Litter and biomass traits of some dominant Moroccan understorey fuels in five fire-prone forest regions

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Photo 1.
Undergrowth after a fire in the Western Rif, Morocco.
Photo M. Qarro.

Doi : 10.19182/bft2019.342. a31588 – Droit d'auteur © 2019, Bois et Forêts des Tropiques © Cirad – Date de soumission : 18 juin 2018 ;
date d'acceptation : 4 mars 2019 ; date de publication : 15 octobre 2019.

Citer l'article / To cite the article
Essaghi S., Hachmi M., Yessef M., Dehhaoui M., Sesbou A., 2019. Litter and biomass traits of some dominant Moroccan understorey fuels in five fire prone forest regions. Bois et Forêts des Tropiques, 342: 3-16.
Doi: https://doi.org/10.19182/bft2019.342.a31588

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RÉSUMÉ

Caractéristiques de la litière et de la biomasse de certains combustibles de sous-étage marocains dominants dans cinq régions forestières sujettes au feu

Au Maroc, des efforts ont été faits pour prévenir les feux de forêt, même si les résultats ont été limités parce que les propriétés pyrotechniques des combustibles forestiers n'ont pas été quantifiées de façon adéquate. Pour corriger ce manque, les masses volumiques apparentes de litière, d'arbustes individuels et de biomasse par classe de taille ont été évaluées dans cinq régions forestières propices aux incendies. L'étude a couvert un ensemble de 35 sites, sur des pentes exposées au nord et au sud des régions suivantes : Plateau central, Moyen Atlas (occidental et oriental), Rif occidental et pré-Rif. Les profondeurs de la litière vont de 1,1 (*Ononis natrix* L.) à 7,5 cm (*Daphne laureola* L.), et la masse volumique apparente des buissons individuels varie entre 0,35 (*D. laureola*) et 4,64 mg/cm^3 (*Thymelaea tartonraira* L.). La plus basse masse volumique apparente de combustible fin a été trouvée pour *D. laureola* (0,22 kg/m^3), et la plus haute pour *T. tartonraira* (4,05 kg/m^3). Quant à la masse volumique apparente des buissons individuels, aucune différence intra-espèce significative n'a été trouvée entre les régions étudiées, sauf pour *Arbutus unedo* L., alors que l'effet de la région sur la biomasse du combustible fin n'était pas significatif pour toutes les espèces. Des fonctions linéaires ont été utilisées pour ajuster la biomasse du combustible fin pour l'effet du volume de buissons individuels. Ces ajustements seront très utiles pour les gestionnaires forestiers, parce qu'ils permettent d'estimer la biomasse de combustible fin contenue dans un buisson à l'aide de mesures simples et indépendantes de la taille du buisson. L'intégration des données sur des traits structurels des combustibles dans des systèmes de prédiction du comportement du feu facilitera les estimations du risque d'incendie dans les régions étudiées, et guidera les décideurs dans leurs tâches de protection des ressources humaines et naturelles.

Mots-clés : masse volumique apparente, biomasse en fonction de la taille, combustible fin, buissons, incendies, risque d'incendie, modélisation, Maroc.

ABSTRACT

Litter and biomass traits of some dominant Moroccan understorey fuels in five fire-prone forest regions

In Morocco, efforts have been made to prevent wildfires, although with limited results because the pyric properties of forest fuels have not been adequately quantified. In order to remedy this gap, the bulk densities of litter and individual shrubs and biomass per size class were assessed in five fire-prone forest regions. The study covered a total of 35 sites, on both north and south-facing slopes in the Central Plateau, the Middle Atlas (Western and Eastern), the Western Rif and the Pre-Rif regions. Litter depths ranged from 1.1 (*Ononis natrix* L.) to 7.5 cm (*Daphne laureola* L.), and the bulk density of individual shrubs varied from 0.35 (*D. laureola*) to 4.64 mg/cm^3 (*Thymelaea tartonraira* L.). The lowest fine fuel bulk density was found for *D. laureola* (0.22 kg/m^3), and the highest for *T. tartonraira* (4.05 kg/m^3). As for the bulk density of individual shrubs, no significant intra-species differences were found between the sampled regions, except for *Arbutus unedo* L., while the effect of the region on fine fuel biomass was not significant in all species. Linear functions were used to adjust the fine fuel biomass for the effect of individual shrub volume. Such adjustments will be very useful for forest managers, since they will make it possible to estimate the fine fuel biomass contained in a shrub using simple, independent measurements of the shrub size. Integrating data on the structural traits of fuels into fire behaviour prediction systems will facilitate estimations of fuel hazards in the regions studied and thus guide decision-makers in their task of protecting both humans and natural resources.

Keywords: bulk density, biomass per size class, fine fuel, shrubs, wildfires, fuel hazard, modelling, Morocco.

RESUMEN

Características de la hojarasca y la biomasa de algunos combustibles dominantes en el bosque bajo marroquí, en cinco regiones forestales propicias a los incendios

En Marruecos se han realizado esfuerzos para evitar fuegos incontrolados, aunque con resultados limitados porque las propiedades pirotécnicas de los combustibles forestales no se han cuantificado de la forma adecuada. Para remediar esta falta de datos, se evaluaron en cinco regiones forestales con riesgo de incendio: las densidades aparentes de hojarasca y arbustos individuales, y la biomasa por categoría de tamaño. El estudio abarcó un total de 35 zonas, tanto en pendientes de orientación norte como de orientación sur, en las regiones: Meseta Central, Atlas Medio (occidental y oriental), Rif occidental y pre-Rif. Las profundidades de hojarasca fueron de 1,1 (*Ononis natrix* L.) a 7,5 cm (*Daphne laureola* L.), y la densidad aparente de arbustos individuales varió de 0,35 (*D. laureola*) a 4,64 mg/cm^3 (*Thymelaea tartonraira* L.). La densidad aparente de broza inflamable más baja se encontró para *D. laureola* (0,22 kg/m^3), y la más alta para *T. tartonraira* (4,05 kg/m^3). Para la densidad aparente de arbustos individuales no se encontraron diferencias significativas intraespecies entre las regiones muestreadas, excepto para *Arbutus unedo* L. En cambio, el efecto de la región en la biomasa de broza inflamable no fue significativo en ninguna especie. Se utilizaron funciones lineales para ajustar la biomasa de broza inflamable para el efecto del volumen de arbustos individuales. Tales ajustes serán muy útiles para los gestores forestales, ya que harán posible estimar la biomasa de broza inflamable contenida en un arbusto utilizando medidas simples e independientes del tamaño de los arbustos. La integración de datos sobre las características estructurales de los combustibles en sistemas de predicción del comportamiento del fuego facilita las estimaciones de riesgos de incendio en las regiones estudiadas y, por consiguiente, guía a los responsables de toma de decisiones en la protección de los recursos tanto humanos como naturales.

Palabras clave: densidad aparente, biomasa por tamaño, broza inflamable, arbustos, fuegos incontrolados, riesgo de incendio, modelado, Marruecos.

Introduction

In order to prevent wildfires, there is an urgent need to assess the fuel hazard, especially under severe climatic conditions associated with recurrent droughts and heat waves (White and Zipperer, 2010; Ganteaume *et al.,* 2013; Anderson *et al.,* 2015). The fuel hazard can be assessed by quantifying the pyric properties of the species (Dimitrakopoulos and Panov, 2001), determining thereby its flammability (Papió and Trabaud, 1990; Dimitrakopoulos, 2001). Flammability and fire behaviour are mainly determined by the physical arrangement of the plant biomass (Doran *et al.,* 2004; Schwilk, 2015). Indeed, the size and shape of the fuel have, in addition to the environmental conditions, a significant influence on the amount of potential fuel that is actually burned during a fire (Bond and Wilgen, 1996; Pyne *et al.,* 1996; Behm *et al.,* 2004). The flammability of a plant can, therefore, be manipulated using horticultural practices (Narog *et al.,* 1991; Schwilk, 2003; Behm *et al.,* 2004; Ganteaume *et al.,* 2013). Silvicultural operations that alter the shape and size of shrub individuals may be considered as part of forest fire management. In this sense, the quantification of the fuel bulk density (live aboveground biomass or litter) is an effective tool for assessing the overall fuel load of the forest (Keane *et al.,* 2005), while the estimation of its distribution by size class subsequently gives an idea of the degree of vulnerability of forests to catch fire (Papió and Trabaud, 1990; Behm *et al.,* 2004).

Indeed, the bulk density and fuel load per size class are among the most important characteristics of the fuel particles involved in fire risk determination (Papió and Trabaud, 1990; Schwilk, 2003). In addition, bulk density and fuel load per size class are input variables in fire behaviour prediction systems, such as BehavePlus (Andrews, 2014) and FARSITE (Finney, 1998). Their integration would help to predict fire behaviour and contribute to the prevention of wildfires (Keane, 2015). The bulk density and the proportion of fine fuels are also considered the best descriptors of flame duration (Ganteaume, 2018). The fuel bulk density influences the individual shrub flammability, especially the flame spread rate, combustion efficiency and heat release (Rothermel, 1972; Doran *et al.,* 2004; Scarff and Westoby, 2006; Fernandes and Cruz, 2012; Pausas *et al.,* 2012; Pausas and Moreira, 2012; Keane, 2015; Schwilk, 2015; Grootemaat *et al.,* 2017; Pausas *et al.,* 2017). Indeed, bulk density is inversely related to fire spread rate and fire intensity (Thomas, 1971; Rothermel, 1972; Butler *et al.,* 2004; Scarff and Westoby, 2006). It affects the thermal conductivity of the fuel by acting on the air/fuel mixture and subsequently on the ignition delay (Anderson, 1970; Rothermel, 1972; Dimitrakopoulos and Panov, 2001; Schwilk, 2003). The role of bulk density in determining fire behaviour is all the more critical, in that it can replace fuel chemistry and morphology in determining fire hazards by cancelling their effect (Grootemaat *et al.,* 2017). Moreover, litter fuel load is among the factors that determine the individual shrub flammability at the organ, individual and population scales (Pausas *et al.,* 2017). It is interesting that, in some ecosystems, forest soil elements represent most of the fuel burned during a wildfire. Their quantification contributes largely to the estimation of the damage that can be caused by the passage of fires, in terms of tree mortality, loss of nutrients, soil erosion or air pollution (Hardy *et al.,* 2001; Fowler, 2003; Johnston *et al.,* 2004; Hiers *et al.,* 2005; Ottmar and Andreu, 2007). In addition, a high bulk density is associated with high soil temperatures during a fire and a longer residence time (Bradstock and Auld, 1995; Santana *et al.,* 2011; Pausas *et al.,* 2012; Pausas and Moreira, 2012). Thus, the characterization of the surface layers of forest soil (land cover and soil organic horizons) is of major importance in modelling the effects of forest fires (Ottmar and Andreu, 2007).

In addition, fine fuel biomass (‹ 6 mm in diameter) is a component that determines fuel consumability (Behm *et al.,* 2004), one of the four components of flammability (Martin *et al.,* 1994). The value of considering the contribution of fine fuel biomass is demonstrated by the fact that the size and shape of the fuel influences the potential amount of fuel likely to be burned during a forest fire (Bond and Wilgen, 1996; Pyne *et al.,* 1996; Baeza *et al.,* 2002; Ganteaume *et al.,* 2013). Fine fuel is more flammable than coarse fuel, because fine particles are ignited more easily and release heat more quickly than thicker particles of an equivalent total weight (Wilson, 1992). Leaf biomass is also a major flammability factor (Fernandes and Rego, 1998; Etlinger and Beall, 2004), as the leaf is the most flammable part of the individual shrub (Dimitrakopoulos and Papaioannou, 2001; Grootemaat *et al.,* 2015). The high flammability of foliage and fine individual shrub particles can also be explained *a fortiori* by their high surface area-to-volume ratio (Rothermel and Anderson, 1966; Rundel, 1981; Chandler *et al.,* 1983).

In Morocco, wildfires burn an average of 3,023 ha each year. This area is limited, compared to the average area burned in other countries under similar conditions, particularly in the Mediterranean, although it is worrying, given the major role of forests and the difficulties of their rehabilitation and regeneration in the national socio-economic and environmental situation (HCEFLCD, 2018). In this regard, efforts were made in Morocco to prevent fuel hazards. In addition to assessing the intensity, severity and other characteristics of wildfires across a geographic area (Cherki and Gmira, 2012, 2013; Bacciu and Trigo, 2014; Mharzi Alaoui *et al.,* 2015, 2017), some work has focused on predicting the risk of fire (Assali *et al.,* 2016). The latter work, which could only predict 58% of the fires, concluded that the prediction needs to be made more accurate through a quantification of the fuel load, bulk density and other pyric properties of the fuel in the field (Papió and Trabaud, 1990; Dimitrakopoulos, 2001; Dimitrakopoulos and Panov, 2001; Assali *et al.,* 2016), and not only on the basis of expert opinion (Assali *et al.,* 2016). Indeed, creating fuel maps requires the assessment of fuel parameters in the field (Duff *et al.,* 2017). Some efforts have been made in this spirit (Hachmi *et al.,* 2011a, b; Essaghi *et al.,* 2016, 2017a, b) although they had not addressed the fuel load and structural traits of forest fuel for which there is still a lack. Therefore, there is a pressing need for structural trait data on individual shrubs in Morocco in order to help decision-makers better manage the threat of fire to human populations and natural resources. In addition, the determination of the fine fuel biomass contained in a given shrub requires tedious destructive procedures (Papió and Trabaud, 1990; Pereira *et al.,* 1995; Behm *et al.,* 2004); hence the interest of proposing an easy and rapid non-destructive method that allows for the estimation of the fine fuel biomass from a simple measurement of the volume of an individual shrub.

The initial objective of this study is to fill these gaps by collecting data on bulk density (whether litter or aboveground biomass) and the distribution of fuel size classes in the most fire prone forests in Morocco. In the second stage, an easy and efficient method for the estimation of the biomass of fine fuel, by a simple measurement of the volume of the shrub, will be proposed.

Methods

Study sites

Eighteen localities were chosen in five forest regions, representing the most subjected areas to wildfires in Morocco. These regions included the Western Rif, Pre-Rif, Western Middle Atlas, Eastern Middle Atlas and Central Plateau. Each region experienced no fires for at least three years and comprised shrub species characterizing the respective regions. All studied sites are managed by the Moroccan High Commission for Forests and Combating Desertification.

The distribution of the regions and localities, sampled during the present work, is shown in table I.

In each region, the sampled sites were based on an altitudinal gradient. Indeed, the surveys started from the Larache (Atlantic coast) cork oak forest to the Chefchaouen pinewood in the Western Rif, and from the Marticha pine forests (600 m) to the Bab Boudir (~1,600 m) cedar forests in the Middle Eastern Atlas. Another altitudinal gradient was also followed from the Harcha holm oak forest (the Central Plateau), at ~900 m elevation, to the pine forest of Tamrabta (1,770 m) in the Western Middle Atlas, with the aim of covering most of the characteristic shrub species in the target regions.

Species selection and sampling

In each of the studied regions, the shrub species were chosen according to their abundance in the sites. In order to reach all the characteristic species of each locality, both north- and south-facing slopes (extreme exposures) were sampled at each locality, since the spatial distribution of some species is aspect-induced (Desta *et al.,* 2004; Kimball *et al.,* 2017). Each site corresponds to one aspect, *i.e.*, two sites per locality, as shown in table II. In each site and for each species, three individuals of different sizes were sampled. In total, 333 individuals were harvested from the sites. The individual shrubs were examined during the springs of the years 2014, 2015 and 2016.

The litter and aboveground biomass measurements were carried out in accordance with the method of Behm *et al.* (2004). To assess the litter layer beneath each sampled individual, measurements of the litter depth were performed in three repetitions within a quadrat of 25 cm x 25 cm. The litter was then cut along the inside edge of the quadrat, removed and placed into a sealed plastic bag. Before harvesting the individual shrub, the total height and the height of the lowest branch were measured for each individual. The individual shrubs were not disturbed nor physically extended to take these measurements. The lowest branch measurement was made from the bottom of the litter layer to the point of the

Table I.
Distribution of the localities and sampled regions.

Region	Locality	Longitude North	Latitude West	Altitude (m)
Western Rif	Larache	35° 13’ 45.9”	6° 14’ 25.0”	25
	Ahl Srif	35° 0’ 18.1”	5° 41’ 26.0”	142
	Souk L’Qolla	35° 5’ 4.7”	5° 34’ 18.0”	263
	Dardara	35° 9’ 16.4”	5° 18’ 26.8”	406
	Tanghaya	34° 59’ 32.1”	5° 12’ 1.9”	1,408
	Bellota	34° 56’ 55.0”	5° 31’ 56.1”	128
Pre-Rif	Marticha	34° 27’ 42”	4° 10’ 32.5”	600
	Kaf L’Ghar	34° 29’ 45.2”	4° 10’ 35.7”	861
Western Middle Atlas	Tamrabta	33° 36’ 0.0”	5° 0’ 50.3”	1,770
	Ait Nouh	32° 55’ 41.0”	5° 31’ 35.1”	1,408
	Oum Errabia sources	33° 3’ 45.6”	5° 25’ 0.6”	1,254
Eastern Middle Atlas	Ras L’Ma	34° 4’ 1.9”	4° 7’ 54.0”	1,584
	Bouchfaa	34° 3’ 22.3”	4° 14’ 21.9”	1,067
	Bab Azhar	34° 2’ 47.0”	4° 11’ 39.2”	1,250
Central Plateau	West Harcha	33° 28’ 43.0”	6° 11’ 46.0”	895
	East Harcha	33° 29’ 7.7”	6° 7’ 26.5”	950
	Ait Alla	33° 22’ 21.5”	5° 52’ 23.5”	1,229

lowest vegetation on a branch. If multiple stems from the same individual emerged from beneath the litter layer, then the height to the lowest branch was recorded as zero. Two measurements of the crown width were taken, representing the maximum and minimum widths (widths 1 and 2). The individual shrub was then harvested at the soil line for aboveground biomass measurements (drying and weighing, as explained below). The bulk density was calculated for both shrub individuals and the litter. The bulk density of the individual shrub was calculated by dividing the total dry biomass by the gross individual shrub volume (Behm *et al.*, 2004; Keane, 2015). The gross individual shrub volume is calculated by multiplying the maximum width, the minimum width of the shrub crown and the height of the individual shrub (Behm *et al.*, 2004; Keane, 2015). Thus, the solid assimilated to the individual shrub volume is the rectangular parallelepiped, as suggested by Behm *et al*. (2004) and Keane (2015):

$$\text{Bulk density of individual shrubs} = \frac{\text{dry individual shrub biomass}}{\text{height} \times \text{width}_1 \times \text{width}_2}$$

Table II.
Distribution of the collected species from the sampling sites.

Region	Locality	Aspect	Species collected
Western Rif	Larache	Flat terrain	*Cistus salviifolius* L.
	Ahl Srif	North	*Cistus monspeliensis* L., *Cistus salviifolius*, *Pistacia lentiscus* L.
		South	*Cistus crispus* L., *Cistus monspeliensis*, *Pistacia lentiscus*
	Souk L'Qolla	North	*Cistus albidus* L., *Cistus monspeliensis*, *Pistacia lentiscus*
		South	*Cistus albidus*, *Cistus monspeliensis*, *Pistacia lentiscus*
	Dardara	North	*Arbutus unedo* L., *Cistus albidus*, *Cistus crispus*, *Cistus monspeliensis*, *Erica arborea* L., *Myrtus communis* L., *Pistacia lentiscus*
		South	*Arbutus unedo*, *Cistus crispus*, *Cistus monspeliensis*, *Cistus salviifolius*, *Erica arborea*, *Lavandula stœchas* L., *Pistacia lentiscus*
	Tanghaya	North	*Cistus crispus*, *Cistus monspeliensis*, *Cistus salviifolius*
		South	*Cistus albidus*, *Cistus crispus*, *Cistus monspeliensis*, *Cistus salviifolius*
	Bellota	North	*Arbutus unedo*, *Cistus monspeliensis*, *Cistus salviifolius*, *Erica arborea*, *Myrtus communis*
		South	*Arbutus unedo*, *Cistus albidus*, *Cistus monspeliensis*, *Erica arborea*, *Lavandula stœchas*, *Myrtus communis*, *Pistacia lentiscus*
Pre-Rif	Marticha	North	*Arbutus unedo*, *Cistus creticus* L., *Cistus ladanifer* L., *Cistus salviifolius*, *Pistacia lentiscus*
		South	*Arbutus unedo*, *Cistus creticus*, *Cistus ladanifer*, *Cistus salviifolius*, *Erica arborea*, *Lavandula stœchas*, *Pistacia lentiscus*
	Kaf L'Ghar	North	*Arbutus unedo*, *Cistus creticus*, *Cistus ladanifer*, *Cistus salviifolius*, *Erica arborea*, *Lavandula stœchas*
		South	*Cistus creticus*, *Ononis natrix* L., *Pistacia lentiscus*
Western Middle Atlas	Tamrabta	North	*Cistus incanus* L., *Cytisus triflorus Lam.*, *Thymelaea tartonraira* L.
		South	*Arbutus unedo*, *Cistus incanus*, *Cistus creticus*, *Cytisus triflorus*, *Phillyrea angustifolia* L., *Thymelaea tartonraira* L.
	Ait Nouh	North	*Cistus salviifolius*, *Phillyrea angustifolia*
		South	*Cistus salviifolius*, *Phillyrea angustifolia*
	Oum Errabia sources	North	*Phillyrea angustifolia*
		South	*Cistus salviifolius*, *Phillyrea angustifolia*, *Pistacia lentiscus*
Eastern Middle Atlas	Ras L'Ma	North	*Cytisus grandiflorus (Brot.)* DC, *Cytisus triflorus*, *Daphne laureola* L.
		South	*Cytisus grandiflorus*, *Daphne laureola*
	Bouchfaa	North	*Cistus salviifolius*, *Erica arborea*
		South	*Cistus salviifolius*, *Erica arborea*
	Bab Azhar	North	*Arbutus unedo*, *Cistus salviifolius*
		South	*Cistus salviifolius*, *Erica arborea*
Central Plateau	West Harcha	North	*Cistus ladanifer*, *Daphne gnidium* L.
		South	*Cistus ladanifer*, *Daphne gnidium*
	East Harcha	North	*Cistus salviifolius*, *Daphne gnidium*
		South	*Cistus crispus*, *Cistus salviifolius*, *Lavandula stœchas*
	Ait Alla	North	*Arbutus unedo*, *Phillyrea angustifolia*, *Pistacia lentiscus*
		South	*Phillyrea angustifolia*, *Pistacia lentiscus*

The bulk density of the litter was calculated by dividing the dry litter biomass by the product of the litter depth and the area of the quadrat as follows:

$$\text{Bulk density of litter} = \frac{\text{dry litter biomass}}{\text{litter depth} \times \text{quadrat area}}$$

The bulk densities of the individual shrub and litter are in milligrams per cubic centimetre (mg/cm^3), the dry biomass of the individual shrub and litter in milligrams (mg), the height, width 1, width 2 and the depth of the litter in centimetres (cm). The area of the quadrat is 625 cm^2.

To determine the distribution of the biomass by size class, the aboveground biomass was separated into stems of the following size classes: ‹ 6 mm, 6-25 mm, 26-75 mm, › 75 mm and foliage (Brown *et al.*, 1982; Pereira *et al.*, 1995; Dimitrakopoulos and Panov, 2001).

Litter, leaves and stems less than 6 mm in diameter were dried at 70 °C for 72 hours. The stems with a diameter greater than 6 mm were dried at 70 °C to a constant weight, as suggested by Behm *et al.* (2004). The total dry biomass was calculated for each sample based on

Table III.
Litter and individual shrubs structural traits related to Moroccan forest fuels. Litter depth, height to lowest branch, total height, width and the bulk density of individual shrubs measurements are displayed per species and with ± standard error. Within a column, the species followed by the same letters are not significantly different (p › 0.05) in Tukey's pairwise comparison within a region.

Region	Species	Litter depth (cm)	Litter bulk density (mg/cm^3)	Lowest branch (cm)	Total height (cm)	Width (cm)	Bulk density of individual shrubs (mg/cm^3)
Western Rif	*Arbutus unedo* L.	2.4 ± 0.3b,c	106.0 ± 11.7a	45.0 ± 0.6e	186.5 ± 22.2d	74.7 ± 9.2d	1.88 ± 0.30b
	Cistus albidus L.	2.0 ± 0.3a,b	105.0 ± 13.7a	0.0 ± 0.1a	68.8 ± 5.6a,b	36.6 ± 3.1a	1.47 ± 0.31a,b
	Cistus crispus L.	2.8 ± 0.2b,c	93.1 ± 9.7a	0.0 ± 0.1a	43.4 ± 2.2a	39.6 ± 3.0a	1.11 ± 0.13a
	Cistus monspeliensis L.	2.5 ± 0.2b,c	101.6 ± 10.0a	0.0 ± 0.1a	104.1 ± 5.1b,c	48.2 ± 2.6a,b,c	0.84 ± 0.08a
	Cistus salviifolius L.	2.5 ± 0.2b,c	151.9 ± 15.8a	1.2 ± 0.3b	76.6 ± 6.4a,b	44.5 ± 3.6a,b	1.08 ± 0.12a
	Erica arborea L.	2.1 ± 0.2a,b	117.5 ± 18.4a	2.1 ± 0.2c	137.3 ± 15.8c,d	67.3 ± 8.0b,c,d	0.77 ± 0.08a
	Lavandula stœchas L.	1.2 ± 0.1a	138.3 ± 34.6a	0.0 ± 0.1a	61.5 ± 5.9a,b	35.9 ± 3.2a	0.86 ± 0.18a
	Myrtus communis L.	2.1 ± 0.2a,b	119.5 ± 34.7a	0.0 ± 0.0a	107.2 ± 17.8b,c	53.7 ± 4.4a,b,c,d	0.87 ± 0.11a
	Pistacia lentiscus L.	3.3 ± 0.3c	127.8 ± 12.5a	5.9 ± 0.0d	141.1 ± 14.6c,d	73.0 ± 7.7c,d	0.97 ± 0.12a
Pre-Rif	*Arbutus unedo*	3.6 ± 0.5b	116.6 ± 13.7a,b	29.4 ± 13.5a	190.2 ± 53.4a	117.1 ± 15.1a,b	0.61 ± 0.17a
	Cistus creticus L.	1.5 ± 0.2a,b	180.2 ± 21.9a,b	5.1 ± 3.1a	82.8 ± 11.3a	72.9 ± 10.4a,b	0.49 ± 0.05a
	Cistus ladanifer L.	1.5 ± 0.3a,b	94.0 ± 29.6a	14.9 ± 3.2a	98.2 ± 17.8a	67.3 ± 14.2a,b	0.79 ± 0.08a
	Cistus salviifolius	1.5 ± 0.3a,b	185.3 ± 41.9a,b	0.0 ± 0.0a	72.3 ± 11.2a	67.1 ± 8.7a,b	0.46 ± 0.06a
	Erica arborea	2.6 ± 0.6a,b	93.6 ± 29.0a	4.8 ± 4.8a	129.6 ± 33.4a	100.2 ± 22.4a,b	0.59 ± 0.14a
	Lavendula stœchas	1.6 ± 0.6a,b	291.8 ± 90.4b	0.7 ± 0.7a	49.7 ± 4.4a	41.3 ± 6.9a	0.74 ± 0.20a
	Ononis natrix L.	1.1 ± 0.5a	137.3 ± 137.3a,b	0.0 ± 0.0a	105.0 ± 25.2a	120.5 ± 33.3a,b	0.43 ± 0.15a
	Pistacia lentiscus	3.2 ± 0.5b	154.1 ± 20.5a,b	9.4 ± 9.4a	136.8 ± 25.8a	147.0 ± 35.3b	0.85 ± 0.15a
Western Middle Atlas	*Arbutus unedo*	4.7 ± 0.6b	160.7 ± 38.1a	0.0 ± 0.0a	119.7 ± 42.9a,b,c	163.7 ± 59.7a	1.06 ± 0.27a
	Cistus creticus	3.1 ± 0.6a,b	39.7 ± 15.3a	1.7 ± 1.7a	87.7 ± 28.0a,b,c	61.8 ± 15.6a	0.58 ± 0.10a
	Cistus incanus L.	2.9 ± 0.4a,b	139.4 ± 36.1a	0.0 ± 0.0a	97.2 ± 10.0a,b,c	102.8 ± 12.3a	1.09 ± 0.16a
	Cistus salviifolius	2.2 ± 0.4a	58.4 ± 16.8a	0.0 ± 0.0a	49.9 ± 7.7a,b	38.2 ± 5.4a	1.08 ± 0.22a
	Cytisus triflorus Lam.	2.3 ± 0.3a	143.6 ± 28.4a	3.6 ± 3.6a	180.6 ± 27.2b,c	142.8 ± 21.1a	0.47 ± 0.04a
	Phillyrea angustifolia L.	3.0 ± 0.3a,b	70.0 ± 7.6a	29.7 ± 12.6a	205.6 ± 25.0c	172.4 ± 27.9a	0.60 ± 0.11a
	Pistacia lentiscus	3.1 ± 0.3a,b	69.5 ± 10.8a	5.3 ± 5.3a	148.3 ± 75.2a,b,c	140.3 ± 36.7a	0.79 ± 0.02a
	Thymelaea tartonraira L.	1.9 ± 0.3a	64.8 ± 20.4a	0.0 ± 0.0a	25.4 ± 2.3a	46.5 ± 5.4a	4.64 ± 0.36b
Eastern Middle Atlas	*Arbutus unedo*	6.4 ± 0.9b,c	65.0 ± 8.2a	10.7 ± 6.4b	186.7 ± 66.4b	200.3 ± 54.6b	0.44 ± 0.15a
	Cytisus grandiflorus (Brot.) DC	2.0 ± 0.3a	157.2 ± 11.9a	1.2 ± 1.2a	92.0 ± 20.9a,b	95.9 ± 13.7a,b	0.48 ± 0.16a
	Cistus salviifolius	3.1 ± 0.4a,b	129.0 ± 20.4a	0.2 ± 0.2a	60.4 ± 12.0a	57.7 ± 7.7a	0.73 ± 0.17a
	Cytisus triflorus	3.1 ± 0.7a,b	168.8 ± 55.3a	0.0 ± 0.0a	81.0 ± 27.0a,b	43.5 ± 6.0a	0.36 ± 0.13a
	Daphne laureola L.	7.5 ± 2.2c	153.8 ± 40.3a	0.8 ± 0.8a	88.7 ± 14.4a,b	102.2 ± 22.0a,b	0.35 ± 0.06a
	Erica arborea	4.0 ± 0.6a,b,c	157.6 ± 12.4a	0.0 ± 0.0a	125.8 ± 25.7a,b	163.2 ± 31.9a,b	0.48 ± 0.09a
Central Plateau	*Arbustus unedo*	1.8 ± 0.4a	61.7 ± 25.4a	168.3 ± 23.8b	370.7 ± 107.2b	212.0 ± 34.0b,c	2.19 ± 0.36b
	Cistus crispus	2.1 ± 0.3a,b	49.9 ± 20.5a	0.0 ± 0.0a	69.3 ± 23.6a	74.2 ± 17.9a,b	0.99 ± 0.41a
	Cistus ladanifer	1.6 ± 0.3a	85.6 ± 18.3a	3.8 ± 2.4a	141.6 ± 31.3a	75.3 ± 10.8a,b	0.66 ± 0.09a
	Cistus salviifolius	1.7 ± 0.2a	85.4 ± 18.9a	1.0 ± 1.0a	59.0 ± 9.4a	54.7 ± 9.9a	0.81 ± 0.17a
	Daphne gnidium L.	3.6 ± 0.4b	74.5 ± 11.4a	5.3 ± 5.3a	98.4 ± 14.9a	94.8 ± 11.7a,b,c	0.46 ± 0.05a
	Lavendula stœchas	1.6 ± 0.4a	46.0 ± 7.1a	0.0 ± 0.0a	47.5 ± 0.5a	49.3 ± 10.6a	1.00 ± 0.09a
	Phillyrea angustifolia	2.1 ± 0.3a,b	114.8 ± 16.6a	23.3 ± 23.3a	203.0 ± 36.1a,b	237.4 ± 54.2c	0.83 ± 0.19a
	Pistacia lentiscus	1.8 ± 0.3a	107.1 ± 16.1a	0.0 ± 0.0a	155.7 ± 43.5a	241.8 ± 48.0c	1.09 ± 0.22a

the moisture content of the subsample dried in the oven (Pereira *et al.*, 1995; Behm *et al.*, 2004; Liodakis *et al.*, 2005). The subsample dry weights were measured using an AND GF-3000 balance with a maximum of 3,100 g and an accuracy of ± 0.1 g.

Statistical analysis

One-way ANOVA ($p \leq 0.05$) and Tukey's multiple range tests were performed, after checking the assumption of normality, to assess the effect of the region on the bulk density and fine fuel load for each species. Linear and non-linear regression models were tested to find the model functions with the best fit for fine fuel biomass and gross individual shrub volume.

Results

Biomass measurements

Measurements of the litter and structural traits of forest fuels are presented in table III. Litter depth average values varied from 1.1 cm (*Ononis natrix* L. in the Pre-Rif) to 7.5 cm (*Daphne laureola* L. in the Eastern Middle Atlas). In the Western Rif, the litter depth was the highest under *Pistacia lentiscus* L. (3.3 cm). In the Pre-Rif and Western

Table IV.
Biomass components. Dry weight of fuel biomass components (foliage and stems per diameter class) and the total biomass are displayed per individual shrub and with ± standard error. Within a column, the species followed by the same letters are not significantly different (p › 0.05) in Tukey's pairwise comparison within a region.

Region	Species	Foliage (g)	Stems diameter class (g)					Total biomass (g)
			‹ 2 mm	2-6 mm	6-25 mm	25-75 mm	› 75 mm	
Western Rif	*Arbutus unedo* L.	90.8 ± 12.3a,b,c	8.7 ± 2.0a	74.5 ± 10.7a,b	245.8 ± 74.2b	399.2 ± 66.7b	0.0 ± 0.0a	819.0 ± 126.2d
	Cistus albidus L.	36.6 ± 8.1a,b	12.4 ± 2.4a	40.1 ± 9.5a,b	10.2 ± 3.3a	0.0 ± 0.0a	0.0 ± 0.0a	99.3 ± 19.7a,b
	Cistus crispus L.	24.9 ± 4.0a	13.7 ± 2.7a	21.1 ± 4.0a	3.7 ± 3.2a	0.0 ± 0.0a	0.0 ± 0.0a	63.4 ± 9.7a
	Cistus monspeliensis L.	45.9 ± 5.5a,b	22.7 ± 3.0a	49.1 ± 5.7a,b	36.5 ± 7.2a,b	1.2 ± 1.2a	0.0 ± 0.0a	155.4 ± 17.3a,b,c
	Cistus salviifolius L.	28.1 ± 3.5a	24.1 ± 3.1a	45.6 ± 6.1a,b	10.6 ± 2.8a	0.0 ± 0.0a	0.0 ± 0.0a	108.3 ± 13.3a,b
	Erica arborea L.	164.2 ± 43.7c	72.5 ± 14.4b	124.8 ± 30.4b	137.8 ± 37.3a,b	105.8 ± 65.7a	0.0 ± 0.0a	605.0 ± 177.8c,d
	Lavendula stœchas L.	20.4 ± 10.7a	21.6 ± 6.2a	23.1 ± 6.2a	5.5 ± 2.8a	0.0 ± 0.0a	0.0 ± 0.0a	70.6 ± 19.7a
	Myrtus communis L.	60.2 ± 13.5a,b,c	28.0 ± 6.1a	54.9 ± 11.1a,b	77.3 ± 38.5a,b	0.0 ± 0.0a	0.0 ± 0.0a	220.3 ± 53.7a,b,c
	Pistacia lentiscus L.	139.1 ± 34.8b,c	23.3 ± 5.2a	118.1 ± 31.5b	231.9 ± 83.9a,b	50.5 ± 9.3a	0.0 ± 0.0a	562.9 ± 157.0b,c,d
Pre-Rif	*Arbutus unedo*	163.3 ± 60.1a,b	0.0 ± 0.0a	103.2 ± 43.7a	220.6 ± 104.7a,b	75.4 ± 75.4a	0.0 ± 0.0a	562.5 ± 274.2a,b
	Cistus creticus L.	30.7 ± 10.7a	4.9 ± 2.8a,b	43.1 ± 20.2a	42.4 ± 29.8a	0.0 ± 0.0a	0.0 ± 0.0a	121.1 ± 61.6a,b
	Cistus ladanifer L.	35.3 ± 9.7a	4.0 ± 3.1a,b	64.4 ± 31.4a	37.6 ± 16.6a	0.0 ± 0.0a	0.0 ± 0.0a	141.2 ± 44.2a,b
	Cistus salviifolius	14.4 ± 4.4a	13.6 ± 4.3a,b	17.1 ± 5.4a	8.3 ± 4.4a	0.0 ± 0.0a	0.0 ± 0.0a	53.3 ± 16.8a
	Erica arborea	34.6 ± 18.7a	9.8 ± 2.4a,b	13.1 ± 6.6a	34.4 ± 26.0a	0.0 ± 0.0a	0.0 ± 0.0a	92.0 ± 52.4a
	Lavendula stœchas	8.5 ± 2.1a	9.6 ± 1.9a,b	17.0 ± 5.5a	11.4 ± 7.2a	0.0 ± 0.0a	0.0 ± 0.0a	46.6 ± 14.4a
	Ononis natrix L.	321.5 ± 237.6b	0.0 ± 0.0a	543.2 ± 454.7b	637.5 ± 573.7b	0.0 ± 0.0a	0.0 ± 0.0a	1,502.2 ± 1264.7b
	Pistacia lentiscus	151.0 ± 65.8a,b	38.0 ± 18.2b	166.1 ± 84.4a	186.0 ± 122.1a,b	232.7 ± 232.7a	0.0 ± 0.0a	773.9 ± 506.7a,b
Western Middle Atlas	*Arbutus unedo*	427.6 ± 395.6a	34.4 ± 29.1a	125.4 ± 116.2a	416.3 ± 408.3a	0.0 ± 0.0a	0.0 ± 0.0a	1,003.7 ± 949.2a
	Cistus creticus	34.6 ± 20.9a	23.5 ± 11.5a	55.0 ± 28.0a	114.9 ± 92.8a	0.0 ± 0.0a	0.0 ± 0.0a	228.1 ± 152.1a
	Cistus incanus L.	192.7 ± 42.3a	33.3 ± 9.2a	224.3 ± 77.5a	300.6 ± 98.2a	0.0 ± 0.0a	0.0 ± 0.0a	750.8 ± 213.7a
	Cistus salviifolius	13.4 ± 4.6a	12.7 ± 4.2a	14.5 ± 5.0a	3.8 ± 3.8a	0.0 ± 0.0a	0.0 ± 0.0a	44.4 ± 16.2a
	Cysitus triflorus Lam.	19.4 ± 6.6a	60.1 ± 20.9a	256.9 ± 64.3a	341.7 ± 142.9a	0.0 ± 0.0a	0.0 ± 0.0a	678.1 ± 227.1a
	Phyllirea angustifolia L.	220.1 ± 71.5a	155.7 ± 66.7a	369.2 ± 110.5a	813.9 ± 272.2a	520.6 ± 404.3a	0.0 ± 0.0a	2,079.5 ± 747.1a
	Pistacia lentiscus	195.2 ± 130.9a	20.5 ± 1.2a	141.7 ± 101.0a	126.2 ± 96.4a	11.5 ± 11.5a	0.0 ± 0.0a	495.0 ± 341.0a
	Thymelaea tartonraira L.	105.8 ± 48.5a	50.4 ± 22.0a	84.8 ± 31.7a	30.9 ± 10.0a	0.0 ± 0.0a	0.0 ± 0.0a	271.8 ± 107.3a
Eastern Middle Atlas	*Arbutus unedo*	85.6 ± 46.7a	0.0 ± 0.0a	124.8 ± 81.1a	218.0 ± 166.2a	552.5 ± 552.5b	0.0 ± 0.0a	980.9 ± 846.5b
	Cytisus grandiflorus (Brot.) DC	16.5 ± 4.9a	56.4 ± 24.5a	50.5 ± 16.2a	69.1 ± 44.5a	0.0 ± 0.0a	0.0 ± 0.0a	192.4 ± 69.2a,b
	Cistus salviifolius	11.7 ± 4.6a	20.4 ± 7.9a	20.4 ± 6.7a	10.7 ± 5.8a	0.0 ± 0.0a	0.0 ± 0.0a	63.2 ± 22.1a
	Cytisus triflorus	6.3 ± 1.1a	37.6 ± 17.8a	26.7 ± 13.5a	34.5 ± 25.3a	0.0 ± 0.0a	0.0 ± 0.0a	105.0 ± 57.5a
	Daphne laureola	40.8 ± 21.2a	0.0 ± 0.0a	62.4 ± 43.4a	198.4 ± 167.3a	0.0 ± 0.0a	0.0 ± 0.0a	301.6 ± 231.4a,b
	Erica arborea	112.9 ± 61.2a	39.0 ± 16.0a	58.9 ± 26.1a	133.3 ± 56.0a	0.0 ± 0.0a	0.0 ± 0.0a	344.1 ± 153.8a,b
Central Plateau	*Arbutus unedo*	1,157.1 ± 655.8b	126.4 ± 92.2a	720.5 ± 416.2b	908.9 ± 303.2a	2,337.5 ± 1163.0b	10,838.0 ± 3,507.0b	16,088.3 ± 6028.4b
	Cistus crispus	20.6 ± 6.4a	22.9 ± 11.4a	36.0 ± 0.2a,b	17.5 ± 17.5a	0.0 ± 0.0a	0.0 ± 0.0a	97.1 ± 35.5a
	Cistus ladanifer	77.4 ± 32.4a	27.7 ± 12.6a	77.7 ± 27.2a,b	104.4 ± 59.4a	8.9 ± 8.9a	0.0 ± 0.0a	296.1 ± 138.0a
	Cistus salviifolius	20.1 ± 9.1a	27.8 ± 11.2a	37.1 ± 19.1a,b	3.3 ± 2.2a	0.0 ± 0.0a	0.0 ± 0.0a	88.3 ± 38.3a
	Daphne gnidium L.	52.6 ± 21.5a	61.4 ± 19.3a	106.6 ± 40.5a,b	153.3 ± 69.6a	0.0 ± 0.0a	0.0 ± 0.0a	374.0 ± 145.3a
	Lavendula stœchas	12.1 ± 1.9a	12.8 ± 5.4a	18.7 ± 3.2a	0.0 ± 0.0a	0.0 ± 0.0a	0.0 ± 0.0a	43.6 ± 4.0a
	Phyllirea angustifolia	365.6 ± 125.7a,b	116.0 ± 45.6a	363.4 ± 151.9a,b	702.8 ± 272.2a	1,138.1 ± 421.3a,b	0.0 ± 0.0a	2,686.0 ± 704.4a
	Pistacia lentiscus	356.7 ± 201.7a,b	71.0 ± 45.6a	351.1 ± 227.5a,b	666.6 ± 498.3a	210.6 ± 105.3a	0.0 ± 0.0a	1,656.0 ± 1024.9a

Middle Atlas, *Arbutus unedo* L. had the greatest litter depth (3.6 and 4.7 cm, respectively). In the Eastern Middle Atlas, *D. laureola* had the highest litter depth (7.5 cm). In the Central Plateau, the litter depth under *Daphne gnidium* L. was the highest (3.6 cm).

Litter depth, height to lowest branch, total height, width and the bulk density of individual shrubs measurements per species ± standard error. Within a column, the species followed by the same letters are not significantly different ($p > 0.05$) in Tukey's pairwise comparison within a region.

The height to the lowest branch varied from 0 (*e.g.* *Cistus albidus* L., *Cistus crispus* L. and *Cistus monspeliensis* L. in the Western Rif) to 168.3 cm (*A. unedo* in the Central Plateau), whilst the total height ranged from 25.4 cm (*Thymelaea tartonraira* L. All. in the Western Middle Atlas) to 370.7 cm (*A. unedo* in the Central Plateau). *Arbutus unedo* had the longest total height in all regions, except in the Western Middle Atlas. In the latter region, *Phillyrea angustifolia* L. averaged 205.6 cm in total height and was thereby taller than the other species (table III).

The average values of individual shrub width varied from 35.9 cm (*Lavandula stœchas* L. in the Western Rif) to 241.8 cm (*P. lentiscus* in the Central Plateau), as presented in table III. The bulk density of individual shrubs ranged from 0.35 mg/cm^3 (*D. laureola* in the Eastern Middle Atlas) to 4.64 mg/cm^3 (*T. tartonraira* in the Western Middle Atlas).

The biomass components observed in the individual shrubs studied are presented in table IV. In the Western Rif, the fine fuel biomass per individual (foliage and stems with a diameter of less than 6 mm) was the greatest for *Erica arborea* L. However, *A. unedo* had a higher coarse fuel biomass (6-25 mm and 25-75 mm). *Arbutus unedo*, *E. arborea* and *P. lentiscus* contained the highest total fuel biomass per individual.

In the Central Plateau, the foliage biomass, stem biomasses of 2-6 mm, 25-75 mm and more than 75 mm, and total biomass per individual were the highest for *A. unedo*. There were no significant differences between the stem

Table V.
ANOVA tests for the effect of the region on the bulk density of individual shrubs.

Species	Source of variation	SS	d.f.	MS	F	F test
Arbutus unedo L.	Method	10.021	3	3.340	7.509	0.001*
	Error	9.787	22	0.445		
Cistus creticus L.	Method	0.020	1	0.020	0.745	0.407
	Error	0.297	11	0.027		
Cistus crispus L.	Method	0.038	1	0.038	0.138	0.716
	Error	4.139	15	0.276		
Cistus ladanifer L.	Method	0.050	1	0.050	1.054	0.325
	Error	0.569	12	0.047		
Cistus salviifolius L.	Method	2.677	4	0.669	2.361	0.066
	Error	13.888	49	0.283		
Cytisus triflorus Lam.	Method	0.020	1	0.020	1.724	0.246
	Error	0.057	5	0.011		
Erica arborea L.	Method	0.373	2	0.187	2.716	0.092
	Error	1.306	19	0.069		
Lavandula stœchas L.	Method	0.108	2	0.054	0.273	0.766
	Error	2.177	11	0.198		
Phillyrea angustifolia L.	Method	0.180	1	0.180	1.134	0.302
	Error	2.705	17	0.159		
Pistacia lentiscus L.	Method	0.310	3	0.103	0.468	0.707
	Error	7.078	32	0.221		

* Significant difference ($p \leq 0.05$) between regions regarding the bulk density of individual shrubs in Tukey's pairwise comparison. SS: sum of squares due to the source; d.f.: degree of freedom; MS: mean sum of squares due to the source.

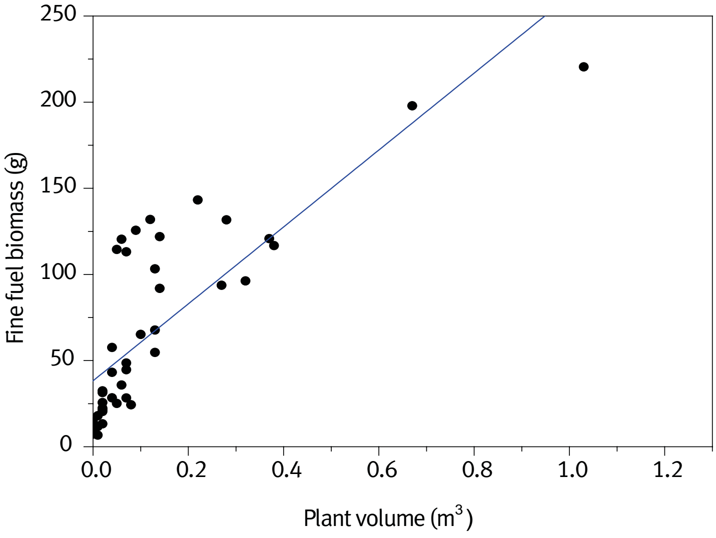

Figure 1.
Variations in the biomass of fine fuel, as a function of the individual shrub volume for *Cistus salviifolius* L., with an appropriate trend curve.

biomasses of 0-2 mm and 6-25 mm among the Central Plateau species (table IV). No sampled individual had stems with a diameter of more than 75 mm, except for *A. unedo* in the Central Plateau.

The effect of the region on bulk density and fine fuel biomass

ANOVA tests were performed to determine the effect of the region on the bulk density of individual shrubs and fine fuel biomass, and the results are presented by species in tables V and VI. The analysis of variance was conducted only for species that are represented in more than one region. ANOVA and Tukey's multiple comparison tests (95% confidence level) showed no significant effect of the region on the bulk density of individual shrubs for all species sampled in different regions, except for *A. unedo* (table V), for which the bulk density values were significantly different in the Central Plateau, compared to those in the other regions. However, the same tests revealed no significant effect of the region on the fine fuel biomass for all of the species sampled in different regions (table VI).

Since the fine biomass content of a shrub does not change with the region, adjusting the fine fuel biomass for the effect of the individual shrub volume can therefore be carried out without differentiating the region. The model functions, used to adjust the fine fuel biomass for the effect of the individual shrub volume, are presented by species in table VII, with their corresponding Pearson's correlation coefficients and coefficients of determination. All model functions were linear, and the Pearson's correlations were significant to highly significant. The coefficients of determination varied from 60 to 99% (table VII). For all species, the fine fuel biomass followed a linear upward trend in relation to the individual shrub volume, as shown in the case of *Cistus salviifolius* L., shown in figure 1, which was chosen due to its availability in all of the studied regions (table II).

Discussion

Arbutus unedo, with a total height exceeding 3 m (tree class) in the Central Plateau, was tree-like, while the total height of all of the collected species is less than 3 m (shrub-like species). The litter depth and individual shrub width average values were close to the values recorded by Behm *et al.* (2004) and Ottmar and Andreu (2007), whereas the height of the lowest branch and total height average value ranges were above those found by Behm *et al.* (2004) and Etlinger and Beall (2004). The bulk density of individual shrubs and fine fuel biomass values were close to the values obtained by Fernandes (2001), in a study involving common species (*Cistus ladanifer* L. and *E. arborea*), and also by Etlinger and Beall (2004), in another work, but went beyond the variation ranges presented by Behm *et al.* (2004). The values of fine biomass and total height were close to those recorded by Weise *et al.* (2005), although they were in some cases outside the variation range of the latter. The variation range of coarse fuel and total biomass went beyond the variation intervals noted by Behm *et al.* (2004), Etlinger and Beall (2004) and Ganteaume *et al.* (2013). While the respective proportions of stems in the studied shrub species with diameters of 0 to 2 mm and 2 to 6 mm varied within the same interval observed by Ganteaume *et al.* (2013), and the proportions of leaves varied according to a wider amplitude than that indicated by these authors. All biomass components with a diameter below 25 mm evolved within the same range of variation found by Pereira *et al.* (1995), whereas the total biomass and biomass components, with a diameter above 25 mm, exceeded the range indicated by the these authors. However, all biomass components studied for *E. arborea* varied within the same range of variation expected by Pereira *et al.* (1995) for this species.

Table VI.
ANOVA tests for the effect of the region on fine fuels (foliage and stems < 6 mm).

Species	Source of variation	SS	d.f.	MS	F	F test
Arbutus unedo L.	Method	1,007,196.183	4	251,799.046	2.889	0.047*
	Error	1,830,601.239	21	87,171.488		
Cistus creticus L.	Method	2,752.167	1	2,752.167	0.258	0.621
	Error	117,117.104	11	10,647.009		
Cistus crispus L.	Method	691.389	1	691.389	0.580	0.459
	Error	16,701.262	14	1,192.947		
Cistus ladanifer L.	Method	66,725.136	1	66,725.136	2.600	0.133
	Error	307,908.294	12	25,659.025		
Cistus salviifolius L.	Method	27,409.607	4	6,852.402	2.182	0.086
	Error	144,456.335	46	3,140.355		
Cytisus triflorus Lam.	Method	121,214.464	1	121,214.464	6.299	0.054
	Error	96,215.614	5	19,243.123		
Erica arborea L.	Method	74,359.879	2	37,179.940	0.281	0.758
	Error	2,774,895.364	21	132,137.874		
Lavandula stœchas L.	Method	483.505	2	241.752	0.447	0.652
	Error	5,413.770	10	541.377		
Phillyrea angustifolia L.	Method	4,663.995	1	4,663.995	0.008	0.931
	Error	10,252,714.935	17	603,100.879		
Pistacia lentiscus L.	Method	648,080.921	3	216,026.974	1.418	0.258
	Error	4,265,973.296	28	152,356.189		

* Non-significant difference of fine fuels ($p \leq 0.05$) between regions according to Tukey's pairwise comparison test. SS: sum of squares due to the source; d.f.: degree of freedom; MS: mean sum of squares due to the source.

The parameters measured in this paper, namely, litter depth and height of the lowest branch, bulk density and fine fuel biomass are linked to ignitability, sustainability/combustibility and consumability, respectively, as stated by Behm *et al.* (2004) and Fernandes and Cruz (2012). These parameters would can therefore reveal insights into the vulnerability to catch fire for the examined species. Indeed, *A. unedo*, by containing the greatest fine fuel biomass, presents the characteristic of high consumability. Its low to moderate bulk density is an indicator of a moderate spread rate and fire intensity. The bulk density of *T. tartonraira* was the highest, implying that it has the lowest spread rate among all the examined species. This species also has a poor ignitability due to its low litter depth.

On the other hand, *D. laureola* showed the lowest bulk density average value, indicating that this species has a higher fire spread rate and a greater fire intensity. It also had the highest litter depth and a very low height of the lowest branch, which would impart to *D. laureola* a high ignitability, though it contained a relatively low fine fuel biomass. For *C. salviifolius* and *L. stœchas*, since they contained the lowest fine fuel biomass, they are expected to be the least consumable species. However, these species had a low height of the lowest branch and low bulk density, which suggests the characteristic of a high ignitability and high fire spread and intensity.

The effect of the region on the bulk density of individual shrubs was not significant, except for *A. unedo*. Indeed, for this species, according to Tukey's multiple range test, the bulk density in the Central Plateau was significantly greater than in other regions. This is similar to the findings of Pausas *et al.* (2012) on *Ulex parviflorus* Pourr., which revealed a difference in bulk density from one region to another. The noted difference in bulk density may be attributed to the particular grazing conditions in the Central Plateau in relation to the other regions (the Middle Atlas, Western Rif and Pre-Rif), since the grazing conditions has a striking effect on the individual shrub bulk density by reducing the total fuel biomass. The Middle Atlas region is known for its high grazing activity, resulting in a low bulk density. However, in the Western Rif, where grazing is less prevalent, the bulk density of *A. unedo* is greater. Moreover, *A. unedo* leaves are the least drought-resistant species among evergreen sclerophyllous (Gratani and Ghia, 2002). Overgrazing coupled with drought periods therefore weakens the individual shrub and leads to a considerable reduction of its biomass in a more profound manner than in the other species, corroborating our findings. Our findings regarding *A. unedo* are also supported by Kazanis *et al.* (2012), who inferred that the long-term rate of fuel accumulation in the understory of *Pinus halepensis* Mill. was very different from one stand to another.

On the other hand, the overall indifference of bulk density to the region shows that bulk density is a species-specific trait, although it is influenced by extreme site-related phenomena, such as overgrazing, which significantly alters the individual shrub's structure and fuel arrangement. However, the region had no impact on fine fuel biomass for all species, implying that fine fuel biomass is a species-specific characteristic that remains unchanged regardless of the region.

The regions sampled in this work were selected for their vulnerability to wildfires (San-Miguel-Ayanz *et al.*, 2017), since the forest regions involved are the most frequently burned (65% of the total number of fires) (San-Miguel-Ayanz *et al.*, 2017) and the most wooded ones (M'Hirit and Benchekroun, 2006). The canopy cover included several high-value tree species, such as *Pinus pinaster* var. *maghrebiana* Villar, *Cedrus atlantica* Manetti and others, broadly facing serious obstacles to regeneration *e.g. Quercus suber* L. and *Quercus rotundifolia* Lam. The Rif is known to experience frequent fires, although the ecological conditions of the environment are among the most favourable (Benabid, 1985). In 2017, 31% of fires occurred in this forest region (HCEFLCD, 2018). On the other hand, the Central Plateau generally comprises degrading or even degraded forests (Benabid, 1985).

The fragility of these ecosystems makes them vulnerable to natural hazards and, more particularly, wildfires. To this end, the model functions that best fit the relationship between individual shrub volume and fine fuel biomass, as presented

Table VII.
Model functions used for the adjustment of the fine fuel biomass for the effect of individual shrub volume by species.

Species	Pearson's correlation coefficient	Model function	R²
Arbutus unedo L.	0.84**	FF = 80.939V + 124.052	0.71
Cistus albidus L.	0.77*	FF = 681.59V + 9.577	0.60
Cistus creticus L.	0.93**	FF = 193.892V + 24.013	0.87
Cistus crispus L.	0.88**	FF = 1182.29V – 0.055	0.76
Cistus incanus L.	0.99*	FF = 873.702V – 60.063	0.99
Cistus ladanifer L.	0.97**	FF = 196.306V + 45.89	0.95
Cistus monspeliensis L.	0.84**	FF = 268.528V + 51.49	0.70
Cistus salviifolius L.	0.80**	FF = 223.282V + 38.262	0.64
Cytisus grandiflorus (Brot.) DC	0.98*	FF = 52.876V + 31.847	0.96
Cytisus triflorus Lam.	0.89**	FF = 163.936V + 53.376	0.79
Daphne gnidium L.	0.96**	FF = 179.299V + 47.254	0.92
Daphne laureola	0.99**	FF = 57.377V + 23.953	0.99
Erica arborea L.	0.87**	FF = 129.552V + 168.338	0.76
Lavandula stœchas L.	0.98**	FF = 310.259V + 7.853	0.96
Myrtus communis L.	0.94*	FF = 347.087V + 32.163	0.89
Phillyrea angustifolia L.	0.93**	FF = 119.079V + 151.263	0.86
Pistacia lentiscus L.	0.92**	FF = 256.737V + 121.02	0.85
Thymelæa tartonraira L.	0.99**	FF = 5023.897V – 28.17	0.98

FF: fine fuel biomass (g); V: individual shrub volume (m^3);
R²: coefficient of determination.

in table VII, would make the estimation of fine fuel biomass, which requires cutting the shrub, separating the fine biomass from the coarse biomass, oven drying and weighing, easier and more efficient. These model functions can now shorten this tedious experimental procedure by requiring only a measurement of the gross volume of the shrub. The collection of such data, which needs to be accurate, on individual pyric characteristics by shrub species, albeit time-consuming, is necessary to set up a fire behaviour prediction system. The concept of the latter is based on the combined action of all the individual characteristics involved in the ignition and spread of a wildfire by species, taking into account the weighting of each tree and shrub species at a given forest site, using its frequency and crown cover. Therefore, the fine fuel biomass contained in an individual shrub is one of several parameters to be integrated into models that can be applied on-site to determine the forest fuel model types present in the studied ecosystems. This will enable the development of wildfire risk maps, which will be of great use to forest managers, since they would help to concentrate fire-fighting resources and teams in the most risk-prone sites in order to ensure optimal prevention and effectiveness.

Conclusion

In response to the enormous lack of data on the structural characteristics of shrubs in Morocco, measurements of the bulk density of the litter, individual shrubs and biomass per size class were carried out in five forest regions that are considered to be among the most vulnerable to wildfire. Overall, both the bulk density of the individual shrubs and the fine fuel biomass have been indifferent to changes of region for all species, except *A. unedo*, which was the only species for which the region significantly affected the bulk density of individual shrubs. For all species, linear model functions were found to best fit the relationship between fine fuel biomass and individual shrub volume. The resultant model functions would be of great relevance to forest managers, as simple measurements of the shrub individual may lead to the estimation of the fine fuel biomass contained in this individual, thereby aiding the assessment of the fuel hazard that it could cause. The data collected during the present work, when integrated into an adequate fire behaviour prediction system, would lead to an estimate of the fire risk in the areas concerned.

Acknowledgements
We are grateful to the students, M’barek Alibouch, Mhammed Halloumi, Abderrahim Raji, George Kwasi Arhin, Rachid Nidlahadj, Fahed El Amarty and Badr El Hallay, from *École Nationale Forestière d’Ingénieurs* of Morocco, for their assistance in field and laboratory work. We also thank Mohammed Rhaz for his technical help in the laboratory work and Rachid Azzam, Lahcen Benkassou and Benacer Ouled Boumehdi for their help in the fieldwork. We also acknowledge three anonymous reviewers for their great contribution in the improvement of the quality of the present paper. Many thanks to Professor Mohamed Qarro for the photo.

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Bois et Forêts des Tropiques - Revue scientifique du Cirad

Cirad - Campus international de Baillarguet, 34398 Montpellier
Cedex 5, France - Contact : bft@cirad.fr - ISSN : L-0006-579X