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Can Shrub Flammability be Affected by Goat Grazing? Flammability Parameters of Mediterranean Shrub Species under Grazing

Juan Manuel Mancilla-Leytón [1], Carmen Hernando [2,3], Jesús Cambrollé [1], Sara Muñoz-Vallés [1], Rafael Pino-Mejías [4] and Ángel Martín Vicente [1,*]

1 Departamento de Biología Vegetal y Ecología, Facultad de Biología, Universidad de Sevilla, 41012 Sevilla, Spain; jmancilla@us.es (J.M.M.-L.); cambrolle@us.es (J.C.); saramval@us.es (S.M.-V.)
2 INIA, Forest Research Centre, Department of Forest Dynamics and Management, Forest Fire Laboratory, Ctra. Coruña Km 7,5, 28040 Madrid, Spain; lara@inia.es
3 iuFOR, University Institute for Sustainable Forest Management, UVA-INIA, 28040 Madrid, Spain
4 Departamento de Estadística e Investigación Operativa, Universidad de Sevilla, 41013 Sevilla, Spain; rafaelp@us.es
* Correspondence: angelm@us.es; Tel.: +34-954557063

Abstract: In this study, we evaluated changes in the potential flammability of different Mediterranean shrub species in a pine (*Pinus pinea*) forest in the Doñana Natural Park (of SW Spain) as a result of goat grazing. Plant height, total biomass, fine fuel biomass and leaves/wood ratio were measured in individual plants of each species in both grazed and ungrazed areas. Moisture content, mean time of ignition, mean time of combustion, gross heat of combustion (GHC) and flammability class of the studied shrub species were determined in the laboratory. The results of this experiment showed that grazing influenced the flammability characteristics of the studied shrub species. However, the strength of this effect was insufficient to modify the flammability index of these plants, except in the case of *Myrtus communis*, in which grazed plants presented a lower flammability index. According to Valette's classification, *Cistus salviifolius*, *Halimium halimifolium* and *Pistacea lentiscus* are flammable species, *Rosmarinus officinalis* is a flammable-highly flammable species, and *M. communis* is non-flammable. The GHC values obtained were generally "intermediate", except for those of *R. officinalis*, which were classified as "high". The flammability parameters of the study species did not show a very marked trend in relation to grazing, but the vertical structure of plants did change by presenting reduced biomass of leaves and fine twigs. This change altered the physical characteristics of these plants and possibly acted to reduce the inherent fire risk of the shrublands.

Keywords: goat grazing; phytovolume; wildfire; Doñana Natural Park; *Rosmarinus officinalis*; *Myrtus communis*

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1. Introduction

Over recent decades, the dynamics of land use change (abandonment of rural areas and agricultural activities, exclusion of livestock from forests and expansion of urban-wild interface areas, among others) have aggravated fire hazards and the potential for disaster in Mediterranean countries [1]. In fact, the incidence of wildfires in many European countries has increased compared to previous decades, reaching an annual average of 14,000 wildfires in Spain (2009–2019) and affecting an average of 74,000 ha per year [2].

One of the main methods for preventing wildfire is to reduce the fuel load and continuity of forest stands (by shrub clearing, pruning or thinning), using either mechanical means or prescribed burning [3]. However, livestock grazing represents a less aggressive and/or expensive alternative for controlling shrub encroachment in order to reduce the risk of forest fires [4–6]. In some parts of the world, firebreaks in the vegetation are already maintained by controlled grazing, and prevention of forest fires by grazing is a well-acknowledged regulating ecosystem service [6,7]. Practices such as grazing combined with prescribed burning and/or mechanical treatments (thinning and shrub clearance/removal) to prevent fuel accumulation are beginning to show excellent results and have the added advantage of providing several positive externalities for rural livelihoods and the environment that contribute to sustainable rural development [6,8,9].

Goats are suitable for the purpose of fuel control because of their capacity for browsing; it has been shown that, at adequate stocking rates, they can reduce woody biomass (reducing the risk of wildfire), avoid the incidence of monospecific shrubs, promote grass, etc. [10–12]. Plant responses to single-event or repeated grazing vary greatly depending on the availability of leaf biomass, meristems, stored nutrients and soil resources, as well as the frequency and intensity of defoliation [13]. Through their modular structure and development, nutritional values and anti-nutritional compounds, plants are to a certain extent pre-adapted to compensate for losses caused by grazing [13,14]. The evolution of nutritional, chemical and phenological defences in grazing plants, as well as the adverse effects of these changes on the herbivore diet, have been studied [8–11]; however, there are very few studies analysing Mediterranean shrubland flammability in relation to fuel management by grazing.

Plant flammability (the ability of a species to ignite and sustain fire) is a complex phenomenon, the direct measurement of which under laboratory conditions is both difficult and equivocal, given the lack of standard methodologies. According to White and Zipperer [15], forest fuel characteristics have hindered the standardization of methods and protocols. In addition, several definitions of 'flammability' have been proposed by different authors. The most commonly accepted definition is that proposed by Anderson [16], which considers four components of flammability: ignitability, combustibility, sustainability and consumability [12,17–19]. There are many studies on this topic, adopting several methods and conducted for various purposes, but most of these methods are based on measuring the time to ignition of a given plant sample [20]. The flammability components described are influenced in different ways by a multitude of factors: overall fuel arrangement, structural characteristics, moisture content and chemical composition (lignins, carbohydrates, minerals and isoprenoids) [21]. In this sense, fuel flammability depends on the local circumstances at a given time and under particular weather conditions [19]. The aim of this study was to evaluate, during the critical summer period, changes of flammability parameters associated with the ignition, combustion and fire propagation processes of different Mediterranean shrub species caused by goat grazing in a pine forest in southern Spain.

2. Materials and Methods

2.1. Study Area and Species Selection

The experimental site was established in the Doñana Natural Park, one of the most important nature reserves in Europe due to its high biological diversity (SW Spain, 37°14′ N, 6°20′ W).

The studied forest stand is dominated by *Pinus pinea* (100 ha), with an average density of 217 trees/ha and average diameter at breast height (dbh) of 26.92 cm. The climate is Mediterranean, with a mild and rainy winter (monthly average temperature is 10 °C in December and January) and a long dry summer, (mean temperature of 25 °C in July and August). Mean annual rainfall is around 540 mm, with 80% of precipitation occurring from October to March.

The study area is used for timber production, hunting (rabbit, partridge) and grazing (domestic ungulates); however, wild herbivores (deer) were eliminated in 1970 and domestic goats were excluded from 2002 to 2007. During this 5-yr period, grazing was completely excluded from the study area and the natural vegetation was not subjected to any form of management. As a consequence, it grew and accumulated rapidly. In the spring of 2007, a herd of adult domestic goats (average weight 40–45 kg) was therefore introduced into the area at a stocking rate of 2.7 ungulates ha^{-1} yr^{-1} (characterized as moderate grazing) [10]. This livestock management can be considered semi-extensive, although in order to exploit the 100 ha in a uniform manner, the goats were closely controlled and moved around by a goatherd. In 1990, five plots (2–3 ha each) were chosen at random within the study area and fenced off in order to exclude them from goat grazing and to evaluate the effects of changes in shrubland composition. Since 2007, the vegetation from both areas (ungrazed and grazed) has been sampled [22]. The study area thus comprised these five fenced plots established in 1990 (ungrazed area, 5.5 t ha^{-1} potential grazing biomass) and the remaining unfenced area, which has been under continuous grazing from 2007 (3.2 t ha^{-1} potential grazing biomass) by a herd of adult domestic goats.

Five understory species (*Cistus salviifolius* L., *Halimium halimifolium* L., *Myrtus communis* L., *Pistacia lentiscus* L. and *Rosmarinus officinalis* L.) were used to study various parameters of flammability. These species were chosen based on their abundance within the study area (jointly representing 80% of the understory cover) and high rates of consumption by the goats [22].

2.2. Previous Characterization

In spring of 2011, plant height, total aboveground biomass, fine fuel biomass (leaves and twigs < 6 mm) and leaves/wood ratio were measured in 30 plants per species (15 inside and 15 outside each exclusion plot) in order to characterize the structure of the selected species. These variables were considered relevant because of their potential influence on species flammability.

2.3. Field Sampling

In June 2011, five plants of each species, growing under similar microclimatic conditions (mean daily temperature and light intensity), were randomly chosen and marked in each plot in order to enable the collection of data from the same plants at every sampling session. Outside each fenced plot, five other plants of each species, with characteristics similar to those of the adjacent ungrazed plot, were randomly selected and marked in the grazed area. Vegetation sampling took place on three occasions during the season of highest fire risk, between June and September [at the beginning (10 June–12 July), middle (13 July–15 August) and end (16 August–20 September) of summer], producing fifteen pairs. Figure 1 presents average monthly temperature and rainfall values recorded in the different sampling times: first (average max. temperature = 32.37 °C, mean rainfall = 6.41 mm), second (average max. temperature = 34.10 °C, mean rainfall = 0 mm) and third (average max. temperature = 31.97 °C, mean rainfall = 17.01 mm) collections. In each period, in order to estimate the flammability of the live fresh fuel, 10 cm samples of terminal twigs, with their leaves, were collected in a homogeneous manner from mature plants of each species and area, and immediately placed in large sealed plastic bags and stored in a cooler for transportation to the laboratory. A subsample, of approximately 160 g of each species, plot and area (inside/outside of the fence), was immediately taken in the laboratory and separated into three sets of fifty 1 g samples: (i) the first set of samples was subjected to a flammability test (Valette's protocol, [23]), (ii) the second set was used for moisture content determination, in which samples were placed in an oven at 100 $\pm$ 5 °C for 48 h, after which the moisture content was expressed as the percentage of oven-dry weight (% ODW), and (iii) the third set was used for Gross Heat Content tests. For moisture content determination, six values were calculated for each species, plot and area (inside/outside of the fence); the average of these six values was taken as the final estimate. In this way, for each species, five pairs of values inside/outside of the plots were computed.

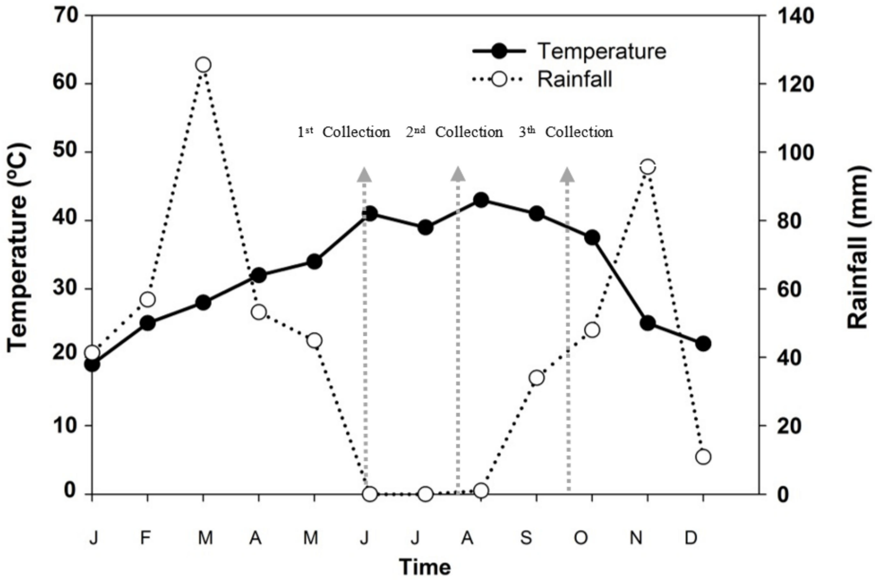

Figure 1. Monthly temperature and rainfall average recorded in Doñana Natural Park (SW, Spain) during 2011.

2.4. Description of Laboratory Procedures

2.4.1. Flammability Testing Method

The laboratory flammability test was performed using an electric radiator, an ignition apparatus with an electric heating resistance (500 watts of heat capacity) beneath a 10 cm diameter ceramic plate located 4 cm below a pilot flame [23,24]. The flammability test method described by Valette [23], was applied as follows: when the electric radiator reached the required temperature, we placed a 1 g sample from each species on to the heated ceramic surface and simultaneously started a chronometer in order to measure time to ignition (TI) and time of combustion (TC), in seconds. For each species, plot, treatment and sampling time, 50 flammability tests were performed and the results used to calculate mean time to ignition (MTI) and mean time of combustion (MTC). The total number of positive ignition tests was used to calculate the ignition frequency (IF), which was expressed as a percentage [23]. Ignition frequency and time to ignition were both used to calculate the flammability index, according to the table proposed by Valette [23] (Table A1).

2.4.2. Gross Heat of Combustion Testing Method

The gross heat of combustion (GHC), also known as high calorific value, of the fine live fuel (leaves and particles <6 mm in diameter) was determined following the Spanish Standard UNE 164001 EX (according to the Spanish Association for Standardization and Certification) [19]. For each species, treatment and sampling time, a fuel sample was ground in a mill. Pellets of approximately 1 g were produced from the ground material using a hand press, oven-dried at 100 ± 5 °C for 24 h and weighed. Measurements were taken using an adiabatic bomb calorimeter equipped with a platinum resistance sensor (PT 100). The calorific value of benzoic acid (26.44 kJ·kg^{-1}) was used to calibrate the calorimeter. Two or three measurements of calorific value were taken from each sample, and any values differing by more than 2% from other values obtained with the same sample were eliminated.

2.5. Data Analysis

Data obtained from the flammability tests were statistically analysed. A repeated-measures ANOVA model was fitted for each dependent variable (flammability (mean time to ignition and mean time to combustion), gross heat of combustion and fuel moisture content). The model included two within-unit factors: treatment (grazed and ungrazed), and time (three sampling times; beginning, middle and end of summer). We considered treatment type as a within-unit factor since the sampling units are paired (plants inside and outside each exclusion plot). The ANOVA model included treatment, time and interaction terms. The linear model used for each parameter was as follows: Yijk = μ + FGi + Mj + (FG ′ M)ij + εijk; where Yijk = observations for dependent variables; μ = overall mean; FGi = fixed effect of feeding group (i = grazing or ungrazed); Mj = fixed effect of time (j = beginning, middle and end of summer); FG ′ M = interactions between and among these factors, and εijk = random effect of residual. The compound symmetry structure of the covariance matrix was tested with the Mauchly procedure. To test each effect (treatment, time and interaction) the corresponding Mauchly test of sphericity was first performed. In the case of rejection of the null-hypothesis (considering 0.05 to be the probability of type I error), the adjusted test based on Huynh-Feldt corrections for departure from sphericity was used; otherwise, the normal parametric test was used. A paired t-test was used to determine the mean difference in species biometric characteristics between grazed and ungrazed area. IBM SPSS 20.0 for Windows (SPSS Inc., Chicago, IL, USA) was used in all statistical analyses. Finally, the relationships among moisture content, time to ignition, and time of combustion were explored through Pearson correlation.

3. Results

3.1. Previous Fuel Characterization

Table 1 presents the different characteristics of the species in the grazed and ungrazed areas. Since 2007, over a period of four years, goat grazing continuously decreased the total phytovolume of the monitored shrubs located in grazed areas. The response of each species to goat grazing was different; *M. communis* was the species most affected by the presence of goats, with only rosemary (*R. officinalis*) presenting similar values. Total accumulated aboveground biomass, leaf/wood ratio and vertical structure (height) were significantly lower in grazed compared to ungrazed plants ($p \leq 0.05$). Biomass of highly flammable fuel (leaves and twigs <6 mm) was also significantly lower in the grazed shrubs (Table 1).

Table 1. Characterization of each study species present in the grazed (GA) and ungrazed area (UA) of a Mediterranean pine forest understory in Doñana Natural Park, SW Spain, prior to beginning the experiments (spring 2011). Different letters indicate significant differences between treatments ($p < 0.05$).

		Total Aboveground Biomass (g m^{-2})	Foliar Biomass (g m^{-2})	Leaves + Twigs < 6 mm (g m^{-2})	Leaves /Wood	Height (cm)	[2] Browsing Pressure
Cistus salviifolius	UA	712 a [1]	155 a	334 a	0.44 a	97 a	–
	GA	517 b	46 b	150 b	0.08 b	47 b	High
Halimuim halimifolium	UA	896 a	126 a	536 a	0.34 a	106 a	–
	GA	611 b	3 b	225 b	0.14 b	88 b	High
Myrtus communis	UA	1374 a	269 a	717 a	0.37 a	126 a	–
	GA	1004 b	49 b	305 b	0.04 b	84 b	Very high
Pistacia lentiscus	UA	2049 a	485 a	500 a	0.46 a	193 a	–
	GA	1753 b	196 b	264 b	0.14 b	148 b	Medium
Rosmarinus officinalis	UA	1100 a	333 a	483 a	0.62 a	98 a	–
	GA	1152 a	321 a	390 a	0.49 a	82 a	Low

Note: [1] Different letters indicate significant differences between treatments ($p < 0.05$); [2] Values obtained from Mancilla-Leytón et al. [22].

3.2. Flammability Test Parameters

Means of moisture content, time to ignition (MTI), time of combustion (MTC), as well as flammability index (FI) values, are presented in Table 2. The corresponding least square means for each grazing treatment, standard error of the mean and *p*-value, according to the ANOVA results, are presented in Table A2.

Table 2. Mean values of moisture content and the flammability test parameters observed for forest fuel samples collected in 2011 at different times of the summer (early, mid and late) and areas [grazed (GA) and ungrazed (UA)] from different Mediterranean species in Doñana Natural Park (SW, Spain).

Species	Sampling Time of Summer	Treatment	Moisture Content [%]	Time to Ignition [s]			Time of Combustion [s]			[1] FI
				Min.	Mean	Max.	Min	Mean	Max.	
Cistus salviifolius	Early	UA	130	13	25	36	2	12	21	3
		GA	136	20	23	25	9	11	14	3
	Mid	UA	88	16	20	24	10	15	18	3
		GA	89	16	18	22	13	16	18	3
	Late	UA	160	22	27	34	6	9	13	3
		GA	155	22	26	32	9	13	17	3
Halimiun halimifolium	Early	UA	148	22	27	31	6	9	12	3
		GA	146	21	24	27	8	10	12	3
	Mid	UA	104	16	19	22	12	15	20	3
		GA	97	12	16	21	11	17	22	3
	Late	UA	150	17	20	24	9	12	15	3
		GA	138	17	20	25	8	11	14	3
Myrtus communis	Early	UA	167	22	32	45	1	3	9	1
		GA	103	14	26	51	2	24	65	0
	Mid	UA	133	13	22	36	3	9	14	1
		GA	79	11	23	44	11	38	57	0
	Late	UA	125	12	19	28	7	12	21	3
		GA	97	15	29	53	3	24	58	0
Pistacia lentiscus	Early	UA	144	10	17	29	5	9	14	1
		GA	129	11	16	32	5	9	17	1
	Mid	UA	122	5	10	16	9	15	23	3
		GA	103	5	12	21	9	16	25	3
	Late	UA	141	9	16	34	6	11	21	3
		GA	100	9	17	28	5	11	21	3
Rosmarinus officinalis	Early	UA	140	19	25	33	3	8	15	3
		GA	107	16	24	33	5	10	17	3
	Mid	UA	93	9	16	22	7	12	17	4
		GA	70	11	15	19	6	12	20	4
	Late	UA	149	20	26	35	5	7	14	3
		GA	135	20	24	28	5	10	17	3

Note: [1] In order to understand the effect of moisture on the remaining variables, and to allow estimation of natural experimental variability, maximum and minimum values are also included in this table. Flammability Index (FI) classification scale proposed by Valette [23]: 0–1 = Non-flammable; 2 = Slightly flammable; 3 = Flammable; 4 = Highly flammable.

The climatic differences (temperature and precipitation, Figure 1) were reflected in the fuel moisture content (FMC) of the samples (Table 2). The FMC did not show a significant interaction between treatments and time in any of the species, but a significant interaction was found with time; the values for early and late summer being significantly higher than those of mid-summer (FMC ranged between 70–167%). With the exception of *C. salviifolius*, significant differences were found in FMC between grazed and ungrazed plants in all of the species. The FMC also significantly decreased in grazed plants (Tables 2 and A2).

The shortest MTI was recorded for *P. lentiscus*, while *M. communis* presented a short MTC that increased as summer progressed, especially in ungrazed plants (Table 2). Regarding MTI, all species, except for *C. salviifolius*, showed significant interactions between treatments and time of sampling. In the presence of goats, MTI decreased significantly in *C. salviifolius*, *H. halimifolium* and *R. officinalis* (p = 0.000, 0.000 and 0.041, respectively, Table 2) but tended to significantly increase in *M. communis* and *P. lentiscus* (p = 0.043 and 0.032, respectively). All species showed a significant interaction with time, and the lowest MTI was recorded in the second sampling event (midsummer) (Tables 2 and A2).

Regarding MTC, the results showed a significant interaction between treatments and time in all species (Table A2). Under goat grazing, MTC significantly increased in all species (this effect was very pronounced in *M. communis*), except in the case of *P. lentiscus*, which did not differ significantly between treatments (Tables 2 and A2). Regarding MTC, all species showed a significant interaction with time; the highest values were recorded in the second sampling event (mid-summer) (Tables 2 and A2).

Based on the flammability index classification proposed by Valette [23], almost all of the species tested in this study were found to be flammable (FI = 3) (Table 2). *C. salviifolius*, *H. halimifolium*, *P. lentiscus* and *R. officinalis* presented flammability index values equal to or greater than 3. Although differences in MTI and MTC were statistically significant in most species, goat grazing did not affect the flammability index of any of the studied species, except for *M. communis*. Most differences in these values were small (a few seconds) and thus produced little change in the flammability index of the vegetation samples. Overall, the species flammability index remained constant in grazed plants (index = 0) during the study period but increased (from 1 to 3) over time in the ungrazed plants (Table 2). The Pearson correlations showed that changes in moisture content were negatively correlated with time of combustion ($r = -0.69$, $p \leq 0.05$) and positively correlated with time to ignition ($r = 0.44$, $p \leq 0.05$).

3.3. Gross Heat of Combustion

Figure 2 shows the results of the gross heat of combustion (GHC) values of the studied species in the different (grazed and ungrazed) sampling areas and events. For all species, except *H. halimifolium*, the results showed a significant interaction between treatments and sampling events (Table A2). The species *R. officinalis* presented the highest GHC value ($F = 39.433$, $p \leq 0.01$) (Figure 2). Only *P. lentiscus* and *R. officinalis* showed significant differences between treatments; calorific values were significantly lower in the ungrazed than in the grazed samples ($p \leq 0.000$) (Table A2). Finally, all species showed a significant interaction with time; in general, the calorific values of the species increased as summer progressed (maximum values in late summer, Figure 2 and Table A2).

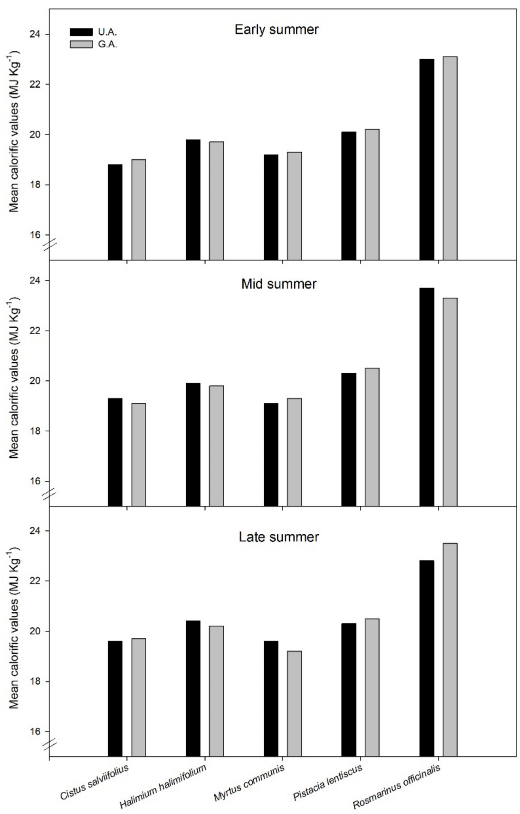

Figure 2. Mean calorific values (MJ Kg^{-1}) of forest fuel samples collected from different areas (grazed (GA) and ungrazed (UA)) of a Mediterranean pine forest understory in Doñana Natural Park (SW, Spain) (n = 3).

4. Discussion

Mediterranean shrubland is extremely heterogeneous in terms of flammability, and the combustible properties of different species, among other variables, are determined mainly by their pyrophytism (e.g., *R. officinalis*), which can make certain plant communities more fire-prone than others [17,23,25]. Any modification to the vegetation, such as grazing, can modify these properties. The results of this experiment show that grazing affected the flammability characteristics (MTI and MTC) of the studied shrub species. However, the change was insufficient to alter the flammability index of these shrubs, apart from *M. communis,* in which grazed plants presented a lower flammability index than ungrazed plants. The results therefore suggest that the species did not change their flammability characteristics in response to herbivory, but rather maintained these characteristics. According to Valette's classification, which takes ignition frequency and time to ignition into account, the studied species were ranked from 0 to 4 according to timing and grazing (Table 2). *C. salviifolius, H. halimifolium* and *P. lentiscus* were classified as flammable species, *R. officinalis* as flammable-highly flammable and *M. communis* as non-flammable [17,24,26].

As stated above, determination of flammability is not straightforward and classification can be made only in a general sense [23]. The most important parameter in ranking the flammability of forest species is TI [17,27]; however, Valette [23] combined the mean time to ignition (MTI) classes with those of the parameter IF under a crosslink table that helped to determine flammability index values. This procedure diminishes the importance of TI. There is no standard method for testing forest species flammability, since the parameter of flammability is a plant property that has no unit integrating all of the three components cited above (ignitability, combustibility and sustainability) [16]. Recent studies have therefore included other parameters that were not included in the classification method proposed by Valette, such as the dimensions of flames (FH), an indicator of the volatilized essential oils contained in vegetal leaves, and a sustainability component (TC), which characterizes the ability of fuel to sustain combustion over a prolonged period. Unfortunately, these parameters were not measured in the present study, but the information obtained is still valuable in terms of initiating this line of research. Monitoring how the chemical components of study species change throughout the season and/or in the presence of grazing may provide further valuable information and should be a consideration for future research.

The structural properties of each plant species are considered major factors in their flammability [15,16]. Physical structure and components (e.g., canopy architecture, fine fuel biomass, leaf size and shape and retained dead material) and physiological or cellular elements (e.g., volatile oils and resins, moisture content, mineral content, lignin and waxes) usually affect the flammability characteristics of a species [19,28]. From a physical perspective, the surface area-to-volume ratio of fuel particles is often considered a significant factor in flammability [29]. However, for whole plants, flammability depends mainly on the physical arrangement of the plant biomass [30]. It has been recognized that fine forest fuels play an important role in wildfire initiation and propagation [12]. Fine particles ignite more readily and release their heat quicker than thicker particles of an equivalent total weight. A long-term absence of disturbance in shrublands leads to an accumulation of large amounts of dead plant material [31]. Grazing animals have been thought to inhibit the accumulation of dead biomass through consumption of foliage [32]. Where grazing pressure is sufficient to develop grazing lawns, plants are maintained in a state of continuous regeneration [33] and the proportion of accumulated dead material can be very low, thus reducing fire risk [18]. In the study area, from 2007 to 2011, continuous and moderate goat grazing had significant effects on the phytovolume and height of the studied shrubs. A previous study by Mancilla-Leytón et al. [10] showed that, after 42 months, goat grazing significantly reduced species phytovolume by 34%, increased bare soil by 51% and decreased the flammability of the area by 22%. The significant reduction of the combustible understorey biomass and the horizontal vegetation cover found in this study area translates into a reduced fire risk. All of the studied species, except *R.*

officinalis, presented significantly lower phytovolume and height when grazed, while the percentage of fine fuel was also significantly reduced. The degree to which grazing reduces fuel load is determined by the density of grazers, their rate of food intake and the growth rates of the plants [14,34]. The impact of grazing on shrubland fuel load varies among the vegetation components due to variations in feeding preferences and in the behavioural, morphological and physiological traits that influence food intake [22]. Thus, the effect of grazing was most evident in *M. communis* (highly grazed), but less pronounced in *R. officinalis* (very lightly grazed) (Table 1). The effect of light to moderate grazing intensities on vegetation (breaking the continuity between shrubs and creating 'regeneration gaps' for the implantation of grassland) controls the combustible biomass, thus reducing the fire risk and allowing the co-existence of species that were previously suppressed by the densely packed dominant species.

From a physiological perspective, volatile organic compounds are produced by many Mediterranean plant species and are related to secondary metabolism processes [35]. These compounds have a low ignition temperature and, when the ambient temperature increases as a result of exposure to the sun or radiation from a flame front, they create a flammable gas mixture. The gross heat of combustion of the tested species was generally lower than that of common Mediterranean forest fuels [12]. According to the classification proposed by Elvira and Hernando [26], the GHC values obtained were generally "intermediate" (18.81–20.90 MJ kg^{-1}), except for those of *R. officinalis* (Figure 2). The calorific value of plants increases as stems are lignified (due to the higher calorific value of lignin in comparison to cellulose). The most lignified species and those with a higher content of volatile organic compounds (resins, terpenes and essential oils) (e.g., *R. officinalis*) present a high calorific value. The increased calorific values found in the grazed species can be attributed to the fact that the goats remove the tender shoots, thus increasing the proportion of the most lignified parts in each plant.

Both the physical and physiological factors involved in the flammability of the studied plant species are time-dependent. These properties may vary within the same species due to changes in plant status (in flower, undergoing regrowth, woody, etc.) or environmental conditions (temperature, humidity, rainfall, etc.). This means that their flammability characteristics (MTI, MTC, etc.) may change depending on the status of these factors, which is in turn largely determined by the time of year [26]. For instance, the season of highest fire risk is dictated by the co-occurrence of high ignition values and low fuel moisture [25]. This is usually the driest time of the year, which varies with regional climate. In Mediterranean-type shrublands, summer is the season of highest fire risk [10]. While we have evaluated only one season in this study, the FMC values differed among the three summer-time points examined, reflecting changes in the temperature and precipitation (Tables 1 and 2). Furthermore, these changes in FMC were negatively correlated with MTC and positively with MTI. Therefore, temporal changes could play a relatively greater role in the analysed flammability characteristics than the practice of goat grazing.

As consumers of fine fuels, the role of native and introduced domestic herbivores in reducing fire risk has been well documented [4,11,25]. Herbivores may select plants with particular chemical or morphological traits, alter competitive hierarchies and directly modify vegetation structure in ways that can either promote or reduce potential wildfire activity [25,36]. White and Zipperer [15] showed that the flammability characteristics of a particular species were influenced not only by the species itself but also by its environment. It should also be noted that ignition and spreading of fire could be difficult where there is discontinuity in the vegetation. Under such a scenario, even highly flammable species may not present a high risk [37]. The opposite is also true: less flammable species, presented in horizontal and/or vertical continuity, represent a higher risk by complicating firefighting and suppression conditions/practices.

The specific characteristics (i.e., ecological, economic and/or social aspects) of each forest area should serve as the basis for selecting the most appropriate fuel treatment in each case (mechanical treatments, prescribed burning or controlled grazing). However, there is no single ideal technique for wildfire prevention and, in general, the most suitable fuel management plans are those that combine different practices [38]. It is important to understand the benefits and limitations of each fuel manipulation method in order to ensure their correct application and realize their potential for achieving management objectives [39]. Several studies on the pre- and post-fire effects of introduced herbivores, conducted across a broad range of forest and shrubland types, have shown that herbivore pressure (1) impedes the regeneration of obligate-seeding tall tree species [40], (2) reduces the phytovolume and height growth of shrub and tree seedlings, reducing the likelihood of the development of a closed canopy [10] and (3) favours the invasion and spread of forbs [41].

Preventive silviculture, including supervised goat and sheep grazing, are especially relevant tools [42]. Through good practices in grazing, suitable management of the ecosystems is possible. Grazing has also acquired an environmental dimension in the last decade: controlled grazing can favour the provision of ecosystem services, mainly environmental, but also add economic, social and cultural value, for example, through quality recognition of the animal products obtained when Protected Origin status is awarded [43].

5. Conclusions

The studied flammability parameters did not present a very marked trend in relation to grazing, especially when compared to other fire hazard components or to the effect of sampling time. However, from a physical perspective, goat grazing reduced phytovolume, significantly decreased horizontal and vertical (height) plant cover and increased the area of bare ground, implying that the practice can make a potentially valuable contribution to a progressive reduction in the inherent fire risk of shrublands. The results indicate the need for future research to evaluate some flammability parameters including heat release rate, which is crucial for understanding the flammability process.

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Appendix A

Table A1. Flammability values according to the Valette methods [23]. Flammabiliy Index classification scale: 0–1 = Non-flammable; 2 = Slightly flammable; 3 = Flammable; 4 = Highly flammable.

Mean Time to Ignition [s]	Ignition Frequency (%)					
	100–95	94–90	89–85	84–80	79–50	<0
<12.5	5	4	3	3	2	1
12.6–17.5	4	3	3	2	1	1
17.6–22.5	3	3	2	2	1	0
22.6–27.5	3	2	2	1	0	0
27.6–32.5	2	2	1	1	0	0
>32.6	2	1	1	0	0	0

Appendix B

Table A2. Overall (averaged over time) least squares means for each grazing treatment (grazed and ungrazed), Standard Error of the Mean (SEM) and p-values for the hypothesis of the main effects (treatment, time and interaction) found in the understory of a Mediterranean pine forest in Doñana Natural Park (SW Spain) over summer 2011.

Variable	Means		SEM	*p*-Values		
	Ungrazed	Grazed		Treatment	Time	Interaction
Cistus salviifolius						
Moisture content (%)	126	127	2.2	0.482	0.000	0.075
Mean time ignition (s)	24	22	0.5	0.000	0.001	0.133
Mean time combustion (s)	12	13	0.4	0.000	0.000	0.009
Calorific values (MJ kg^{-1})	19	19	0.1	0.109	0.000	0.000
Halimium halimifolium						
Moisture content (%)	136	125	2.4	0.001	0.000	0.900
Mean time ignition (s)	22	20	0.4	0.000	0.000	0.008
Mean time combustion (s)	12	13	0.4	0.019	0.000	0.022
Calorific values (MJ kg^{-1})	20	20	0.2	0.051	0.000	0.410
Myrtus communis						
Moisture content (%)	143	94	3.6	0.000	0.000	0.067
Mean time ignition (s)	24	26	0.7	0.043	0.000	0.001
Mean time combustion (s)	8	28	3.1	0.021	0.000	0.006
Calorific values (MJ kg^{-1})	19.27	19.25	0.1	0.070	0.000	0.000
Pistacia lentiscus						
Moisture content (%)	125	108	2.3	0.000	0.000	0.356
Mean time ignition (s)	14	15	0.5	0.032	0.000	0.005
Mean time combustion (s)	12	12	0.3	0.057	0.000	0.090
Calorific values (MJ kg^{-1})	20	20	0.1	0.000	0.001	0.004
Rosmarinus officinalis						
Moisture content (%)	127	104	4.2	0.001	0.000	0.083
Mean time ignition (s)	22	21	0.6	0.041	0.000	0.043
Mean time combustion (s)	9	11	0.5	0.018	0.001	0.037
Calorific values (MJ kg^{-1})	23	24	0.1	0.000	0.000	0.000

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