to April 2023 and included four soil cover assessments and three herbaceous biomass assessments.

The structural characteristics of the vegetation were assessed using the line-intercept method (Canfield 1941). Vegetation cover was estimated on the basis of growth forms (shrubs and grasses). In each treatment (grazed and ungrazed), five 20 m transects were established and the length occupied by each shrub and herb species was recorded. In Addition, the modal height of each shrub species was measured to assess phytovolume (Fig. 2).

Herbaceous biomass was assessed using samples of 0.25 m^2, cut at ground level, stored at 4 °C and then dried in an oven at 60 °C. The dry matter (DM) was weighed to the nearest 0.1 g. The data were calculated and the units converted to kg DM ha^{-1}. Herbaceous cover, which included several species, was assessed as a whole, while shrub cover was assessed by species. Five replicates were used for each treatment, similar to the procedure used for the transects.

The assessment schedule was as follows: The first assessment took place before the introduction of animals in July 2020 (Time 0). The second assessment took place after the end of grazing in July 2021 (Time 1). A third assessment was carried out in April 2022, eight months after grazing (Time 2), and the fourth and final assessment was carried out in April 2023 (Time 3), twenty months after the end of grazing.

Variables estimation

On the basis of the ground cover, the shrub and herbaceous cover, litterfall and the phytovolume were calculated. Total vegetation cover represents the area of land covered by vegetation expressed as a percentage and is calculated using the following Eq. (1):

$$\text{Plant cover}(\%) = (100 - (\text{bare soil} + \text{forest litter biomass}\ ) \quad (1)$$

Bare soil: Percentage of visible soil surface not covered by plants or litter. Forest litter biomass: Dead organic matter, such as fallen leaves and small twigs, covering the ground. This formula subtracts the area of bare soil covered by litter from the total cover (100%) to estimate the proportion of soil actually occupied by plants.

The cover of a given species corresponds to the area projected horizontally by the plant onto the ground, indicating the extent of the surface covered by the plant's canopy. This value is expressed as a percentage and calculated as follows (Eq. 2):

$$\text{Cover Spp}(\%) = \frac{\text{Total distance}(\text{Spp}A)}{\text{Total distance of line}} \times 100 \quad (2)$$

The understorey phytovolume was calculated, by shrub species, by multiplying the modal height (the most common) of the shrub by its canopy cover for

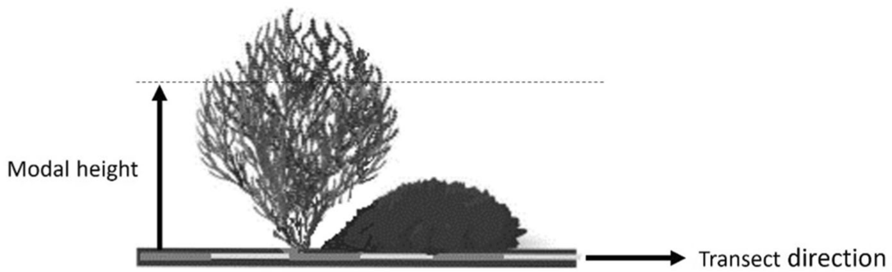

Fig. 2 Line intercept method and method used to measure modal heights

each plant (Eq. (3)); the phytovolume in each transect was obtained by summing the volumes of each plant.

$$\text{Phytovolume}\left(m^3\right) = \text{Cover}Sppi(\%) \times \text{Modal height}(m) \quad (3)$$

Finally, the pytovolume was estimated based on the assumption that a 50 percent shrub cover on a hectare corresponds to 5000 m^2 are occupied by the shrubs (Eq. 4).

$$50\%\ \text{coverage} = \frac{10.000m^2}{100\%}x50\% \quad (4)$$

Statistical analysis

The statistical analysis was performed using two-way analysis of variance ANOVA — Type III SS, with sampling date and treatments as sources of variation. Tukey's honestly significant difference test was used for pairwise comparisons between groups ($p < 0.05$). Means and standard deviations by group (treatment and sampling date) were calculated. All statistical analyses were performed using the SISVAR® 5.6 software package.

Results

Prior to the start of the grazing period (time 0), there were some differences, not statistically significant, in the values of the ground cover variables between treatments. Following the introduction of grazing, significant statistical differences in these variables emerged between treatments and persisted for up to two years (time 3, Table 1).

At time 1, at the end of the grazing period, the herbaceous cover in the grazed plots was 6.09% (±2.85 SD), while it was significantly lower in the ungrazed plots at 0.8% (±0.4 SD). Shrub cover averaged values of 9.28% (±3.55 SD) in the grazed plots compared to 45.30% (±5.76 SD) in the ungrazed plots. Litter cover varied from 51.43% (±4.81 SD) between the grazed plots to 34.00% (±3.80 SD) in the ungrazed plots, with statistically significant differences ($p < 0.001$). At time 2 (eight months after the end of the grazing period), shrub cover was 16.91% (±2.89 SD) and 42.80% (±5.47 SD) and herbaceous cover of 3.09% (±0.86 SD) and 5.52% (±1.08 SD) between grazed and ungrazed plots, respectively ($p < 0.001$) (Table 1).

At time 3 (twenty months after the end of the grazing period), the shrub cover was similar between treatments, averaging around 50%. Meanwhile, the herbaceous cover in the grazed plots was 11.00% (±4.59 SD), the highest values observed in the study, while the ungrazed plots showed 1.85% (±0.76 SD), the highest values observed in the study. Litter cover averages of 47.10% (±9.70 SD) and 32.00% (±9.48 SD) for the ungrazed and grazed plots, respectively (Table 1).

Table 1 Evolution of vegetation and litter cover over time in treatments

Time		Cover (%)			
		Shrub	Herbaceous	Plant	Forest litter biomass
0	grazed	39.00 A (±8.12)	4.07 A (±2.75)	43.00 A (±6.23)	42.00 A (±9.70)
	ungrazed	29.27 A (±4.48)	4.50 A (±0.66)	33.77A (±5.75)	44.52 A (±4.62)
1	grazed	9.28 B (±3.55)	6.09 A (±2.85)	15.37 B (±4.64)	51.43 A (±4.81)
	ungrazed	45.30 A (±5.76)	0.80 B (±0.40)	46.10 A (±7.01)	34.00 B (±3.80)
2	grazed	16.91 B (±2.89)	3.09 B (±0.86)	20.00 B (±5.43)	53.74 A (±3.59)
	ungrazed	42.80 A (±5.47)	5.52 A (±1.08)	48.32 A (±6.12)	38.2 B (±3.25)
3	grazed	49.30 A (±8.90)	11.00 A (±4.59)	60.30 A (±5.68)	32.00 B (±9.48)
	ungrazed	51.05 A (±10.13)	1.85 B (±0.76)	52.90 A (±9.69)	47.10 A (±9.70)

Means followed by different letter indicate significant difference among treatments (grazed and ungrazed) for each timing (0, 1, 2 and 3) and variable (Shrub cover, Herbaceous cover and litter) according to the Tukey Test at 5% probability, while values within parentheses represent the standard deviation

Phytovolume

C. ladanifer, *C. scoparius*, and *L. stoechas* were the most abundant in the study area. The initial mean phytovolume (time 0) in the grazed area was 2879.31 m^3 ha^{-1} for *C. ladanifer*, followed by *C. scoparius* with 1635.94 m^3 ha^{-1}, and *L. stoechas* with 272.92 m^3 ha^{-1}. In the ungrazed area the values were 1972.54 m^3 ha^{-1} for *C. ladanifer*, 1411.56 m^3 ha^{-1} for *C. scoparius*, and 198.12 m^3 ha^{-1} for *L. stoechas*. These species were dominant in both areas, with *C. ladanifer* being the most frequent.

The effect of grazing was most evident in the phytovolume, which decreased by 93.43% from time 0 to time 1. At time 1, phytovolume was 276.84 $^{B}\pm 93.64$ m^3 ha^{-1} for grazed plot and 5741.05$^{A}\pm 865.17$ m^3 ha^{-1} for ungrazed plot ($p<0.001$).

At time 2, in 2022, the phytovolume values were 1001.14$^{B}\pm 118.66$ m^3 ha^{-1} for the grazed plot and 5832.75$^{A}\pm 1078.29$ m^3 ha^{-1} for the ungrazed plot. At time 3, in 2023, the differences between the plots were no longer significant. The values recorded were 5459.95$^{A}\pm 536.22$ m^3 ha^{-1} for the grazed plot and 6760.95$^{A}\pm 1080.79$ m^3 ha^{-1} for the ungrazed plot.

The grazed plot showed an increase in phytovolume over time (Fig. 3), but at different rates, 1001.14 ± 118.66 m^3 ha^{-1} in the first year and 5459.95 ± 536.22 m^3 ha^{-1} in the second. After two years of grazing, there was no significant difference between the plots.

On the basis of the results it was possible to establish mathematical models to estimate the phytovolume over time in plots with and without grazing. For the grazed plot: $y=2109.3x^2—10112x+12{,}210$, with an R^2 of 0.9975. For the ungrazed plot: $y=-265.45x^2+2239.4x-1913.9$, with an R^2 of 0.9223. In the equation, the variable x represents the time in years with or without grazing.

The increase in forest litter biomass and the decrease in plant phytovolume were inversely proportional, highlighting the impact of goat grazing. At time 1, a decrease in plant cover was observed, reaching 15.37% (±4.64 SD), while forest litter biomass cover increased to 51.43% (±4.81 SD). This pattern was maintained at time 2, when forest litter biomass reached 53.74% (±3.59 SD). Subsequently, the percentages began to decrease as the plots no longer showed significant differences and the plant cover began its recovery process.

Herbaceous biomass

Herbaceous biomass showed a significant difference between the grazed and ungrazed treatments ($p<0.001$). At the first observation (time 1), the herbaceous biomass ranged from 1244.64$^{A}\pm 130.90$ kg ha^{-1} in the grazed plots to

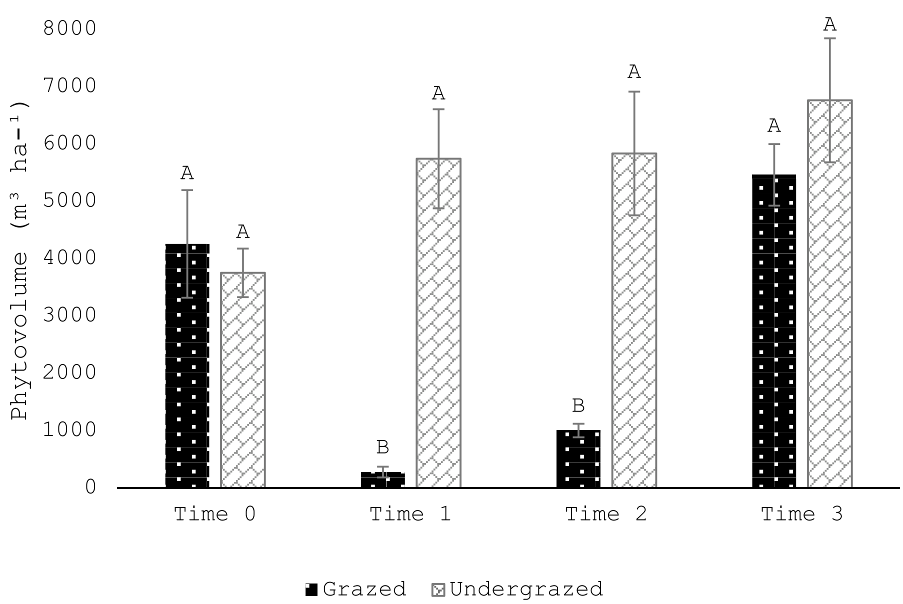

Fig. 3 Phytovolume development from July 2020 to April 2023. Bars represent the mean ± SD

177.60^B ± 67.90 kg ha^{-1} in the ungrazed plots. In the subsequent observation (time 2), although the values remained different, the difference was no longer statistically significant, with grazed plots at 242.96^A ± 69.50 kg ha^{-1} and ungrazed plots at 319.20^A ± 67.90 kg ha^{-1} (Fig. 4).

Discussion

Plant cover

Grazing caused significant changes in vegetation structure, with a reduction in shrub cover of over 75%. However, there was a very rapid regeneration of shrub cover two years after animal removal, with no differences between grazed and ungrazed plots. Our study highlights the rapid regeneration of shrub vegetation after grazing cessation in cork oak ecosystems located in northern Portugal, in agreement with previous studies (e.g. Bar Massada et al. 2008; Agra and Ne'eman 2011; Dias et al. 2016).

The development of the herbaceous cover was significantly greater in the grazed plot, and this effect persisted for more than two years after the end of grazing. Studies carried out in Mediterranean oak forests (López-Sánches et al. 2016) confirm our results, indicating that the introduction of livestock in these ecosystems leads to an increase in herbaceous cover. Fernández-Lugo et al. (2013) and Díaz et al. (2007) report a positive effect of grazing on the increase of annual species in Mediterranean climates worldwide.

The response of graminoid and herbaceous cover to grazing varies along gradients of productivity after shrub removal (Lezama et al. 2014), and these species may emerge at later stages as the ecosystem recovers. Grazing has several effects on ecosystem dynamics, including an increase in relative humidity. This increase in humidity, as stated by Dovrat et al. (2021) and Oikonomou et al. (2023), facilitates seed germination by breaking dormancy. This process contributes to the enrichment of the vegetation cover.

On the other hand, as shown in this study, grazing promotes a significant increase in litter accumulation in the soil, due to the overturning and trampling of shrubs and faeces deposition. This contributes to an increase in surface organic matter concentrations (0–5 cm), mainly due to the incorporation of animal excreta and the humification of trampled plant components. This soil enrichment is supported by studies by Herrero et al. (2016), Fonseca and Figueiredo (2018) and Fielding (2022), which highlight the role of grazing in soil and vegetation health.

Phytovolume

A grazing strategy with a stoking density of 400 goats per hectare effectively reduced the phytovolume by more than 90%, from 4.255.03 m^3 ha^{-1} to 276.84 m^3 ha^{-1}. This result is consistent with the findings of Carreira et al. (2023), who demonstrated that grazing systems could reduce phytovolume by 50% or more, depending on the grazing intensity and the management practices used. Ameray et al. (2022) found that grazing 3.88 sheep ha^{-1} in an open *Quercus* forest

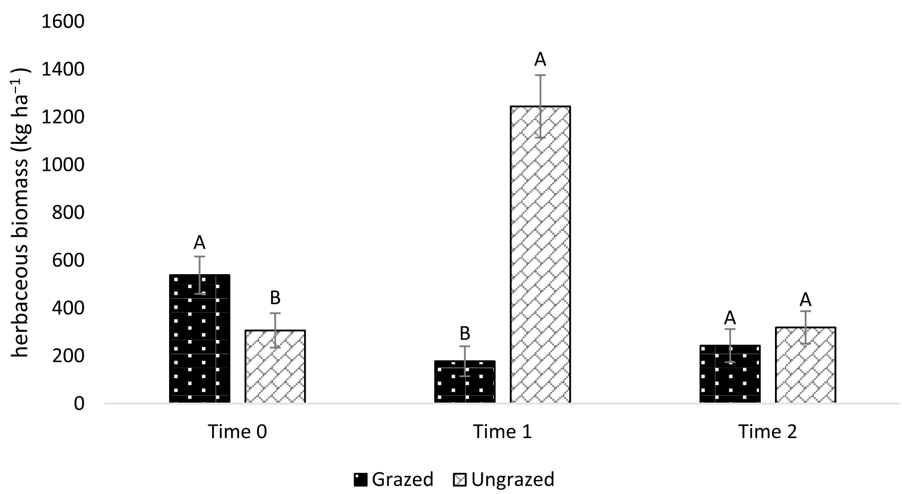

Fig. 4 Evolution of herbaceous biomass over time in grazed and ungrazed plots. Bars represent the mean ± SD

in north-eastern Portugal reduced phytovolume by 45.29%. The variation in results between studies highlights the importance of grazing intensity, as suggested by Tohiran et al. (2023), which is directly related to the effectiveness of vegetation management in silvopastoral systems.

This targeted grazing study used high grazing pressure for short, scattered periods (1–2 h per day), making it difficult to compare with traditional extensive grazing. For example, Etienne et al. (1993) in southern France recommended a grazing density of 0.6 to 1.4 sheep ha^{-1} in open landscapes, with a higher density of up to 1.65 sheep ha^{-1} in forest ecosystems. Similarly, in Spain, Evlagon et al. (2010) documented grazing densities between 1.25 and 2.01 goats per hectare in areas dominated by woody vegetation and 0.98–1.40 goats per hectare in regions characterised by herbaceous vegetation. In comparison, both studies represent a pressure four times lower than that observed in the present study when considering the number of days per year.

In Portugal, in the northeast of Trás-os-Montes, studies by Castro et al. (2022) showed good results with a pressure of 35 animals ha^{-1} combined with mechanical treatments. These studies show that livestock can play a crucial role in controlling fuel development, as other studies have shown (Mosley and Roselle 2006; Thornes 2005; Davies et al. 2010). The determination of optimal grazing pressure is therefore highly context dependent, influenced by factors such as ecosystem type, local environmental conditions and the desired outcomes of its application (Ameray et al. 2022). This dependency highlights the integral relationship between grazing strategies and their primary objective: the effective reduction of fuel loads. The selection of appropriate grazing intensities therefore requires a nuanced understanding of the specific ecological context and management objectives to ensure that the desired level of biomass removal is achieved (Firn et al. 2013; Díaz-Pereira et al. 2020; Fernández et al. 2020).

Herbaceous biomass

Under Mediterranean conditions, herbaceous biomass typically ranges from 500 kg ha^{-1} and 5000 kg ha^{-1} dry mass varies throughout the growing season depending on the type of pasture and whether the area is open or wooded. This variation is influenced by factors such as climate, grazing patterns and landscape characteristics (Psyllos et al. 2022).

In this study, the herbaceous biomass value was 1.244.60 kg ha^{-1}, which is consistent with values reported by different researchers in different ecosystems. For example, Castro et al. (2009) found a range from 1.773.30 kg ha^{-1} to 445.30 kg ha^{-1} in *Q. pyrenaica* woodlands in northern Portugal. Similarly, Fernández-Moya (2011) observed 1.552.50 kg ha^{-1} in *dehesas* (scattered tree systems), a value confirmed by López-Carrasco et al. (2015), both in the province of Toledo, central Spain.

In addition, a higher value of 1.975 kg ha^{-1} was observed in *montado* ecosystems in the southern regions of Portugal, which can be attributed to the presence of more widely spaced trees (Serrano et al. 2022). However, two years after the cessation of grazing, there was a significant decrease in these values to 243.00 kg ha^{-1} for the grazed plot and 319.20 kg ha^{-1} for the ungrazed plot.

The reduction in biomass availability in the ungrazed plot between times 1 and 2 is mainly due to the lower precipitation recorded during the winter and spring. From January to April 2022, the accumulated precipitation of 89.6 mm was significantly lower than the 336.3 mm recorded during the same period in 2021. Furthermore, the increase in the average maximum temperature in January and February 2022 may have contributed to this decline. Studies carried out in Mediterranean wooded pastures confirm that herbaceous availability is strongly dependent on precipitation and temperature, with biomass declines commonly observed in summer and autumn in similar studies (Chebli et al. 2017; Rigueiro-Rodriguez et al. 2009; Schlecht et al. 2006). Furthermore, the process of ecological succession suggests that as the shrub layer expands, there is a reduction in the herbaceous layer (Díaz-Villa et al. 2003; Castro et al. 2010).

Vegetation management

Over the last four decades, forest fires have emerged as a major environmental challenge in European Mediterranean countries (San Emeterio et al. 2016). Several studies have highlighted the role of accumulated fuel loads in increasing the frequency and severity of fires (Serra et al. 2008a, b; Santana et al. 2010; Villar et al. 2016; Lasanda et al. 2018). However, fire policies in European Mediterranean countries have traditionally prioritised firefighting over prevention, a trend that has only recently begun to change (Birot 2009; San-Miguel-Ayanz et al. 2013). The current study is in line with previous research (Ruiz-Mirazo et al. 2011; Etienne 2001) on the temporary effect of grazing in reducing flammable material to levels considered safe to minimise the risk of ignition and fire spread. Specifically, understory phytovolume values greater than 2500m^3 ha^{-1} are associated with increased fire risk (Oliveira 2020).

Livestock grazing management, including timing, frequency and intensity, as well as type of grazing animals, plays an important role in shaping silvopastoral strategies that improve both fuel management and farm profitability.

Studies have shown that integrated crop-livestock-forestry systems provide significant benefits for both environmental sustainability and smallholder profitability (Vinholis et al. 2022). It is therefore essential that future research focuses on assessing grazing pressure and establishing sustainable grazing intervals to ensure effective understorey control. Furthermore, integrating economic evaluations of these methods will provide land managers with the necessary decision-making tools to efficiently manage biomass fuels and achieve their objectives.

Conclusion

The study shows that high grazing pressure, specifically a stocking rate of 400 goats per hectare for 12 non-consecutive days, can significantly reduce wildfire risk by reducing fuel loads and altering vegetation structure, achieving over 90% reduction in shrub volume and 25% reduction in shrub cover in Mediterranean cork oak forests. However, without annual grazing, these effects diminish rapidly, with vegetation recovering within one year and nine months after grazing; highlighting the transient nature of grazing's effects on fuel reduction. Further research is needed to identify the ideal grazing patterns- duration and intensity, species, class to suit the specific vegetation dynamics of each area.

Acknowledgements National funding by FCT, Foundation for Science and Technology, through the individual research grant 2022.12880.BD of Júlio Henrique Germano de Souza.

Author contributions Conceptualization, M.M.C and R.M.L; Research, J.H.G.S. and M.M.C.; Data analysis, J.H.G.S., M.M.C., and R.M.L. Writing—original draft, J.H.G.S. and M.M.C. Editing, J.H.G.S., M.M.C., and M.M.L. Supervision, M.M.C. and M.M.L. All authors read and approved the final manuscript.

Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

References

Agra H, Ne'eman G (2011) Quercus calliprinos regrowth advantage under grazing in Mediterranean maquis and its management implications. For Ecol Manage 261:143–147. https://doi.org/10.1016/j.foreco.2010.09.032

Alló M, Loureiro ML (2020) Assessing preferences for wildfire prevention policies in Spain. Forest Policy Econ 102145:1389–9341. https://doi.org/10.1016/j.forpol.2020.102145

Ameray A, Castro JP, Castro M (2022) Potential greenhouse gas emissions mitigation through increased grazing pressure: a case study in North Portugal. Carbon Manag 13(1):142–153. https://doi.org/10.1080/17583004.2022.2029575

Bailey DW, Mosley JC, Estell RE, Cibils AF, Horney M, Hendrickson JR, Burritt EA (2019) Targeted livestock grazing: prescription for healthy rangelands. Rangel Ecol Manage 72(6):865–877

Bar-Massada A, Gabay O, Perevolotsky A, Carmel Y (2008) Quantifying the effect of grazing and shrub-clearing on small scale spatial pattern of vegetation. Landscape Ecol 23:327–339

Birot Y (2009) Living with wildfires: what science can tell us-a contribution to the science-policy dialogue (No. 15). European Forest Institute.

Canfield R (1941) Application of the line interception method in sampling range vegetation. J Forest 39:388–394

Cardoso RM, Soares PMM, Lima DCA, Miranda PMA (2019) Mean and extreme temperatures in a warming climate: EURO CORDEX and WRF regional climate highresolution projections for Portugal. Clim Dyn 52:129–157. https://doi.org/10.1007/s00382-018-4124-4

Carreira E, Serrano J, Castro JL, Shahidian S, Pereira AF (2023) Montado Mediterranean ecosystem (soil–pasture–tree and animals): a review of monitoring technologies and grazing systems. Appl Sci 13(10):6242. https://doi.org/10.3390/app13106242

Castro M, Castro J, Antonio GS (2009) Efeito da pastorícia tradicional na redução de combustíveis finos em bosques de *Quercus pyrenaica* = effect of livestock grazing on combustibles decreasing in *Quercus pyrenaica* woodlands. Silva Lusitana 0870–6352(17):159–169

Castro H, Fortunel C, Freitas H (2010) Effects of land abandonment on plant litter decomposition in a Montado system: relation to litter chemistry and community functional parameters. Plant Soil 333:181–190. https://doi.org/10.1007/s11104-010-0333-2

Castro M, Ameray A, Castro JP (2020) A new approach to quantify grazing pressure under mediterranean pastoral systems using GIS and remote sensing. Int J Remote Sens 41(14):5371–5387. https://doi.org/10.1080/01431161.2020.1731930

Castro M, Castro JP, Castro J (2022) Understory clearing in open grazed mediterranean oak forests: assessing the impact on vegetation. Sustainability 14:10979. https://doi.org/10.3390/su141710979

Chebli Y, Chentouf M, Hornick JL, Cabaraux JF (2017) Extensive goat production systems in northern Morocco: Production and use of pastoral resources. In A. Porqueddu, C. Franca, A. Lombardi, G. Molle, G. Peratoner, e G. Hopkins (Eds.), Grassland resources for extensive farming systems in marginal lands: Major drivers and future scenarios (pp. 131–133). Wageningen Academic Publishers.

Chowdhury S, Manjón-Cabeza J, Ibáñez M, Mestre C, Broncano MJ, Mosquera-Losada MR, Plaixats J (2022) Responses in soil carbon and nitrogen fractionation after prescribed burning in the montseny biosphere reserve (NE Iberian Peninsula). Sustainability 14:4232. https://doi.org/10.3390/su14074232

European Commission (2019) European ecological pact. https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_pt. Accessed 23 June 2022.

Davies KW, Boyd CS, Bates JD (2016) Winter grazing can reduce wildfire size, intensity and behaviour in a shrub-grassland. Int J Wildland Fire 25(2):191–199. https://doi.org/10.1071/WF15055

Davies KW, Bates JD, Svejcar TJ, Boyd CS (2010) Effects of long-term livestock grazing on fuel characteristics in Rangelands: an example from the sagebrush steppe. Rangeland Ecol Manage. 63(6):662–669. https://doi.org/10.2111/REM-D-10-00006.1

Davies KW, Gearhart A, Boyd CS (2017) Fall and spring grazing influence fire ignitability and initial spread in shrub steppe communities. Int J Wildland Fire 26(6):485. https://doi.org/10.1071/WF17065

Dias FS, Miller DL, Marques TA, Marcelino J, Caldeira MC, Orestes Cerdeira J, Bugalho MN (2016) Conservation zones promote oak regeneration and shrub diversity in certified Mediterranean oak woodlands. Biol Cons 195:226–234

Díaz S, Lavorel S, McIntyre S, Falczuk V, Casanoves F, Milchunas DG, Campbell BD (2007) Plant trait responses to grazing–a global synthesis. Glob Change Biol 13(2):313–341. https://doi.org/10.1111/j.1365-2486.2006.01288.x

Díaz-Pereira E, Romero-Díaz A, de Vente J (2020) Sustainable grazing land management to protect ecosystem services. Mitig Adapt Strateg Glob Change 25:1461–1479. https://doi.org/10.1007/s11027-020-09931-4

Díaz-Villa MD, Marañón T, Arroyo J, Garrido B (2003) Soil seed bank and floristic diversity in a forest-grassland mosaic in southern Spain. J Veg Sci 14(5):701–709. https://doi.org/10.1111/j.1654-1103.2003.tb02202.x

DiTomaso JM, Kyser GB, George MR, Doran MP, Laca EA (2008) Control of medusahead (*Taeniatherum caput-medusae*) using timely sheep grazing. Invas Plant Sci Manag 1(3):241–247. https://doi.org/10.1614/IPSM-07-031.1

Dovrat Y, Moshe G, Lichtenstein M (2021) The effect of increased humidity on seed germination and vegetation cover. J Plant Sci 43(2):155–166. https://doi.org/10.1016/j.jplantsci.2021.01.005

Elsa V, Górriz-Mifsud E, Ruiz-Mirazo J, López-i-Gelats F (2018) Payment for targeted grazing: integrating local shepherds into wildfire prevention. Forests 8:464. https://doi.org/10.3390/f9080464

Étienne M (2001) Aménagement de la forêt méditerranéenne contre les incendies et biodiversité. Revue Forestière Française 53:149–155

Etienne M, Armand D, Julian P, Napoleone M (1993) Un contrat d'entretien de pare-feu par des moutons. Bilan 1987–1992. Avignon, France: INRA.

European Commission (2022) Forest Fires in Europe, Middle East and North Africa 2022. European Commission. https://effis-gwis-cms.s3.eu-west-1.amazonaws.com/effis/reports-and-publications/annual-fire-reports/Annual_Report_2022_final_231117_online.pdf. Accessed 20 may 2021

Evlagon D, Kommisarchik S, Glasser T et al (2010) How much browse is available for goats that graze mediterranean woodlands. Small Rumin Res 94(1–3):103–108. https://doi.org/10.1016/j.smallrumres.2010.07.008

FAO (2006) Fire management: voluntary guidelines. Principles and strategic actions. Fire Management Working Paper 17. Rome (also available at www.fao.org/forestry/site/35853/en).

Fernández JA, Del Pozo A, Baumgartl T, Mateos E (2020) Grazing intensity effects on soil carbon balance in an Atlantic temperate grassland. Agric Ecosyst Environ 294:106930

Fernández-Lugo S, De Nascimento L, Mellado M, Bermejo L (2013) Grazing impact on vegetation structure and plant species composition in a Mediterranean ecosystem. J Veg Sci 24(5):707–719. https://doi.org/10.1111/jvs.12057

Fernández-Moya J, San Miguel-Ayanz A, Cañellas I, Gea-Izquierdo G (2011) Variability in Mediterranean annual grassland diversity driven by small-scale changes in fertility and radiation. Plant Ecol 212:865–877. https://doi.org/10.1007/s11258-010-9869-8

Fielding D (2022) Unravelling the Terminology and Impacts of Rotational Grazing – What Evidence is There for Environmental Benefits? Scotland UK: The James Hutton Institute, 25p.

Firn J, Price JN, Whalley RD (2013) Using strategically applied grazing to manage invasive alien plants in novel grasslands. Ecol Process 2:26. https://doi.org/10.1186/2192-1709-2-26

Fonseca F, Figueiredo T (2018) Carbon and nitrogen in forest floor and mineral soil under four forest species in the Mediterranean Region. Span J Soil Sci 8(1):42–56. https://doi.org/10.3232/sjss.2018.v8.n1.04

Fuhlendorf SD, Engle DM, Kerby JAY, Hamilton R (2009) Pyric herbivory: rewilding landscapes through the recoupling of fire and grazing. Conserv Biol 23(3):588–598

Gea-Izquierdo G, Montero G, Cañellas I (2009) Changes in limiting resources determine spatio-temporal variability in tree–grass interactions. Agrofor Syst 76:375–387. https://doi.org/10.1007/s10457-009-9211-4
Herrero C, Turrión MB, Pando V, Bravo F (2016) Carbon content of forest floor and mineral soil in Mediterranean *Pinus* Spp. and oak stands in acid soils in Northern Spain. Forest Syst 25(2):e065. https://doi.org/10.5424/fs/2016252-09149
Hoerling M, Eischeid J, Perlwitz J, Quan X, Zhang T, Pegion P (2012) On the increased frequency of mediterranean drought. J Climate 25:2146–2161. https://doi.org/10.1175/JCLI-D-11-00296.1
Hosu S, Mushunje A (2013) Optimizing resource use and economics of crop-livestock integration among small farmers in semiarid regions of South Africa. Agroecol Sustain Food Syst. https://doi.org/10.1080/21683565.2013.802755
IPCC (2022) Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (H. -O. Pörtner, D.C. Roberts, M.)
IPMA (2020) Portuguese Institute of the Sea and Atmosphere. https://www.ipma.pt/pt/otempo/prev.localidade.hora/. Accessed 20 may 2021.
Lasanta T, Khorchani M, Pérez-Cabello F, Errea P, Sáenz-Blanco R, Nadal-Romero E (2018) Clearing shrubland and extensive livestock farming: Active prevention to control wildfires in the Mediterranean mountains. J Environ Manag 227:256–266. https://doi.org/10.1016/j.jenvman.2018.08.104
Launchbaugh K, Walker J (2006) Targeted Grazing: A Natural Approach to Vegetation Management and Landscape Enhancement. American Sheep Industry Association.
Lezama F, Baeza S, Altesor A, Cesa A, Chaneton EJ, Paruelo JM (2014) Variation of grazing-induced vegetation changes across a large-scale productivity gradient. J Veg Sci 25:8–21. https://doi.org/10.1111/jvs.12053
Lionello P, Scarascia L (2018) The relation between climate change in the Mediterranean region and global warming. Reg Environ Change 18:1481–1493. https://doi.org/10.1007/s10113-018-1290-1
López-Carrasco C, López-Sánchez A, San Miguel A, Roig S (2015) The effect of tree cover on the biomass and diversity of the herbaceous layer in a Mediterranean dehesa. Grass Forage Sci 70(4):639–650
López-Sánchez A, Perea R, Dirzo R, Roig S (2016) Livestock vs. wild ungulate management in the conservation of Mediterranean dehesas: implications for oak regeneration. Forest Ecol Manag 362:99–106
Lovreglio R, Meddour-Sahar O, Leone V (2014) Goat grazing as a wildfire prevention tool: a basic review. Iforest-Biogeosci Forest 7(4):260
Mantero G, Morresi D, Marzano R, Motta David J, Ladenoff M, Motta R, Mladenoff DJ, Garbarino M (2020) The influence of land abandonment on forest disturbance regimes: a global review. Landscape Ecol 35(2723):2744. https://doi.org/10.1007/s10980-020-01147-w
Mauri E, Hernández Paredes E, Núñez Blanco I, García Feced C (2023) Key Recommendations on Wildfire Prevention in the Mediterranean. European Forest Institute. https://doi.org/10.36333/rs6. Accessed 10 april 2024.
Milchunas DG, Sala OE, Lauenroth WK (1988) A generalized model of the effects of grazing by large herbivores on grassland community structure. Am Nat 132:87–106
Moinardeau C, Rigolot E, Balent G (2019) Grazing as a wildfire prevention tool: A simulation study of the effects of different management strategies in south-eastern France. Ecol Model 409:108765. https://doi.org/10.1016/j.ecolmodel.2019.108765
Moinardeau C, Mesléard F, Ramone H, Dutoit T (2020) Using mechanical clearing and goat grazing for restoring understorey plant diversity of embankments in the Rhône valley (Southern France). Plant Biosyst Int J Deal All Asp Plant Biol 154(5):746–756
Mosley JC, Roselle L (2006) Targeted livestock grazing to suppress invasive annual grasses. In: Launchbaugh K, editor. Targeted grazing: a natural approach to vegetation management and landscape enhancement. Centennial (CO): American Sheep Industry Association, pp 67–76.
Mosquera-Losada MR, Santiago-Freijanes JJ, Rois-Díaz M, Moreno G, Den Herder M, Aldrey-Vázquez JA, Ferreiro-Domínguez N, Pantera A, Pisanelli A, Rigueiro-Rodríguez A (2018) Agroforestry in Europe: a land management policy tool to combat climate change. Land Use Policy 78:603–613. https://doi.org/10.1016/J.LANDUSEPOL.2018.06.052
Oikonomou N, Tsiouvaras C, Tsarouhas K (2023) Humidity effects on seed germination and its implications for vegetation dynamics. Ecol Res 38(4):733–744. https://doi.org/10.1007/s11284-023-00153-0
Oliveira T (2020) Characterization of the undercover of the stands of Pinheiro Bravo (*Pinus pinaster* Aiton, 1789) and Pine Pinheiro (*Pinus pinea* Linnaeus, 1753) of the Tapada Nacional de Mafra. Dissertation, Technical University of Lisbon.
Paut R, Sabatier R, Tchamitchian M (2021) Integrating livestock grazing into fire-prone Mediterranean forests: A dynamic modeling approach to evaluate trade-offs between fire prevention and forage production. Agric Syst 186:102982. https://doi.org/10.1016/j.agsy.2020.102982
Psyllos G, Hadjigeorgiou I, Dimitrakopoulos PG, Kizos T (2022) Grazing land productivity, floral diversity, and management in a semi-arid Mediterranean landscape. Sustainability 14(8):4623. https://doi.org/10.3390/su14084623
Rathfon RAS, Fei J, Tower K, Andries M, Neary (2014) Prescribed grazing for management of invasive vegetation in a hardwood forest understory. In: Groninger, John W.; Holzmueller, Eric J.; Nielsen, Clayton K.; Dey, Daniel C., eds. Proceedings, 19th Central Hardwood Forest Conference; 2014 March 10–12; Carbondale, IL. General Technical Report NRS-P-142. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station pp 220–232.
Rigueiro-Rodriguez A, McAdam J, Mosquera-Losada MR (2009) Agroforestry in Europe: Current status and future prospects. Springer Science & Business Media, pp 449.
Rodríguez-Rigueiro F, Santiago-Freijanes J, Mosquera-Losada MR, Castro M, Silva-Losada P, Pisanelli A, Pantera A, Rigueiro-Rodríguez A, Ferreiro-Domínguez N (2021)

Silvopasture policy promotion in European Mediterranean areas. PLoS ONE 16:101371. https://doi.org/10.1371/journal.pone.0245846
Ruiz-Mirazo J, Robles AB, González-Rebollar JL (2011) Two-year evaluation of fuelbreaks grazed by livestock in the wildfire prevention program in Andalusia (Spain). Agr Ecosyst Environ 141(1–2):13–22
Salt CA, Mayes RW, Elston DA (1992) Effects of season, grazing intensity and diet composition on the radiocaesium intake by sheep on re-seeded hill pasture. J Appl Ecol 29(2):378–387. https://doi.org/10.2307/2404511
San Emeterio L, Múgica L, Ugarte MD, Goicoa T, Canals RM (2016) Sustainability of traditional pastoral fires in highlands under global change: effects on soil function and nutrient cycling. Agric Ecosyst Environ 235:155–163. https://doi.org/10.1016/j.agee.2016.10.009
San-Miguel-Ayanz J, Schulte E, Schmuck G, Camia A, Strobl P, Liberta G, Giovando C, Boca R, Sedano F, Kempeneers P, McInerney D, Withmore C, de Oliveira S S, Rodrigues M, Durrant T, Corti P, Oehler F, Vilar L, Amatulli G (2012) Comprehensive monitoring of wildfires in Europe: The European Forest Fire Information System (EFFIS). In J. Tiefenbacher (Ed.), Approaches to managing disaster – Assessing hazards, emergencies and disaster impacts (pp. 267–286). InTech. https://doi.org/10.5772/39447
San-Miguel-Ayanz J, Durrant T, Boca R, Maianti P, Liberta G, Artes Vivancos T, Jacome Felix Oom D, Branco A, De Rigo D, Ferrari D, Pfeiffer H, Grecchi R, Nuijten D, Onida M, Loffler P (2021) Wildfires Europe, Middle East and North Africa 2020, EUR 30862 EN, Publications Office of the European Union, Luxembourg. https://doi.org/10.2760/216446, JRC126766
San-Miguel-Ayanz J, Moreno JM, Camia A (2013) Analysis of large fires in European Mediterranean landscapes: lessons learned and perspectives. For Ecol Manage 294:11–22. https://doi.org/10.1016/j.foreco.2012.10.050
San-Miguel-Ayanz J, Durrant T, Boca R, Maianti P, Liberta G, Artes Vivancos T et al. (2021) Forest Fires in Europe, the Middle East and North Africa 2020, EUR 30862 EN, Publications Office of the European Union, Luxembourg 978–92–76–42351–5. https://doi.org/10.2760/216446.
Santana JM, Cabezudo B, Ortega P (2010) Fire-induced deforestation in drought-prone Mediterranean forests: Drivers and unknowns from leaves to communities. Ecol Monogr 88(2):141–169. https://doi.org/10.1002/ecm.1285
Santana J, Porto M, Reino L, Beja P (2011) Long-term understory recovery after mechanical fuel reduction in Mediterranean cork oak forests. Forest Ecol Manag 261(3):447–459. https://doi.org/10.1016/j.foreco.2010.10.030
Schlecht E, Hiernaux P, Kadaouré I, Hülsebusch C, Mahler FA (2006) Spatio-temporal analysis of forage availability and grazing and excretion behaviour of herded and free grazing cattle, sheep, and goats in Western Niger. Agric Ecosyst Environ 113(3–4):226–242. https://doi.org/10.1016/j.agee.2005.10.003
Schmelzer L, Perryman B, Bruce B, Schultz B, McAdoo K, McCuin G, Swanson S, Wilker J, Conley K (2014) Case study: reducing cheatgrass (*Bromus tectorum* L.) fuel loads using fall cattle grazing. Profession Animal Sci 30(2):270–278. https://doi.org/10.15232/S1080-7446(15)30112-1
Serra JM, Ibáñez JJ, Vallejo R, Romero J (2008a) Fire regime and vegetation dynamics in the Mediterranean Basin: A review. Plant Ecology 194(1):1–13. https://doi.org/10.1007/s11258-007-9333-2
Serra P, Pons X, Saurí D (2008b) Land-cover and land-use change in a Mediterranean landscape: a spatial analysis of driving forces integrating biophysical and human factors. Appl Geogr 28(3):189–209
Serrano J, Roma L, Shahidian S, Belo ADF, Carreira E, Paniagua LL, Moral F, Paixão L, Marques da Silva J (2022) A Technological approach to support extensive livestock management in the Portuguese Montado ecosystem. Agronomy 12:1212. https://doi.org/10.3390/agronomy12051212
Soares PMM, Cardoso RM, Lima DCA, Miranda PMA (2017) Future precipitation in Portugal: high-resolution projections using WRF model and EUROCORDEX multi-model ensembles. Clim Dyn 49:2503–2530. https://doi.org/10.1007/s00382-016-3455-2
Spinoni J, Naumann G, Vogt JV (2017) Pan-European seasonal trends and recent changes of drought frequency and severity. Global Planet Change 148:113–130. https://doi.org/10.1016/j.gloplacha.2016.11.013
Thornes JB (2005) Coupling erosion, vegetation and grazing. Land Degrad Dev 16(2):127–138. https://doi.org/10.1002/ldr.655
Tohiran K, Nobilly F, Zulkifli R, Yahya MS, Norhisham A, Rodi MDZR, Azhar B (2023) Multi-species rotational grazing of small ruminants regenerates undergrowth vegetation while controlling weeds in the oil palm silvopastoral system. Agric Syst 210:103720. https://doi.org/10.1016/j.agsy.2023.103720
Tonini M, Parente J, Pereira MG (2018) Global assessment of rural–urban interface in Portugal related to land cover changes. Nat Hazards Earth Syst Sci 18:1647–1664. https://doi.org/10.5194/nhess-18-1647-2018
Turco M, Palazzi E, Von Hardenberg J, Provenzale A (2015) Observed climate change hotspots. Geophys Res Lett 42:3521–3528. https://doi.org/10.1002/2015GL063891
Varela E, Calvo L, Marcos E (2018) Effectiveness of traditional pastoral practices in wildfire prevention and control in Mediterranean ecosystems: A case study in NW Spain. Land Degrad Dev 29(3):397–408. https://doi.org/10.1002/ldr.2874
Villar L, Rodríguez MÁ, Chaves RA, Navarro S, González M, López JA (2016) Climate drivers of the 2017 devastating fires in Portugal. Sci Rep 9:1–10. https://doi.org/10.1038/s41598-019-50281-2
Vinholis MMB, Carrer MJ, Souza Filho HM, Bernardo R (2022) Sistemas de integração lavoura-pecuária-floresta no estado de São Paulo: estudo multicasos com adotantes pioneiros. Rev De Economia e Sociologia Rural 60(1):e232501. https://doi.org/10.1590/1806-9479.2022.232501

Woodmansee RG, Duncan DA (1980) Nitrogen and phosphorus dynamics and budgets in annual grasslands. Ecology 61(4):893–904. https://doi.org/10.2307/1936759