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Modelling aboveground biomass and fuel load components at stand level in shrub communities in NW Spain

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ABSTRACT

Shrub-dominated ecosystems cover large areas globally and play essential roles in ecological processes. Aboveground biomass expressed on an area basis (AGB) is central to many of the ecological processes and services provided by shrublands and is important as the main fuel source for wildfires. Hence, its accurate estimation in shrublands is crucial for ecologists and land managers. This is especially relevant in fire-prone regions such as NW Spain, where shrublands are an important part of the landscape, providing multiple services, but are severely impacted by wildfires. Although biomass models are available for numerous shrub species at the individual plant level, operational models based directly on easily measured shrub stand attributes are scarce. In this study, equations for estimating AGB and loads of different fuel components by size and condition (live and dead) from stand biometric variables were developed for the nine most prevalent shrub communities in NW Spain. Non-linear iterative seemingly unrelated regression was used to fit compatible systems of equations for estimating fuel loads, with shrub stand height and cover and litter depth as predictors for individual shrub communities and all data combined. In general, the goodness-of-fit statistics indicated that the estimates were reasonably accurate for all communities (grouped and ungrouped). The best results were obtained for AGB and total fuel load, including litter, whereas the poorest results were obtained for standing live and dead fine fuel load. Model performance was reduced when height was the only independent variable, although the reduction was small for most fuel categories, except litter load for which the variability was adequately explained by the litter depth. These results illustrate the feasibility of the stand level approach for constructing operational models of shrub fuel load that are accurate for most of fuel components, while also highlighting the ongoing challenges in live and dead fine fuel modelling. The equations developed represent an appreciable advance in shrubland biomass assessment in the region and areas with similar characteristics and may be instrumental in generating fuel maps, fire management improvement and better C storage assessment by vegetation, among other many uses.

1. Introduction

Shrublands cover large areas globally (Di Vittorio et al., 2018) and play essential roles in ecological processes (Lombardo et al., 2020; Lozano et al., 2020; Paz-Kagan et al. 2016; Tubbesing et al., 2021). Shrubs also provide important ecosystem services (Marquart et al., 2020; Paton et al. 2002; Viana et al., 2012).

On a global scale there has been an increasing shrubland expansion

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in the last decades affecting a wide variety of biomes with significant ecological effects (Archer et al., 2017; Eldridge et al., 2011; Frost et al., 2018; Van Auken, 2009). Land abandonment, cessation of farming and grazing and climate change have been argued as main driving factors of shrub encroachment (Archer et al., 1995; Fernandes et al., 2014; Naito and Cairns, 2011; Prishchepov et al., 2021). In addition, the conversion of forests to scrubland, due to more frequent wildfires, has been a relevant driver of the above-mentioned expansion in Mediterranean ecosystems (Díaz-Delgado et al. 2002; Fernández-García et al., 2020; Lloret et al., 2003) and it is now considered a widespread phenomenon (Kukavskaya et al., 2016; Coop et al., 2020).

AGB assessment is central for determining the structure, function, primary productivity, and ecosystem services provision of shrublands (Archer and Predick, 2014). Regarding fire ecology, AGB is crucial, as fire can only spread when there is enough biomass to burn (Bradstock's "first fire switch", 2010), and is critical to the response of fire activity to biomass productivity gradients (Krawchuk and Moritz, 2011), in the so-called "intermediate fire productivity hypothesis" (Pausas and Ribeiro, 2013).

In terms of fire management, fuel load (equivalent to AGB) is considered the most important fuel characteristic (Keane, 2013; 2015; Weise and Wright, 2014). In fact, fuel load supplies the energy required for fire ignition and spread, thus modulating fire intensity and severity (Byram, 1959; Fernández-Alonso et al., 2017; Keane, 2015; Parks et al., 2014; Pyne et al., 1996). Furthermore, this information, broken down by fuel stratum, size class (fine, medium and coarse) and condition (live and dead), i.e., the fuel components sensu Keane (2015), is a necessary input in wildland fire behaviour modelling (Larini et al., 1998; Morvan and Dupuy, 2004; Rothermel, 1972) and in derived operational tools (Andrews, 2014; Finney, 1998; 2006). In addition, estimates of greenhouse gas emissions from vegetation fires depend on biomass consumed, also mediated by pre-fire fuel load (Andreae, 2019; van der Werf et al., 2017).

For the above reasons, providing ecologists and forest managers with models that accurately estimate shrub fuel loads is imperative (Botequim et al., 2015). This is particularly determinant in fire-prone areas such as the NW Spain, where about 2% of the forest land is burned annually (period 1978–2019) and some two-thirds of which correspond to shrublands (López-Santalla and López-Garcia, 2019; Xunta de Galicia, 2020). This type of vegetation, forming part of ancient cultural landscapes in the region (Fagúndez, 2013), has been profoundly affected by dramatic changes in land use occurred particularly in the last decades (Corbelle-Rico and Crecente-Maseda, 2014; Ramil-Rego et al., 2013). In many cases, these changes have led to high fuel accumulation and more severe wildfires in the region (Vega et al., 2021). The expected increase in fire risk in Southern Europe (Dupuy et al., 2020), also affecting NW Spain (Vega et al., 2009), adds further urgency to the need for adequate fuel load assessment in the area. This is further reinforced by the sensitivity of fire activity to climate change in moderately-highly productive ecosystems (Briones-Herrera et al., 2019; Pausas and Ribeiro, 2013), such as in the study region (Del Grosso et al., 2008; Sánchez Palomares and Sánchez, 2000). Global change is likely to continue affecting the region in the future, requiring new land use planning and including strategic fuel reduction initiatives (Vega et al., 2021). Therefore, the demand of appropriate models to estimate fuel loading at stand level is likely to increase eventually.

Despite shrublands extent and their ecological relevance, estimation of their biomass expressed on an area basis (AGB) has received comparatively less attention than AGB in forest stands (Conti et al., 2019; Poley et al., 2020).

While double sampling is the rule for estimating AGB (Bonham, 2013; Catchpole and Wheeler, 1992; Chojnacky and Milton, 2008; Etienne 1989; Shiver and Borders, 1996), two different approaches are used: at the individual plant level and at the stand level. In the first approach, destructive sampling is used to develop allometric equations relating individual species-specific biomass with biometric attributes. These equations are then used in conjunction with density sampling of those species to estimate ABG. Comparatively, most of the shrub biomass modelling effort has been made through this approach (Blanco-Oyonarte and Navarro-Cerrillo, 2003; Brown, 1976; Conti et al., 2019; De Cáceres et al., 2019; Hierro et al., 2000; Huff et al., 2017; Paul et al., 2016; Pimont et al., 2018; Yao et al., 2021; Zeng et al, 2010). However, problems associated with its high cost and the impracticability of measuring in dense stands of multi-stemmed plants often make this method unfeasible at large scale. This is the case in the NW Spain communities.

In the second approach, allometric fuel load equations are developed at the stand level, using stand attributes directly as predictors (Botequim et al., 2015; Davies et al., 2008; Fernandes and Rego, 1998a; Fonseca et al., 2012; Montero et al., 2020; Pasalodos-Tato et al., 2015; Pearce et al., 2010; Ruiz-Peinado et al., 2013; Viana et al., 2013)

Litter layer load estimation is also important due to its critical roles in shrublands (Aerts and Chapin, 1999; Eckstein and Donath, 2005; Facelli and Pickett, 1991; Vega et al., 2005). For fire ecology and fire management, litter load assessment is also relevant, as its combustion contributes substantially to fire emissions (Russell-Smith et al., 2009) while its consumption degree is a determinant factor of soil burn severity (Vega et al., 2013). Nonetheless, relatively few studies have modelled the shrub litter load as a function of its physical attributes (Arellano-Pérez, 2011; Davies et al., 2008; Fonseca et al., 2012; Kittredge, 1955; Lade, 2010; McCaw, 1997; Montero et al., 2020).

The presence in the NW Spain of abundant shrub communities from both the Euro Atlantic and the Mediterranean biogeographic domains, provides a broad range of conditions suitable for fuel loading modelling. Accordingly, the objectives of this study were to construct additive allometric equations from biometric variables, at stand level, and to evaluate their performance for estimating: (i) AGB, i.e. total fuel load of the standing shrub stratum, (ii) litter and shrub total fuel load, and (iii) shrub standing stratum fuel component loads (differentiated by size range and condition –live/dead-) for each one of the most significant shrub communities in NW Spain, for groups of these communities and for all of these together.

2. Material and methods

2.1. Study area, shrub communities considered and inventory plots

This study was carried out in Galicia (NW Spain), a region comprised between 41°40′ and 43°48′ N and 6°44′ and 9°18′W, where shrublands cover about 607,000 ha (some 20% of the total area and 30% of the forest land in the region). Most of the shrublands in Galicia are included in the dry heath communities (Ojeda, 2009), part of the habitat 4030 of the European habitat classification (Council Directive 92/43 CEE), with gorses (*Ulex* sp.) and heaths (*Erica* sp.) being the dominant plant genera in terms of area occupied (MARM, 2011b). Most of the Galician shrublands are included in the *Calluno-Ulicetea* syntaxonomical class (Izco et al., 2006). The gorse-dominated communities cover about 55% of the shrubland area, heath-dominated ones occupy around 22% and broom (*Cytisus* sp.) fields 11%. The rest of the shrublands is distributed between areas with scarce or no vegetation (55 thousand ha), frequently affected by high fire recurrence, grasslands (8 thousand ha) and rock roses (*Cistus* sp. and *Halimium* sp.) with 7,000 ha. The boundary of the Eurosiberian and Mediterranean biogeographic regions traverses Galicia, resulting in a transitional climate with a larger area under oceanic influence, nuanced by the effects of a complex relief (Rodríguez Guitián and Ramil-Rego, 2007). The continentality increases from the coast to inland areas, where summers are dryer, while the maximum temperature increases and the minimum decreases from NW to SE (Retuerto and Carballeira, 1992). The mean annual rainfall is 1200 mm, varying spatially between 500 and 1800 mm, and the mean annual temperature is 13.3 °C, ranging seasonally from 8.5 to 19 °C (Martínez-Cortizas and Pérez-Alberti, 1999). These climate conditions favour a high rate of shrub biomass

Table 1

Shrub communities, number of inventoried plots, codes* and dominants and main secondary species. n = number of inventory plots.

Shrub community	n	Code	Dominant shrub species	Main secondary species
Gum rockrose	23	*Cl*	*Cistus ladanifer* L.	
Low broom (White Spanish broom)	47	*Cm*	*Cytisus multiflorus* (L'Hér.) Sweet	*Pterospartum tridentatum* (L.) Willk., *Pteridium aquilinum*(L.) Kuhn, *Cistus salvifolius* L.
High broom (Common broom)	44	*Cs*	*Cytisus striatus* (Hill) Rothm.	*Ulex minor* Roth., *Erica umbellata* Loefle ex L., *Pterospartum tridentatum* (L.) Willk., *Pteridium aquilinum*(L.)Kuhn
			Cytisus scoparius (L.) Link	*Pteridium aquilinum* (L.) Kuhn, *Ulex europaeus* L.
			Genista obstusiramea J. Gay ex Spach.	*Pterospartum tridentatum* (L) Willk.
High heath (Spanish heath)	125	*Ea*	*Erica australis* L.	*Pterospartum tridentatum* (L) Willk., *Halimium lasianhtum* subsp. *alyssoides* (Lam.), *Erica arborea* L., *Ulex europaeus* L.
			Erica arborea L.	*Pteridium aquilinum* (L.) Kuhn
			Erica scoparia L.	*Ulex europaeus* L *Pterospartum tridentatum* (L.) Willk., *Pteridium aquilinum*(L.)Kuhn
Low heath (Dwarf Spanish heath)	68	*Eu*	*Erica umbellata* Loefle ex L.	*Pterospartum tridentatum* (L.) Willk., *Ulex gallii* Planch, *Ulex minor* Roth., *U. Europaeus* L., *Pteridium aquilinum* (L.) Kuhn
			Erica mackaiana Bab.	*Erica cinerea* L., *Calluna vulgaris* (L.) Hull, *Ulex gallii* Planch., *Pteridium aquilinum* (L.) Kuhn
Bracken fern	49	*Pa*	*Pteridium aquilinum* (L.) Kuhn in Kersten	*Ulex gallii*, Planch., *U. minor* Roth., *Erica cinerea* L.
Prickled broom	69	*Pt*	*Pterospartum tridentatum* (L.) Willk.	*Erica umbellata* Loefl. ex L., *Halimium lasianhtum* subsp.*alyssoides* (Lam.), *E. australis* L., *Ulex gallii* Planch., *U. minor* Roth., *U. europaeus* L., *Pteridium aquilinum* (L.) Kuhn
Gorse	191	*Ue*	*Ulex europaeus* L.	*Ulex gallii* Planch, *U. minor* Roth., *Erica umbellata* Loefle ex L, *E. cinerea* L., *Pteridium aquilinum* (L.) Kuhn,
Low gorse (Western gorse)	106	*Ug*	*Ulex gallii* Planch. *Ulex minor* Roth.	*Ulex europaeus* L., *Erica umbellata* Loefle ex L, *Daboecia cantabrica* (thuds.) K.Koch, *Pterospartum tridentatum* (L.)Willk., *Cistus psilosepalus* Sweet, *Pteridium aquilinum*(L.) Kuhn

*The shrub communities with similar structural characteristics were considered jointly and identified by a code comprising the initials of the scientific name of the dominant species for which the largest number of plots were inventoried.

growth (Montero et al., 2020). Shrublands typically occur on Regosols and Leptosols and to a lesser extent on Cambisols and Umbrisols developed mainly on granitic and schist substrates (Carballas et al., 2016).

Nine shrub communities were considered in the present study, each characterized by a dominant species (in terms of coverage in the case of multi-woody species communities). These communities cover about 90% of the shrublands in the region (Izco and García-San León, 1999; MARM, 2011a, 2011b). These are, except for fern (*Pteridium aquilinum* L.)-dominated communities, primarily composed of perennial, multi-stemmed (or highly branched) evergreen woody species (shrubs and sub-bushes), which typically form dense (high number of plants per area) and closed (high coverage) stands ranging in height from medium to moderately high (0.5–3 m). These shrub fuel complexes commonly encompass two strata: the standing shrub and the litter. A few herbaceous plants, including ferns, are occasionally present as understory. Although ferns are non-woody plants and display strong seasonal variations in biomass, *P. aquilinum*-dominated communities were considered in this study due to these communities forming extensive patches often only temporarily, and occurs after some type of disturbance, accumulating substantial amounts of fine fuel in summer and frequently involved in fires in the region. The shrub communities with similar structural characteristics were considered jointly and identified by a code comprising the initials of the scientific name of the dominant species for which the largest number of plots were inventoried (Table 1). Some communities included more than one dominant species, although with some common structural characteristics allowing them to be combined in a group (e.g., high broom, high heath or low heath).

Sites covered with the above-mentioned nine major shrub communities (including bracken fern-dominated community) were selected at random based on the information of the treeless shrub-covered polygons of the Spanish Forest Map 1:25000 (MARM, 2011b). Given the recent and rapid changes in land use in the area (Corbelle-Rico et al., 2012), field reconnaissance was carried out to confirm the persistence of the vegetation composition mapped and site accessibility. Within the corresponding sites the centres of circular shrub inventory plots, in which destructive sampling was conducted, were positioned by randomly selecting an azimuth and a distance within the stand, from a point of access (Marsden-Smedley and Catchpole, 1995; Pereira et al., 1995; Dalgleish et al. 2015; Duff et al., 2017). The number of inventory plots in each shrub community was approximately proportional to the area covered by each in Galicia (MARM, 2011b) and a total of 722 circular plots were inventoried.

Some types of community of concern for fire management, such as gum rock rose, which occupies a relatively small area in the region, are over-represented in the sample in order to yield a sufficient sample size to fit the corresponding allometric models. A field survey was conducted to locate fern-covered areas where inventory plots were subjectively established.

From the centre of each circular sample plot, a random azimuth for one diameter (20–30 m length, depending on shrub height) was established and another diameter was drawn perpendicular to the first. Four destructive sampling subplots (quadrats) were located at the centre of the four plot radii corresponding to the aforementioned diameters (Fig. 1, middle right). The area of each quadrat ranged from 4 to 36 m^2, depending on shrub height: for shrubs smaller than 1.0 m in height, 4 m^2 quadrats were destructively sampled; for shrubs taller than 1.0 m, the quadrat size varied from 3 m × 3 m to 6 m × 6 m.

2.2. Biomass sampling

We followed the approach of Pearce et al. (2010) for biomass sampling in fairly continuous dense shrub communities, with some modifications, and recommendations by Pitt and Schwab (1988), Carswell et al. (2001) and Payton et al. (2004). Each quadrat was physically delimited by four wooden poles or extendable graduated metallic marker poles (in the higher stands), and a linear transect was laid out, (with a tape), following the perimeter and a diagonal of the quadrat. A strip was carefully cleared around the quadrat to allow correct positioning of markers for subsequent measurements. The vegetation growing inside the quadrat was carefully clipped along the lateral boundaries, taking care to exclude portions of plants growing within the quadrat but hanging outside the boundary. The horizontal lengths of the

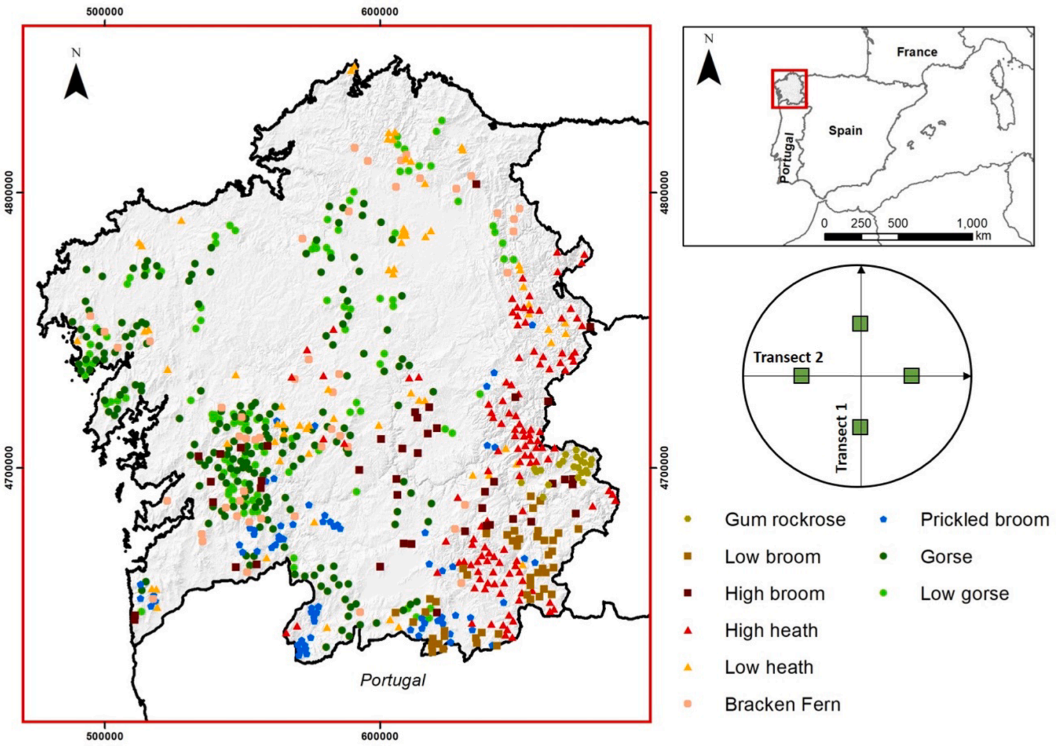

Fig. 1. Geographical location of the 722 inventory plots in Galicia comprising nine shrub communities (left). Coordinate system ETRS89, Zone 29 N (EPGS: 25829). Layout of inventory plot showing transects and location of four destructive sampling subplots (quadrats m, in green) in each inventory plot (middle right). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

intercepted crown of the standing shrub species were measured (cm) along the length of the transect, with a graduated tape (Canfield, 1941; Kent and Coker, 1992; Bonham, 2013), to determine the linear cover by the shrubs in terms of the percentage of the transect length intercepted (maximum 100%). Shrub height was determined as the vertical distance (cm) between the surface of leaf litter and the top of the plant canopy and was measured with a graduated tape every 50 cm, on the transect. All vegetation portions of the standing shrub stratum in the vertical projection of the sampling quadrat area were carefully harvested at ground level and placed in bags, which were labelled appropriately and transported to the laboratory. After removal of standing dominant shrub stratum, the understory stratum, if present, was harvested similarly. A wooden frame (1 m × 1 m) was placed at random inside the quadrat area; the litter depth was measured at ten points along the perimeter and diagonal of the frame, and the litter was then collected. The litter was basically formed by dead fine organic material with coarse debris practically absent. This is usual in these shrubs (Fernandes et al., 2000), in which dense branching in the standing shrub stratum often prevents the detached dead material from reaching the ground, leaving it suspended (Plucinski, 2003). Litter is usually shallow and duff (Oe + Oa horizons) is often lacking. The distinction between litter and duff and even between duff and the surface mineral soil is frequently imprecise in these ecosystems (Wallén, 1980), as in the forest floor of many forest ecosystems (Crosby and Loomis, 1974; Brown et al., 1982, Federer, 1982; Yanai et al., 2003). However, different organic layers can be recognized in senescent gorse stands (Hely and Forgeard, 1998) and wet *E. mackaiana* heathlands. Given the subjectivity in distinguishing litter and duff in most cases and the frequent contamination of duff with mineral soil particles during sampling (Kittredge, 1955; Federer, 1982; Yanai et al., 1999, 2003), both layers (when present) were collected together and classified for the sake of simplicity as *litter*, in this study. This material was bagged and transported to the laboratory.

The shrub and litter biometric measurements made on each one of the four sampling quadrats and frames, respectively, of each circular plot were averaged to obtain a value per inventory plot of shrub cover (Cov_{Shr}); mean shrub height ($\overline{h_{Shr}}$) and mean litter depth ($\overline{d_{Litt}}$).

In the laboratory, the material of the standing shrub stratum was physically separated by size-class into fine fuels (diameter < 0.6 cm, hereafter *G1*), medium fuels (0.6 cm ≤ diameter < 2.5 cm, hereafter *G2*) and coarse fuels (2.5 cm ≤ diameter < 7.5 cm, hereafter *G3*) by using a go-no go gauge (Brown et al., 1982). The material was further subdivided by condition (live and dead), determined by visual inspection. The size categories were selected according to their different surface to volume ratios and, for dead fuels, because they coincide with the size ranges defined by Fosberg et al. (1970), due of the contrasting water absorption and desorption rates (time lags of respectively 1 h, 10 h and 100 h). These three size ranges have also been used to construct custom fuel models for predicting fire behaviour (Burgan and Rothermel, 1984; Finney, 1998; Scott and Burgan, 2005). Once classified, the material was weighted and dried in forced air-drying chambers (105 °C for 24 h for fine fuels and 48 h for coarse fuels) for determination of the dry biomass of each fraction. Litter samples were oven-dried for 48 h to 105° and one oven-dried subsample from each sample was combusted in a muffle furnace at 550 °C for 4 h (Federer, 1982) to determine the loss on ignition to correct for mineral soil contamination and ash. The litter load values in this study thus include the organic mass of the floor (Oi + Oe + Oa horizons) per unit area. The fuel load of each fraction was obtained by dividing the respective dry biomass by the respective sampling area. Thus, seven different loads of the respective biomass fractions were computed. Five were related to the standing shrub stratum: $W_{Shr\_G1\_dead}$ = dead fine shrub load, $W_{Shr\_G1\_live}$ = live fine shrub load, W_{Shr_G1} = fine shrub load (dead + live), W_{Shr_G23} = coarse shrub load and W_{Shr} = total shrub load = $W_{Shr\_G1} + W_{Shr\_G23}$ = AGB at stand level. Fractions G2 and G3 were grouped to avoid loss of data as fraction G3 is infrequent in many of the communities. Given the much higher fuel load in the standing shrub stratum than in the herbaceous understory, the load of the latter (always corresponding to G1) was added to that shrub fraction in all cases. Thus, the term *shrub* actually encompasses all standing

Table 2

Mean values of the standing shrub and litter fuel strata characteristics. Std. dev. = standard deviation, n = number of plots, $\overline{h_{Shr}}$ = shrub height, Cov_{Shr} = shrub cover, $\overline{d_{Litt}}$ = litter depth, $W_{Shr+Litt}$ = shrub and litter fuel load, W_{Shr} = total shrub fuel load, W_{Litt} = litter fuel load, W_{Shr_G23} = coarse shrub fuel load, W_{Shr_G1} = fine shrub fuel load, $W_{Shr\_G1\_dead}$ = dead fine shrub fuel load, $W_{Shr\_G1\_live}$ = live fine shrub fuel load. See definitions in the text.

Variable	Statistic	*Cl*	*Cm*	*Cs*	*Ea*	*Eu*	*Pa*	*Pt*	*Ue*	*Ug*
	n	23	47	44	125	68	49	69	191	106
$\overline{h_{Shr}}$	mean	120.04	114.49	241.70	110.40	51.75	105.24	90.54	115.09	74.99
(cm)	std. dev.	38.33	52.91	157.43	76.30	19.09	31.63	52.13	60.08	27.77
Cov_{Shr}	mean	69.26	85.09	84.59	89.77	92.18	83.49	83.76	84.62	93.38
(%)	std. dev.	14.90	16.29	17.26	17.38	14.46	13.43	17.47	22.74	14.40
$\overline{d_{Litt}}$	mean	1.13	2.26	2.83	2.06	2.36	2.87	1.49	4.02	3.09
(cm)	std. dev.	0.44	1.32	1.66	2.05	1.70	1.16	0.79	2.94	1.80
$W_{Shr+Litt}$	mean	1.45	3.05	6.19	3.31	2.96	1.81	3.01	4.73	3.98
(kg m^{-2})	std. dev.	0.43	1.46	4.00	2.49	1.48	0.68	1.58	2.28	1.52
W_{Shr}	mean	1.11	2.37	5.37	2.47	1.97	1.05	2.49	3.36	2.84
(kg m^{-2})	std. dev.	0.34	1.06	3.60	1.84	0.88	0.52	1.30	1.45	0.89
W_{Litt}	mean	0.34	0.69	0.81	0.84	0.99	0.75	0.51	1.37	1.14
(kg m^{-2})	std. dev.	0.14	0.46	0.55	0.71	0.68	0.29	0.34	1.04	0.79
W_{Shr_G23}	mean	0.29	0.84	3.54	0.99	0.26	0.17	0.63	1.26	0.56
(kg m^{-2})	std. dev.	0.18	0.78	3.18	1.23	0.26	0.14	0.69	1.06	0.54
W_{Shr_G1}	mean	0.82	1.52	1.83	1.48	1.71	0.88	1.86	2.10	2.28
(kg m^{-2})	std. dev.	0.20	0.34	0.61	0.77	0.71	0.40	0.74	0.68	0.65
$W_{Shr\_G1\_dead}$	mean	0.07	0.49	0.48	0.40	0.56	0.43	0.70	0.82	0.77
(kg m^{-2})	std. dev.	0.04	0.36	0.25	0.28	0.33	0.32	0.29	0.37	0.39
$W_{Shr\_G1\_live}$	mean	0.74	1.04	1.36	1.07	1.15	0.45	1.16	1.28	1.51
(kg m^{-2})	std. dev.	0.20	0.28	0.46	0.53	0.44	0.24	0.56	0.43	0.41

Cl = Cistus ladanifer, Cm = Cytisus multiflorus, Cs = Cytisus striatus, Ea = Erica australis, Eu = Erica umbellata, Pa = Pteridium aquilinum, Pt = Pterospartum tridentatum, Ue = Ulex europaeus and *Ug = Ulex gallii*

vegetation. In addition, W_{Litt} = litter load and $W_{Shr+Litt}$ = total (shrub and litter) fuel load were also computed.

The basic descriptive statistics of shrub and litter strata for the main structural characteristics of each shrub community are shown in Table 2.

2.3. Statistical analysis

Equations were developed for estimating the load of each of the seven fractions of the shrub fuel complex for each community. Allometric models ($y = b_0 \cdot X_i^{b_i}$) for estimating fuel loads were tested for all the biomass fractions considering the mean shrub height ($\overline{h_{Shr}}$) and the transformed shrub cover (Cov_{Bliss}) as independent variables to be tested. The latter variable was obtained by arcsine-square root transformation of the shrub cover (Cov_{Shr}) to stabilize the variance and improve normality (Bliss, 1938). Moreover, the mean litter depth ($\overline{d_{Litt}}$) was also considered an independent variable for modelling the litter fuel load because in a preliminary analysis it was the most important independent variable, in terms of reduction of root mean square, when modelling litter fuel load for all shrub communities.

Allometric equations must fulfil the property of additivity, i.e. the sum of biomass predictions from separate fuel fractions must equal the biomass prediction from the total biomass model (e.g. the sum of dead fine and live fine shrub load estimates must equal fine shrub load estimates or the sum of fine and coarse shrub load estimates must equal total shrub load estimates). Therefore, in a first step, the equation of each fuel fraction of each shrub community was fitted separately, and the complete system of seven equations (one for fraction) was then fitted simultaneously for each shrub community to guarantee additivity.

(1) Equation for estimating litter fuel load ($\widehat{W_{Litt}}$)

$$\widehat{W_{Litt}} = a_0 \cdot \overline{h_{Shr}}^{a_1} \cdot Cov_{Bliss}^{a_2} \cdot \overline{d_{Litt}}^{a_3} \tag{1}$$

(2) Equation for estimating shrub fuel load ($\widehat{W_{Shr}}$)

$$\widehat{W_{Shr}} = b_0 \cdot \overline{h_{Shr}}^{b_1} \cdot Cov_{Bliss}^{b_2} \tag{2}$$

Two equations discriminated between fine ($\widehat{W_{Shr\_G1}}$) and coarse fuel loads ($\widehat{W_{Shr\_G23}}$) by disaggregating equation (2):

$$\widehat{W_{Shr\_G23}} = exp\left[c_{0_{g23}} + c_{1_{g23}} log(\overline{h_{Shr}}) + c_{2_{g23}} log(Cov_{Bliss})\right]$$

$$\widehat{W_{Shr\_G1}} = exp\left[c_{0_{g1}} + c_{1_{g1}} log(\overline{h_{Shr}}) + c_{2_{g1}} log(Cov_{Bliss})\right]$$

$$\frac{\widehat{W_{Shr\_G23}}}{\widehat{W_{Shr}}} = \frac{\widehat{W_{Shr\_G23}}}{\left(\widehat{W_{Shr\_G23}} + \widehat{W_{Shr\_G1}}\right)} = \frac{1}{1 + \left(\widehat{W_{Shr\_G1}} / \widehat{W_{Shr\_G23}}\right)}$$

The equation for estimating the coarse fuel loads was then obtained as follows:

$$\widehat{W_{Shr\_G23}} = \frac{\widehat{W_{Shr}}}{1 + exp[c_0 + c_1 log(\overline{h_{Shr}}) + c_2 log(Cov_{Bliss})]} \tag{3}$$

with $c_i = c_{ig1} - c_{ig23}$; and the equation for estimating the fine fuel load was as follows:

$$\widehat{W_{Shr\_G1}} = \widehat{W_{Shr}} - \widehat{W_{Shr\_G23}} = \frac{\widehat{W_{Shr}} \cdot exp[c_0 + c_1 log(\overline{h_{Shr}}) + c_2 log(Cov_{Bliss})]}{1 + exp[c_0 + c_1 log(\overline{h_{Shr}}) + c_2 log(Cov_{Bliss})]} \tag{4}$$

(3) Two equations discriminated between dead fine ($\widehat{W_{Shr\_G1\_dead}}$) and live fine fuel loads ($\widehat{W_{Shr\_G1\_live}}$) loads by disaggregating equation (4):

$$\widehat{W_{Shr\_G1\_dead}} = exp\left[d_{0_{g1\_dead}} + d_{1_{g1\_dead}} log(\overline{h_{Shr}}) + d_{2_{g1\_dead}} log(Cov_{Bliss})\right]$$

$$\widehat{W_{Shr\_G1\_live}} = exp\left[d_{0_{g1\_live}} + d_{1_{g1\_live}} log(\overline{h_{Shr}}) + d_{2_{g1\_live}} log(Cov_{Bliss})\right]$$

$$\frac{\widehat{W_{Shr\_G1\_dead}}}{\widehat{W_{Shr\_G1}}} = \frac{\widehat{W_{Shr\_G1\_dead}}}{\left(\widehat{W_{Shr\_G1\_dead}} + \widehat{W_{Shr\_G1\_live}}\right)} = \frac{1}{1 + \left(\widehat{W_{Shr\_G1\_live}} / \widehat{W_{Shr\_G1\_dead}}\right)}$$

The equation for estimating the fine dead fuel loads was then obtained:

$$\widehat{W_{Shr\_G1\_dead}} = \frac{\widehat{W_{Shr\_G1}}}{1 + exp[d_0 + d_1 \cdot log(\overline{h_{Shr}}) + d_2 \cdot log(Cov_{Bliss})]} \tag{5}$$

Table 3

Parameter estimates and approximate standard errors obtained by simultaneously fitting the system of seven equations (Eqs. (1)–(7)) for each shrub community. W_{Litt} = litter fuel load, W_{Shr} = total shrub fuel load, W_{Shr_G23} = coarse shrub fuel load, W_{Shr_G1} = fine shrub fuel load, $W_{Shr\_G1\_dead}$ = dead fine shrub fuel load, $W_{Shr\_G1\_live}$ = live fine shrub fuel load.

Variable	Parameter	Statistic	*Cl*	*Cm*	*Cs*	*Ea*	*Eu*	*Pa*	*Pt*	*Ue*	*Ug*
W_{Litt}	a_0	Estimate	0.2988	0.0799	0.2180	0.5413	0.3866	0.3685	0.0675	0.4165	0.4012
		Approx. Std. error	0.0112	0.0169	0.0373	0.0125	0.0495	0.0119	0.0116	0.0166	0.0160
	a_1	Estimate	–	0.2955	–	–	–	–	0.3421	–	–
		Approx. Std. error	–	0.0530	–	–	–	–	0.0385	–	–
	a_2	Estimate	–	–	–	–	0.8291	–	–	–	–
		Approx. Std. error	–	–	–	–	0.2584	–	–	–	–
	a_3	Estimate	0.9966	0.9031	1.2047	0.7310	0.8060	0.7172	1.0652	0.8912	0.9521
		Approx. Std. error	0.0897	0.0522	0.1188	0.0153	0.0515	0.0285	0.0425	0.0190	0.0263
W_{Shr}	b_0	Estimate	0.0176	0.0818	0.0372	0.0294	0.0343	0.0010	0.0834	0.1111	0.1639
		Approx. Std. error	0.0074	0.0223	0.0125	0.0031	0.0130	0.0005	0.0103	0.0132	0.0338
	b_1	Estimate	0.8670	0.7009	0.9019	0.9054	1.0245	1.4630	0.7230	0.7087	0.6292
		Approx. Std. error	0.0853	0.0571	0.0580	0.0235	0.0914	0.0964	0.0289	0.0240	0.0486
	b_2	Estimate	0.3568	0.3352	–	0.5545	–	0.3705	0.7533	0.2868	0.4081
		Approx. Std. error	0.1356	0.1075	–	0.0798	–	0.1162	0.0820	0.0484	0.1077
W_{Shr_G23}	c_0	Estimate	6.7665	6.9849	7.7831	8.7639	7.8354	5.0526	8.6549	6.1173	11.4396
W_{Shr_G1}		Approx. Std. error	1.5595	0.9589	0.9210	0.5986	1.4702	1.3247	0.7898	0.3740	1.1045
	c_1	Estimate	−1.1772	−1.3238	−1.4833	−1.6587	−1.4537	−0.7193	−1.5952	−1.1590	−2.2453
		Approx. Std. error	0.3104	0.1882	0.1548	0.1127	0.3437	0.2704	0.1566	0.0738	0.2362
	c_2	Estimate	–	–	–	–	–	–	–	–	–
		Approx. Std. error	–	–	–	–	–	–	–	–	–
$W_{Shr\_G1\_dead}$	d_0	Estimate	–	–	3.1796	2.4096	3.6971	–	0.8831	1.6570	2.2733
$W_{Shr\_G1\_live}$		Approx. Std. error	–	–	0.5518	0.3062	0.6179	–	0.0453	0.3165	0.5907
	d_1	Estimate	–	–	−0.4028	−0.3032	−0.7410	–	−0.0708	−0.2582	−0.3746
		Approx. Std. error	–	–	0.0993	0.0610	0.1488	–	0.0097	0.0657	0.1348
	d_2	Estimate	–	–	–	–	–	–	–	–	–
		Approx. Std. error	–	–	–	–	–	–	–	–	–

Cl = *Cistus ladanifer*, *Cm* = *Cytisus multiflorus*, *Cs* = *Cytisus striatus*, *Ea* = *Erica australis*, *Eu* = *Erica umbellata*, *Pa* = *Pteridium aquilinum*, *Pt* = *Pterospartum tridentatum*, *Ue* = *Ulex europaeus* and *Ug* = *Ulex gallii*.

with $d_i = d_{ig1\_live}$ - d_{ig1_dead}; and the following equation was fitted to estimate the live fine fuel load:

$$\widehat{W_{Shr\_G1\_live}} = \widehat{W_{Shr\_G1}} - \widehat{W_{Shr\_G1\_dead}} =$$

$$= \frac{\widehat{W_{Shr\_G1}} \cdot exp\left[d_0 + d_1 log\left(\overline{h_{Shr}}\right) + d_2 log\left(Cov_{Bliss}\right)\right]}{1 + exp\left[d_0 + d_1 log\left(\overline{h_{Shr}}\right) + d_2 log\left(Cov_{Bliss}\right)\right]} \quad (6)$$

(4) Finally the equation for estimating the total shrub and litter fuel load ($\widehat{W_{Shr+Litt}}$) was obtained by aggregating equations (1) and (2):

$$\widehat{W_{Shr+Litt}} = a_0 \cdot \overline{h_{Shr}}^{a_1} \cdot Cov_{Bliss}^{a_2} \cdot \overline{d_{Litt}}^{a_3} + b_0 \cdot \overline{h_{Shr}}^{b_1} \cdot Cov_{Bliss}^{b_2} \quad (7)$$

Due to the special biology of *P. aquilinum* and its wide structural and physiological variability throughout the year, the fine fuel load was not disaggregated in this shrub community. The allometric equations for fern should be applied for upstanding plants only.

In addition to the systems fitted for the 9 shrub communities, other systems with the same structure (Eqs. (1)–(7)) were fitted to the pooled data of all the shrub communities, excluding the fern-dominated community, and for three different groups of shrub communities with similar structural characteristics or frequent association: i) brooms (*Cm* + *Cs* = *Cytisus multiflorus* and *Cytisus striatus*), ii) gorses (*Ue* + *Ug* = *Ulex europaeus* and *U. gallii*) and iii) low heath and prickled broom (*Eu* + *Pt* = *Erica umbellata* and *Pterospartum tridentatum*). The first two groups are included in the classification of shrub communities used in the Spanish Forest Map SFM25 (MARM, 2011b) within the shrub formations 230 and 240, respectively, based on their similar physiognomic features. The group of low heath and prickled broom includes dominant species of different genus (*Eu* and *Pt*), which usually form part of the *Pterosparto lasianthi-Ericetum cinereae* phytosociological association (Rivas-Martínez et al., 2002), within the *Ericenion umbellatae* suballiance (Rivas-Martínez, 1979) and frequently dominated by *P. tridentatum* and *E. umbellata* (Fernandes and Rego, 1998a). The *Ea* community was not included in this third group because of its very different fuel structural characteristics (shrub height, bulk density and fuel load), regardless of the existing *Pterosparto lasianthi-Ericetum aragonensis* phytosociological association (Rivas-Martínez et al., 2002), included in the *Ericenion aragonensis* suballiance (Rivas-Martínez, 1979) and frequently dominated by *E. australis* in the area.

Moreover, to explore the predictive potential of $\overline{h_{Shr}}$ and to provide more operational tools to assess shrub AGB and fuel load, simplifying where appropriate the collection of biometric data at stand level or to use with remote sensing data, the system of seven equations was refitted to each of the nine communities and each of the four groups of communities with $\overline{h_{Shr}}$ as the only independent variable.

To evaluate the presence of multicollinearity among variables in the equations fitted, the condition number was used. According to Myers (1990) condition numbers higher than $\sqrt{1000}$ indicate problems associated with multicollinearity. The presence of heteroscedasticity was analysed by the White test (White, 1980) and by visual inspection of studentized residuals plotted against fitted values. When heteroscedasticity was detected, each observation was weighted by the inverse of its estimated variance ($\widehat{\sigma}_i^2$), assuming that this variance can be modelled as a power function of the independent variables (Cailliez, 1980), i.e. $\widehat{\sigma}_i^2 = (X_i)^k$. The value of the exponential term k was optimized to provide the most homogeneous studentized residual plot by using the method proposed by Harvey (1976).

The systems were fitted using the nonlinear seemingly unrelated regression (NLSUR) method, which considers the cross-equation correlations, using the cross-equation error covariance matrix obtained by ordinary least squares to initiate the iterative procedure. The weighting factor for heteroscedasticity, when necessary, was programmed in the MODEL procedure of SAS/ETS® (SAS Institute Inc., 2004).

Two goodness-of fit statistics were used to check the accuracy of estimates: model efficiency (*ME*) (Vanclay and Skovsgaard, 1997) and root mean square error (*RMSE*).

Table 4

Goodness-of fit statistics and weights used to correct heteroscedasticity for fuel load estimates in each fuel fraction and shrub community. $W_{Shr+Litt}$ = shrub and litter load, W_{Shr} = AGB = total shrub load, W_{Litt} = litter load, W_{Shr_G23} = coarse shrub load, W_{Shr_G1} = fine shrub load, $W_{Shr\_G1\_dead}$ = dead fine shrub load and $W_{Shr\_G1\_live}$ = live fine shrub load.

Equation	Statistic	*Cl*	*Cm*	*Cs*	*Ea*	*Eu*	*Pa*	*Pt*	*Ue*	*Ug*
$W_{Shr+Litt}$	RMSE (kg m^{-2})	0.1449	0.5102	1.9637	0.7381	0.5560	0.2109	0.5227	0.7331	0.6872
	ME	0.8921	0.8806	0.7642	0.9131	0.8601	0.9044	0.8924	0.8969	0.7980
	Bias (kg m^{-2})	0.0042	−0.0296	0.0238	0.0282	0.0003	−0.0140	0.0108	−0.0486	−0.0182
	weight	–	–	–	$(\overline{h_{Shr}}\cdot Cov_{Bliss})^{-1.32}$	–	–	$(\overline{h_{Shr}}\cdot Cov_{Bliss})^{-0.95}$	–	–
W_{Shr}	RMSE (kg m^{-2})	0.1412	0.4788	1.8950	0.6691	0.4961	0.1803	0.4992	0.5909	0.5019
	ME	0.8327	0.8001	0.7286	0.8693	0.6870	0.8801	0.8552	0.8345	0.6879
	Bias (kg m^{-2})	0.0049	−0.0252	0.0226	0.0076	0.0052	−0.0036	−0.0032	−0.0145	0.0062
	weight	–	–	–	$(\overline{h_{Shr}}\cdot Cov_{Bliss})^{-1.32}$	–	–	$(\overline{h_{Shr}}\cdot Cov_{Bliss})^{-0.95}$	–	–
W_{Litt}	RMSE (kg m^{-2})	0.0437	0.1044	0.2142	0.2054	0.2417	0.1338	0.1254	0.4049	0.3829
	ME	0.9045	0.9298	0.8019	0.9153	0.8617	0.7066	0.8683	0.8458	0.7679
	Bias (kg m^{-2})	−0.0007	−0.0052	0.0137	0.0215	−0.0053	−0.0108	0.0104	−0.0352	−0.0244
	weight	–	$(\overline{h_{Shr}}\cdot\overline{d_{Litt}})^{-1.05}$	–	–	–	$(\overline{d_{Litt}})^{-1.01}$	$(\overline{d_{Litt}})^{-1.05}$	$(\overline{d_{Litt}})^{-0.65}$	$(\overline{d_{Litt}})^{-1.05}$
W_{Shr_G23}	RMSE (kg m^{-2})	0.1068	0.3968	1.7408	0.4552	0.1735	0.0792	0.2625	0.4616	0.3240
	ME	0.6553	0.7463	0.7006	0.8632	0.5467	0.7019	0.8584	0.8117	0.6314
	Bias (kg m^{-2})	0.0072	−0.0250	0.0229	0.0032	0.0047	0.0010	0.0096	−0.0036	0.0062
W_{Shr_G1}	RMSE (kg m^{-2})	0.0988	0.1920	0.4056	0.3901	0.4479	0.1503	0.4104	0.4798	0.4873
	ME	0.7612	0.6936	0.5705	0.7425	0.6055	0.8610	0.6958	0.5033	0.4342
	Bias (kg m^{-2})	−0.0023	−0.0002	0.0018	−0.0024	0.0005	0.0007	−0.0013	−0.0108	−0.0031
$W_{Shr\_G1\_dead}$	RMSE (kg m^{-2})	–	–	0.1237	0.1504	0.1957	–	0.2120	0.2914	0.3256
	ME	–	–	0.7601	0.7102	0.6594	–	0.4605	0.3948	0.3060
	Bias (kg m^{-2})	–	–	−0.0012	−0.0010	0.0008	–	0.0017	−0.0059	−0.0018
$W_{Shr\_G1\_live}$	RMSE (kg m^{-2})	–	–	0.3943	0.3200	0.3391	–	0.3728	0.3443	0.3566
	ME	–	–	0.2704	0.6421	0.4170	–	0.5596	0.3543	0.2626
	Bias (kg m^{-2})	–	–	0.0030	−0.0014	−0.0003	–	−0.0030	−0.0049	−0.0014

Cl = *Cistus ladanifer, Cm* = *Cytisus multiflorus, Cs* = *Cytisus striatus, Ea* = *Erica australis, Eu* = *Erica umbellata, Pa* = *Pteridium aquilinum, Pt* = *Pterospartum tridentatum, Ue* = *Ulex europaeus* and *Ug* = *Ulex gallii*

Table 5

Parameter estimates and approximate standard errors obtained by simultaneously fitting the system of seven equations (Eqs. (1)–(7)) for each fuel fraction and group of shrub communities. W_{Litt} = litter fuel load, W_{Shr} = total shrub fuel load, W_{Shr_G23} = coarse shrub fuel load, W_{Shr_G1} = fine shrub fuel load, $W_{Shr\_G1\_dead}$ = dead fine shrub fuel load, $W_{Shr\_G1\_live}$ = live fine shrub fuel load.

Variable	Par.	Statistic	*Cm* + *Cs*	*Eu* + *Pt*	*Ue* + *Ug*	*All-Pa*
W_{Litt}	a_0	Estimate	0.2299	0.4099	0.3921	0.4140
		Approx. Std. error	0.0073	0.0123	0.0125	0.0092
	a_1	Estimate	–	–	–	–
		Approx. Std. error	–	–	–	–
	a_2	Estimate	–	–	–	–
		Approx. Std. error	–	–	–	–
	a_3	Estimate	1.2295	0.9335	0.9445	0.8752
		Approx. Std. error	0.0257	0.0215	0.0186	0.0172
W_{Shr}	b_0	Estimate	0.0379	0.0913	0.1276	0.0582
		Approx. Std. error	0.0048	0.0133	0.0072	0.0021
	b_1	Estimate	0.8966	0.7155	0.6688	0.7962
		Approx. Std. error	0.0236	0.0314	0.0118	0.0080
	b_2	Estimate	–	0.6275	0.4775	0.5536
		Approx. Std. error	–	0.1049	0.0301	0.0256
W_{Shr_G23} W_{Shr_G1}	c_0	Estimate	6.7573	7.9918	7.3568	8.2607
		Approx. Std. error	0.2976	0.4989	0.3194	0.1998
	c_1	Estimate	−1.3047	−1.4643	−1.3979	−1.5653
		Approx. Std. error	0.0529	0.1015	0.0642	0.0380
	c_2	Estimate	–	–	–	–
		Approx. Std. error	–	–	–	–
$W_{Shr\_G1\_dead}$ $W_{Shr\_G1\_live}$	d_0	Estimate	–	1.3662	2.2010	1.5991
		Approx. Std. error	–	0.3006	0.2733	0.1806
	d_1	Estimate	–	−0.1755	−0.3662	−0.1990
		Approx. Std. error	–	0.0674	0.0585	0.0376
	d_2	Estimate	–	–	–	–
		Approx. Std. error	–	–	–	–

Brooms (*Cm* + *Cs* = *Cytisus multiflorus* and *Cytisus striatus*), low heather and prickled broom (*Eu* + *Pt* = *Erica umbellata* and *Pterospartum tridentatum*), gorses (*Ue* + *Ug* = *Ulex europaeus* and *U. gallii*) and the pooled data for all shrub communities excluding the fern-dominated community (*All-Pa*).

$$ME = 1 - \frac{\sum_{i=1}^{n}(Y_i - \widehat{Y}_i)^2}{\sum_{i=1}^{n}(Y_i - \overline{Y})^2} \qquad (8)$$

$$RMSE = \sqrt{\frac{\sum\limits_{i=1}^{n}(Y_i - \widehat{Y}_i)^2}{n-1}} \qquad (9)$$

Table 6

Goodness-of fit statistics and weights used to correct heteroscedasticity in fuel load estimates for each fuel fraction and group of shrub communities. $W_{Shr+Litt}$ = shrub and litter load, W_{Shr} = AGB = total shrub load, W_{Litt} = litter fuel load, W_{Shr_G23} = coarse shrub load, W_{Shr_G1} = fine shrub load, $W_{Shr\_G1\_dead}$ = dead fine shrub load and $W_{Shr\_G1\_live}$ = live fine shrub load.

Equation	Statistic	*Cm* + *Cs*	*Eu* + *Pt*	*Ue* + *Ug*	*All-Pa*
$W_{Shr+Litt}$	RMSE (kg m^{-2})	1.4225	0.5729	0.7308	0.9877
	ME	0.8226	0.8609	0.8759	0.8290
	Bias (kg m^{-2})	−0.0009	0.0184	0.0026	0.0159
	weight	$(\overline{h_{Shr}})^{-1.21}$	–	$(\overline{h_{Shr}}\cdot Cov_{Bliss})^{-0.35}$	$(\overline{h_{Shr}}\cdot Cov_{Bliss})^{-0.96}$
W_{Shr}	RMSE (kg m^{-2})	1.3844	0.5092	0.5824	0.8924
	ME	0.7915	0.8033	0.8009	0.7562
	Bias (kg m^{-2})	0.0060	0.0109	0.0437	0.0146
	weight	$(\overline{h_{Shr}})^{-1.21}$	–	$(\overline{h_{Shr}}\cdot Cov_{Bliss})^{-0.35}$	$(\overline{h_{Shr}}\cdot Cov_{Bliss})^{-0.96}$
W_{Litt}	RMSE (kg m^{-2})	0.1825	0.2355	0.3994	0.3283
	ME	0.8288	0.8363	0.8267	0.8401
	Bias (kg m^{-2})	−0.0171	0.0078	−0.0420	0.0537
	weight	$(\overline{d_{Litt}})^{-2.12}$	$(\overline{d_{Litt}})^{-0.96}$	$(\overline{d_{Litt}})^{-0.85}$	$(\overline{d_{Litt}})^{-0.98}$
W_{Shr_G23}	RMSE (kg m^{-2})	1.2231	0.2268	0.4356	0.6085
	ME	0.7963	0.8345	0.7991	0.8126
	Bias (kg m^{-2})	0.0128	0.0140	0.0140	0.0129
W_{Shr_G1}	RMSE (kg m^{-2})	0.3310	0.4367	0.5073	0.5604
	ME	0.5928	0.6425	0.4336	0.4451
	Bias (kg m^{-2})	−0.0024	−0.0031	0.0297	0.0093
$W_{Shr\_G1\_dead}$	RMSE (kg m^{-2})	–	0.2137	0.3053	0.3182
	ME	–	0.5517	0.3565	0.3248
	Bias (kg m^{-2})	–	0.0016	0.0098	0.0073
$W_{Shr\_G1\_live}$	RMSE (kg m^{-2})	–	0.3628	0.3705	0.3948
	ME	–	0.4838	0.2845	0.3345
	Bias (kg m^{-2})	–	−0.0046	0.0199	0.0089

Brooms (*Cm* + *Cs* = *Cytisus multiflorus* and *Cytisus striatus*), low heather and prickled broom (*Eu* + *Pt* = *Erica umbellata* and *Pterospartum tridentatum*), gorses (*Ue* + *Ug* = *Ulex europaeus* and *U. gallii*) and the pooled data for all shrub communities excluding the fern-dominated community (*All-Pa*).

where Y_i, $\hat{Y}_i$ and $\overline{Y}$ are the observed, predicted and mean values of the dependent variable and n is the number of observations used to fit the equation.

3. Results

3.1. Fuel load equations for shrub community with no restrictions on independent variables

The values of the parameter estimates and the asymptotic standard errors of the system of seven equations fitted to each of the nine shrub communities are shown in Table 3. As previously commented, equations for estimating $W_{Shr\_G1\_dead}$ and $W_{Shr\_G1\_live}$ for *Pa* were not fitted. Moreover, for *Cl* and *Cm* it was not possible to disaggregate the estimates of these two fractions ($W_{Shr\_G1\_dead}$ and $W_{Shr\_G1\_live}$) due to problems associated with convergence of the complete system.

The goodness-of-fit statistics of the equations and the weighting factors used to prevent heteroscedasticity are shown in Table 4. The results of the White test indicated moderate problems of heteroscedasticity only for three fractions in some shrub communities: total shrub and litter fuel load ($W_{Shr+Litt}$), total shrub load (W_{Shr} = AGB) and especially litter load (W_{Litt}). The values of the condition number did not indicate problems of multicollinearity for any fuel fraction of any shrub community.

According to the partial values of ME, the mean shrub height ($\overline{h_{Shr}}$) was the most important independent variable for all the shrub-layer fuel fractions of the nine communities studied and was the only significant variable for $W_{Shr\_G1\_dead}$ and $W_{Shr\_G1\_live}$ equations for all the communities where these fractions were disaggregated. The litter depth ($\overline{d_{Litt}}$) was the most important independent variable for estimating the fuel load of the litter layer (W_{Litt}), in terms of partial values of ME and, except for *Cm* and *Pt*, for which $\overline{h_{Shr}}$ was also included in the equation, and *Eu*, for which Cov_{Bliss} was also significant, $\overline{d_{Litt}}$ was the only significant variable ($p < 0.05$) for estimating this fraction.

The values and signs of all the parameters were biologically consistent, and graphical inspection of the studentized residuals showed random patterns of residuals around zero with homogeneous variance and no discernible trends. Plots of observed versus predicted values of AGB (W_{Shr}) and W_{Litt} are shown in Figure SM1 in Supplementary Material.

Overall, the best results were obtained for *Ea* and *Pt* communities and the poorest results for *Ug* and *Cs* communities. The best goodness-of-fit statistics were obtained for the equations fitted to estimate $W_{Shr+Litt}$ and W_{Litt}, with ME values ranging from 0.7642 to 0.9131 for the first fuel load and from 0.7066 to 0.9298 for the second. The equations used to estimate AGB (W_{Shr}) explained between 68.70 and 88.01% of the observed variance; the percentage of observed variance explained by the equations used to estimate W_{Shr_G1} and W_{Shr_G23} ranged from 43.42 to 86.10% for the fine fuel fraction and from 54.67 to 85.84% for the coarse fuel fraction. Finally, the worst results, in terms of goodness-of-fit statistics, were obtained for the equations used to disaggregate the fine fraction, especially for $W_{Shr\_G1\_live}$, with ME values ranging from 0.2626 for *Ug* to 0.6421 for *Ea*.

3.2. Fuel load equations for groups of communities and pooled data with no restrictions on independent variables

As previously commented, some communities were combined and four groups were considered: (i) brooms (*Cm* + *Cs*), (ii) gorses (*Ue* + *Ug*), (iii) low heath and prickled broom (*Eu* + *Pt*) and iv) pooled data for all shrub communities excluding the fern-dominated community (*All-Pa*). The values of the parameter estimate and the asymptotic standard errors of the system of seven equations fitted to each of these four groups are shown in Table 5 and the goodness-of-fit statistics and the weighting factors used to prevent heteroscedasticity are shown in Table 6.

The results obtained were similar to those corresponding to the nine shrub communities, i.e. moderate heteroscedasticity was only observed for $W_{Shr+Litt}$, W_{Shr} and W_{Litt}; no multicollinearity was detected for any equation; taking into account the partial values of ME, $\overline{h_{Shr}}$ was the most important independent variable for all the shrub fuel fractions of the four groups and was the only significant variable for $W_{Shr\_G1\_dead}$ and

Table 7
Increase in RMSE (%) produced by using the equations fitted for each fuel fraction load of four groups of communities relative to the equations fitted for each community independently, in both cases without restriction on independent variables. $W_{Shr+Litt}$ = shrub and litter, W_{Shr} = AGB = total shrub, W_{Litt} = litter, W_{Shr_G23} = coarse shrub, W_{Shr_G1} = fine shrub, $W_{Shr\_G1\_dead}$ = dead fine shrub and $W_{Shr\_G1\_live}$ = live fine shrub. ≈ indicates values < 2%.

	Increase in RMSE (%)			
	Cm + Cs	***Eu + Pt***	***Ue + Ug***	***All-Pa***
$W_{Shr+Litt}$	≈	6.59	2.08	22.51
W_{Shr}	2.26	2.70	4.02	24.16
W_{Litt}	9.92	24.45	≈	9.85
W_{Shr_G23}	≈	2.16	4.42	7.94
W_{Shr_G1}	6.04	2.07	5.32	31.84
$W_{Shr\_G1\_dead}$	–	5.10	≈	36.10
$W_{Shr\_G1\_live}$	–	2.15	6.42	20.27

Brooms (*Cm* + *Cs* = *Cytisus multiflorus* and *Cytisus striatus*), low heather and prickled broom (*Eu* + *Pt* = *Erica umbellata* and *Pterospartum tridentatum*), gorses (*Ue* + *Ug* = *Ulex europaeus* and *U. gallii*) and the pooled data for all shrub communities excluding the fern-dominated community (*All-Pa*).

$W_{Shr\_G1\_live}$ equations for all the groups for which these fractions were disaggregated, whereas $\overline{d_{Litt}}$ was the only significant independent variable for estimating W_{Litt} for all the groups.

As found for the nine communities, the values and signs of all the parameters were biologically consistent and a homogeneous variance distribution of studentized residuals without visual trends was observed for all the equations. Plots of observed versus predicted values of W_{Shr} and W_{Litt} are shown in Figure SM2 in Supplementary material.

The *Eu* + *Pt* group yielded the best overall results from the four groups analysed. Nonetheless, for all four groups very accurate estimates were obtained for all the fractions (ME ranging from 0.7562 to 0.8759), except for fine fuels and its disaggregated fractions (W_{Shr_G1}, $W_{Shr\_G1\_dead}$ and $W_{Shr\_G1\_live}$), with percentages of observed variance explained ranging from 28.45 to 64.25%. Table 7 shows the percentage increase in RMSE, i.e., reduction in accuracy, resulting from using the equations fitted for each of the four groups relative to the equations fitted for each community independently. The reduction in the accuracy of estimates is particularly remarkable in the *All-Pa* group and in the W_{Litt} equations for *Cm* + *Cs* and *Eu* + *Pt* groups.

3.3. *Fuel load equations for each community with $\overline{h_{Shr}}$ as the only independent variable*

The system of seven equations was refitted to each of the nine communities and each of the four groups of communities with $\overline{h_{Shr}}$ as the only independent variable used to estimate shrub fuel loading at stand level. The goal was to explore the predictive potential of $\overline{h_{Shr}}$ and to provide additional operational tools for assessing shrub AGB and fuel load by simplifying, where appropriate, the collection of biometric data at stand level or by using remote sensing data.

The parameter estimates and their associated asymptotic standard errors and the goodness-of-fit statistics are shown in Appendix 1 (Tables A1 and A2 for the nine communities and in Tables A3 and A4 for the four groups considered, respectively). All comments about the structure and distribution of the residuals of the previously fitted systems of equations are also valid for the systems refitted using only $\overline{h_{Shr}}$ as the independent variable.

Regarding the nine communities, overall, the most accurate estimates were obtained for *Ea* (ME ranging from 0.5860 for $W_{Shr\_G1\_live}$ to 0.8875 for $W_{Shr+Litt}$) and the worst results were obtained for *Ug* (ME ranging from 0.1604 for W_{Litt} to 0.6430 for W_{Shr}). As expected, the litter layer (W_{Litt}) was the fraction for which the accuracy of estimates, in terms of percentage increase in RMSE, was relatively more affected than estimates based on equations also including shrub cover or litter depth, with increases in RMSE (%) ranging from 53.07% for *Ea* to 147.14% for *Cl* (Table 8). For all the communities except *Cs*, the equation $W_{Shr+Litt}$ was also greatly affected, with increases in RMSE ranging from 13.68% for *Ea* to 63.29% for *Ug* (Table 8).

3.4. *Fuel load equations for groups of communities and pooled data with $\overline{h_{Shr}}$ as the only independent variable*

For the four groups of communities, overall, the most accurate estimates were obtained for *Cm* + *Cs* (ME ranging from 0.5900 for W_{Shr_G1} to 0.8155 for $W_{Shr+Litt}$) and the poorest results were obtained for *All-Pa* (ME ranging from 0.2346 for W_{Litt} to 0.8133 for W_{Shr_G23}).

Comparison of the RMSE values of the systems fitted using $\overline{h_{Shr}}$ as the

Table 9
Increase in RMSE (%) produced by using the equations fitted for each fuel fraction load of the four groups of communities with $\overline{h_{Shr}}$ as the only independent variable, relative to the equations fitted for the four groups of communities with no restrictions on independent variables. $W_{Shr+Litt}$ = shrub and litter, W_{Shr} = AGB = total shrub, W_{Litt} = litter, W_{Shr_G23} = coarse shrub, W_{Shr_G1} = fine shrub, $W_{Shr\_G1\_dead}$ = dead fine shrub and $W_{Shr\_G1\_live}$ = live fine shrub. ≈ indicates values < 2%.

Equation	*Cm* + *Cs*	*Eu* + *Pt*	*Ue* + *Ug*	*All-Pa*
$W_{Shr+Litt}$	2.28	75.79	56.84	42.09
W_{Shr}	≈	12.59	7.59	5.76
W_{Litt}	90.68	138.94	95.42	126.17
W_{Shr_G23}	≈	4.67	≈	≈
W_{Shr_G1}	≈	11.40	11.93	9.35
$W_{Shr\_G1\_dead}$	–	3.79	4.72	5.03
$W_{Shr\_G1\_live}$	–	9.37	9.39	7.09

Brooms (*Cm* + *Cs* = *Cytisus multiflorus* and *Cytisus striatus*), low heather and prickled broom (*Eu* + *Pt* = *Erica umbellata* and *Pterospartum tridentatum*), gorses (*Ue* + *Ug* = *Ulex europaeus* and *U. gallii*) and the pooled data for all shrub communities excluding the fern-dominated community (*All-Pa*).

Table 8
Increase in RMSE (%) produced by using the equations fitted for each fuel fraction load and community with $\overline{h_{Shr}}$ as the only independent variable, relative to the equations fitted with no restrictions on independent variables. $W_{Shr+Litt}$ = shrub and litter, W_{Shr} = AGB = total shrub, W_{Litt} = litter, W_{Shr_G23} = coarse shrub, W_{Shr_G1} = fine shrub, $W_{Shr\_G1\_dead}$ = dead fine shrub and $W_{Shr\_G1\_live}$ = live fine shrub. ≈ indicates values < 2%.

	Increase in RMSE (%)								
	Cl	***Cm***	***Cs***	***Ea***	***Eu***	***Pa***	***Pt***	***Ue***	***Ug***
$W_{Shr+Litt}$	32.78	19.76	≈	13.91	48.90	33.48	35.60	55.18	61.03
W_{Shr}	10.91	9.52	≈	3.29	≈	8.26	8.65	8.56	6.50
W_{Litt}	147.14	111.21	78.43	53.07	99.13	61.96	102.55	100.00	89.45
W_{Shr_G23}	3.28	5.85	≈	≈	≈	≈	3.50	≈	2.84
W_{Shr_G1}	13.56	10.36	≈	4.31	≈	12.51	11.57	9.15	7.00
$W_{Shr\_G1\_dead}$			≈	1.80	≈			4.60	2.70
$W_{Shr\_G1\_live}$			≈	7.91	≈			6.51	5.36

Cl = *Cistus ladanifer*, *Cm* = *Cytisus multiflorus*, *Cs* = *Cytisus striatus*, *Ea* = *Erica australis*, *Eu* = *Erica umbellata*, *Pa* = *Pteridium aquilinum*, *Pt* = *Pterospartum tridentatum*, *Ue* = *Ulex europaeus* and *Ug* = *Ulex gallii*.

Table 10
Increase in RMSE (%) produced by using the equations fitted for each fuel fraction load of four groups of communities relative to the equations fitted for each community independently, in both cases with $\overline{h_{Shr}}$ as the only independent variable. $W_{Shr+Litt}$ = shrub and litter, W_{Shr} = AGB = total shrub, W_{Litt} = litter, W_{Shr_G23} = coarse shrub, W_{Shr_G1} = fine shrub, $W_{Shr\_G1\_dead}$ = dead fine shrub and $W_{Shr\_G1\_live}$ = live fine shrub. ≈ indicates values < 2%.

	Increase in RMSE (%)			
	Cm + Cs	***Eu + Pt***	***Ue + Ug***	***All-Pa***
$W_{Shr+Litt}$	≈	31.24	≈	34.49
W_{Shr}	2.39	10.91	3.65	27.48
W_{Litt}	13.01	48.74	≈	28.71
W_{Shr_G23}	≈	4.40	≈	7.65
W_{Shr_G1}	4.44	7.86	8.77	35.09
$W_{Shr\_G1\_dead}$	–	–	≈	–
$W_{Shr\_G1\_live}$	–	–	9.75	–

Brooms (*Cm* + *Cs* = *Cytisus multiflorus* and *Cytisus striatus*), low heather and prickled broom (*Eu* + *Pt* = *Erica umbellata* and *Pterospartum tridentatum*), gorses (*Ue* + *Ug* = *Ulex europaeus* and *U. gallii*) and the pooled data for all shrub communities excluding the fern-dominated community (*All-Pa*).

only independent variable for the four groups of communities with those obtained for the four groups of communities without restriction on independent variables (Table 9), showed that the litter layer (W_{Litt}) was again the fraction most affected, with increments ranging from 90.68% for *Cm* + *Cs* to 138.84% for *Eu* + *Pt*. For all the groups except *Cm* + *Cs*, the $W_{Shr+Litt}$ equation was also strongly affected, with increases in RMSE (%) ranging from 42.03% for *All-Pa* to 75.48% for *Eu* + *Pt*.

Finally, the reduction in accuracy of estimates produced by using the equations fitted for the four groups instead of the equations of each community separately when $\overline{h_{Shr}}$ was the only independent variable is shown in Table 10. The reduction in the accuracy of estimates was again particularly remarkable in the *All-Pa* group and in the W_{Litt} equations for *Cm* + *Cs* and *Eu* + *Pt* groups.

4. Discussion

4.1. Models of W_{Shr} and W_{Shr_G1} for each shrub community

The variability in W_{Shr} explained by the equations developed in this study for the individual shrub communities at stand level using $\overline{h_{Shr}}$, Cov_{Shr} and $\overline{d_{Litt}}$ as independent variables (68.7% to 88.1%) was within the range of the values usually reported in previous studies modelling W_{Shr} by using stand variables as predictors. This was the case for similar communities in the same biogeographic region (Fernandes and Rego, 1998a; Fernandes, 2001; Seijas et al., 2009; Viana et al., 2009, 2013), for Mediterranean shrublands (Pasalodos-Tato et al., 2015), moorland (Davies et al., 2008; Egan et al., 2000;) and for shrubs dominated by gorse in New Zealand (Fogarty and Pearce, 2000; Pearce et al., 2010). Furthermore, the values of relative RMSE were comparable to the previous studies.

Fine fuel is an abundant component of the standing shrub stratum in all communities analysed, with an important role in the active flaming phase of fire (Burrows and McCaw, 1990; Fernandes et al., 2002; Fraser et al., 2016; Rothermel, 1972). The accuracy of estimating fine fuel loads is therefore valuable for wildland fire management. In general, the goodness of fit of our models was in line with, or was slightly higher than, most of the scarce similar studies modelling this fuel component at stand level (Davies et al., 2008; Fogarty and Pearce, 2000; Sağlam et al., 2008; Seijas et al., 2009; Pearce et al., 2010; Westcott et al., 2014). Furthermore, the slight poorer performance for W_{Shr_G1} models than for W_{Shr} models is consistent with the results from the aforementioned few studies modelling these fuel fractions. For instance, the relatively lower performance in modelling of W_{Shr_G1} for *Ulex sp.*, compared to communities dominated by other woody species, agrees with the findings of Pasalodos-Tato et al. (2015), Fogarty and Pearce (2000) and Pearce et al. (2010). Most studies developing species-specific equations for biomass estimation have also reported a lower predictive ability for the fine fuel fraction than for W_{Shr} (Champlin, 1982; Duguy et al., 2015; Huff et al., 2017; Krivtsov et al, 2009; Roussopoulos and Loomis, 1979; Sah et al., 2004) although other studies did not observe this effect (Hierro et al., 2000; McGinnis et al., 2010). The reason for the generally greater instability in predicting fine fuel biomass is not clear, but a rapid response in that fraction of plants to change in environmental conditions (Reiner et al., 2010; Rittenhouse and Sneva, 1977) and size and age-associated changes (e.g., Countryman, 1982; Dalgleish et al., 2015; Hierro et al., 2000; Roussopoulos and Loomis, 1979) may be a contributing factor. Intraspecific variability in biomass allocation to stems, leaves and roots is known to respond to environmental factors, once plant size (and age) is accounted for (McCarthy and Enquist, 2007). A stand basis approach could increase those differences, due to the multi-species composition of communities and probably more varied specific responses in biomass allocation patterns with plant size (Brown, 1976), environmental factors (Plucinski et al., 2009; Poorter et al., 2012; Sanaei et al., 2018) and competition (Poorter et al., 2015).

Overall, our focus on shrub communities, with the associated mixing of species, may have led to increased variability in fine fuels, translated into a comparatively higher relative RMSE in the equations predicting fuel loading at stand level than usually obtained of fine fuel biomass from the species-specific equations (e.g., De Cáceres et al., 2019; Hierro et al., 2000; Huff et al., 2017, 2018; Murray and Jacobson, 1982). Even if these values are not strictly comparable, improved performance of individual plant biomass equations for estimating species biomass does not necessary indicate better estimation of fuel load at stand level (Návar et al., 2002b), and the species-specific approach entails other issues, as previously commented. Compliance of the additivity condition and simultaneous fitting could also comparatively reduce the explained variability of fine fuels, relative to that of an equation intended only to estimate the load of a particular fuel fraction (Návar et al. 2002a), although at the cost of other limitations.

Most shrub community-level existing models in mesic climates consider shrub stand height, alone or together with shrub cover, as the main independent variable (e.g., Easdale et al., 2015; Fernandes and Rego, 1998b; Fogarty and Pearce, 2000; Pasalodos-Tato et al., 2015; Pearce et al., 2010; Ruiz-Peinado et al., 2013; Sağlam et al., 2008; Sanaei et al., 2018). This contrasts with arid sites where vegetation cover is usually the main predictive variable for individual or stand biomass (e.g., Flombaum and Sala, 2007; Sanaei et al., 2018; Zhang et al., 2016), although also is included in other very different ecosystems (e.g. Viana et al., 2009). Some stand level models in multi-specific communities have combined height with stand basal area (Seijas et al. 2009) with similar or slightly higher explained variability, although they are much more labour intensive (Chojnacky and Milton, 2008). Several studies have used only age or age plus shrub height and cover to estimate stand fuel loading (e.g., Marsden-Smedley and Catchpole, 1995; Pimont et al. 2018; (Viana et al., 2009, 2013; Westcott et al., 2014). Although age is very useful when analysing the trends in fuel variables and loads over time, in our study it was not considered a potential independent variable because its inclusion would have reduced the practicality of the models, as it the date of the last perturbation is often not know and determining the age of shrubs on a large scale is not practically feasible.

4.2. Dead and live fractions of standing shrub fine load

Disaggregation of the W_{Shr_G1} equation into live and dead fractions was not possible for all shrub communities or groups of communities analysed. The dead and live fractions of fine fuel loads have seldomly been modelled, despite their recognized influence in fuel hazard (McColl-Gausden et al., 2020), flammability (Cawson et al., 2020; Madrigal et al., 2012; Resco de Dios, 2020; Weise et al., 2005), fire propagation (Fontaine et al., 2012; Jolly, 2007), surface heating and heating duration (Fontaine et al., 2012), fire intensity (Baeza et al., 2002, 2011), and fire severity (Keeley et al., 2008). Furthermore, this type of modelling has mainly been conducted using the individual plant approach. The results of the comparison of the performance obtained in these two fractions with W_{Shr} and W_{Shr_G1} have not been conclusive at stand level (Champlin, 1982; Dalgleish et al., 2015; Fernandes and Rego, 1998b; Sağlam et al., 2008), and the same applies to the dead fine fuel - live fine fuel comparison (Champlin, 1982). At the individual plant scale, poorer estimation of fine dead fraction load than of the live fraction or total shrub load has been frequently reported (De Luis et al., 2004; Duguy et al., 2015; Gray, 1982; Hughes et al., 1987; Krivtsov et al., 2009; Ludwig et al., 1975; Murray and Jacobson, 1982; Puentes and Basanta, 2002; Puentes et al., 2016), but not always (Baeza et al., 2006). The different response suggests strong dependence on interspecific variability in the community composition and potentially high sensitivity to local factors. The comparatively lower predictive capacity of dead fine fuel load estimation in our case was expected, given that species heterogeneity is common in the communities considered, and that there are marked differences in age and abiotic parameters. Furthermore, high intraspecific variability in plant biomass is often observed in shrub species (Alías et al., 2015; Armand et al., 1993) and high variability in dead and live fractions has been reported to be associated with factors such as plant age (Baeza et al., 2006; Fernandes and Rego, 1998b; Rothermel and Philpot, 1973), level of competition (Dalgleish et al., 2015; Westcott et al., 2014) and plant phenological state and season (Puentes and Basanta, 2002; Resco de Dios, 2020). Likewise, the influence of soil depth and topographic factors has been reported (Dalgleish et al., 2015; Enes et al., 2020; Fernández, 2021; Fraser et al., 2016; Keane, 2015; Marsden-Smedley and Catchpole, 1995), although a lack of any apparent relationship with age or community specific composition has also been observed (Pausas et al., 2012; Paysen and Cohen, 1990; Regelbrugge and Conard, 2002). The interannual variability in climate and the associated plant physiological response can also be particularly important (Resco de Dios, 2020). Another point adding complexity to dead and live fine fuel modelling is the frequent apparent randomness in the spatial distribution of dead material observed in field sampling (Anderson and Anderson, 2010). Collection of such material is problematic because part of the elevated material can easily fall during harvesting. In addition, discrimination between live and dead woody fractions in the laboratory is not easy, particularly in species such as *P. tridentatum* and *Ulex* sp. (Fernandes, 1997), and segregation is a delicate and time-consuming task, especially with thorny species.

4.3. Standing shrub coarser fraction

The relatively high uncertainty (in terms of relative RMSE) associated with the larger diameter fuel fraction (6–75 mm) has been inconsistently observed in the few stand-level approach studies (Champlin, 1982; Seijas et al., 2009). However, it has been more frequently and consistently reported in individual-level modelling approach, with similar and also larger values of relative RMSE than in this study (Cleary et al., 2008; Duguy et al., 2015; Fernandes and Rego, 1998a; Hierro et al., 2000; Huff et al., 2017; Murray and Jacobson, 1982; Northup et al., 2005). It should be noted that, from the point of view of forest fire prevention, coarse shrub fuels are assumed to make a smaller contribution to fire behaviour variables that depend on active flames, such as fire spread rate and fire line intensity (Morvan and Dupuy, 2004; Rothermel, 1972), due to the smaller surface area-volume ratio and generally higher percentage of living fuels relative to fine fuels.

4.4. Models aggregating morphologically similar communities

The predictive potential of the systems fitted for morphologically similar or associated species decreased as the number of species increased, and the structural and functional differences increased, from groups of two species ($Cm + Cs$, $Eu + Pt$ and $Ue + Ug$) to the pool that includes all shrub communities except the fern community (*All-Pa*). Similar results were reported in studies comparing species-specific and mixed-species equations to estimate AGB at individual level (e.g., Conti et al., 2013; De Cáceres et al., 2019; Návar et al., 2002b; Sah et al., 2004) or stand-level (Viana et al., 2013), although in other studies similar performance has been obtained with both types of equations (Ali et al., 2015; Conti et al., 2019; Freedman, 1984; He et al., 2018; Paul et al., 2016). Nevertheless, the systems fitted for groups of communities are especially useful for estimating fuel loads over large areas with remote sensing technologies because of the possible difficulties in differentiating between species with these sources of information (e.g., Kerr and Ostrovsky, 2003).

4.5. Litter modelling

Overall, our equations for estimating litter load (W_{Litt}) showed good predictability for each community and also when grouped together, providing new information on an important and generally disregarded fuel stratum of shrub communities. The reasonably high variability explained for the individual communities (77–90%) and moderately low relative RMSE encourages the use of litter depth as a simple measurement with good predictive potential of the litter biomass. The results of this study confirm the usefulness of litter depth to predict litter load, as was found in previous shrub studies at stand level (Arellano-Pérez, 2011; Davies et al. 2008; Fonseca et al. 2012; Kittredge, 1955; Lade, 2010) while extending its validity to other shrub communities. However, the goodness of fit was relatively poor in the equations of litter load fitted only with $\overline{h_{Shr}}$ because the most important explanatory variable was litter thickness.

4.6. Models using only stand height as predictive variable

As expected, the accuracy of estimates decreased when $\overline{h_{Shr}}$ was the only explanatory variable. Still, the equations used to estimate $W_{Shr+Litt}$ in *Cs* and $Cm + Cs$ were not strongly affected, probably because in these communities the only independent variables involved in the estimates were $\overline{d_{Litt}}$ and $\overline{h_{Shr}}$ without including *Cov* and therefore, the reduction in the explanatory potential of the model was lower.

A wide range of remote sensing techniques such as laser scanning, structure from motion photogrammetry, spectral analysis and imaging synthetic aperture radar, used at ground level, from aircraft or UAV, alone or in combination, have opened up new avenues and opportunities for providing rapid and detailed shrub structural geospatial information among which the height and cover of the shrubbery occupy a prominent position. These techniques are quickly proving to have direct application to AGB and fuel loading assessment of shrublands in moderately-size areas (e.g., Alonso-Rego et al., 2020; Anderson et al., 2018; Cunliffe et al., 2016; Eisfelder et al., 2012; Lamelas-Gracia et al., 2019; Li et al., 2017; Poley et al., 2020; Schrader-Patton and Underwood, 2021), although their use also posed some challenges (Anderson et al., 2018; Cooper et al., 2020; Estornell et al., 2011; Li et al., 2017). This information can be used together with aerial and satellite imagery to generate fuel maps for large areas (D'Este et al., 2021; Greaves et al., 2015; Lin et al., 2021; Lippitt et al., 2018; Marino et al., 2016; Riaño et al., 2007), which provide essential data for forest and land management. Nonetheless, all remote sensing methods must be validated with ground data (Chave et al., 2019; Duncanson et al., 2019), supported by *ad hoc* destructive sampling surveys or, alternatively, the application of allometric models such as those fitted in the present study.

5. Conclusions

In this study a novel system of equations was developed, enabling estimation of AGB (on a per area basis) and of the amounts of different fuel components in shrub communities in NW Spain, including the litter load. Given the paucity of equations available for estimating these fuel fractions at stand level, and their importance in ecological processes and services and in forest and land management, we consider that these equations could contribute substantially to filling an appreciable knowledge gap.

Although the field data for the experimental basis of those equations were collected in NW Spain, the results of this research may also be applicable to other areas in the north-western Iberian Peninsula with similar climate, soils and vegetation.

Two alternative systems, based on different independent variables, are provided for the nine most frequent shrub communities (including a fern-dominated community) in the region, groups of these, and for the pooled data of all the communities, excluding the fern community. Each of these alternatives has associated benefits, but the decision regarding which to use will ultimately depend on the study objectives, the characteristics of the shrubland in the study area and the budget available for obtaining the input variables of the equations. As pointed out by Wang (2006), the selection of the appropriate allometric equation to estimate biomass involves a trade-off between precision, simplicity and practical application.

The proposed equations require simple biometric measurements, at stand level, such as shrub height ($\overline{h_{Shr}}$), shrub cover (Cov_{Shr}) and litter depth ($\overline{d_{Litt}}$), which can be easily measured in linear transects. Inclusion of these measurements, in large scale forest inventories does not imply great effort or economic cost, relative to destructive inventories, especially those requiring individual plant level and plant density measurements.

In addition to the biometric variables included in this and many other studies, the inclusion of other factors such as age, climatic variables, topography, soil characteristics, site quality and medium-term disturbance history would probably improve the accuracy of the estimates, although severely hampering their practical use. This an open question for future research. The study findings illustrate the feasibility of stand level approach to constructing operational models of shrub fuel loading with reasonably good accuracy for most of fuel components, while also evidencing the pending challenges in live and dead fine fuel modelling. Comparison between the fuel load estimated by stand-level and individual-level approaches, in terms of cost, practicality and accuracy also require future attention.

The fuel load equations presented in this study may be useful for various purposes such as research on carbon and nutrient stockage and cycling, plant competition and facilitation, land restoration and the potential of biomass as an energy source. In the fire management framework, our models could be useful for predicting and assessing fuel hazard fire risk and fire behaviour. They may also be useful for comparing different fuel management strategies, characterising and delimiting wildlife habitats, designing prescribed burns and estimating wildfire emissions. Therefore, it is also expected that in the near future the proposed equations can be used as a basis for mapping these functions in the area, together with airborne or UAV-borne LiDAR, structure from motion photogrammetry or terrestrial laser scanning (TLS), among other remote sensing and geospatial techniques.

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CRediT authorship contribution statement

José A. Vega: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Writing – original draft, Supervision, Project administration, Funding acquisition. **Stéfano Arellano-Pérez:** Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Writing – original draft. **Juan Gabriel Álvarez-González:** Conceptualization, Methodology, Data curation, Formal analysis, Writing – original draft. **Cristina Fernández:** Data curation, Writing – original draft. **Enrique Jiménez:** Data curation, Writing – original draft. **José María Fernández-Alonso:** Data curation, Writing – original draft. **Daniel J. Vega-Nieva:** Data curation, Writing – original draft. **Carlos Briones-Herrera:** Data curation, Writing – original draft. **Cecilia Alonso-Rego:** Data curation, Writing – original draft. **Teresa Fontúrbel:** Data curation, Supervision, Writing – original draft, Project administration, Funding acquisition. **Ana Daría Ruiz-González:** Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Writing – original draft, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

See Tables A1–A4

Table A1
Parameter estimates and approximate standard errors obtained by simultaneously fitting the system of seven equations (Eqs. (1)–(7)) for each shrub community by using $\overline{h_{Shr}}$ as the only independent variable. W_{Litt} = litter fuel load, W_{Shr} = total shrub fuel load, W_{Shr_G23} = coarse shrub fuel load, W_{Shr_G1} = fine shrub fuel load, $W_{Shr\_G1\_dead}$ = dead fine shrub fuel load, $W_{Shr\_G1\_live}$ = live fine shrub fuel load.

Variable	Parameter	Statistic	*Cl*	*Cm*	*Cs*	*Ea*	*Eu*	*Pa*	*Pt*	*Ue*	*Ug*
W_{Litt}	a_0	Estimate	0.0081	0.0073	0.0547	0.0070	0.0094	0.0943	0.0115	0.0209	0.0353
		Approx. Std. error	0.0008	0.0019	0.0038	0.0012	0.0007	0.0058	0.0031	0.0082	0.0142
	a_1	Estimate	0.7810	0.9803	0.5129	1.0163	1.1841	0.4579	0.8494	0.8863	0.7847
		Approx. Std. error	0.2143	0.0549	0.1188	0.0336	0.1795	0.1310	0.0552	0.0774	0.0860
W_{Shr}	b_0	Estimate	0.0157	0.0692	0.0403	0.0266	0.0342	0.00086	0.0592	0.1018	0.1419
		Approx. Std. error	0.0075	0.0198	0.0137	0.0028	0.0128	0.00044	0.0092	0.0129	0.0283
	b_1	Estimate	0.8882	0.7540	0.8884	0.9650	1.0257	1.5211	0.8365	0.7421	0.6936
		Approx. Std. error	0.0967	0.0584	0.0589	0.0207	0.0902	0.1046	0.0324	0.0253	0.0446
W_{Shr_G23}	c_0	Estimate	6.6787	6.6551	7.6278	9.4165	7.8856	5.0771	8.5082	6.1429	11.2808
W_{Shr_G1}		Approx. Std. error	1.5828	0.9350	0.9190	0.6109	1.4720	1.3241	0.8217	0.3790	1.1401
	c_1	Estimate	−1.1595	−1.2609	−1.4575	−1.7805	−1.4655	−0.7255	−1.5671	−1.1630	−2.2058
		Approx. Std. error	0.3152	0.1839	0.1545	0.1149	0.3441	0.2705	0.1632	0.0748	0.2437
$W_{Shr\_G1\_dead}$	d_0	Estimate	–	–	3.2162	2.2997	3.6870	–	–	1.6045	2.3857
$W_{Shr\_G1\_live}$		Approx. Std. error	–	–	0.5508	0.2971	0.6156	–	–	0.3114	0.5825
	d_1	Estimate	–	–	−0.4096	−0.2834	−0.7385	–	–	−0.2461	−0.3953
		Approx. Std. error	–	–	0.0992	0.0594	0.1483	–	–	0.0646	0.1328

Cl = Cistus ladanifer, Cm = Cytisus multiflorus, Cs = Cytisus striatus, Ea = Erica australis, Eu = Erica umbellata, Pa = Pteridium aquilinum, Pt = Pterospartium tridentatum, Ue = Ulex europaeus and *Ug = Ulex gallii.*

Table A2
Goodness-of fit statistics and weights used to correct heteroscedasticity in fuel load estimates for each fuel fraction and shrub community for systems fitted using $\overline{h_{Shr}}$ as the only independent variable. $W_{Shr+Litt}$ = shrub and litter, W_{Shr} = AGB = total shrub, W_{Litt} = litter W_{Shr_G23} = coarse shrub, W_{Shr_G1} = fine shrub, $W_{Shr\_G1\_dead}$ = dead fine shrub and $W_{Shr\_G1\_live}$ = live fine shrub .

Equation	Statistic	*Cl*	*Cm*	*Cs*	*Ea*	*Eu*	*Pa*	*Pt*	*Ue*	*Ug*
$W_{Shr+Litt}$	RMSE (kg m^{-2})	0.1924	0.6110	1.9971	0.8408	0.8279	0.2815	0.7088	1.1376	1.1066
	ME	0.8141	0.8307	0.7580	0.8875	0.6915	0.8313	0.8036	0.7522	0.4743
	Bias (kg m^{-2})	0.0044	−0.0820	0.0223	0.0033	−0.0002	−0.0058	−0.0192	−0.0102	0.0173
	weight	–	–	–	$(\overline{h_{Shr}})^{-1.26}$	–	–	$(\overline{h_{Shr}})^{-0.85}$	–	–
W_{Shr}	RMSE (kg m^{-2})	0.1566	0.5244	1.8764	0.6911	0.4937	0.1952	0.5424	0.6415	0.5345
	ME	0.7896	0.7576	0.7298	0.8598	0.6870	0.8580	0.8278	0.8044	0.6430
	Bias (kg m^{-2})	0.0056	−0.0493	0.0216	−0.0065	0.0044	−0.0054	−0.0137	−0.0098	0.0149
	weight	–	–	–	$(\overline{h_{Shr}})^{-1.26}$	–	–	$(\overline{h_{Shr}})^{-0.85}$	–	–
W_{Litt}	RMSE (kg m^{-2})	0.1080	0.2205	0.3822	0.3144	0.4813	0.2121	0.2540	0.8098	0.7254
	ME	0.4167	0.8097	0.5898	0.8130	0.5435	0.4588	0.4600	0.4179	0.1604
	Bias (kg m^{-2})	−0.0012	−0.0385	0.0091	0.0102	−0.0050	−0.0005	−0.0055	−0.0006	0.0125
	weight	–	$(\overline{h_{Shr}})^{-1.98}$	–	$(\overline{h_{Shr}})^{-1.32}$	–	–	$(\overline{h_{Shr}})^{-0.30}$	–	$(\overline{h_{Shr}})^{-0.88}$
W_{Shr_G23}	RMSE (kg m^{-2})	0.1103	0.4200	1.7306	0.4601	0.1733	0.0767	0.2717	0.4581	0.3332
	ME	0.6403	0.7188	0.7298	0.8601	0.5467	0.6907	0.8494	0.8143	0.6215
	Bias (kg m^{-2})	0.0067	−0.0440	0.0221	0.0365	0.0050	−0.0001	−0.0011	0.0033	0.0057
W_{Shr_G1}	RMSE (kg m^{-2})	0.1122	0.2119	0.4059	0.4069	0.4474	0.1691	0.4579	0.5237	0.5214
	ME	0.6985	0.6307	0.5683	0.7194	0.6056	0.8258	0.6242	0.4077	0.3549
	Bias (kg m^{-2})	−0.0011	−0.0053	0.0016	−0.0430	−0.0004	0.0001	−0.0127	−0.0131	−0.0008
$W_{Shr\_G1\_dead}$	RMSE (kg m^{-2})	–	–	0.1258	0.1531	0.1969	–	–	0.3048	0.3344
	ME	–	–	0.7570	0.7395	0.6594	–	–	0.3409	0.2759
	Bias (kg m^{-2})	–	–	−0.0012	−0.0195	0.0004	–	–	−0.0038	0.0003
$W_{Shr\_G1\_live}$	RMSE (kg m^{-2})	–	–	0.3981	0.3453	0.3412	–	–	0.3667	0.3757
	ME	–	–	0.2706	0.5860	0.4170	–	–	0.2707	0.1901
	Bias (kg m^{-2})	–	–	0.0028	−0.0235	−0.0008	–	–	−0.0094	−0.0011

Cl = Cistus ladanifer, Cm = Cytisus multiflorus, Cs = Cytisus striatus, Ea = Erica australis, Eu = Erica umbellata, Pa = Pteridium aquilinum, Pt = Pterospartium tridentatum, Ue = Ulex europaeus and *Ug = Ulex gallii.*

Table A3

Parameter estimates and approximate standard errors obtained by simultaneously fitting the system of seven equations by using $\overline{h_{Shr}}$ as the only independent variable for estimating fuel load in each group of shrub communities. W_{Litt} = litter fuel load, W_{Shr} = total shrub fuel load, W_{Shr_G23} = coarse shrub fuel load, W_{Shr_G1} = fine shrub fuel load, $W_{Shr\_G1\_dead}$ = dead fine shrub fuel load, $W_{Shr\_G1\_live}$ = live fine shrub fuel load.

Variable	Parameter	Statistic	*Cm* + *Cs*	*Eu* + *Pt*	*Ue* + *Ug*	*All-Pa*
W_{Litt}	a_0	Estimate	0.0873	0.1632	0.0307	0.0613
		Approx. Std. error	0.0311	0.0746	0.0093	0.0068
	a_1	Estimate	0.4459	0.3678	0.8153	0.5835
		Approx. Std. error	0.0650	0.1043	0.0614	0.0218
W_{Shr}	b_0	Estimate	0.0383	0.0852	0.1426	0.0710
		Approx. Std. error	0.0050	0.0135	0.0139	0.0033
	b_1	Estimate	0.8937	0.7699	0.6790	0.7947
		Approx. Std. error	0.0242	0.0343	0.0201	0.0091
W_{Shr_G23} W_{Shr_G1}	c_0	Estimate	6.9230	8.2184	7.1055	7.9263
		Approx. Std. error	0.3100	0.5425	0.3413	0.1822
	c_1	Estimate	−1.3344	−1.5086	−1.3471	−1.5051
		Approx. Std. error	0.0550	0.1101	0.0689	0.0348
$W_{Shr\_G1\_dead}$ $W_{Shr\_G1\_live}$	d_0	Estimate	–	1.2967	2.0839	1.4574
		Approx. Std. error	–	0.3011	0.2611	0.1660
	d_1	Estimate	–	−0.1607	−0.3408	−0.1643
		Approx. Std. error	–	0.0673	0.0559	0.0348

Brooms (*Cm* + *Cs* = *Cytisus multiflorus* and *Cytisus striatus*), low heather and prickled broom (*Eu* + *Pt* = *Erica umbellata* and *Pterospartum tridentatum*), gorses (*Ue* + *Ug* = *Ulex europaeus* and *U. gallii*) and the pooled data for all shrub communities excluding the fern-dominated community (*All-Pa*).

Table A4

Goodness-of fit statistics and weights used to correct heteroscedasticity for each fuel fraction load and group of shrub communities for systems fitted using $\overline{h_{Shr}}$ as the only independent variable. $W_{Shr+Litt}$ = shrub and litter load W_{Shr} = AGB = total shrub load, W_{Litt} = litter load, W_{Shr_G23} = coarse shrub load, W_{Shr_G1} = fine shrub load, $W_{Shr\_G1\_dead}$ = dead fine shrub load and $W_{Shr\_G1\_live}$ = live fine shrub load.

Equation	Statistic	*Cm* + *Cs*	*Eu* + *Pt*	*Ue* + *Ug*	*All-Pa*
$W_{Shr+Litt}$	RMSE (kg m^{-2})	1.4549	1.0071	1.1462	1.4034
	ME	0.8155	0.5712	0.6950	0.6549
	Bias (kg m^{-2})	0.0180	0.0389	−0.0070	0.0680
	weight	$(\overline{h_{Shr}})^{-1.21}$	–	–	$(\overline{h_{Shr}})^{-1.01}$
W_{Shr}	RMSE (kg m^{-2})	1.3824	0.5733	0.6266	0.9438
	ME	0.7909	0.7494	0.7690	0.7270
	Bias (kg m^{-2})	0.0238	0.0236	−0.0086	0.0484
	weight	$(\overline{h_{Shr}})^{-1.21}$	–	–	$(\overline{h_{Shr}})^{-1.01}$
W_{Litt}	RMSE (kg m^{-2})	0.3480	0.5627	0.7805	0.7425
	ME	0.6031	0.1233	0.3626	0.2346
	Bias (kg m^{-2})	−0.0068	0.0159	0.0016	0.0125
	weight	–	–	–	$(\overline{h_{Shr}})^{-0.75}$
W_{Shr_G23}	RMSE (kg m^{-2})	1.2270	0.2374	0.4215	0.6074
	ME	0.7962	0.8185	0.8119	0.8133
	Bias (kg m^{-2})	0.0295	0.0188	−0.0040	0.0089
W_{Shr_G1}	RMSE (kg m^{-2})	0.3330	0.4865	0.5678	0.6128
	ME	0.5900	0.5557	0.2901	0.3365
	Bias (kg m^{-2})	−0.0009	0.0049	−0.0046	0.0040
$W_{Shr\_G1\_dead}$	RMSE (kg m^{-2})	–	0.2218	0.3197	0.3342
	ME	–	0.5198	0.2962	0.2560
	Bias (kg m^{-2})		0.0016	−0.0018	0.0029
$W_{Shr\_G1\_live}$	RMSE (kg m^{-2})	–	0.3968	0.4053	0.4228
	ME	–	0.3865	0.1460	0.2375
	Bias (kg m^{-2})		0.0032	−0.0028	0.0015

Brooms (*Cm* + *Cs* = *Cytisus multiflorus* and *Cytisus striatus*), low heather and prickled broom (*Eu* + *Pt* = *Erica umbellata* and *Pterospartum tridentatum*), gorses (*Ue* + *Ug* = *Ulex europaeus* and *U. gallii*) and the pooled data for all shrub communities excluding the fern-dominated community (*All-Pa*).

Appendix B. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foreco.2021.119926.

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