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ORIGINAL PAPER

A simple model for shrub-strata-fuel dynamics in *Quercus coccifera* L. communities

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Abstract

- ***Key message*** **We model the dynamics of fuel characteristics in shrub strata dominated by *Quercus coccifera* L. with data gathered in available literature. The model expresses the variability of this important fire-prone fuel type thanks to yield classes, and it can be used to investigate management scenarios. The approach could easily be applied to other shrub communities.**
- ***Context*** Characterizing fuel is a basic requirement for fire hazard assessment. *Quercus coccifera* L. is present in several Mediterranean fire-prone communities, and its fuel characteristics have been studied over various Mediterranean countries, but no general model describes its dynamics.
- ***Aims*** Herein, we present such a general model, initially developed for operational purposes at the French Forest Service.
- ***Methods*** We review available literature and fit statistical relationships to predict the dynamics of fuel height and biomass, by size categories of fine fuel elements.
- ***Results*** The model estimates fuel characteristics from shrub-strata age, overstorey cover, and yield class with a reasonable degree of accuracy considering the heterogeneity of the datasets. It shows that bulk density is highly sensitive to overstorey, and in a lesser extent to strata age, which could lead to significant bias when assessing fuel properties from general allometries. The model is integrated in the FuelManager software, which is devoted to fuel modeling for physics-based-fire-behavior models.
- ***Conclusion*** This simple approach enables to provide a fuel model for the *Quercus coccifera* L. shrub strata in the Mediterranean basin. It is more general than the existing relationships available for local data. This approach could be generalized to other fire-prone communities.

Keywords Fire hazard · Mediterranean basin · Fuel accumulation · Understorey · Kermes oak · Fuel load

1 Introduction

Wildland fire behavior is a product of weather, topography, human intervention, and fuel properties at the time a fire occurs (Duff et al. 2017). Characterizing fire hazard generally requires the quantification of fine fuel elements that can be expressed directly as fuel properties, such as fuel load (in kg m^{-2}) or more commonly as the potential fire behavior (Hogenbirk and Sarrazin-Delay 1995). Significant effort has been made to estimate the potential fire behavior as the fireline intensity (energy released by meter of fireline length, in kWm^{-1}) at several scales, from laboratory to landscape scales, with a large variety of tools from empirical to physics-based models (Sullivan 2009a, b). Most models require the strata height, load, and moisture of fine fuel elements, potentially by status (living or dead) and size category (e.g., Anderson et al. 2015; Rothermel 1972). Other characteristics may be required, such as mass-to-volume and surface-to-volume ratios, as well as spatial fuel distributions (e.g., in Pimont et al. 2011; Pimont et al. 2016).

Shrubland is one of the most important fuel types in the Mediterranean basin and has long been associated with

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frequent forest fires. *Quercus coccifera* (*QC*) is a slow-growing, stress-tolerant, evergreen, resprouting oak that is present in the meso-Mediterranean belt (Paraskevopoulos et al. 1994; Moreno and Oechel 1994). It mostly grows in shrub strata below 2 m, and hardly exceeds 1 m in the thermo-Mediterranean (Le Houérou 1981). *QC* is a dominant species in fire-prone communities that cover 2 million ha, in open mixture of sclerophyllous species (garrigues) and in the understorey of *Pinus brutia* and *Pinus halepensis* forests (Le Houérou 1981; Koukoura 1987). In such fuel types, the open mixture or the understorey consists of a layer of the fuel complex, later referred to as *QC* strata. Characterizing *QC* strata have received attention in several studies, but field data are often scattered across publications.

The fuel characteristics of *QC* strata can be averaged over various sites (Dimitrakopoulos 2002). However, there is an increasing recognition of the dynamic nature of fuel and of the loss of information resulting from the summarization into site level classes (Duff et al. 2017; Terrier et al. 2017). Recent research has shown the limits of predefined fuel types when characterized by their dominant species only, since the variability within a fuel type is often of similar magnitude than the variability between fuel types (Thomson et al. 2016). The development stage is recognized as a major factor of variability within plant communities (Baesa et al. 2006) that affects management scenarios (Cassagne et al. 2011). Fuel accumulation models or biophysical models account for the development stage, through the age of the shrub strata (Gould et al. 2011; Duff et al. 2012), but similar models are not available in the Mediterranean basin, to the best of our knowledge. The dynamics of Mediterranean shrublands has mostly been modeled as a gap model, which estimates species occurrence and cover (Pausas et al. 1999; Rego et al. 1993), but seldom the other fuel characteristics. Landscape fire-succession models apply functional processes to vegetation cohorts and include fuel accumulation (Keane et al. 2004; Mouillot et al. 2001). However, the fuel accumulation is a secondary objective in these types of model.

Several factors affect the dynamics of fuel characteristics in the *QC* strata. The presence of overstorey modifies the light availability, which affects its growth (Koukoura 1987; Pimont 2004), architecture (Pimont 2004), leaf angle (Werner et al. 2001; Balaguer et al. 2001), size (Koukoura 1987; Balaguer et al. 2001; Pimont 2004), and area-to-mass ratio (Balaguer et al. 2001), even if the sensitivity to light is more limited than in other Mediterranean communities (Valladares et al. 2000). The dynamics are also affected by soil and climate (Braun-Blanquet et al. 1952) and historical disturbances, such as land abandonment, fire, fuel-treatment type, and frequencies (Delitti et al. 2005). First signs of senescence are observed after 30 years old (Trabaud 1991).

The aim of the present paper is to build simple temporal models for fuel loads (leaves and twigs of shrubs, herbs) and for height of the whole shrub strata (which can be either garrigue or pine understorey) in communities dominated by *QC*. We review published and unpublished literature reporting measurements of fuel loads and height in these communities, and we apply statistical analysis to parameterize the fuel models based on a total number of 113 sampled plots. To formulate the models, we hypothesize that the temporal variations (i.e., age) of fuel load and strata height depend on (1) the productivity of the sampled plot and (2) the presence of a significant tree cover, which affects energy supply to the understory. In particular, we grouped sampled plots in five yield classes, each characterized by a potential shrub fuel load or height reached by old communities. We then discuss the model results and applications.

2 Material and methods

2.1 Available data

The different datasets used in the present study are summarized in Table 1. Among studies reporting biomass in *QC*-dominated shrub strata, we select those including the date of the last disturbance (generally a clearing or a fire). This time period since last disturbance is referred later as the strata "age" as in Gould et al. (2011), even if this term is not entirely appropriate for a resprouter. Total loads and strata age are reported in Trabaud et al. (1985), Sala and Sabaté (1987), Trabaud (1990, 1991), Cañellas and San Miguel (2000), or Kaye et al. (2010). Estimations of fine fuel loads, such as herb, leaves, or fine twigs require fastidious vegetation sorting so that the fuel biomass per size category is less frequently available (Landreau 1988; Sala and Sabaté 1987; Trabaud 1990; Bardaji Mir 1996; Cañellas and San Miguel 2000; Delitti et al. 2005). Strata are referred to as "Understorey" or "Garrigue", depending on the presence of pine canopy above the strata. Studies reporting height and age are rather limited (Sala et al. 1987; Cañellas and San Miguel 2000; Pimont 2004). Pimont (2004) analyzed the architecture of 84 stems collected in Southern France in 12 different growth environments (dataset G9 and F4 in Table 1).

2.2 Statistical analysis and model assumptions

A variance analysis showed that strata age (AGE) and tree canopy presence/absence (P_{Tree}) or tree canopy cover (C_{Tree}) were significant for fuel load and height. Several classical accumulation or growth distributions, including Gompertz, Lundqvist-Matern, Lundqvist-Korf, Chapman-Richards, as well as usual Weibull, logistic, logarithmic, power, and exponential functions (Panik 2014) were fitted to the data, as a function of strata age and canopy cover/presence. Only the best function forms are presented in the next section for concision.

Table 1 Main characteristics of the datasets reporting a date since last disturbance of *QC* strata (strata age)

Code	Strata location	Plot number	Age range (years old)	Overstorey	Collected data description	Reference
G1	Eastern Spain	18	[1–40]	No	Leaf and total loads	Cañellas and San Miguel (2000)
G2	Southern France	17	[2–36]	No	Shrub and herbaceous loads	Trabaud (1991)
G3	Southern France	3	[3–33]	No	Leaf, small twigs ([0–2.5 mm], and [2.5–5 mm]) shrub loads	Trabaud (1990)
G4	Eastern Spain	10	[3.5–40]	No	Herb, shrub, and total loads	Delitti et al. (2005)
G5	South-Eastern France	16	[0.7–3.7]	Very low cover	Total, leaf, small twigs, ([0–2 mm] and [2–6 mm]) biomass	Landreau (1988)
G6	Eastern Spain	5	[1–13]	No	Leaf fraction	Sala and Sabaté (1987)
G7	South-Eastern France	3	[2.7–30]	No	Phytomass: total, leaf, small twigs ([0–2 mm] and [2–6 mm])	This study
G8	South-Eastern France	3	[1–6]	No	Phytomass: total, leaf, small twigs ([0–2 mm] and [2–6 mm])	Bardaji Mir (1996)
G9	Southern France	4	[1–15]	No	192 annual shoot lengths (21 stems)	Pimont (2004)
F1	Southern France	17	[0.7–30]	*Pinus halepensis*	Shrub and herbaceous biomass	Trabaud et al. (1985)
F2	Southern France	15	[1–27]	*Pinus halepensis*	Shrub and herbaceous biomass	Trabaud et al. (1985)
F3	Eastern Spain	17	[0.5–32]	*Pinus halepensis*	Total biomass. Herb fraction for 6 of them	Kaye et al. (2010)
F4	Southern France	8	[1–15]	*Pinus halepensis*	575 annual shoot lengths (63 stems)	Pimont (2004)

F4 and G9 datasets provided diachronic time series for height, through annual growth measurements on identified stems as a function of canopy cover. The residual variability of fitted time series was modeled as a random effect in a mixed-effect model. For the sake of simplicity, we assumed (Assumption 1) that the random effect applied to potential height only (i.e., the height reached when strata is old). Potential-height estimates were used to define five yield classes, corresponding to the means of potential-height quintiles.

Since other datasets, which provided load, were synchronic, a similar approach could not be applied. We thus assumed that the yield of a given site could be expressed by its potential load W_∞ (i.e., the load reached when strata are old). We first fitted a regression model of total fuel load with age and tree presence as independent variables by merging all sampled plots. Then, for each of the 113 load samples, we estimated W_∞ from this regression model (Assumption 2) and used these estimates to define five yield classes, corresponding to potential load quintiles. Finally, we carried out a mixed-effect regression on grouped data to compute estimates of W_∞ for each yield class and final parameter estimates for age and tree presence effects.

The load model was fitted using a binary variable describing the presence/absence P_{Tree}, since the actual tree canopy cover was not often available. We then assumed that the effect of the tree cover fraction on the shrub load was linear and that sites referred to as "garrigue" and "forest" respectively correspond to tree cover fraction close to C_{Tree} of 0 and 0.75 (a typical cover fraction in Aleppo pine ecosystems, Assumption 3). The model can thus be function of the tree canopy cover (instead of presence/absence) to account for the intermediate range of overstorey observed in nature.

We expressed the leaf load as its ratio to total load and the twig load as its ratio to leaf load. These ratios are typically function of the development stage (Baesa et al. 2006), the leaf ratio decreasing with age (Sala and Sabaté 1987). Since leaf and twig samples were small (36 and 9, respectively), we neglect the site-dependency of these ratios and modeled them as a function of strata age only (Assumption 4).

Finally, we assumed that the five yield classes obtained for height and load models are identical (i.e., smallest shrubs exhibit the lowest load, etc. Assumption 5). This assumption was supported by the positive correlation observed between load and height in *QC* shrubland (e.g., Landreau 1988; Bardaji Mir 1996; Yasin and Bahtiyar 2014), as well as in other shrublands (e.g., Pearce et al. 2010).

The regression analysis was carried out using the Statistical Toolbox of the *MATLAB software*. Non-linear and non-linear mixed-effect regression used functions *nlinfit* and *nlmefit*. For concision, standard errors on model coefficients are reported in Supplementary 1.

Data availability All data generated or analyzed during this study are included in this published article and its supplementary information files.

3 Results

3.1 Total biomass model

The best regression model for total load (kg m^{-2}) without distinction of yield classes is based on a Lundqvist-Korf distribution (Panik 2014), and includes an effect of the overstorey presence/absence:

$$\hat{W}^{tot}(AGE, P_{Tree}) = W_\infty \exp\left(-2.91 AGE^{-0.419} - 0.706\, P_{Tree}\right) \quad (1)$$

with $W_\infty = 5.33$ kgm^2 and $P_{Tree} = 0$ for "garrigue" and $P_{Tree} =$ 1 for "understorey."

The determination coefficient is $R^2 = 0.835$. The RMSE is 0.299 kg m^{-2} (31.5% of the mean value).

The model is generalized replacing P_{Tree} by $C_{Tree}/0.75$, with C_{Tree} the overstorey cover fraction (Assumption 3). Following Assumption 2, the mixed-effect regression based on grouped load samples leads to

$$W^{tot}(AGE, W_\infty, C_{Tree}) = W_\infty \exp\left(-2.74 AGE^{-0.383} - 0.902\, C_{Tree}\right) \quad (2)$$

with $W_\infty \in \{3.22, 4.20, 5.10, 6.07, 7.36\}$ kg m^2, corresponding to five yield classes.

Field data and predictions from Eq. 2 for the five yield classes are shown in Fig. 1. Loads are much higher in "Garrigue" (subplot a), than in "Understorey" (subplot b). The range of variability of the model includes the field data, with the exception of earlier stages.

3.2 Fine fuel model

The fine fuel of shrub W^{fine}_{Shrub} (in kg m^{-2}) is (Assumption 4)

$$W^{fine}_{Shrub} = W^{tot}\, F_l (1 + F_{02\_l} + F_{26\_l}) \quad (3)$$

where F_l is the ratio of leaf to total load and F_{02_l} and F_{26_l} are respectively the ratios of 0–2-mm twigs and 2–6-mm twigs to leaf loads.

Fitted with datasets G1, G3, G4, G6, G7, and G8, the model fits for these ratios are (Fig. 2)

$$F_l = \frac{0.792}{(2.93 + AGE)^{0.402}} \quad (4)$$

$$F_{02\_l} = 0.501\, AGE^{0.173} \quad (5)$$

$$F_{26\_l} = 0.520\, AGE^{0.300} \quad (6)$$

Combining Eqs. 3 to 6, the fine fuel model for shrub is

$$W^{fine}_{Shrub}(AGE, W_\infty, C_{Tree}) = W^{tot}(AGE, W_\infty, C_{Tree})\, F_l(AGE)(1 + F_{02\_l}(AGE) + F_{26\_l}(AGE)) \quad (7)$$

3.3 Herb load model

The herb load model (Eq. 8) suggests that the load reaches a maximum value 8 to 10 years after fire (Fig. 3):

$$W_{Herb} = (0.0226\, AGE + 0.0767)\exp(-0.0760\, AGE) \quad (8)$$

However, the determination coefficient of the regression is poor ($R^2 = 0.15$) and the RMSE is high (61% of the mean value).

An alternative approach based on phytomass/phytovolume relations (Armand et al. 1993) is probably more accurate than Eq. 8 above, when cover fraction and height are known. In this case, herb load can be roughly estimated, assuming a typical 0.3-m-height strata with a 1.5 kg m^{-3} bulk density:

$$W_{Herb}\,(C_{Herb}) = 0.45\, C_{Herb} \quad (9)$$

3.4 Fuel height model

The mixed-effect model fitted on datasets G9 and F4, with a random effect α related to plot productivity, is

$$H(AGE, \alpha, C_{Tree}) = (\alpha + 0.143\, C_{Tree})\log(AGE + 0.736) \quad (10)$$

The determination coefficient of the regression is 0.944, and the RMSE is 8.3% of mean height. The model fit is shown in Fig. 4 for the four C_{Tree} classes. We define yield classes by

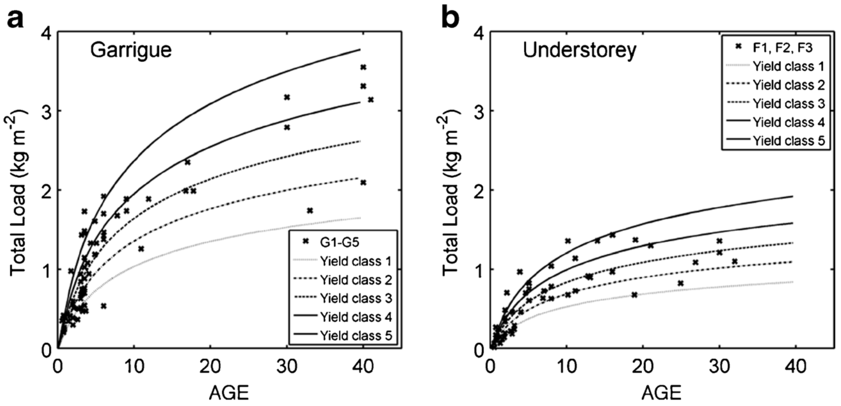
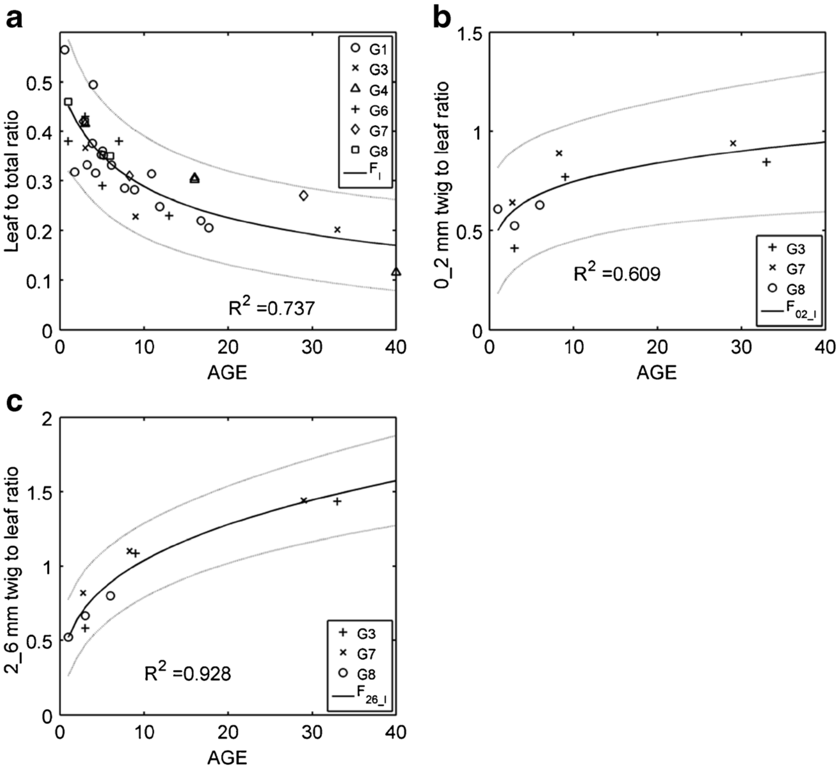


Fig. 1 Prediction of the load models, as a function of AGE (in years) (Eq. 3), and field data. **a** W^{tot} for garrigue ($C_{Tree} = 0$). **b** W^{tot} for understorey ($C_{Tree} = 0.75$)

Fig. 2 Model fits for fine fuel and field data, as a function of AGE (in years). **a** Leaf to total load ratio. **b** 0–2-mm twig to leaf load ratio. **c** 2–6-mm twig to leaf load ratio. Note that twig loads from G3 are multiplied by respectively 2.5/2 and (6–2.5)/(5–2.5) since raw data are originally sampled on 0–2.5- and 2.5–5-mm twigs



the five quintiles of the distribution of the α estimates obtained for each stem ($\overline{\alpha}\in\{0.153; 0.206; 0.240; 0.282; 0.364\}$). We assume that yield classes match the load classes defined above (Assumption 5). Since we found that $\alpha = 0.0479\mathrm{W}_\infty$ ($R^2 = 0.989$), Eq. 10 becomes

$$\begin{aligned}&\mathrm{H}(\mathrm{AGE}, \mathrm{W}_\infty, \mathrm{C}_{\mathrm{Tree}})\\&\quad = (0.0479\mathrm{W}_\infty + 0.143\ \mathrm{C}_{\mathrm{Tree}})\log(\mathrm{AGE} + 0.736) \qquad (11)\end{aligned}$$

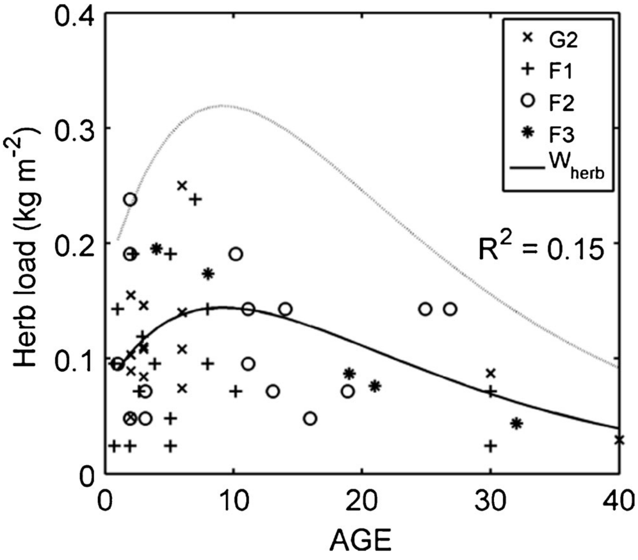


Fig. 3 Herb load model and field data, as a function of AGE (in years)

3.5 Fuel model for fine fuel loads, height, and bulk densities

The fuel model is the combination of Eqs. 7, 2, 4, 5, 6, 8 (or 9), and 11. The mean bulk density (kg m^{-3}) is the ratio between the fine fuel load (Eq. 7) and the strata height (Eq. 11). Simulation examples are shown in Supplementary 2, for three yield classes, three canopy covers, and for strata age ranging between 1 and 30 years old. These simulations show that the fuel bulk density varies within a 0.65 to 3 kg m^{-3} range, depending on strata age and tree canopy cover, and to a lesser extent on strata yield class. Supplementary 3 shows the strata composition (herb, leaf, 0–2- and 2–6-mm twigs), expressed in terms of fuel load.

4 Discussion

4.1 Comparison of the model predictions with other existing data

The above model predicts the main fuel characteristics (fine fuel loads per class size, corresponding bulk densities, and height) in a dynamic model able to account for fuel accumulation over time (strata age) and environmental factors such as overstorey cover and yield classes, and thus accounts for the observed variability between sites. With the exception of herb

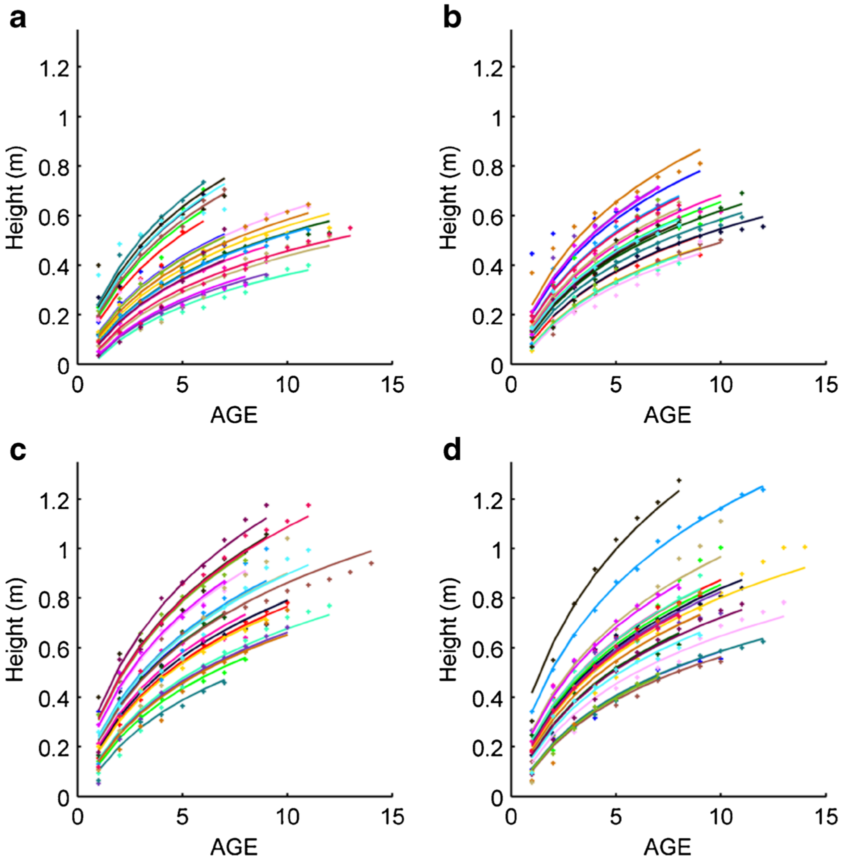


Fig. 4 Height model adjustment for four different canopy covers, as a function of AGE (in years). **a** $C_{Tree} = 0$. **b** $C_{Tree} = 0.25$. **c** $C_{Tree} = 0.5$. **d** $C_{Tree} = 0.75$. Each color corresponds to a given stem, the dots corresponding to field data, whereas the line corresponds to model fit

loads, model fits are generally satisfactory, but need further evaluation. Indeed, we used all datasets for which strata age were reported to fit our models, so that no independent dataset remained for evaluation. However, we checked the model likelihood with the datasets for which strata age and yield class are unknown, by inversing our models to infer potential corresponding strata age and yield class. The fuel model for the Greek *QC* garrigue reported in Dimitrakopoulos (2002) is 1.24-m high and has fuel loads of 0.675 and 1.27 kg m^{-2} for leaves and 0–6-mm twigs, respectively. Our model predicts similar characteristics (within less than 10%), for a 25-year-old strata in a yield class intermediate between 4 and 5. Saura-Mas et al. (2010) report a fine to total load ratio for non-seeders of 0.68 in Spain. This corresponds to a 24-year-old garrigue with our model. The total load is between 2 and 3 kg m^{-2}, which corresponds to 24-year-old garrigue of the 2nd and 3rd yield classes. Sağlam et al. (2008) reported fine fuel loads between 0.62 and 2.93 kg m^{-2}, and a mean value of 1.39 kg m^{-2} in Turkey. This is typically the range of prediction of the fine fuel model, and the mean value corresponds to a medium-yield-20-year-old garrigue. Yasin and Bahtiyar (2014) reported a leaf-to-branch mass ratio of 0.348 in South-West Turkey and heights between 0.37 and 1.90 m. This again matches the prediction of our model for a 24-year-old garrigue. Regarding the effect of canopy openness on load, Koukoura (1987) reports a production that is 48% higher in sun plant than shade plants, which corresponds to a canopy cover of a little more than 50% according to our model.

Regarding strata heights, Cañellas and San Miguel (2000) report nine strata heights in Spain for shrublands between 0.6 and 40 years old. According to our model, they correspond to yield classes 3 to 5, with the exception of a 5-year-old garrigue of 1.2-m height, that is out of range of model prediction (Fig. 4a). Sala and Sabaté (1987) in Spain reported four maximum heights for shrublands between 1 and 13 years old, corresponding to the 5th yield class. Similar data are provided in Trabaud (1983) in France and corresponds to a yield class intermediate between 3 and 4. Under a pine canopy with 50% cover, Konstantinidis et al. (2005) reported a 49-year-old-strata height of 1.49 m, which is between yield classes 4 and 5, but 1- and 2-year-old resprouts of 0.8 and 0.9 m, which is much higher than the model prediction for the same classes (0.23 and 0.43 m). Regarding the effect of the light environment, Trabaud and de Chanterac (1985) report shoot lengths significantly longer in the presence of the overstorey, as in our model (30% compared to 28% for the 8-year-old stand). However, the observed effect for the first year is much higher (157%) than with the model. This effect is due to competition for light (Koukoura 1987; Pimont 2004). Koukoura (1987) reports an average increase by 35%, which is again in agreement with the predictions of our height model (30%).

The above comparison shows that model predictions are at least plausible with data collected around the Mediterranean basin, with the exception of the very early stages (1- or 2-year-old strata), for which both height and load can be underestimated by the model.

4.2 Model limitations

This inability of the model to render the observed variability in the earlier stages can also be seen in Fig. 1 for total biomass, Fig. 3 for herb biomass, or Fig. 4 for height. The initial growth depends on parameters such as climate or fire/prescribed burning intensity (Trabaud and de Chanterac 1985) and the role of multiple disturbances (Diaz-Delgado et al. 2002), which are not included in the model. Such effects are difficult to account for and tend to lessen over years. However, the residual variability remains very high for herb load. A part of the observed variability is explained by disturbance type and frequency, as well as shrub cover (Trabaud 1991; Lloret and Vilà 1997; Delitti et al. 2005; Trabaud et al. 1985). As suggested above, the alternative approach based on phytovolume is more appropriate when height and cover are known. It should be noticed that Eq. 9 is supported by Dimitrakopoulos (2002), who reported a 0.485 kg m^{-2} load in a 0.3-m-height grassland (with $C_{Herb} = 1$).

More generally, despite the remarkable capacity of *QC* to withstand disturbances (Tsiouvaras et al. 1986), increasing disturbance frequency tends to limit the fraction of *QC* and its growth rate, leading to higher herb loads and lower shrub loads in frequently disturbed ecosystems (Trabaud 1990, 1991; Delitti et al. 2005; Landreau 1988). Although visible in datasets (e.g., Supplementary 4), including such an effect in our simple model is not trivial, since the period of interest for "recent" disturbances is neither clearly defined nor reported in publications. When considering fine fuel however, it is noteworthy that the reduction of total load induced by high disturbance frequency might at least be partially compensated by slightly higher leaf fraction (Delitti et al. 2005; Landreau 1988). In addition, the grazing pressure may also affect fuel mass, with a reduction of 8.5% of the aboveground biomass (Papatheoudorou et al. 1998). Another limit of the present model is that it does not predict shrub-strata cover fraction, contrary to other approaches (e.g., Pausas et al. 1999).

The yield classes of the model are designed to account for the natural variability of QC strata. This can, however, be seen as a limitation since it is not necessarily easy to determine the appropriate yield class of a given site. When the strata age and height are known, the yield class can be estimated inversing the height model or using abacus (Supplementary 2). When this information is not available, the species associated with QC in strata determine the community (Braun-Banquet et al. 1952). The different communities are known to belong to various yield classes (*Rhamno lycoioidis-quercetum cocciferae*, potential *bupleuro-quercetum rotundifoliae*)—from low in association with *Cistus*, *Brachypodium retusum*, and *Rosmarinus officinalis* to high in association with *Bupleuro* or *Ulex* (Dureau 2003; Trabaud 1991; Cañellas and San Miguel 2000).

4.3 Model outcomes

Our approach shows a significant impact of strata age and canopy overstorey on fuel properties of the QC strata. Height and load both increase with age, before saturating after roughly 15 and 30 years (Supplementary 2). The impact of tree canopy is more contrasted, since strata are higher, but also lighter under pine forest. It is thus important to consider this factor, when estimating *QC*-strata fuel loads (typically in fire prevention plan). Also, the bulk density of the strata, which is the ratio between load and height, strongly decreases with canopy cover, leading to a wide range of values (1–3 kg m^{-3}) depending also on the canopy cover. This outcome has several important consequences. First, given a same wind speed above the shrub strata (i.e., the wind that drives the fire in the shrub strata, as in Rothermel 1972 for example) and same moisture conditions, the fire spread rate is expected to be faster in the shrub strata when a canopy cover is present than in the open, because spread rate decreases as bulk density increases (i.e., effect of fuel layer compactness, Rothermel 1972; Marino et al. 2012). More generally, the bulk density affects the fire behavior in a complex manner, because fire intensity is proportional to both the fuel load (product of bulk density and fuel height) and the rate of spread (negatively correlated to bulk density).

Second, the approach based on phytomass/phytovolume allometries, which is a common method for the estimation of fuel loads (e.g., Armand et al. 1993), should be applied with caution to the QC strata. Indeed, the differences between bulk densities suggest that the allometric equations differ, whether an overstorey is present or not. Such differences would lead to an overestimation of fuel load by a factor three, if, for example, an allometry fitted with data collected in open stands was applied to a shrubland below a dense tree cover, leading to a wrong estimate of fire behavior. In a lesser extent, bulk density is also affected by strata age, slightly decaying over time. This suggests that strata age should also be considered when assessing fuel properties with allometric equations. Existing allometries should thus be applied with caution to different environments. It is noteworthy, however, that the dependency of bulk density to yield class is weak, even if it might partly be a consequence of Assumption 5. Our results demonstrate the importance of designing models of fuel dynamics, hence depending on age, and to incorporate factors such as tree canopy cover, to avoid strong bias in predictions of fuel load.

This model was initially developed for application to fire risk assessment in fire prevention plan by the French Forest

Service (ONF). It has been used to provide ranges to fuel loads corresponding to three typical garrigue fuel types of various heights and to the understorey of three pine forest fuel types with various cover. It is integrated in the FuelManager (http://capsis.cirad.fr/capsis/help/fireparadox, Pimont et al. 2016), which is a software, designed to virtually build 3D fuel inputs for physics-based fire models.

5 Conclusion

The present study develops a dynamic model to describe the characteristics of *Quercus coccifera* fuel strata in the context of fire hazard assessment. Based on datasets available over the Mediterranean basin, a model for strata height and fine fuel loads is proposed and present a reasonable degree of accuracy considering the heterogeneity of the datasets. The model development relies on simple assumptions that are consistent with existing data when available. Such a model is useful to assess fire hazard, when combined with a fire model, which can thus be expressed as a function of the time since the last disturbance, the yield class, and the overstorey cover. Among other outcomes is the fact that the allometric equations which do not include age and overstorey effects should be applied with caution. The approach used in the present study opens the door to similar generalized models in other fuel types when data are available.

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Compliance with ethical standards

Conflict of interests The authors declare that they have no conflict of interest.

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