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RESEARCH

Allometric equations to calculate living and dead fuel loads in Mediterranean species

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Abstract

Determining the structure and fuel load is key to know the flammability of vegetation in the Mediterranean Basin where forest fires are frequent. Determine which plant structural variable is best related to living and dead fuel to develop allometric equations in nine species in the Western Mediterranean Basin. In the east of the Iberian Peninsula (Valencia Province), we measured four structural variables (basal stem diameter, height, maximum diameter and perpendicular diameter) that were related, by means of allometric equations, to the living and dead fuel separated into different size classes. We also analyze fuel changes across developmental states of the studied species, and the vertical distribution of dead fuel. General equations that consider all development states can be used to determine living fuel. However to obtain dead fuel, we recommend using specific equations for each development state and fuel fraction for better accuracy. The basal stem diameter was the best structural variable in almost all cases for estimating fuel in the studied species. Dead fuel load throughout species' ontological development is a key factor to manage Mediterranean plant communities.

Keywords Basal stem diameter · Flammability · Fuel diameter fractions · Functional trait · Dead fuel height · Structural variables

Introduction

In regions with a Mediterranean climate, ecosystems tend to be affected by forest fires in months with high temperatures and little precipitation. Furthermore, changes in traditional land uses in recent decades have increased fuel load and continuity (Saura-Mas et al. 2010; Keeley et al. 2011; Baeza and Santana 2015), which favors the incidence of fire. This is because fire behavior is modulated by biomass structure, among other factors, especially in the way that living and dead fuel is spatially and temporally distributed as fine and thick fractions (Santana et al. 2011). The amount of dead fuel load, and consequently the dead/living fuel ratio, is typical characteristics of each species which, in turn, influence vegetation's flammability (Pausas and Bradstock 2007; Saura-Mas et al. 2010; Baeza and Santana 2015). These differential flammability traits among plants are key for understanding fire components such as ignition, propagation or fire extinction capacity (Dimitrakopoulos and Papaioannou 2001; Santana and Marrs 2014). Yet knowledge of biomass structure in many plant species and types is still scarce. Therefore, having tools available that enable the vegetation structure to be quickly and accurately obtained to correctly manage and prevent forest fires is key. Furthermore, these same tools can be very useful for fields other than forest fires. Among the many uses that can be given to them are the obtaining of plant production values (Belmonte and López 2003), or the study of aspects related to carbon fixation (Vallet et al. 2006; Singh et al. 2011).

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The amount of biomass that vegetation presents can be influenced by age because living and dead biomasses differently accumulate during ontogenetic vegetation development (Santana et al. 2011; Baeza and Santana 2015; Bohlman et al. 2018). Ignoring the distribution between living and dead biomasses throughout vegetation development implies lack of accurate information, which can be key for fuel management to reduce the fire risk in fire-prone communities. It is possible to calculate vegetation biomass by following different methods; for example, by means of volume, the apparent density or by using allometric equations based on the relationship between specific parts of a given plant (Blanco-Oyonarte and Navarro-Cerrillo 2003; De Cáceres et al. 2019). Allometric equations are an effective method for obtaining individual biomass values (De Cáceres et al. 2019). They can explain variations in a plant's biomass load in relation to simple structural measurements that are easy to take, such as stem height or diameter (Causton and Venus 1981). Although allometric models are specific of each species, one same functional group can sometimes present similarities in its morphological growth pattern and, therefore, the same allometric model can be used for several species (Conti et al. 2013). Nonetheless, checks have been made and found that allometric equations per species obtain better results than those calculated for one same functional group (de Cáceres et al. 2019).

Many studies have applied allometric equations to obtain biomass data in the vegetation regenerated after forest fires (Montès et al. 2004; Baeza et al. 2006; Saura-Mas et al. 2010) to estimate growth and plant production (Belmonte and López-Bermúdez 2003; Llorens et al. 2004), or to know carbon fixation (Vallet et al. 2006; Singh et al. 2011). Other studies discuss which is the most accurate dimensional variable in these equations to simplify the efforts and time needed to calculate biomass (López-Serrano et al. 2005; Conti et al. 2013; De Cáceres et al. 2019). Some studies suggest diameter being the variable that best correlates with biomass (Mitsopoulos and Dimitrakopoulos 2007; Peichl and Arain 2007; Singh et al. 2011), whereas other studies sustain that height (Vallet et al. 2006) or canopy variables (Belmonte and Lopez-Bermúdez 2003; Molina et al. 2014) are the variables that correlate more with biomass. Knowing which structural variable best correlates with fuel amount will help to simplify dimensional measurements and to improve fuel amount estimations and the dead/living fuel ratio between different species.

The main objective of this study is to determine which structural variable of plants is better related to the different living and dead fuel fractions in Mediterranean species. It intends to specifically investigate the relationship of four structural variables, basal stem diameter, height and maximum and perpendicular crown diameter, with different diameter classes of dead and living fuel. With these structural variables, we seek to develop allometric equations that allow the amount of fuel load to be determined in nine dominant species in the Western Mediterranean Basin. Allometric equations were developed by taking into account species' different development states (5, 9, 14, and 26 years since the last fire). Moreover, knowing vegetation's fuel dynamics is also very helpful for forest management, particularly in Mediterranean type ecosystems where the presence of fuel is an indicator of the forest fire risk. Another matter that we considered was how the fuel structure varies, especially its vertical distribution during the studied species' ontogenetic development, because dead fuel height is another determining factor of fire behavior. Dead fuel height could affect different fire components, such as propagation between different vegetation strata by facilitating the vertical continuity of highly flammable fuel (Santana et al. 2011; Baeza and Santana 2015).

Material and methods

The study area is located to the east of the Iberian Peninsula (Valencia Province) in the municipality of Ayora (39°05'−40°5'N, 0°51'−1°59'W). This area is characterized by a dry mesomediterranean climate, where temperatures range between 13 and 17 °C, and average annual rainfall is 400–700 mm. The landscape is occupied mainly by shrublands dominated by *Salvia rosmarinus*, *Ulex parviflorus,* several *Cistus* species and *Quercus coccifera*. Although forest is absent due to historic land use and the incidence of fires, small tree stands can be found, formed generally by *Pinus halepensis*, *Pinus pinaster* and *Quercus ilex.*

Selection of burned areas

Using the fire history records of the Forest Service of the Regional Valencian Government, we selected four areas at the Ayora site which had suffered fires in the summers of 1979, 1991, 1996 and 2000 (30,000, 5000, 600 and 50 ha, respectively). This provides us with a stand-age chronosequence of 5, 9, 14, and 26 years since the last fire. However, for simplicity sake, in this study we respectively named these ages as the development state: young, mature, adult and senescent for shrub species, and sapling, young, mature and adult for trees species. In each fire area, we selected an area with homogeneously laid vegetation. In this area, we delimited a sufficiently big plot of 2–3 ha, who included all species. Between 10 and 12 individuals of each species were randomly selected and separated by at least 5 m (375 individuals in all), and harvested in the autumn–winter of 2004 and 2005. Those individuals that were isolated, dead, broken or grew in especially favorable locations were avoided.

Sampling of species-specific structural variables

At each site, we selected nine woody species, which represented 85–90% of the vegetation cover at the Ayora region (Baeza et al. 2007). These species were: *Cistus albidus, Cistus clusii, Erica multiflora, Juniperus oxycedrus, Pinus halepensis, Quercus coccifera, Quercus ilex, Salvia rosmarinus* and *Ulex parviflorus*. These species included shrubs and trees with different regeneration strategies after fire (seeder and resprouter). For each plant, and before harvesting, we measured four structural variables to be used as independent variables in the allometric equations. We specifically measured (in cm): basal stem diameter; height; maximum crown diameter; perpendicular diameter to maximum crown diameter (hereafter maximum coverage and perpendicular coverage). The dead fuel height in each individual was also measured. For this, we measured the height al which the last dead upper branch was found, that is, we measured the height where the dead fuel ended and the living fuel began. These data were used to determine vertical fuel distribution. After each individual was harvested in the field, living and dead fractions were separated in the laboratory before being sorted according to diameter class: < 6 mm (twigs), 6–25 mm (thin branches), 25.1–75 mm (thick branches) and > 75 mm (trunk) (Brown 1970). Twigs and leaves were included together in the living twigs fraction. In the dead twigs fraction, dead twigs, flowers, fruits and seeds were grouped together. Leaves (or phylloides for *U. parviflorus*) were included in the living thin fraction (< 6 mm). The basal stem diameter of *E. multiflora* was not measured because it had many emerging stems and no clear dominant-main-stem. In all the sampled species and individuals, the presence of dead leaves was negligible, and represented < 1% of all the biomass in all cases. When separated, fuel was dried to constant weight in a forced-air oven at 80ºC. The weight of fuel fractions was measured in grams. In this study, we denominate as fuel the plant biomass.

Data analysis

By means of the R statistical program (version 1.4.1103), regressions were carried out, sorted by species and development state. For it, the first was established the dependent variables (Y) and the independent variables (X). The dependent variables (Fig. 1) used were the total fuel, and the living and dead fuel and their different size classes for the different states of development. Another analysis was also done for leaf weight whenever leaves were available. The employed independent variables (Fig. 1) were the structural basal stem diameter, height and maximum and perpendicular coverage measurements. To fit data to a line, logarithmic transformation ($\log Y = \log a + b \log X$) was applied, thus the different variables were logarithmic transformation. In this equation, *a* and *b* were constants. This transformation tends to homogenize variance within a wide range of Y values, facilitates the calculation and comparison of slopes in different equations and so creases the statistical validly of the analysis. However, it is necessary to multiply a correction

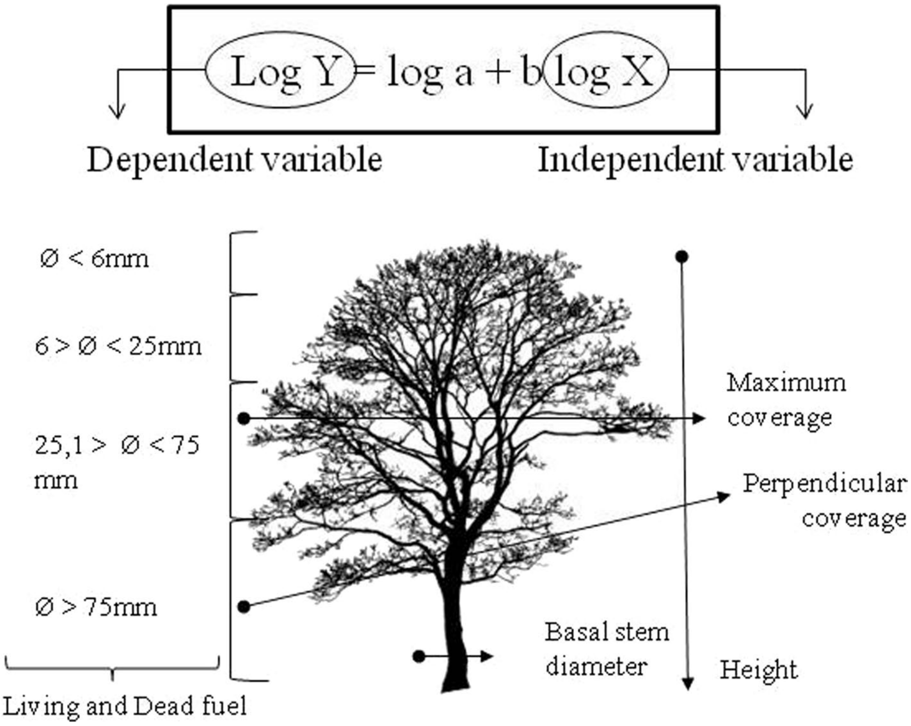

Fig. 1 Scheme where the measured structural variables (independent variables) are on the right, and the diameter class of living and dead fuel (dependent variables) is on the left

factor to counteract the systematic bias than the transformation introduce. This correction factor is calculated from the standard error estimate (SEE; Sprugel 1983).

Linear adjusted regression was applied using least squares. The independent variable with the highest coefficient of determination (r^2) was selected as the best fit. Only significant regressions ($p < 0.05$) were considered. With the slopes of the regressions made for the basal stem diameter (the independent variable with the best results; see below), a graph was built to show how these data varied according to the studied species' development state. When carrying out the regressions, we obtained a large number of results so, in order to focus this study, we decided to use only those that appeared in all the species and all the development states (total living fuel, total dead fuel, living twig, dead twigs). The values of slope (*b*) obtained from the regressions allowed us to know sensitivity to minor changes in the independent variable, which led to major changes in the amount of biomass in each fraction. To find out which fraction indicated the most sensitivity throughout development in each species, we calculated the coefficient of variation (CV) of the slope (*b*) in its different states ($CV = {}^{\sigma}/_{\bar{X}}$, where σ was standard deviation and $\overline{X}$ was arithmetic mean). This informed us if it was appropriate to use a global allometric equation after taking into account all a species' development states or, if on the contrary, a specific equation was needed for each specific development state.

We performed a one-way ANOVA to compare the differences in the living, dead, and total fuel, and the fractions comprising them between the different development states. In this analysis values' fuel was the dependent variable (X) and the development states were the independent variable (Y). To carry out this analysis, variables were homogenized using square root or logarithmic transformations according to the data. After obtaining the results, we ran Tukey's test to check if there were differences within in each the studied species' development states.

Finally, two more regressions were performed with the total height and height of dead fuel in relation to development state. Individuals' age (named development states) were used as the independent variables, while the height data were taken as the dependent variables. With these regressions, we aimed to know the behavior of the different fuel heights during development. At the same time, these variables were used to carry out a one-way ANOVA to check if there were differences in the height of the dead fuel between each studied species' development states. As in the analyze carried out for fuel, in this ANOVA the development states were the independent variable (Y), and the height of dead fuel was the dependent variable (X).

Results

General allometric relationships with all the development states together

After performing the different regressions with the allometric equations, we found that basal stem diameter was the independent variable that generally showed the best fit in the coefficient of determination (r^2) for all the species and development states together (see Appendix Table 4, 5, 6 and 7 to see all allometric equations for all independent variables fitted). Basal stem diameter presented 66% of the significant regressions performed for all the studied species (Table 1), and it was also the variable that best correlated with total and living fuel in all the species ($p < 0.001$ and $r^2 > 0.74$; Appendix Table 4). This variable also presented significant relationships for dead fuel in all the species ($p < 0.001$), but with generally lower coefficients of determination than for living fuel (Appendix Table 4). Height was the second structural variable to present higher coefficient of determination values ($p < 0.0001$ and $r^2 > 0.570$) and was selected as the best independent variable in 14% of the performed

Table 1 The best independent variables selected for the fuel allometric relationships for all ages in nine dominant Mediterranean Basin species. Independent variables: diameter (basal stem diameter); height; max. cover (maximum coverage); perp. cover (perpendicular coverage)

	Total Fuel	Living fractions (total)	Living Twigs	Living Thin branches	Living Thick branches	Dead fractions (total)	Dead twigs	Dead thin branches
C. albidus	Diameter	Diameter	Diameter	Diameter	Height	Diameter	Diameter	Height
C. clusii	Diameter	Diameter	Diameter	Diameter	–	Diameter	Max. Cover	–
E. multiflora	Perp. Cover	Perp. Cover	Perp. Cover	Max. Cover	–	Max. Cover	Max. Cover	–
J. oxycedrus	Diameter	Diameter	Diameter	Diameter	Diameter	Diameter	Diameter	–
P. halepensis	Diameter	Diameter	Perp. Cover	Max. Cover	Diameter	Height	Height	Diameter
Q. coccifera	Diameter	Diameter	Perp. Cover	Diameter	–	Max. Cover	Max. Cover	–
Q. ilex	Diameter	Diameter	Height	Diameter	Height	Diameter	Diameter	–
S. rosmarinus	Diameter	Diameter	Diameter	Diameter	Diameter	Height	Height	–
U. parviflorus	Diameter	Diameter	Diameter	Height	–	Diameter	Diameter	Diameter

regressions (Table 1). Finally, the variables maximum coverage and perpendicular coverage were only selected as the best variable for 11% and 8% of the significant regressions, respectively. Table 1 shows that these structural variables were selected mainly in some of the fuel fractions present in *E. multiflora*, *P. halepensis* and *Q. coccifera.* Table 2 offers the data required to apply the equations that allow different fuel classes to be obtained according to the best fit for each studied species.

Allometric relationships separated by development state

The analysis of these regressions for the different development states showed that basal stem diameter was still the structural variable with higher coefficients of determination (Appendix Table 3 and 4). This variable presented the best fit in 54% of the significant regressions performed for all the species and development states. Perpendicular coverage gave the highest coefficient of determination values in 22% of the significant regressions (Appendix Table 3 and 7) and 18% maximum coverage (Appendix Table 3 and 6). The lowest value for the coefficients of determination was for height, with 5% of the total (Appendix Table 3 and 5).

The slope (*b*) values obtained from the regressions allowed us to know sensitivity to small changes of the independent variable in relation to the fuel amount of each fraction. The regressions carried out for basal stem diameter of species like *C. albidus*, *C. clusii*, *J. oxycedrus* and *S. rosmarinus* showed wide-ranging slope values in the different development states, especially for dead fractions. Conversely, the regression slope of basal stem diameter with total living fuel and living twigs barely varied over development state. By mean of these slope values we observed that sensitivity varied more for dead fuel than for living fuel (Fig. 2), and therefore we found that the living fuel fractions obtained lower coefficient of variation values, while for the dead fractions, in general, they were higher (Appendix Fig. 5).

Table 2 Allometric regressions to estimate fuel (total, total living, total dead fuel) with the best independent variable selected for all the ages of *C. albidus, C. clusii, J. oxycedrus, P. halepensis, Q. coccifera, Q. ilex, S. rosmarinus* and *U. parviflorus*. Fuel can be estimated with $Y = \left((\exp(a)) \times \left(X^b\right)\right) \times \mathrm{CF}$; a and b, constants of the equation ($\log Y = \log a + b \log X$); r^2, coefficient of determination; SEE, standard error of estimation; CF, correction factor

	Dependent variables (Y)	Independent variables (X)	a	b	r^2	SEE	CF
C. albidus	Total fuel	Diameter	3.917	2.350	0.923	0.320	1.053
	Living fuel	Diameter	3.759	2.233	0.909	0.333	1.057
	Dead fuel	Diameter	1.859	2.808	0.805	0.654	1.238
C.clusii	Total fuel	Diameter	3.509	2.330	0.857	0.279	1.040
	Living fuel	Diameter	3.473	2.100	0.743	0.369	1.070
	Dead fuel	Diameter	−0.268	4.284	0.563	1.113	1.858
E. multiflora	Total fuel	Perp. Cover	−1.547	1.871	0.784	0.398	1.082
	Living fuel	Perp. Cover	−1.207	1.770	0.769	0.394	1.081
	Dead fuel	Max. Cover	−17.274	4.518	0.729	1.171	1.985
J. oxycedrus	Total fuel	Diameter	3.885	2.430	0.976	0.214	1.023
	Living fuel	Diameter	3.867	2.396	0.976	0.209	1.022
	Dead fuel	Diameter	−0.520	3.165	0.674	1.238	2.152
P. halepensis	Total fuel	Diameter	3.884	2.318	0.986	0.231	1.027
	Living fuel	Diameter	3.903	2.283	0.984	0.246	1.031
	Dead fuel	Height	−19.068	4.378	0.865	1.078	1.788
Q. coccifera	Total fuel	Diameter	4.056	2.481	0.889	0.365	1.069
	Living fuel	Diameter	4.010	2.432	0.887	0.362	1.068
	Dead fuel	Max. Cover	−8.741	2.865	0.691	0.952	1.573
Q. ilex	Total fuel	Diameter	3.812	2.408	0.951	0.334	1.057
	Living fuel	Diameter	3.783	2.402	0.946	0.351	1.064
	Dead fuel	Diameter	−1.186	3.211	0.769	1.079	1.790
S. rosmarinus	Total fuel	Diameter	3.808	2.255	0.853	0.378	1.074
	Living fuel	Diameter	3.807	2.221	0.850	0.377	1.074
	Dead fuel	Height	−29.687	6.581	0.570	1.455	2.882
U. parviflorus	Total fuel	Diameter	4.335	2.157	0.950	0.399	1.083
	Living fuel	Diameter	3.850	1.985	0.937	0.417	1.091
	Dead fuel	Diameter	2.865	2.913	0.847	1.005	1.657

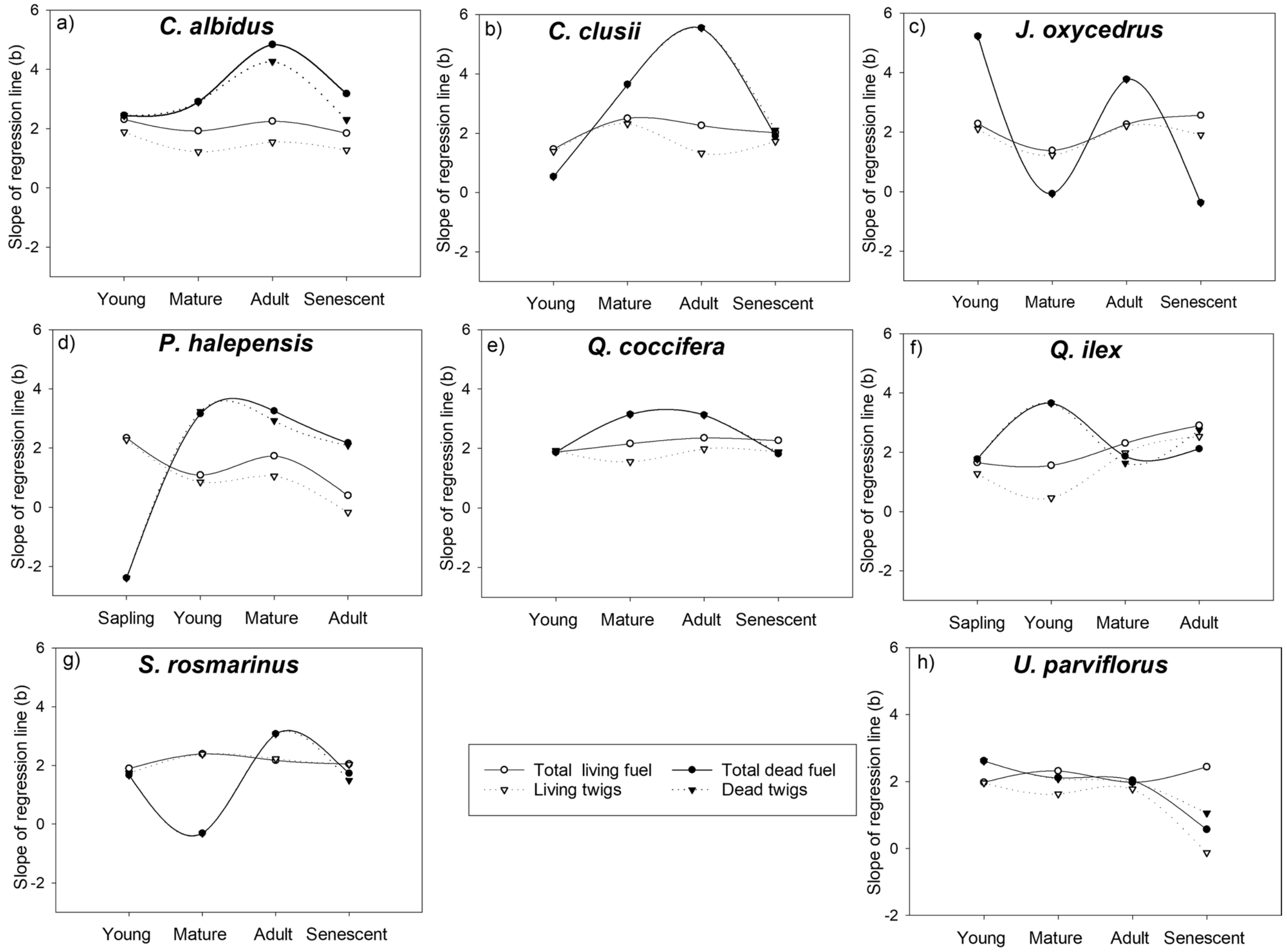

Fig. 2 Slope of the fitted regression lines (*b*) using the basal stem diameter for living fuel, living twigs, dead fuel and dead twigs in the different development states of the studied species (**a**–**h**)

Variability of biomass amount in all the different fractions during individuals' development

Living twigs were the dominant fuel fraction in most species and the different development states, and tended to lower in more advanced development states (Fig. 3). This fraction showed significant differences (one-way ANOVA, $p < 0.001$) in all the species when we analyzed its different development states (Appendix Table 8). Living thin branches were the next most abundant fraction and, although their load generally increased over development states, tree or semitree species like *P. halepensis, Q. ilex* and *J. oxycedrus* (Fig. 3) descended in the most advanced development states owing to the presence of living thick branches.

Most of the studied species obtained increased total dead fuel throughout their development, particularly *C. clusii* and *E. multiflora* ($p < 0.001$; Fig. 3). *J. oxycedrus* was the only species to show no significant increase ($p = 0.23$). Such a differential fuel load pattern in *U. parviflorus* is stressed. This species in their mature state presented the highest dead fuel load values (53%). This dead fuel, which was completely composed of dead twigs in young development states, significantly lowered in the following states, although these load values were higher than in the other species. Conversely, the living fuel in this species tended to increase with development states.

When we analyzed the total height and dead fuel height in the different species sampled throughout their development, species like *C. albidus* obtained similar values between total height and dead height (Fig. 4). However, a bigger difference was found for other species between total height and dead height as their development state advanced. These differences were found for *J. oxycedrus* and *Q. coccifera* with the latter species in its mature development state (Fig. 4d and f, respectively), while these were evidenced in *Q. ilex* or *P. halepensis* from young development states (Fig. 4g). *U. parviflorus* was the only one to show a similar dead height to total heights (Fig. 4i); that is, individuals' total height was

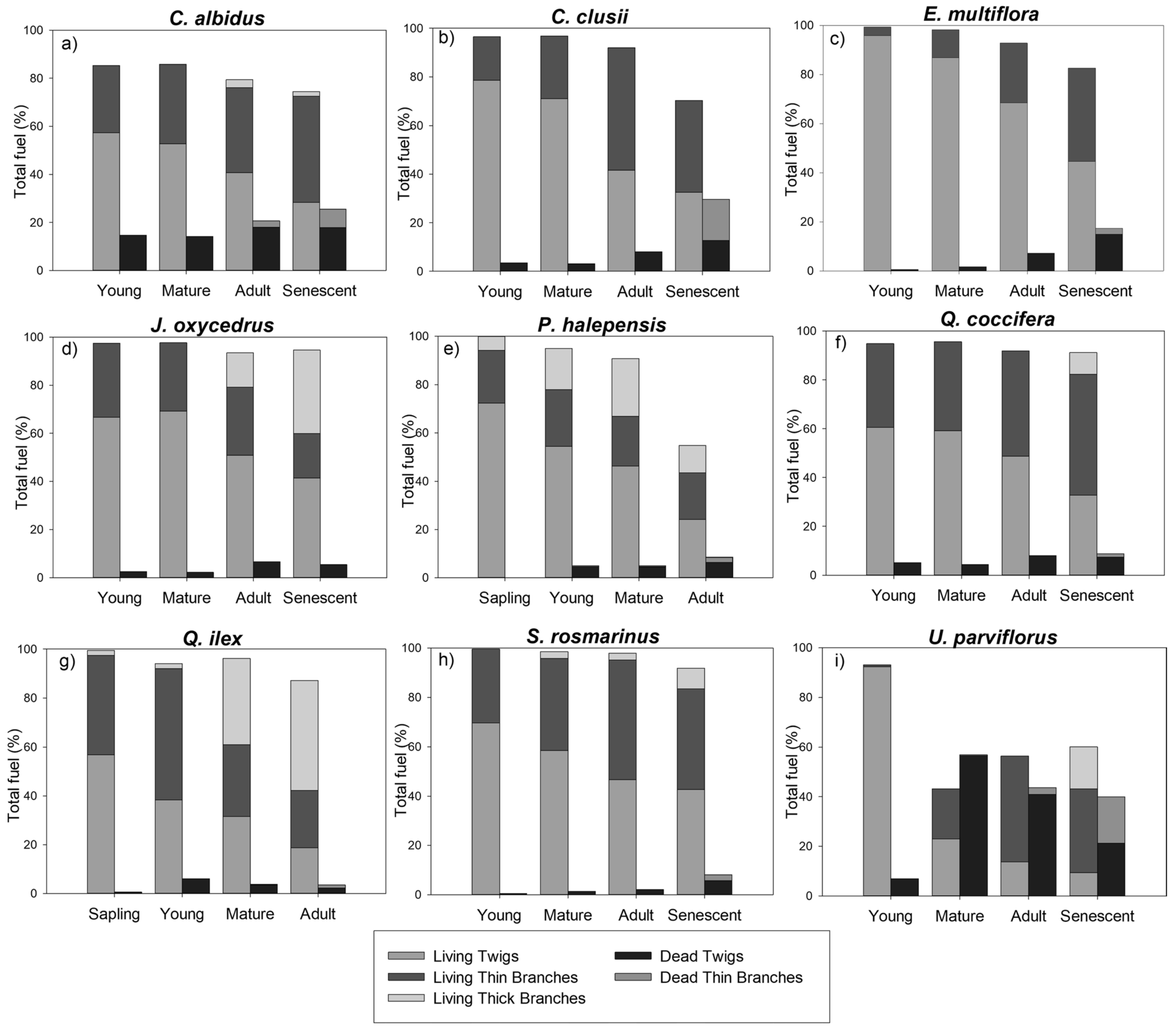

Fig. 3 Percentage of living and dead fuel and their component fractions, twigs, thin branches and thick branches, for each sampled species (**a**–**i**) in the different development states

dominated by dead fuel as development states advanced. Linear regressions were significant ($p < 0.05$) for all the species and fractions, except for the dead fuel of *C. albidus* and *C. clusii* (see Appendix Table 9 for more details of linear regressions).

Discussion

Allometric relationships

Allometric models well predict fuel by describing the relationship that this variable maintains with simple structural measurements in plants (Whittaker and Marks 1975). Our study shows basal stem diameter as the structural variable that explains more variation to estimate fuel in the studied species (Table 1) because it gives the best fit in 66% of the applied allometric relationships. Nonetheless, other variables also have high coefficient of determination values depending on fuel type. Some authors suggest that stem growth can be modeled by disturbances, competition or lack of resources, and these facts are also manifested in vegetation biomass (Causton and Venus 1981; Montero et al. 2005). This relationship between stem diameter and fuel also appears in previous works (Conti et al. 2013; Manolis et al. 2016).

The present study shows high coefficient of determination values between basal stem diameter and fuel,

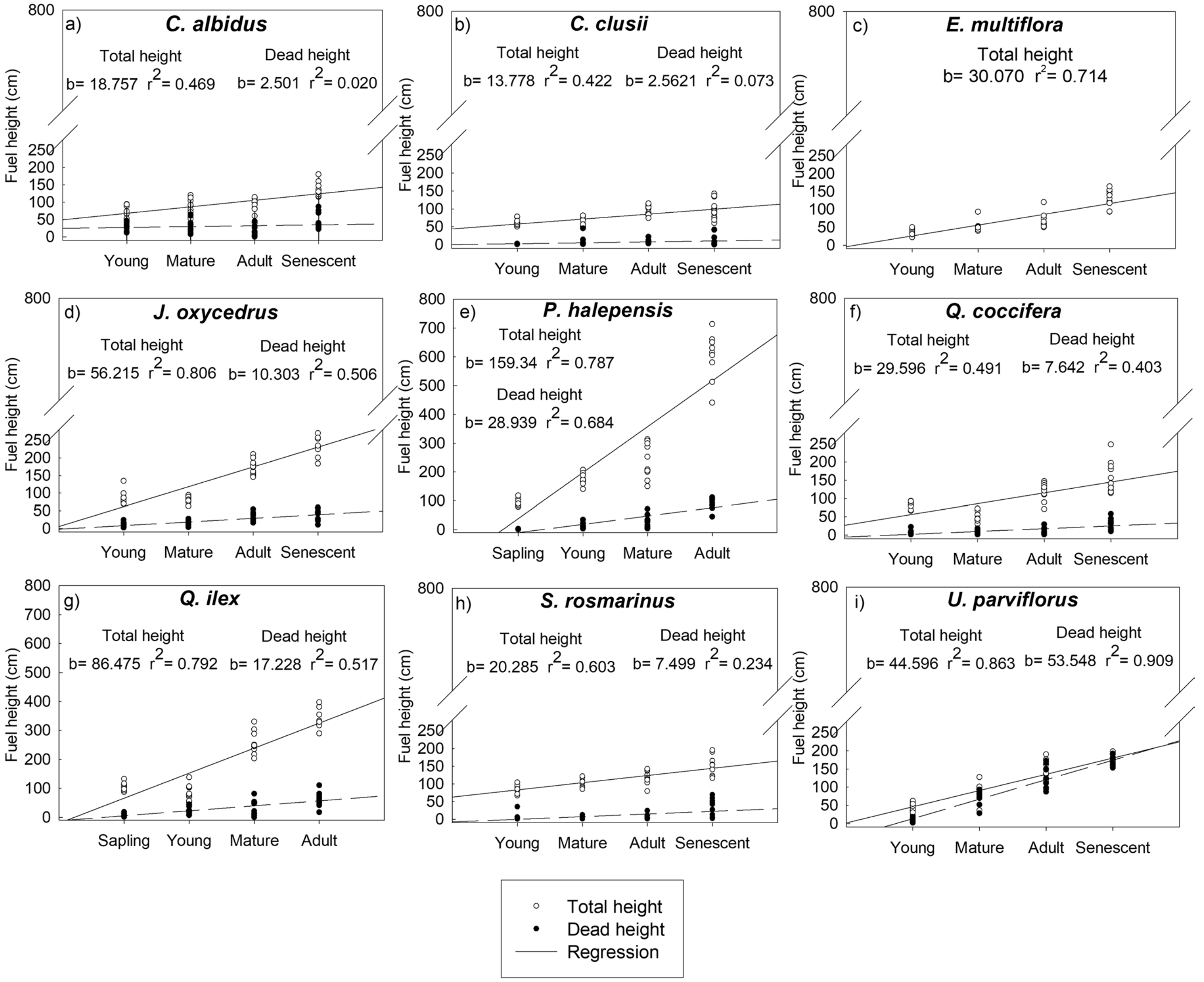

Fig. 4 Regressions of the total and the dead fuel heights for the different species (**a**–**i**) according to their development state. (P-value < 0.0001 except for the dead height of *S. rosmarinus* where $p < 0.01$, and for the dead height of *C. albidus* and *C. clusii* where $p > 0.05$

especially for total and living fuel, and also for other fuel fractions like dead fuel with lower coefficients (Appendix Table 4). This might be due to the observed structural fuel dynamics because, throughout their life time, individuals continuously develop living fuel, mainly in early years, whereas dead fuel tends to appear in smaller amounts in more mature development states (Santana et al. 2011; Baeza and Santana 2015; Bohlman et al. 2018). Dead fuel is also more fragile and vulnerable to losses in the plant structure from physical impacts (e.g., wind, snow, fauna, etc.), which may contribute to allometric relationships becoming less precise. For the four measured structural variables, the finer fractions in both living and dead fuel always obtain lower coefficients than thicker fuel fractions (Mitsopoulos and Dimitrakopoulos 2007; Peichl and Arain 2007; De Cáceres et al. 2019).

The results obtained with the regression slopes (Fig. 2) indicate that dead fuel is more sensitive to changes in load than living fuel, and depend on basal stem diameter. This sensitivity also varies significantly according to development state. This variation might be caused by different dead fuel load tendencies present in the studied species throughout their ontogenetics. Therefore, using specific allometric equations for each development state and fraction is recommended to calculate dead fuel, especially when working with *P. halepensis*, *J. oxycedrus*, *S. rosmarinus* or *U. parviflorus*. However to determine living fuel, equations in which development state is not considered must be used because they are more robust, better reflect morphological variability and are calculated with more individuals. Apart from basal stem diameter, other structural variables like maximum coverage and perpendicular coverage show good correlations in estimations of certain fuel types (Table 1). De Cáceres et al. (2019) suggest employing the crown area to estimate fuel load, but sustain that this variable has a low predictive value for some species. Our results, along with these cited studies, indicate that different structural variables can be used to calculate fuel load. These equations allow living and dead fuel loads to be calculated in distinct diameter classes and different vegetation development states.

Changes in fuel structure during individuals' development

Temporary changes in species' development states allow variations in the structure and distribution of fuel load to be known (Baeza et al. 2006; Peichl and Arain 2007; Pasalodos-Tato et al. 2015). As in our study, other authors have studied how living fuel dynamics vary throughout the development of individuals of different species (Hierro et al. 2000; Peilch and Arain 2007; Baeza and Santana 2015). Nevertheless, higher dead fuel load has been suggested to occur in more mature vegetation development states (Santana et al. 2011; Baeza and Santana 2015; Keane 2015; Bohlman et al. 2018). The present study discovers how fuel load and its fractions vary throughout the studied species' ontogenetic development. Knowing fuel dynamics over time helps to identify changes in vegetation's flammability. The load values of fuel types in their different fractions are determining factors to know the forest fire risk and act as tools to manage vegetation types with higher or lower degrees of flammability.

Our results suggest that fuel load in the studied species follows patterns according to functional trait in response to disturbances. Shrub species like *C. albidus*, *C. clusii*, *S. rosmarinus* and *E. multiflora* present more dead fuel load in more advanced development states (senescent). Nonetheless, *U. parviflorus* displays a different fuel dynamics to these species because it presents a higher dead fuel (twigs) load in the mature state (de Luis et al. 2004; Baeza and Santana 2015), which lowers in more advanced states, but still has high dead fuel percentages (40%). These dead twigs are distributed from the base to a certain height in individuals, which facilitates vertical dead fuel continuity (Santana et al. 2011; Fig. 4). Consequently, the structure of these shrubs is highly flammable (Baeza and Santana 2015). Nevertheless, tree- or semitree-shaped species (*J. oxycedrus*, *Q. coccifera, P. halepensis* and *Q. ilex*) always present low dead fuel load (dead twigs) in more advanced development states. These four above-cited species display higher total height, while the dead height values remain low while they grow (Fig. 4). Those species with postfire seeder strategies present more fine fuel than those with non-seeder strategies (Saura-Mas et al. 2010; Baeza and Santana 2015). Our results coincide insofar as seeder species accumulate more twigs in both living and dead fuel. Resprouters generally present lower dead fuel load than seeders (Baeza and Santana 2015). The living/dead fuel ratio and its change over development state are involved in modulating vegetation's flammability and, therefore, in fuel use and during fires (Keeley et al. 2011; Santana and Marrs 2014; Andrews 2018). High dead fuel loads, especially in fine fractions, can lead to very severe fires (de Luis et al. 2005; Keeley et al. 2008; Fernandes 2013; Santana et al. 2014).

Fuel structure, particularly the relationship between living and dead fuel, is key to control flammable species by means of management. Handling fuel to reduce the fire risk is the normal practice to diminish plant communities' flammability (Turco et al. 2019; Keeley et al. 2011). Mechanically or manually clearing modifies the connectivity and structure of fuel by reducing its flammability and ignition risks (Baeza and Santana 2015; Pausas and Bradstock 2007). It has been argued that clearing in very flammable plant communities of obligate seeder species must be applied to scrublands in mature development states to obtain very efficient results (Baeza et al. 2003; Baeza and Vallejo 2008). These studies evidence that dead fuel height along individuals' stems is key to efficient control these species. The marked dependence between cutting height and dead shoot height could explain the mortality of these individuals. That is to say, the mortality of these individuals depends on the vertical dead fuel distribution. This is evident when clearing machines are used; if they make the cut at the height of the dead fuel, the individual dies, but if the cut is made at the height of the living fuel, this individual survives the clearing treatment (Baeza et al. 2003). We find that certain species possess a fuel structure that may favor vertical connectivity (ladder fuels); for example, *C. albidus* and *U. parviflorus* present a dead fuel height that comes close to individuals' total height. What this tells us is that, throughout development, dead fuel, which is dominated by fine fractions, accumulates until the total height of these species' individuals is reached, which makes them extremely flammable. Mechanical clearing could eliminate 100% *C. albidus* and *U. parviflorus* individuals at intermediate ages of 5–7 years, while clearing in species like *P. halepensis* should wait until the age of 14–15 years. Management for controlling flammable species, like mechanical clearing breaks vertical fuel continuity, reduces the fire risk in tops of tree communities and prevents plant community degradation by conferring the ecosystem greater resilience (de Luis et al. 2005; Keeley et al. 2008; Halofsky et al. 2011; Fernandes 2013).

Conclusion

Knowing simple structural variables like basal stem diameter, height, maximum and perpendicular crown diameters can help to predict the studied species' fuel. Basal stem diameter is the structural variable that explains most variation to estimate fuel in all the studied species and, consequently, presents the highest coefficients of determination. From fuel's structural, we observe that the highest coefficient of determination values are for total and living fuel, with lower values for twigs.

In species' different development states, and particularly in the dead/living fuel relationship, fuel structure allows greater or lesser flammability to be determined among different species. Resprouter species, which are less capable of accumulating dead fuel, are less flammable species than seeder species, which are characterized by accumulating large amounts of dead fuel.

We generally note dead fuel load patterns with development state, which allow optimum ages to be established for applying fuel control treatments to reduce these plant communities' flammability and to, thus, manage the forest fire risk.

Synthesis

1. In this study, we observed that basal stem diameter is the structural variable with the greatest robustness to calculate fuel load of studied species.
2. To know how fuel structure develops throughout species ontogeny, and especially the relationship between living and dead fuel, is key information for planning management actions to reduce fire risk.
3. Fuel discontinuities at intermediate development stages reduce ecosystems flammability, as well as ignition risk. For this reason, it is necessary to know how vegetation grows, not only in terms of fuel load, but also along its vertical structure.

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Author contributions Conceptualization was provided by M.J.B.; methodology was given by M.J.B., L.D. and V.M.S.; formal analysis and investigation were performed by L.D. and V.M.S.; writing—original draft preparation was prepared by L.D.; writing—review and editing were drafted by M.J.B. and V.M.S.; funding acquisition was approved by M.J.B.; resources were developed by M.J.B. and V.M.S.; supervision was conducted by M.J.B. and V.M.S.

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Data availability Once the document is accepted, the data sets generated and analyzed during the current study will be available in a repository.

Declarations

Conflict of interests The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

Code availability Not applicable.

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