Chapter

Evergreen Oak Biomass Residues for Firewood

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Abstract

This chapter presents the assessment of the availability for residential heating of residual biomass from cork and holm oaks in a 12,188 ha agroforest area in Portugal. First, the above-ground biomass of evergreen oaks using very high spatial resolution satellite images was determined, followed by the definition of different scenarios for residues removal from the stands. The useful energy potential of the firewood that can be collected from the study area under the various silviculture scenarios was determined considering different energy conversion technologies: open fireplaces (still popular in Portugal) and more efficient closed burning appliances. Additionally, emissions of airborne pollutants from combusting all the available residual biomass in the study area were determined. Depending on the percentage of residues collected when the trees are pruned and on the conversion technologies used, the energy potential of evergreen oak firewood ranged from 5.0×10^6 MJ year^{-1} to 7.5×10^7 MJ year^{-1}. Heavier pruning combined with the use of open fireplaces generates less useful heat and much higher emissions of pollutants per unit useful energy produced than lighter pruning combined with a more efficient technology. This case study illustrates the need to promote the transition from inefficient to more efficient and cleaner technologies.

Keywords: biomass estimation, remote sensing, silviculture, energy potential, residential heating

1. Introduction

Forests constitute the most important stock of biomass and act as a major sink of carbon [1–3]. Among the various forest systems, the Mediterranean evergreen oak forest systems, mainly composed by cork oak (*Quercus suber*) and holm oak (*Quercus rotundifolia*), comprise two of the most abundant tree species in the Mediterranean basin [4]. They are typically managed as agroforestry systems (called *montado* in Portuguese) and are characterized by stands of low density with periodical pruning and thinning (the latter especially at the early stand development stage) and cuts of dead and diseased trees [5, 6]. Especially the wood of holm oak, but also of cork oak, was traditionally used, and still is used, for firewood and to produce charcoal [5, 6].

Using firewood for residential heating has the potential to reduce the consumption of fossil fuels and greenhouse gas emissions. Factors such as the use of fossil fuels for the production, collection and transport of firewood to households, the efficiency of the conversion systems and the energy vectors used for heating determine the level of the reductions [7]. Additionally, the source of the firewood is also a determinant factor, and the knowledge of the availability of biomass in the vicinity of the consumption points and of the quantity of this firewood that is consumed and how it is consumed are of the upmost importance to define environmental and energy policies.

To determine the availability of firewood obtained from forest residues, it is important to quantify the amount of wood that can be collected at tree level. Several authors [8, 9] report that the average weight of holm oak pruned branches (in dry weight) divided by the diameter of the tree at breast height is in the range of 0.3 to 0.8 kg cm^{-1} for light pruning, 1.4 to 1.5 kg cm^{-1} for moderate pruning and 1.7 to 3.2 kg cm^{-1} for heavy pruning.

For cork oak, a proportion of residues of 17% of the above-ground biomass is considered by Palma et al. [10]. Natividade [6] considers that 30–40% of the crown is removed in moderate prunings. This author also presents the mean weight of pruning residues (in fresh weight basis) for moderate prunings with a periodicity of 5 or 6 years as a function of the tree circumference at breast height (cbh, $cbh = \pi \times dbh$, where dbh is the diameter at breast height) (**Table 1**).

Several studies determined the energy potential of forest residues in Portugal at country or regional level (e.g., [11–16]) and most considered the residual biomass originated from evergreen oaks. These forest species have also been considered in the assessment of the forest energy potentials of other countries (e.g., [17, 18]). Many of the studies referred above used data from field inventories and derived from remote sensing data (e.g., land use maps) in a Geographic Information Systems environment.

This work assesses the energy potential of evergreen oak residues for a region in Alentejo, South Portugal, dominated by holm and cork oaks. Through a case study, the next sections present a method that integrates the estimation of residual biomass from evergreen oaks using very high spatial resolution satellite images and the determination of its energy potential. For the evaluation of the existing forest above-ground biomass, remote sensing data was used to produce a vegetation mask with the delimitation and identification of the tree crowns by species and then calculate the crown horizontal projection. An allometric function developed by Gonçalves et al. [19] was then used to calculate the above ground biomass. Having the knowledge of the amount of above-ground biomass, different scenarios for residues removal from the stands were considered. These scenarios are based on common silvicultural practices. In the last step, the energy potential of the available firewood was calculated. Reference lower heating values for evergreen oak wood obtained from the literature were considered, as were several different conversion technologies: on the one hand, the technology most used in the country for the conversion of this type of residues, and on the other, more efficient conversion technologies. The environmental implications of using more efficient and cleaner technologies are briefly discussed.

cbh **(m)**	**Pruning residues (kg)**
0.8–1.0	30.0
1.0–1.2	37.5
1.2–1.4	50.0
1.4–1.6	72.5
1.6–1.8	100.0
1.8–2.0	140.0

Table 1.
Mean mass of pruning residues (in fresh weight basis) per class of circumference at breast height.

2. Firewood consumption in Portugal

According to the Eurostat [20], the production of firewood (including wood for charcoal) in Portugal was 1178 thousand m^3 in 2018, 8.7% of the total roundwood production in the country. The reported percentage of roundwood that was used as firewood in Portugal is quite small when compared to the average of the 27 member states of the European Union (22.7%). However, the Portuguese share of firewood in the total roundwood must be read with care because its supply is largely untaxed outside urban contexts and often auto-consumption and informal markets exist [21, 22]. For instance, pruning of cork and holm oaks is not recorded as sales of industrial wood [23].

According to DGEG [24], in Portugal, the primary energy production from firewood, forest and plant residues, pellets and other agglomerates was 1575 ktoe (black liquor not included). The uses for this solid biomass are expressed in **Figure 1**, which shows that more than half of the biomass was consumed in the residential sector. The production of electricity in electricity-only power plants used 22% of the solid biomass and the industry, mostly the pulp and paper industry, had a 19% share of the consumption of this type of biomass.

The basis for the estimation of the consumption of wood in the residential sector reported in the Portuguese energy balance were the results of a national survey preformed in 2010 by INE/DGEG [24]. According to that survey [25], 2.7×10^9 kg of firewood was consumed in Portugal between October 2009 and September 2010. This value is significantly higher than the one reported by the Eurostat for all sectors [20]. One of the reasons for this deviation is, as already referred at the beginning of this section, that firewood is often collected for auto-consumption or supplied through informal markets, so it is not recorded (only 40% of the wood consumed in households was bought; the rest was collected in the vicinity of households or had other origin [25]). The amount of pellets and other agglomerates that were consumed in the country in 2018 was 2.25×10^8 kg [26].

National statistics show that, in 2018, electricity was the main energy vector consumed by households in Portugal, followed by primary solid biofuels [24], mainly firewood and forest and plant residues. The latter represented 26% of the energy consumed by the households. However, regional differences are important and consumption of wood in small rural cities in regions with colder weather can be much higher than the national average [27, 28]. Firewood was consumed in 40.1% of the households in 2009–2010 [25]. The various sources of wood were: pine (37.4%), *Eucalyptus* sp. (21.2%), holm oak (7.4%), cork oak (5.7%), other forest residues (4.2%) and other types of wood (24.0%). This implies that between October 2009

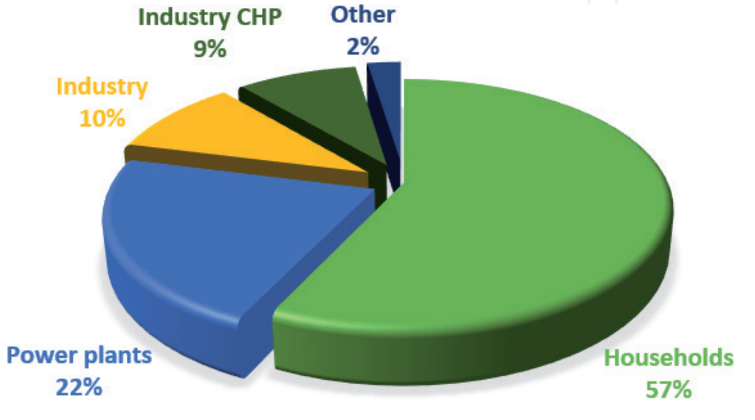

Figure 1.
Share of the various sectors in the Portuguese consumption of firewood, forest and plant residues, pellets and other agglomerates in 2018.

and September 2010, the consumption of holm oak firewood was 2.0×10^5 t and of cork oak firewood 1.5×10^5 t. Oak wood is the mostly consumed as firewood in the South of the country [27], where most of its stands are situated (cork and holm oaks correspond, respectively, to 45.7% and 23.8% of the forest area in Alentejo [29]; **Figure 2** shows the location of this region).

In Portugal, between October 2009 and September 2010, firewood was mostly used in household for space heating (52.0%); other uses are cooking and water heating [25]. Indeed, firewood was the most common energy source for space heating in the country. According to the INE/DGEG survey, the most popular wood-fired equipment for household heating was the open fireplace, followed by the closed fireplace and woodstove (existent in 24%, 11.1% and 7.2% of the Portuguese households, respectively). Fireplaces were also the appliance most used for cooking with biomass. Note that regional differences in terms of technology used also exist and the technologies employed vary throughout the country [27]. For example, the study of Azevedo et al. [28] shows that in a region in the north of Portugal, the most used technologies for biomass heating are closed fireplaces and that open fireplaces only come second.

Independently of regional differences, it can be said that most biomass systems installed in the Portuguese households provide heat locally (central heating systems are not so common) and the percentage of wood that is burned inefficiently in open fireplaces is high. The efficiency of this type of technology is at best 20% [30], being typically below 10% [31]. Closed fireplaces and stoves present much higher efficiencies, which depend on the specific appliance. Efficiency values of closed fireplaces are usually above 50%, but can be as high as 80%, whereas that of batch-fed stoves characteristically range from 40–80% [32]. It is worth highlighting that compared to

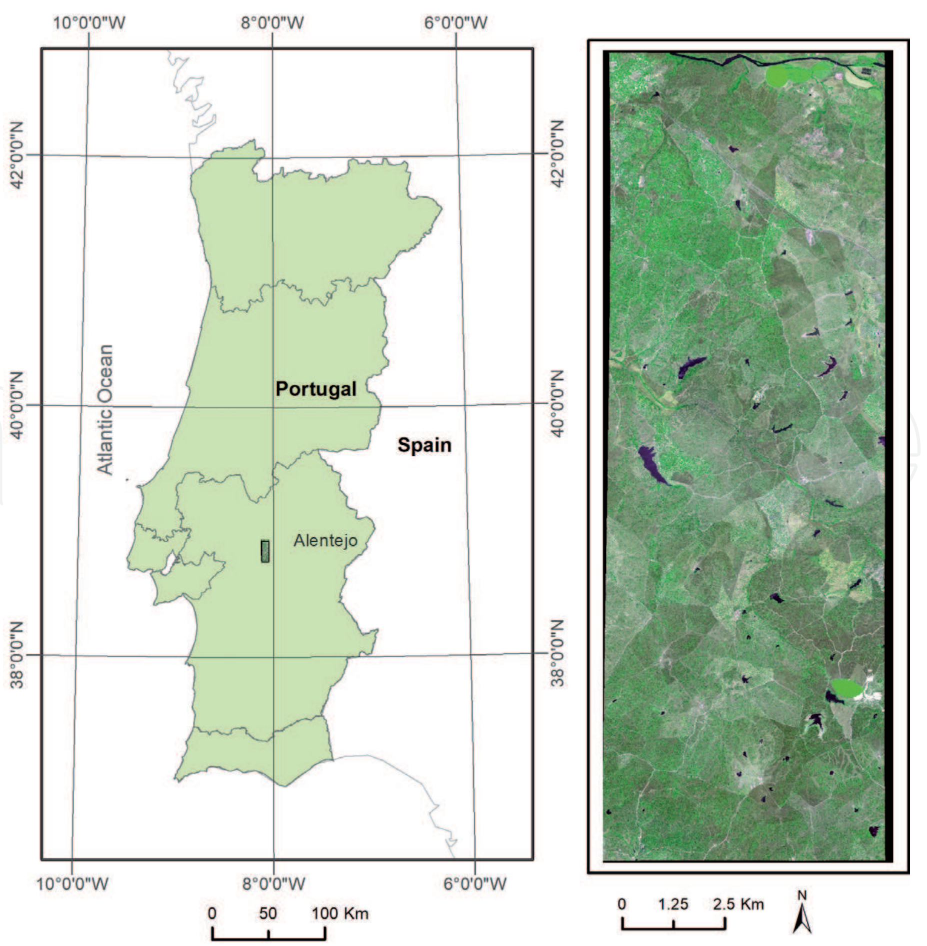

Figure 2.
Map of the study area and the country boundaries for Portugal (left) and the QuickBird satellite image (false color composite, RGB - Red, Near-infrared (NIR), Blue).

Wood	Technology	$PM_{2.5}$	OC[1]	EC[2]	CO	CO_2
Holm oak	Open fireplaces	13.1 ± 8.1	7.2 ± 4.0	0.30 ± 0.11	61.8 ± 24.5	735 ± 193
	Cast iron stove	5.8 ± 3.9	3.0 ± 2.1	0.23 ± 0.1	63.7 ± 55.9	985 ± 570
Cork oak	Open fireplaces	17.9 ± 10	10.1 ± 5.2	0.68 ± 0.40	85.5 ± 22.0	552 ± 306
	Cast iron stove	8.3 ± 6.1	4.8 ± 3.4	0.42 ± 0.33	99.2 ± 92.4	895 ± 693

[1]*OC – Organic carbon.*
[2]*EC – Elemental carbon.*

Table 2.
$PM_{2.5}$, carbonaceous constituents, CO and CO_2 emission factors for closed and open burning appliances used in Portuguese households when combusting oak wood (g kg^{-1}, dry basis).

other countries, for example to the Scandinavian countries, in Portugal the share of high efficiency biomass-fired systems is much lower [33]. However, the situation in Portugal is comparable to the one of other southern European countries (e.g., [34]).

Another important factor to have in mind when comparing different firewood burning appliances is their emissions. Traditional residential heating systems are characterized by considerable emissions of airborne pollutants, namely fine particles, volatile organic compounds and carbon monoxide. In Portugal, one of the largest sources of fine particle emissions is firewood combustion [27, 35]. **Table 2** presents the emission factors for a cast iron stove and a traditional brick open fireplace used in Portuguese households when combusting oak wood [33]. The cast iron wood stove (Portuguese stove) is representative of a closed burning appliance and the traditional open fireplace of an open burning appliance used in Portugal. It should be noted that emissions from wood combustion appliances depend not only on the fuel and appliance used, but also on operational practices and maintenance [36, 37].

3. Availability of evergreen oak firewood in a region in Alentejo, Portugal

Cork and holm oak stands occupy 22.3% and 10.8% of the forest area of Portugal, respectively. They are particularly important in the Alentejo region, which corresponds to about one third of mainland Portugal, and whose forest area is mainly composed by pure and mixed stands of both evergreen oaks (45.7% and 23.8%, respectively, for cork and holm oaks). This corresponds to about 85% of the area of cork oak and circa 91% of the area of holm oak in mainland Portugal [29].

This work presents a case study for the assessment of the availability of residual biomass from these two evergreen oaks in an area of 12,188 ha (**Figure 2**) located in the region of Alentejo in Portugal (central coordinates: 8.07°W, 38.85°N). The area is characterized by plain terrain (mean elevation of approximately 200 m) and Mediterranean soils and climate. The forest stands are composed of pure and mixed stands of cork and holm oaks, and are managed as agroforestry systems. Their main products are bark for cork oak and fruit for both oaks. Additionally, these systems frequently have extensive grazing and pasture as other productions. The area occupied by these agroforestry systems is 9720 ha (corresponding to about 80% of the total area).

The availability of evergreen oak firewood in the study area was assessed using published functions for the estimation of the above-ground biomass [19] and a methodology developed to estimate the amount of residues, as a function of the former, based on the literature [6, 8–10]. The study was done in a Geographical Information Systems (GIS) framework, with data derived from remote sensing techniques, which enabled the estimation for the whole area. The quantification of the biomass residues for the evergreen oaks was done in four steps that are briefly described in the next paragraphs.

In the first step, one image from the QuickBird satellite (with four multispectral bands (Blue, Green, Red and Near-Infrared (NIR)), acquired on August 2006, was selected for the study area. It was orthorectified, georeferenced and atmospherically corrected. Object-based image analysis with contrast split segmentation was used to isolate the tree crowns from the other land uses, then the objects were classified using the nearest neighbor algorithm. More details of the methodology used can be found in [19]. This resulted in a vegetation mask, in which the two species were differentiated (**Figure 3**). The agreement between the classification and ground truth obtained by the Kappa statistic [38, 39] was 76% and the global precision was 87%, which shows a good performance of the applied methodologic procedures.

In the second step of the methodology, the study area was divided in a square grid of 2070.25 m^2 (45.5 × 45.5 m, corresponding to 65 × 65 image pixels) and the vegetation mask was used to identify the composition and to calculate crown cover (the share of the area occupied by the tree crown horizontal projection) per grid.

The data obtained in the previous step was used to calculate above-ground biomass (*AGB,* in t ha^{-1}) per square grid with the function of Gonçalves et al. [19] (Eq. (1), where *CC* is the crown cover, *d* a dummy variable, *QR* holm oak pure stands, *PP* umbrella pine (*Pinus pinea*) pure stands and *QRPP* mixed stands of holm oak and umbrella pine). In this case, no stands of umbrella pine exist, so *dPP* and *dQSPP* are zero and the formula is reduced to the first two terms (in bold).

$$AGB = \mathbf{0.97327} \times \boldsymbol{CC} - 7.\mathbf{81323} \times \boldsymbol{dQR} + 18.93157 \times dPP + 24.72573 \times dQSPP \quad (1)$$

The final step of the methodology consisted in the estimation of the forest residues as a function of above-ground biomass, considering the values referred in the

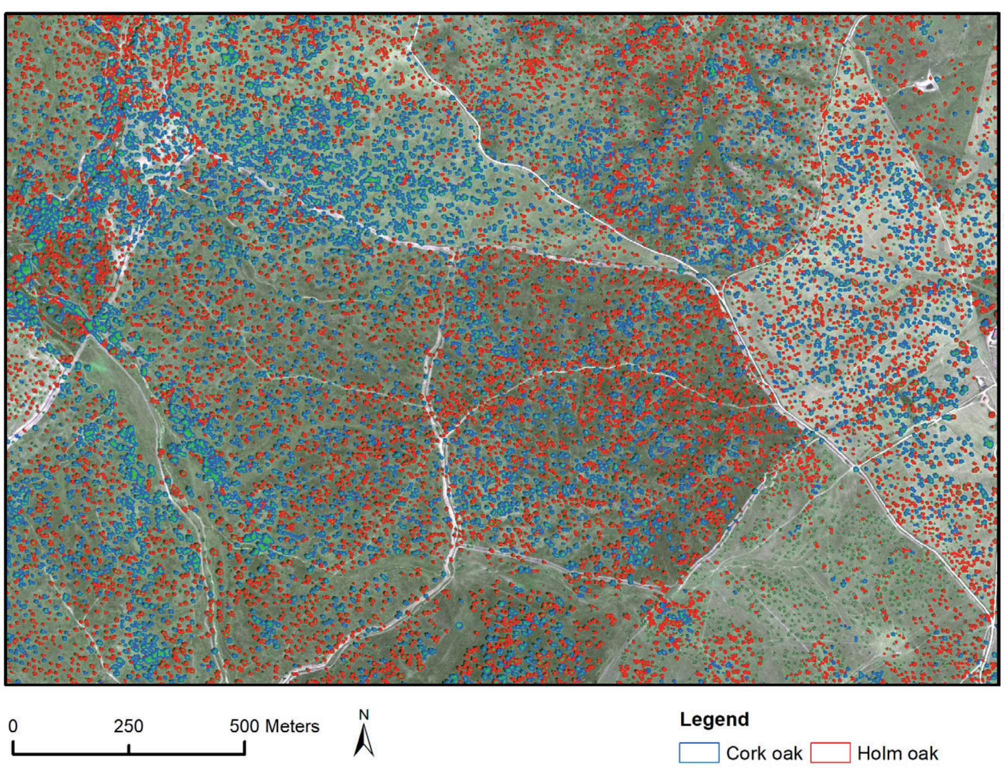

Figure 3.
Illustration of the result of multi-resolution segmentation and object-oriented classification process over the very high spatial resolution image (false color composite, RGB – Red, NIR, Blue).

literature for the share of above-ground biomass removed in pruning. To relate the proportion of residues in relation to the above-ground biomass, a data set of 91 plots of both holm and cork oaks was used. The plots were used to convert the weight of residues at tree level to area level. For each tree the weight of pruning residues was calculated as a function of the diameter at breast height (as referred by [6, 8, 9]). Then, the amount of residues was summed per plot and converted to an area basis (per hectare). Afterwards, the share of pruning residues per plot was determined and compared with the pruning intensity referred in the literature. Five alternatives were considered: 1) 10%; 2) 15%; 3) 20%; 4) 25%; and 5) 30%. The alternatives correspond to light, light-moderate, moderate, moderate-heavy and heavy pruning, respectively.

The total weight of above-ground biomass for the study area estimated by Eq. (1) was 184,887 t. Typical of *montado*, the spatial variability of density is high, which results also in a high variability in above-ground biomass (**Figure 4**).

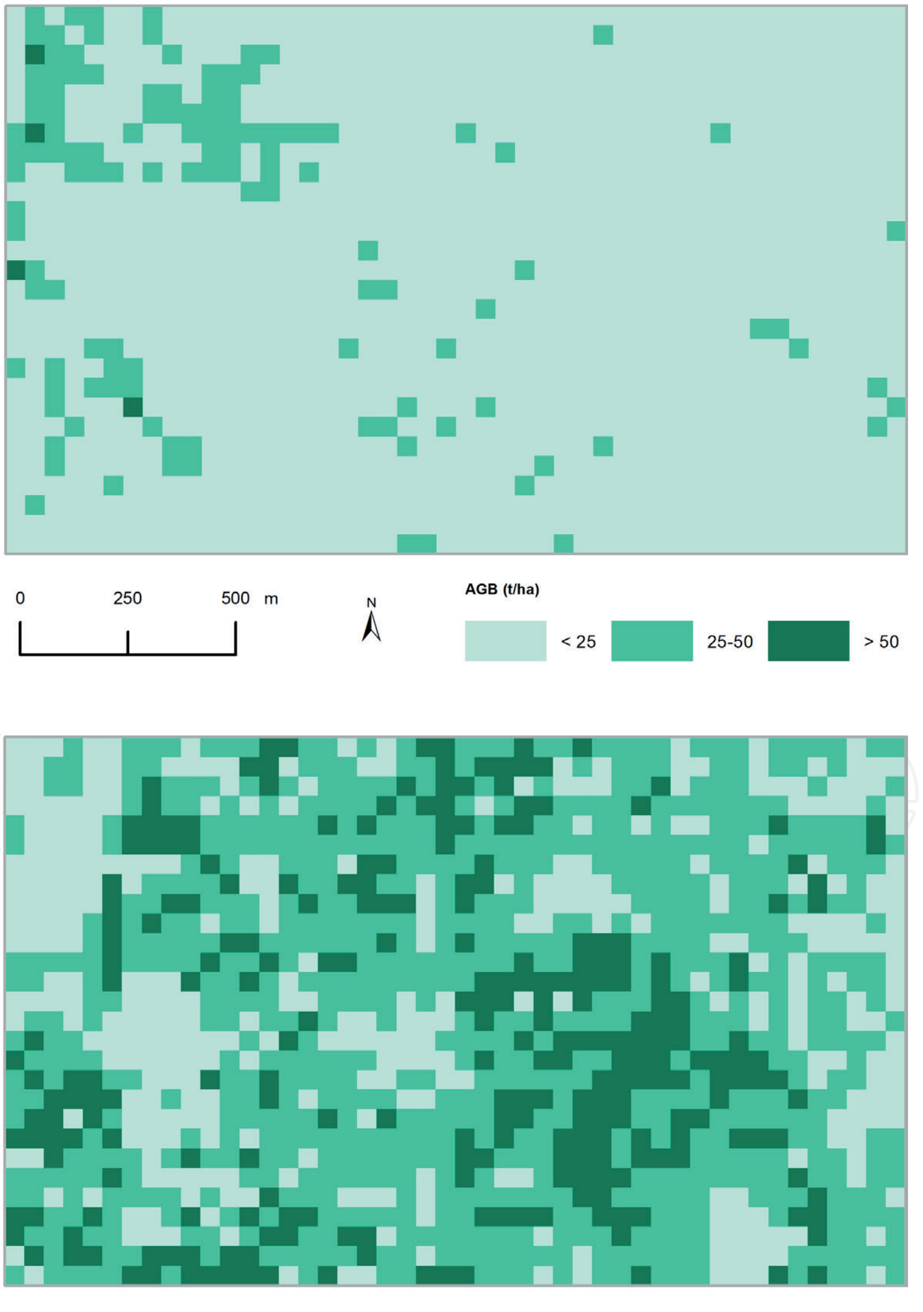

Figure 4.
Above-ground biomass per grid (in t ha^{-1}) for two areas, one with low density (top) and another with high density (bottom).

Grids		Pure		Mixed			Pure and mixed		Total
		QR	QS	QR	QS	total	QR	QS	
AGB		8737	6166	85,158	84,818	169,976	93,895	90,984	184,879
Scenario/Share of AGB removed (%)									
A1	10	874	617	8516	8482	16,998	9390	9098	18,488
A2	15	1311	925	12,774	12,723	25,496	14,084	13,648	27,732
A3	20	1747	1233	17,032	16,964	33,995	18,779	18,197	36,976
A4	25	2184	1542	21,290	21,205	42,494	23,474	22,746	46,220
A5	30	2621	1850	25,547	25,445	50,993	28,169	27,295	55,464

Table 3.
Above-ground biomass and weight of residues for each alternative for residues removal on a 6 year basis for the study area (in t d.b.). QR refers to holm oak and QS to cork oak.

Table 3 presents the above-ground biomass and the weight of residues for each alternative considered for the share of residues removed in pruning. It was assumed that the trees are pruned every 6 years and that the amount of residues per year is 1/6 of the total amount of residues for the all area in a six-year period. Also for grids with both species, it was considered that the weight of biomass of residues per species corresponded to the mean share of crown cover per species for the entire forest area (50.1% for holm oak and 49.9% for cork oak).

4. Energy potential of evergreen oak firewood in the study area

The yearly amounts of oak residues estimated in the last section for the study area under different scenarios were converted to energy using Eq. (2),

$$E_{t,i} = B_i \times LHV_i, \tag{2}$$

where the subscript i refers to the forest species, $E_{t,i}$ is the theoretical energy potential of the residual biomass, B_i the yearly quantity of biomass that can be removed from the study area and LHV_i the lower heating value (given in **Table 4**). The result of computing Eq. (2) represent the theoretical energy potentials of evergreen oak firewood that can be collected in the study area, which are the upper limits for the value of energy that can be obtained from oak biomass residues.

A moisture content of 30% was considered, resulting in LHV (a.r., as received) of 11.1 and 11.6 MJ kg^{-1} for holm and cork oak, respectively. As a comparison, the

Wood	LHV[1] (MJ kg^{-1} a.r.)	LHV[2] (MJ kg^{-1} d.b.)
Holm oak	11.1	16.9
Cork oak	11.6	17.6

[1]*Considering 30% water content.*
[2]*Taken from [17].*

Table 4.
Lower heating value of cork and holm oak firewood.

Portuguese energy balance considers that the lower heating value of firewood is 10.5 MJ kg^{-1}.

Depending on the percentage of residues collected each time the trees are pruned, the amount of evergreen oak firewood that is available in the study area is in the range of 3081 to 9244 t $year^{-1}$. This corresponds to a theoretical energy potential between 5.0×10^7 MJ $year^{-1}$ and 1.5×10^8 MJ $year^{-1}$ (**Table 5**).

The values reported in **Table 5** correspond to the energy content of the residues, but, if they are used for household heating, not all this energy can be converted to heat. There is a conversion efficiency, η, which is dependent on the technology used, and defined by Eq. (3),

$$\eta = E_{u,i} / E_{t,i}, \quad (3)$$

where i refers to the forest species and $E_{u,i}$ is the useful energy obtained from the combustion of the i^{th} firewood type, which is reported on **Table 6** for each of the scenarios considered.

Considering that all of the firewood is burned in open fireplaces, the most popular wood-fired appliance for household heating in Portugal [25], the amount of energy generated from the firewood obtained in the study area would be between 5.0×10^6 MJ $year^{-1}$ and 1.5×10^7 MJ $year^{-1}$ (**Table 6**). If instead, the firewood would be burned in more efficient appliances, the energy that could be obtained would be significantly higher (between 2.5×10^7 MJ $year^{-1}$ and 7.5×10^7 MJ $year^{-1}$). The use of closed burning appliances represents an increase of 400% in the energy produced.

The two alternatives for energy conversion technologies considered in **Table 6**, where only one technology is used to convert all the collected biomass into energy,

Scenario	Amount of firewood (t d.b. $year^{-1}$)		Theoretical energy potential (MJ $year^{-1}$)	
A1	Holm oak	1565	Holm oak	2.5×10^7
	Cork oak	1516	Cork oak	2.5×10^7
	Total	3081	Total	5.0×10^7
A2	Holm oak	2347	Holm oak	3.7×10^7
	Cork oak	2275	Cork oak	3.8×10^7
	Total	4622	Total	7.5×10^7
A3	Holm oak	3130	Holm oak	5.0×10^7
	Cork oak	3033	Cork oak	5.0×10^7
	Total	6163	Total	1.0×10^8
A4	Holm oak	3912	Holm oak	6.2×10^7
	Cork oak	3791	Cork oak	6.3×10^7
	Total	7703	Total	1.2×10^8
A5	Holm oak	4695	Holm oak	7.4×10^7
	Cork oak	4549	Cork oak	7.5×10^7
	Total	9244	Total	1.5×10^8

Table 5.
Yearly amount and theoretical energy potential of the oak firewood obtained in the study area under the different scenarios considered.

Scenario	Available energy (MJ year^{-1})			
	Open fireplace[1]		Cast iron stove[2]	
A1	Holm oak	2.5×10^6	Holm oak	1.2×10^7
	Cork oak	2.5×10^6	Cork oak	1.3×10^7
	Total	5.0×10^6	Total	2.5×10^7
A2	Holm oak	3.7×10^6	Holm oak	1.9×10^7
	Cork oak	3.8×10^6	Cork oak	1.9×10^7
	Total	7.5×10^6	Total	3.7×10^7
A3	Holm oak	5.0×10^6	Holm oak	2.5×10^7
	Cork oak	5.0×10^6	Cork oak	2.5×10^7
	Total	1.0×10^7	Total	5.0×10^7
A4	Holm oak	6.2×10^6	Holm oak	3.1×10^7
	Cork oak	6.3×10^6	Cork oak	3.1×10^7
	Total	1.2×10^7	Total	6.2×10^7
A5	Holm oak	7.4×10^6	Holm oak	3.7×10^7
	Cork oak	7.5×10^6	Cork oak	3.8×10^7
	Total	1.5×10^7	Total	7.5×10^7

[1]10% efficiency [31].
[2]50% efficiency [28].

Table 6.
Energy potential of the oak firewood obtained in the study area under the different scenarios considered.

do not reflect the technological split existent in the country. The biomass technologies used for residential heating are diverse and their shares change over time. The scenario that considers that only open fireplaces are used is a borderline case, which seeks to illustrate the impact of using inefficient equipment. If a technology split close to the one reported in the INE/DGEG survey [25] is considered, the amount of useful heat generated from the firewood obtained in the study area would be between 1.4×10^7 MJ year^{-1} and 4.1×10^7 MJ year^{-1}.

Knowing the amount of firewood consumed under each scenario, it is possible to estimate the emissions of airborne pollutants for each firewood species and technology considered, $EE_{k,i,j}$, using Eq. (4),

$$EE_{k,i,j} = EF_{k,i,j} \times B_{i,j}, \tag{4}$$

where k refers to the pollutant, i to the forest species and j to the technology. $EF_{k,i,j}$ is the emission factor of pollutant k for the j^{th} appliance/equipment when combusting firewood of the i^{th} species and $B_{i,j}$ the quantity of biomass i that is burned in the technology of type j.

The emissions of airborne pollutants that would be generated from the combustion of the firewood that could be collected in the study area are reported on **Table 7** for the scenario that considers heavy pruning (for the other scenarios, the emissions would be lower, but the same conclusions could be drawn). It can be seen that, in general, open fireplaces emit more pollutants than stoves. Additionally, burning cork oak is responsible for more emissions (CO_2 not considered, as it will be discussed in the next paragraph).

Substance / Scenario A5	Emissions[1] (t year^{-1})			
	Open fireplace		Cast iron stove	
$PM_{2.5}$	Holm oak	61.5	Holm oak	27.2
	Cork oak	81.4	Cork oak	37.8
	Total	142.9	Total	65.0
OC	Holm oak	33.8	Holm oak	14.1
	Cork oak	45.9	Cork oak	21.8
	Total	79.7	Total	35.9
EC	Holm oak	1.4	Holm oak	1.1
	Cork oak	3.1	Cork oak	1.9
	Total	4.5	Total	3.0
CO	Holm oak	290.2	Holm oak	299.1
	Cork oak	388.9	Cork oak	451.3
	Total	679.1	Total	750.3
CO_2	Holm oak	3450.8	Holm oak	4624.6
	Cork oak	2511.0	Cork oak	4071.4
	Total	5961.9	Total	8695.9

[1]*Emission factors taken from **Table 2**.*

Table 7.
Emissions of the combustion of the oak firewood obtained in the study area under the scenario were more residues are obtained (A5).

CO_2 emissions reported in **Table 7** are dependent on the carbon content of the biomass and inherent to biomass-fired combustion systems. A higher value of carbon dioxide emissions reflects both the carbon content of the fuel and the completeness of the combustion process (for the same fuel, when all the carbon is oxidized because combustion is complete, the CO_2 emissions are larger than when combustion is not so efficient). The CO_2 emissions are not included in the national emission inventory, though, since biomass is considered carbon neutral [23].

Table 8 presents the amount of airborne pollutants that would be emitted when combusting the firewood that could be collected in the study area divided by the amount of thermal energy that could be usefully used for household space heating (these results are independent of the silvicultural scenario considered). As expected, the use of open fireplaces presents much higher emissions per unit energy obtained for space heating than the use of stoves.

The results presented in **Tables 6–8** show the importance of both the silvicultural practices and energy conversion technologies on the energy that can be obtained from evergreen oak firewood and on the emissions that result from burning that firewood. If the pruning is heavier, more firewood is obtained and in theory more useful energy. However, as shown in **Table 6** this does not imply that more useful energy is obtained. If this firewood is burned in a traditional fireplace, the energy efficiency is so low that more firewood is needed to reach the same useful energy as in a traditional stove. Pruning 30% of the above-ground biomass of evergreen oaks and burning all the firewood in a traditional fireplace results in less energy than pruning 10% of the above-ground biomass to fire a closed burning appliance. Additionally, the emissions of airborne pollutants per unit useful heat generated are

Substance	Emissions[1] (t MJ^{-1})			
	Open fireplace		Cast iron stove	
$PM_{2.5}$	Holm oak	8.26	Holm oak	0.73
	Cork oak	10.80	Cork oak	1.01
	Total	19.06	Total	1.75
OC	Holm oak	4.54	Holm oak	0.38
	Cork oak	6.09	Cork oak	0.59
	Total	10.64	Total	0.96
EC	Holm oak	0.19	Holm oak	0.03
	Cork oak	0.41	Cork oak	0.05
	Total	0.60	Total	0.08
CO	Holm oak	38.97	Holm oak	8.03
	Cork oak	51.59	Cork oak	12.12
	Total	90.57	Total	20.16
CO_2	Holm oak	463.51	Holm oak	124.23
	Cork oak	333.10	Cork oak	109.37
	Total	796.62	Total	233.61

[1]*Emission factors taken from* ***Table 2****.*

Table 8.
Emissions per unit useful energy obtained from the combustion of the oak firewood collected in the study area.

much higher. Also important is the fact that heavier pruning practices have some undesirable environmental impacts. The higher the intensity of pruning, the higher the leaf area removed, and thus the lower the photosynthetic ability. This results in a reduction of growth and production, whether of bark (cork for cork oak) or fruit (for cork and holm oak). This is also reflected in the incomes and in the sustainability of the systems as the evergreen oaks in these type of agroforestry systems have also an important role in the conservation of habitats, soil and water.

According to the concept of "energy ladder" [40], households tend to replace inefficient and more polluting fuels and energy conversion technologies by others that are "better" as their income rises. This is what has been happening in OECD Europe, where households mainly consume natural gas, followed by electricity; biofuels and waste coming third [41]. By mid-19th century, Portuguese households mainly consumed firewood [42], but in 2018 this share was 26% and the dominant energy source in households was electricity [24]. However, the "energy ladder" does not mean that modern biomass technologies should not be used and promoted. Residential biomass is an alternative to the use of fossil fuels and presents many advantages. However, the transition from traditional appliances to more efficient and cleaner technologies should be promoted [43].

5. Conclusions

Cork and holm oak firewood is traditionally used for household heating in Southwest Europe. This wood, as other types of firewood, is mostly traded in informal markets in Portugal. The latter results in a lack of statistics on firewood consumption in the country, which hinders energy and environmental planning. Additionally, the assessment of the amount of wood that can sustainably be removed from the forest is of the upmost importance for the definition of bioenergy policies. In this context, this study used a method based on very high resolution remote sensing data to determine the energy potential of evergreen oak firewood for household heating. Different silvicultural and energy utilization scenarios were considered. The method was applied to an area of 12,188 ha dominated by cork and holm oak stands. The results show that both silvicultural practices and energy conversion technology choices are of primordial importance to the sustainability of the use of firewood for household heating. The use of inefficient equipment, still popular in Portugal, leads to considerable amounts of emissions of airborne pollutants and firewood consumption. The results presented in this study show that the use of open fireplaces results in much larger biomass removals from the stands (for the same amount of useful heat obtained) with various environmental implications. When using more efficient equipment, the same amount of heat could be obtained with less biomass and airborne emissions. This fact is often forgotten in public energy policies, but is of primordial importance in a country where biomass is the most important source for household heating. Through the presentation of a case study, the authors want to put in evidence the need for the development of public policies that are directed to a transition from traditional to modern biomass uses for household heating.

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