Sustainable biomass pellets using trunk wood from olive groves at the end of their life cycle

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ABSTRACT

Forest biomass is the raw material most commonly used to produce quality pellets for domestic households. However, sustainable forest biomass is not available in all regions, but there are other potential raw material sources for biomass heating systems, based on pellets. There are a large number of olive trees in the Mediterranean area, but these are not used as renewable pellet fuel because the bark cannot be used as raw material to produce quality pellets. The aim of this study is to carry out a methodology to estimate the optimal sustainable bioenergy life cycle, and the amount of sustainable residue available (trunk wood) at the end of the life of the olive grove, by optimizing the benefits, through an analysis of costs and income of the whole life process. The methodology determines the potential value of the trunks of olive trees to be used as biomass, in the form of pellets in domestic contexts and in a specific geographical area. In a case study applied to Andalusia, it has been shown that the optimal renewable life-cycle is 97 years. If policies for agricultural and energy sustainability favouring this model were adopted, this region would produce 160,000 tonnes of pellets per year, and 266,500 tonnes per year, if extended to the whole of Spain. This has a potential for providing 70.17% of the current total pellet consumption. The extension of the model to other Mediterranean countries, such as Greece and Italy, would result in an additional 124,000 and 144,000 tonnes of pellets per year, respectively.

1. Introduction

Energy, as a resource, is one of the main indicators of the human development index level (Gouveia et al., 2019; Insah and Bhattacharyya, 2015; Neumayer, 2001). Currently, 77.6% of the European energy supply comes from fossil fuels, whereas 11.7% is supplied by nuclear plants, and 11.1% comes from renewable energy sources. This high dependence on fossil resources produces significant environmental impacts and affects the economy. It motivates policies for promoting the development and use of renewable alternative sources. In the case of the EU-28, the use of renewable energies in 2015 accounted for 16.66% of gross final consumption, compared to 16.13% in 2014. Within these data, regarding the production of heat with biomass, in 2015, bioenergy represented 10% of total energy consumed and 61.34% of the renewable energy used (AEBIOM, 2017), making biofuels currently one of the main renewable energy alternatives.

In this context, the use of agricultural, forestry or food residues, for their use in heating systems in buildings and individual dwellings, is a waste management strategy that offers advantages for the circular economy (Valentín et al., 2016) and reduces the dependence on fossil fuels (Agar, 2017; Cheng, 2017). Although it involves combustion and CO_2 emissions, the whole chain will be CO_2 neutral, being compensated throughout the useful life of the agricultural resource by the process of photosynthesis (Anon; Working Group III IPCC, 2007).

The development of sustainable strategies and policies based on these raw materials, assuring the economic and technical viability of systems based on their use and exploitation, requires the guarantee of medium and long-term supply, as well as a minimum low heat value (Hoogwijk et al., 2003; Werther et al., 2000). Currently, wood chips, agro-industrial residues, firewood and pellets are the main solid biofuels used for this purpose (Karkania et al., 2012; Waheed et al., 2019). Fig. 1 shows the distribution of pellet production and global trade flows (Calderón et al., 2018).

As Fig. 1 shows, Europe is the world's largest consumer of pellets with 20.3 million tonnes in 2015 (European Biomass Association (AEBIOM), 2016), of which, 6.2 million tonnes were
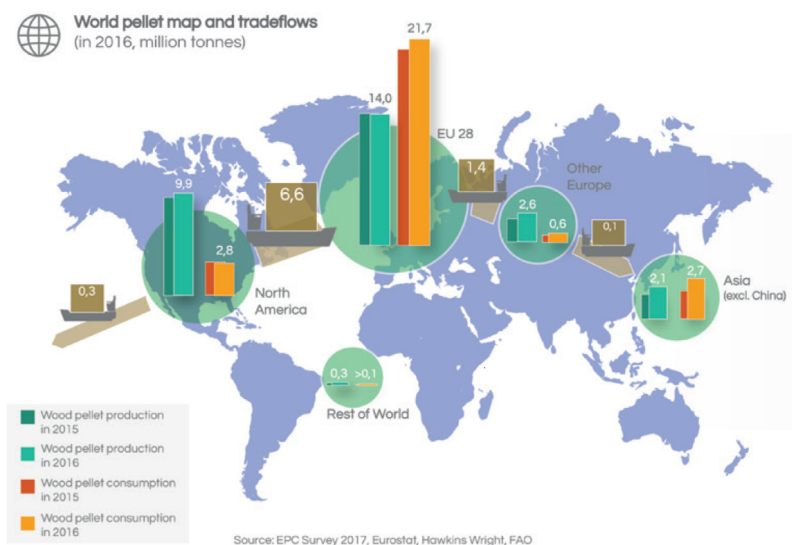
Fig. 1. World pellet map and trade flows in 2017 (Calderón et al., 2018).

imported from America, Russia and Eastern Europe. Optimal energy efficiency depends on the quality of the pellet, defined from the properties of the feedstock and the pelleting process. The ISO 17225-2 (ISO, 2014a) defines different parameters for the classification, according to the quality of the pellet and its use at an industrial or domestic level.

At present, only forest residues have feasible technologies and associated markets for exploitation in Europe (García-Maraver et al., 2015). In the case of the Mediterranean area, those residues coming from the activities of the olive-growing sector are an important source for the manufacture of pellets, the main by-products for energy recovery being pomace "orujillo" (olive cake or post oil-extraction waste) (Valenti et al., 2017), "hojín" (dry leaves that fall from the olive trees and that are buried as a natural fertilizer), pruned remains and olive pits (Agencia Andaluza de la Energía, 2011; Consejería de Agricucltura Pesca y Desarrollo Rural, 2015; Hansen, 2019; Niaounakis and Halvadakis, 2006; Schipfer and Kranzl, 2019). In Andalusia, in particular, the total energy potential of the by-products of the olive agroindustry amount to 567,702 toe/year, in terms of primary energy, data that make the development of forms of energy use from this resource a priority (Ekman et al., 2013; García-Maraver et al., 2012). Even with these benefits and framework, their use as a biofuel is quite reduced (García-Maraver et al., 2015), although different studies analyse the economic feasibility, mechanical behaviour and physical–chemical properties of pellets extracted from different varieties of waste (Carone et al., 2011; Garcia-Maraver et al., 2014; Miranda et al., 2010; Mani et al., 2006). There are different reasons for their low use as a biofuel. Wastes are produced locally and their use involves high costs, either because of the logistical processes required for their transfer to processing or central combustion plants (high storage volume of the feedstock), or the investment required on a small scale in local installations (Barreca and Fichera, 2013, 2014; Caputo et al., 2003; Kinab and Khoury, 2015). Main limitations for its use are associated with *high moisture content, low bulk density, low ash melting point and high volatile matter content* (Werther et al., 2000). It should be noted that, if the pruning feedstock (leaves and branches) of almond, black poplar, holm oak and olive species are compared, the pellets from olive residues have optimum lower heating value (LHV) and its production offers greater density and greater resistance to traction than other feedstock. However, they have a high ash content, and even though it is lower than that of separate olive leaves, it reaches a value above

the threshold of domestic boiler regulation (1.5%). In terms of the different forms of residues [olive wood (bark and trunk) and olive pruning (leaves and branches)], the leaves are responsible for producing the greatest amount of ash, followed by bark and branches (Garcia-Maraver et al., 2014; Velázquez-Martí et al., 2011). On the other hand, the trunk wood offers optimal results that meet the quality required in commercial and residential applications and is therefore the most suitable part for generating pellets for domestic use. Table 1 summarizes the characteristics of the pellets by taking into account the origin of the residue and the quality (A1, A2 or B).

In order to estimate the availability of residue and the potential for pellet generation, it is necessary to evaluate the whole lifecycle of the olive grove, differentiating between biological, productive and energy cycles (Fig. 2). The biological cycle is estimated to be over 2000 years, although the contrasted value in scientific studies is 700 years [27]. This cycle is divided into three stages: (i) youth (0–20 years); (ii) adult period (20–100 years) composed of the production phase (20–50 years) and the decreasing phase (50–100 years); and (iii) senescence (>100 years). Nonetheless, the optimal production cycle is reduced to a range of 40–50 years depending on the variety (Gucci and Cantini, 2000). Old trees can be very productive as long as they are subjected to a rejuvenation process, although as old age is reached, i.e., after 70 years, pruning and harvesting costs increase and annual production decreases (Gucci and Cantini, 2000; Pastor Muñoz Cobo and Guillén, 2015). Lastly, the energy life cycle of an olive grove is calculated as the optimum cost-benefit value of the exploitation, including the income from the sale of wood for its energy recovery.

At present, the biological life cycle is generally given priority over the productive life cycle on olive farms and, in the Mediterranean area in particular, the productive cycle can be longer than 200 years (Bormann, 1985; Bytnerowicz and Omasa, 2007; Paoletti et al., 2010). In most cases, the renewal of plantations is not carried out, due to a lack of knowledge of the optimum cost-benefit value, there are also no economic incentives.

Under this framework, it is of interest to identify the optimum productive and energy cycles of the olive grove, maximizing resource productivity and, subsequently, to identify the capacity for exploitation of available wood residues at the end of life stage as an energy source and economic opportunity for this agri-food sector.

Table 1
Characteristics of the pellet studies and ISO 17225-2:2014 (Garcia-Maraver et al., 2014; ISO, 2014a).

Parameter	Pine spain	Olive wood	Olive pruning	Pellet A1	Pellet A2	Pellet B
Proximate analysis (% wt, as received)						
Moisture	10.1	7.6	8.0	≤10	≤10	≤10
Ash	1.0	1.4	5.5	≤0.7	≤1.5	≤3.0
Ultimate analysis (% wt, dry ash free)						
Nitrogen	0.3	0.3	1.1	≤0.3	≤0.5	≤1.0
Sulphur	0.02	<0.01	0.05	≤0.03	≤0.03	≤0.04
Lower heating value (MJ/kg)	16.9	16.0	16.5	16.5–19	16.3–19	16.0–19
Durability	91.88	98.09	98.92	≥97.5	≥97.5	≥96.5
Bulk Density (kg/ m^3)	544	638	610	≥600	≥600	≥600
Ratio L/D	1.52	3.64	3.86	0.52–40	0.52–40	0.52–40
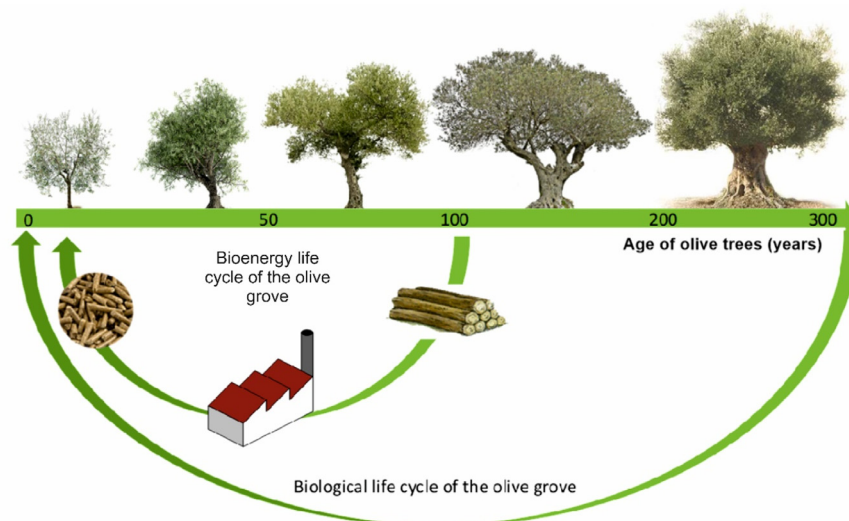
Fig. 2. Biological and bioenergy life cycle of the olive grove.

With this aim, this article develops a methodology to estimate the optimal bioenergy life cycle and the amount of residue available (trunk wood), at the end of life of the olive grove, by optimizing the sustainable exploitation of resources through an analysis of costs and income. With the results, it is possible to evaluate the potential value of the olive tree trunks that could be used as biomass for domestic use in a geographical area. In addition, it is considered that the market value of the pelleted trunk wood will contribute to the required investment for olive tree replacement, replanting for the next productive cycle.

The article is organized as follows: Section 2 describes the proposed methodology; Section 3 develops a case study for the area of Andalusia; and finally, Sections 4 and 5 present the results, discussion and main conclusions of the research.

2. Materials and methods

This Section develops the methodology to estimate the optimal sustainable bioenergy life cycle and the amount of sustainable residue available (trunk wood) at the end of life of the olive grove, by optimizing the benefit, through an analysis of costs and income of the whole life process. The methodology determines the potential value of the trunks of olive trees to be used as biomass, in the form of pellets in domestic contexts in a specific geographical area. In this way, the feasibility analysis sets the renewal and replanting of the olive grove at the end of its optimum productive cycle. This involves an analysis of the costs and income involved in the cultivation of the olive tree for the grower, by taking into account the energy value of the pelleted trunk wood at the end of the life cycle of the olive grove. Fig. 3 illustrates the proposed methodology.

2.1. Step 1: Delimitation and characterization of the study area

The study area is selected by calculating the optimum value of the life cycle of the trees for an energy use as pellets, there are no limits of surface area, and it can be applied to different levels: country, region, locality or crop.

Once selected, the type of olive grove will be characterized. If there is more than one olive variety in the area under study, it will be necessary to determine their percentage and distribution, because production data will vary according to type of olive. After that, a descending order of surface area occupied by variety is established. For an adequate level of accuracy a definition of occupation above 90% of the total is considered.

For the characterization of the area it will be necessary to collect data on: total area occupied [m^2]; olive tree varieties and their area occupied [type, m^2]; production by variety [kg/tree]; cultivation regime (irrigated or dry); density of plantation [olive trees/ha]; age at the start of the production cycle [year]; selling price of the olive [€/kg]; selling price of the tree [€/t]; frequency of production pruning [years]; beginning of production pruning [year]; trunk perimeter growth [cm/year]; and trunk height [m]. These data can be obtained from statistical data publications such as Navero et al. (2017), Fabbri (2004), Gucci and Cantini (2000), Pastor Muñoz Cobo and Guillén (2015).

2.2. Step 2: Calculation of economic variables and estimation of individual functions

The optimal productive cycle of the olive grove depends on four economic variables: production, trunk wood mass, pruning and harvesting of olives. As the objective is to determine the
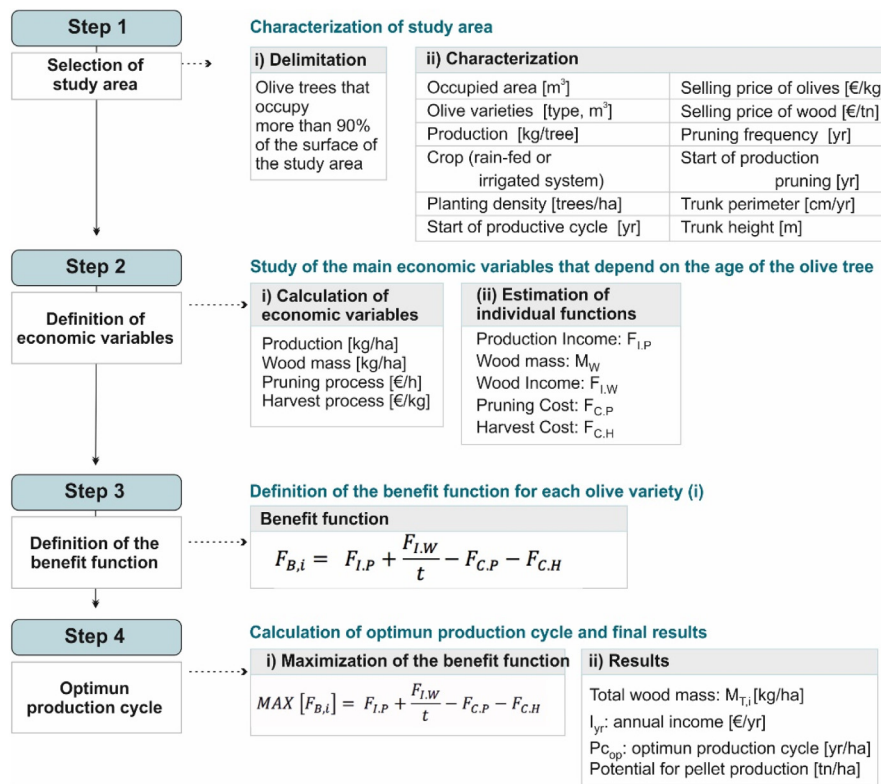
Fig. 3. Proposed methodology for the evaluation of biomass optimized potential for pellet production.

optimum bioenergy cycle of the olive grove, all of these variables depend on the age of the olive tree, which implies a direct relationship with the income and costs of managing the plantation. All those economic variables independent of the age of the olive tree are discarded, as they remain constant on any farm. Income comes from: (i) annual income, due to the production and sale of olives which are present throughout the productive life cycle of the olive grove; and, (ii) specific income, defined as that obtained from the sale of the tree at the end of the life cycle of the olive tree. On the other hand, the costs of an olive farm are quite diverse: pruning, harvesting, soil maintenance, foliar treatments, prevention of pests and diseases, fertilization, etc. However, only those that depend on the age of the olive tree are relevant at this step: (i) cost of annual harvesting; and, (ii) cost of variable pruning, depending on the stage of the biological cycle of the tree.

In the following sections, each economic variable is defined and modelled through a time-dependent function. This study is based on statistical data related to the different parameters and factors which affect the generation and use of olive residues. These data come from studies of species and the exploitation of plantations in the Mediterranean area (Navero et al., 2017; Conserjería de Agricultura y pesca, 2002a; Fabbri, 2004; Gucci and Cantini, 2000; Instituto de Investigación y Formación Agraria y Pesquera (IFAPA), 2010; Pastor Muñoz Cobo and Guillén, 2015; Tous et al., 2014). The functions are approximations to the behaviour of these data, and are chosen as the most optimal to represent each factor.

2.2.1. Olive grove production

Olive grove production is defined as the kilogrammes of olives produced per hectare, the variables that most significantly affect it are: the variety of olive tree, the cultivation regime and the age of the tree (Conserjería de Agricultura y pesca, 2002a). It should be noted that production decreases with ageing once the maximum productive age has been reached. The production of new plantation specimens is estimated at 1956 kg/ha; while that of adult trees is estimated at 2736 kg/ha (Conserjería de Agricultura y pesca, 2002a). The use of irrigated crops increases production with respect to non-irrigated crops, for example, in the *Picudo* variety, irrigation produces 48 kg/tree compared to 27.50 kg/tree without irrigation (Navero et al., 2017; Fabbri, 2004). For the latter case, two alternatives may be considered in the methodology: to select the majority regime in the study area (dry or irrigated), or, to take into account the productive variability by dividing into sub-areas and assigning them the occupied surface with irrigated and dry regimes.

Income from production therefore depends on the previous variables (variety of olive tree, cultivation regime and age of the olive tree) and on the production level, considering: the density of the plantation, the beginning of the production cycle (age at which the specimen begins to produce), and the selling price of the olives. The price of olives varies from season to season, and their yield is taken into account in order for income to be estimated. The methodology provides two alternatives: to use an average estimation of the selling price for the olive grove, or to use a different selling price for each variety of olive tree. F_{IP} [€/ha] will be the time evolution of income for each variety of olive tree.

2.2.2. Income linked to trunk wood mass

In this energy application the optimal productive cycle of the olive tree ends with the use of the trunk wood for the generation of pellets for residential use. The wood that can be harvested is the trunk without bark.

This variable allows us to determine the availability of resources for obtaining biomass in the life cycle of the olive grove or, in other words, the potential for generating pellets from a farm.

Volume and mass are estimated from the diameter and height of the olive tree trunk, which depend on the variety and age of the olive tree (except cutting process, disease or accident). It

Table 2
Variation of trunk diameter according to the variety of olive tree (Instituto de Investigación y Formación Agraria y Pesquera (IFAPA), 2010).

Olive variety	Trunk diameter [cm]
Hojiblanca	10.5
Arbequina	8.5
Picual	12
Picudo	12.5
Arroniz	14
Negral	18

is considered that the perimeter of the olive tree grows by approximately 2.5 cm/year (Arnan et al., 2012), reaching maximum productivity with the diameters shown in Table 2, depending on the variety, whereas the maximum trunk height can vary between 0.8 and 1 m (Gucci and Cantini, 2000; Instituto de Investigación y Formación Agraria y Pesquera (IFAPA), 2010).

In order to calculate the trunk wood mass, the quantity of log without bark M_i [kg] is determined depending on the variety i of the olive tree. First of all, the diameter of the trunk D_i [m] is calculated as a function of the perimeter P_i [m] with the expression (1):

$$D_i = \frac{P_i}{\pi} \tag{1}$$

Then the volume of the trunk V_i [m^3] is calculated by geometric approximation to a cylinder from the expression (2), r_i[m] being the radius of the trunk and h_i [m] the height of the trunk [m], considering h_{max} between 0.8 and 1 m:

$$V_i = \pi \cdot r_i^2 \cdot h_i \tag{2}$$

With the previous data, the quantity of wood M_i [Kg/tree] is calculated depending on the volume V_i [m^3] and the density of the wood d_w [kg/ m^3] depending on the tree variety:

$$M_i = d_w \cdot V_i \tag{3}$$

Next, the expression (4) provides information on the total amount of trunk wood $M_{T,i}$ [kg/ha] that a variety i will be able to produce in the life cycle of the olive grove; and the expression (5) gives information on the total income from the sale of trunk wood I_w [€/ha]. For these, the plantation density D_{ha} [tree/ha] and the selling price of trunk wood P_w [€/kg] must be established.

$$M_{T,i} = M_i \cdot D_{ha} \tag{4}$$

$$I_w = M_{T,i} \cdot P_w \tag{5}$$

If there are different varieties of olive tree in the same plantation, the total mass of the available trunk wood will be calculated with the sum of the quantities $M_{T,i}$ obtained for each variety i.

Finally, the annual income and the amount of annual pellets are calculated for the life cycle of the olive grove. The annual result of incomes I_{yr} [€/yr] is obtained from the expression (6) that relates the total income of the olive grove I_w [€/ha] with the considered productive cycle PC_{op} [years/ha]:

$$I_{yr} = \frac{I_w}{PC_{op}} \tag{6}$$

The pellet generation potential of the farm is determined from the efficiency of the pelleting process, by taking into account the trunk wood mass $W_{T,i}$ [kg], the percentage of wood moisture (25%) and the percentage of wood reduction by the process (15%).

The study of the evolution of this economic variable, with respect to time, will result in the *trunk wood income function* $F_{I,w}$ [€/ha], which models the income derived from the sale of the wood when the olive grove reaches the end of its optimal productive cycle. This study is carried out in Section 3.2.2.

2.2.3. Pruning process

During the biological cycle of the olive tree, three different pruning operations are carried out: formation pruning, production pruning and renewal pruning. The objective, and frequency, of each pruning operation is shown in Fig. 4. Formation pruning is carried out approximately every three years with the aim of remodelling the structure of the olive tree, it is characterized by being minimal because the date of beginning of the production of the olive tree depends on the number of leaves and branches respected in this pruning. The production pruning is carried out during the adult phase of the olive tree, in order to obtain a sufficient volume of crown to assure the maximum amount of harvests, and to lengthen the productive period. After harvesting, the olive tree is pruned for renewal (maintenance), which is carried out when the specimen shows signs of ageing and hardening, with recovery being a way of resolving the problem of excess wood. At this time, a period of imbalance in the leaf/wood ratio begins, which causes a decrease in harvests, a greater alternation of production, and a deterioration in the quality of the fruits (Fabbri, 2004). When the olive tree reaches the senile stage, pruning becomes more frequent and renewals are more severe.

In order to calculate these variables, it is necessary to set: the beginning of pruning, the frequency of the types of pruning and the pruning mechanism. For the latter, it will be necessary to know the hours invested and the hourly cost of the task. It is considered that all varieties of olive trees use the same mechanism, type and cost of pruning.

The study of the evolution of these variables over time will result in the pruning cost function $F_{C,P}$ [€/ha], which models the costs associated with the set of pruning operations and tasks in the study area throughout the biological cycle of the olive grove. This study is carried out in Section 3.2.3.

2.2.4. Olive harvesting process

There are different methods of harvesting olives: traditional (soil harvesting, milking and olive knock down) and mechanical, the choice depends on the characteristics of the soil, the crop and the growth of the crown of the olive tree (Sola-Guirado et al., 2014). The costs associated with harvesting depend on the variety of olive tree, the productivity of the olive grove [kg olive/ha], the harvesting mechanism (which defines the hours required, as well as the hourly cost of labour) and the start of the olive grove production cycle (Tous et al., 2014).

2.3. Step 3: Definition of the benefit function for each olive variety and global benefit function

Once the study area and the economic variables in relation to the farm to be evaluated have been selected, the benefit function is defined for each of the olive tree varieties $F_{B,i}$ to maximize from the income and costs of the olive grove:

$$MAX\left[F_{B,i}\right] = F_{B,i} = F_{I.P} + \frac{F_{I.W}}{t} - F_{C.P} - F_{C.H} \tag{7}$$

where:

- F_B is the benefit function
- $F_{I.P}$ is the production income function [€/ha]
- $F_{I.W}$ is the trunk wood income function [€/ha]
- $F_{C.P}$ is the pruning cost function [€/ha]
- $F_{C.H}$ is the collection cost function [€/ha]
- t is time [years]

It is necessary to consider the different timings of the considered processes. The production income and the cost of harvesting are annual, and occur throughout the productive cycle of the olive grove. The cost of pruning depends on the frequency of the
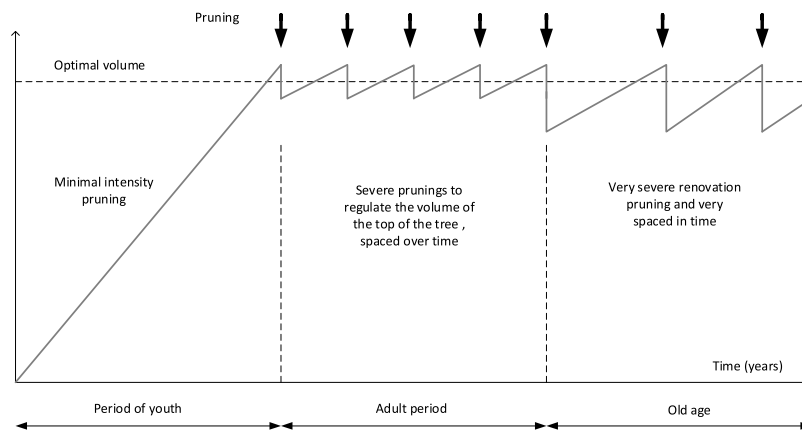
Fig. 4. Pruning and age of olive groves (Pastor Muñoz Cobo and Guillén, 2015).

process, usually every two or three years, depending on the need for maintenance, so transformation to an annual value is required. Finally, income from the sale of trees occurs at the end of the productive cycle of the olive grove, therefore, I_W will be used for the annual cost per trunk wood, as reported in Section 2.2.2.

2.4. Step 4: Maximize benefit function

Calculating the maximum value for the defined function $F_{B,i}$, obtains the optimal duration of the productive cycle for of each variety of olive grove, and thus, the optimal bio-energy cycle period, in years. With this data it is possible to determine the potential of biomass generation for energy [kg/ha].

Finally, the data of the selected study area can be projected to other areas, depending on the cultivated surface of the olive grove and the olive tree varieties, in order to obtain an approximation of the pellet potential of other geographical areas.

3. Results

This section covers the application of the developed methodology to the region of Andalusia, in the South of Spain, in order to determine the potential for generating pellets from waste trunk wood from the olive groves in the region.

3.1. Step 1. Delimitation and characterization of the study area

The Mediterranean area, and Andalusia in particular, has significant tracts of olive plantations and are one of the main sectors for the economy, contributing to the generation of employment and social, territorial and cultural cohesion, as well as producing one of the main products of the Mediterranean diet. The surface area of olive tree groves is approximately 1,500,000 ha. Fig. 5 shows the biomass potential of the territory in t/ha from the Andalusian olive groves (European Union and Junta de Andalucía, 2008).

As was developed in Section 2, the definition of the benefit function, and costs and income for each variety of olive tree, as economic variables, must be defined: production, trunk wood mass, pruning and harvesting. These depend on a set of factors that characterize the area of study and are shown in Table 3: variety of olive tree, type of production, age of the olive tree, density of plantation, age at the beginning of the productive cycle and sale price of the olives. The data have a high level of reliability due to the annual data updates made by growers when they apply for cultivation aids granted by the European Union, and the public register, included in the Agricultural Plots Geographical Information System. SIGPAC (Andalucía, 2018; Consejería de Agricultura Pesca y Desarrollo Rural, 2019).
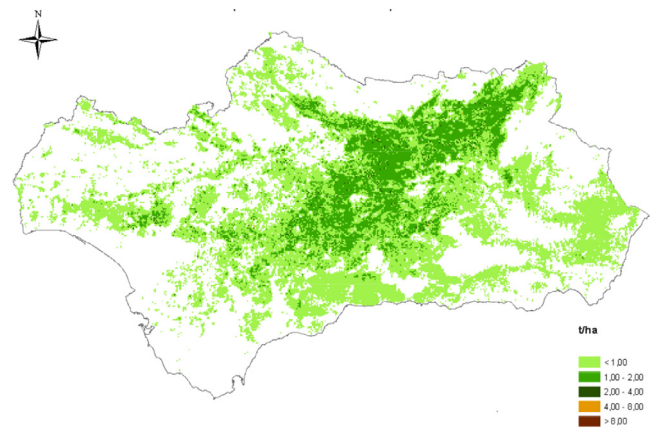

Fig. 5. Potential production of residual biomass from olive groves in Andalusia (European Union and Junta de Andalucía, 2008).

3.2. Step 2: Calculation of economic variables and estimation of individual functions

The following considerations were taken into account for the calculation of economic variables. The varieties of olive tree with an occupation greater than 90% were selected which, in this case, coincides with those listed in Table 3 as the main varieties: *Picual, Hojiblanca, Manzanilla de Sevilla, Lechín de Sevilla, Nevadillo Negro, Picudo and Verdial de Huévar* (Consejería de Agricultura y pesca, 2002a). These have an occupation of 90.58% of the total surface area of the olive grove, disregarding the secondary variables. In relation to the production regime, most of the Andalusian olive groves are cultivated without irrigation (1,102,485 ha, which represents 73.5% of the total area), so the irrigation regime is disregarded. It is considered that the beginning of the productive cycle, for all the varieties of olive trees, begins in the fifth year of age. In addition, an average selling price of 0.65 €/kg is estimated for olives of all varieties (Andalucía, 2018).

3.2.1. Olive grove production

Production depends on the type of olive grove. The data for the estimation of production throughout the life cycle of the olive grove are taken from the analysis of the Andalusian olive groves (Consejería de Agricultura y pesca, 2002b), these are included in Table 4. Although the most productive varieties are Hojiblanca and Picudo, it should be noted that the yield per olive tree depends, in addition to its variety, on other factors such as climate, soil quality, presence of pests or planting density. In

Table 3

Characterization of the study area.

Geographical area	Andalusia 1,500,000 ha of olive grove plantation
Olive varieties	Main (1,358,684 ha; 90.58%): *Picual, Hojiblanca, Manzanilla de Sevilla, Lechín de Sevilla, Nevadillo Negro, Picudo and Verdial de Huévar.*
	Secondary (141,316; 9.42%): *Arbequina, Gordal Sevillana, Aloreña, Verdial de Vélez-Málaga, Lechín de Granada, Pico Limón, Manzanilla Serrana, Alameño Blanco.*
Cultivation regime	Area: 73.5% dry land; 26.5% irrigated land
Density of olive wood	960 kg/m³
Plantation Density	100 olive trees/ha
Age at the start of the production cycle	Age 5
Olive sale price	0.65 €/kg
Trunk wood sale price	30 €/t
Production pruning frequency	2 years
Start of production pruning	20 year old olive grove
Renewal pruning frequency	3 years
Renewal pruning start	50 year old olive grove
Trunk perimeter growth	2.5 cm/year
Trunk height	1 m

Table 4

Average production per olive variety (Conserjería de Agricultura y pesca, 2002b).

Olive variety	Average production [kg/tree]
Hojiblanca	27.00
Lechín de Sevilla	10.42
Manzanilla de Sevilla	20.30
Nevadillo Negro	14.35
Picual	29.04
Picudo	22.63
Verdial de Huévar	12.06

Table 5

Estimation of the *production income function*.

$F_{I.P}$	Parameter values		
Variety	a	b	c
Picual	0.2878	54.55	306.76
Hojiblanca	0.2727	50.03	227.5
Manzanilla de Sevilla	0.2142	39.146	154.45
Lechín de Sevilla	0.1298	23.797	39.428
Nevadillo negro	0.1644	30.084	90.9
Picudo	0.2705	51.384	160.28
Verdial de Huévar	0.1515	27.952	71.133

addition, the choice of variety is made by taking into account the fatty yield of the fruit, with Verdial de Huévar, Picual, Picudo and Nevadillo Negro being the varieties that have better fatty yield compared to Lechín de Sevilla, Manzanilla and Hojiblanca.

Applying the procedure defined in Section 2.2.2, the time evolution of the olive grove is calculated for each variable, obtaining the time production income function $F_{I.P}$. The results are shown in expression (8), Table 5 and Fig. 6.

$$F_{I.P} = -a \cdot t^2 + b \cdot t + c \qquad (8)$$

The relationship of production income (€/ha) to the age of the olive tree (years), gives a quadratic function whose graphical representation is an inverted parabola (a<0). As Fig. 6 shows, the same trend is established for all varieties. Production increases as the olive tree grows to reach the vertex of the parabola, coinciding with the maximum yield of the olive tree, from which time, production begins to decrease.

On the other hand, as Table 5 shows, the value of production differs between varieties (parameters a, b and c), with the foreseeable result as discussed in Table 4, with the highest producing olive varieties being Picual, Picudo, Hojiblanca and Manzanilla de Sevilla, followed by Nevadillo Negro, Verdial de Huévar and Lechín de Sevilla.

3.2.2. Income by quantity of trunk wood mass

For the calculation of the trunk wood mass, the following factors were required: variety of olive, perimeter of the trunk, maximum height of the trunk, and, density of the wood. For the seven selected varieties, it was considered that the perimeter of the trunk grows by 2.5 cm annually, that there is a maximum height of 1 m and a wood density of 960 Kg/m³. Also, to determine the income for trunk wood, the plantation density data (100 olive trees/ha) and sale price (30 €/t) were used. Applying the procedure reported in Section 2.2.2, the evolution of the olive grove is calculated for the economic variable studied, obtaining the time functions of trunk wood mass M_W, and income for trunk wood $F_{I.W}$, the results are shown in expressions (9) and (10), Table 6 and Fig. 7.

$$M_W = a \cdot t^2 + b \cdot t - c \qquad (9)$$
$$F_{I.W} = a \cdot t^2 + b \cdot t - c \qquad (10)$$

[

The relationship between income (€/ha) and the age of the olive tree (years) results in a similar increasing function for all varieties, which can be seen from the parameters listed in Table 6. As Fig. 7 shows, the amount of trunk is directly proportional to the age of the olive tree, with the same trend being established for all varieties. This is due to an increase in the perimeter, when the increase in height of the olive tree is limited to 1 metre. In this case, the variety is not a determining factor. In the first years of the olive tree cycle, the amount of trunk is similar for all varieties, but only in those in the range of 50–100 years can some difference be seen. It can therefore be established that the relationship between income from the sale of the tree and the variety is not significant. There is a difference of only 100€/ha between the varieties of olive trees at 100 years of age.

3.2.3. Olive grove pruning process

For the pruning of the seven varieties of olive tree, the same mechanism, type and cost was used. The following data were taken to characterize the process: beginning of formation pruning at 2 years of age of the tree, carried out with a triennial frequency; beginning of production pruning at 20 years of age, with a biennial frequency; beginning of renovation pruning at 50 years, with triennial frequency. Finally, Table 7 lists the pruning activities, the hours dedicated to these activities, depending on the growth phase of the olive tree, and the cost associated with the process.

As Table 7 shows, and taking into account the assumptions described, a pruning cost of 135.38 €every three years is foreseen,
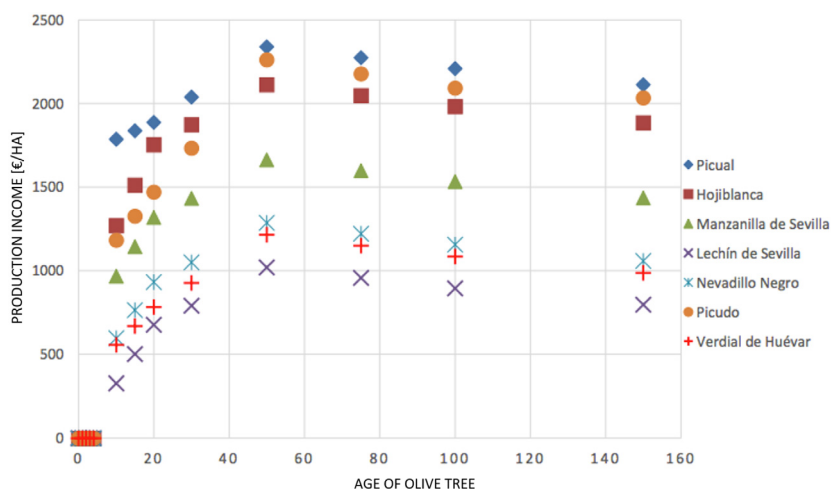
Fig. 6. Distribution of values for *production income function*.

Table 6
Estimation of trunk wood mass and *trunk wood income function*.

Variety	Parameter values for M_W			Parameter values for $F_{I.W}$		
	a	b	c	a	b	c
Picual	14.827	433.66	7130.8	0.0445	1.301	21.392
Hojiblanca	14.798	426.83	707.6	0.0444	1.2805	21.224
Manzanilla de Sevilla	13.598	358.29	6013.2	0.0408	1.1049	18.04
Lechín de Sevilla	13.598	368.29	6013.2	0.0408	1.1049	18.08
Nevadillo negro	13.598	368.29	6013.2	0.0408	1.1049	18.04
Picudo	14.829	433.91	7132.1	0.0445	1.3017	21.396
Verdial de Huévar	13.6	367.93	5998.5	0.0408	1.038	17.995

]

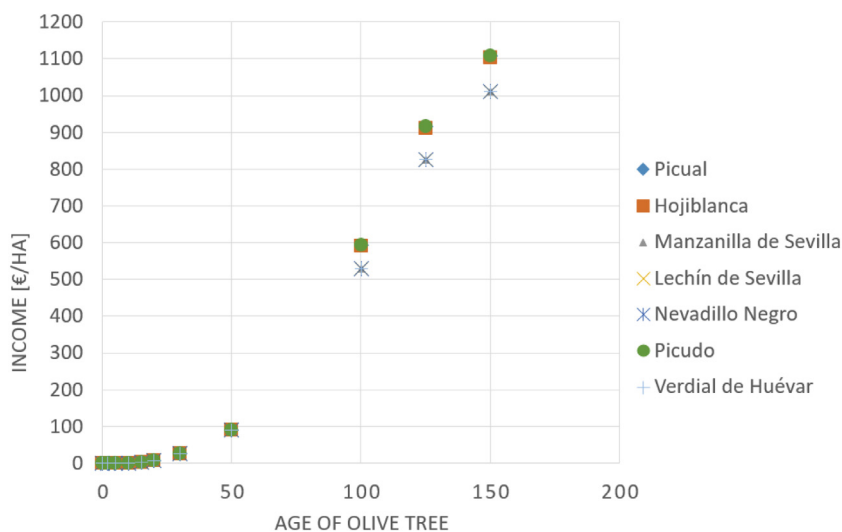**Fig. 7.** Distribution of values for *trunk wood income function*.

Table 7
Pruning mechanism, hourly cost and hours invested (Fundación CITOLIVA, 2007).

Activity	Cost [€/h]	Formation pruning [h]	Production pruning [h]	Renovation pruning [h]
Pruning with chainsaw	12.95	6	12	18
Cleaning and collection of firewood	7.21	4	9	15
Burning of pruning waste	7.21	4	9	15
TOTAL [€/ha]		135.38	285.18	449.4

Table 8
Estimation of the *pruning cost function*.

Variety	Parameter values for $F_{C.P}$	
	a	b
Picual, Hojiblanca, Manzanilla de Sevilla, Lechín de Sevilla, nevadillo negro, picudo, verdial de Huévar	0.5085	96.368

Table 9
Estimation of the *harvesting cost function*.

Variety	Parameter values for $F_{C.H}$			
	a	b	c	d
Picual	0.0019	0.4684	31.108	175.15
Hojiblanca	0.0018	0.4544	30.677	97.981
Manzanilla de Sevilla	0.0014	0.3564	24.034	76.323
Lechín de Sevilla	0.0008	0.2052	14.352	21.705
Nevadillo negro	0.001	0.2692	18.756	24.603
Picudo	0.0016	0.0414	29.213	82.833
Verdial de Huévar	0.0009	0.2257	15.966	36.568

from year 2 to year 19 of the olive tree. In year 20, the biennial pruning cost increases to 285.18 €until year 50, then becoming triennial and amounting to 449.40 €.

Applying the procedure defined in Section 2.2.3, the evolution of the olive grove is calculated for the variable studied, obtaining the pruning cost function $F_{C.P}$ [€/ha]. The results are shown in expression (11), Table 8 and Fig. 8. The function is defined, at intervals, although an annual transformation is made for the different frequencies (biennial and triennial).

$$F_{C.P} = a \cdot t + b \qquad (11)$$

The relationship between pruning costs (€/ha) and the age of the olive tree (years) gives a function defined at intervals. This is due to the fact that pruning operations are biennial, or triennial, depending on the life cycle of the olive grove, thus there is a zero cost in periods without pruning. In order to define the pruning cost function, appropriate to the objective of the study, the average annual cost was considered, giving the representation shown in Fig. 8. As Table 8 shows, a linear relationship is established between the cost of pruning and the age of the olive tree, with the same trend for all varieties. As the age of the olive tree increases, more numerous and intensive pruning operations are required to compensate for the loss of the yield of the tree with age (as described in the production income function in Section 3.2.1).

3.2.4. Olive harvesting process

To calculate the cost of harvesting, the following factors were taken into account: variety, production [kg/ha], harvesting mechanism, and, the beginning of the productive cycle (5 years). The harvesting mechanism varies depending on the type of olive grove. For a traditional mechanized olive grove, (i) milking, (ii) branch vibrator with complementary process (knock down), and, (iii) collection with canvases, depending on the age of the specimens, are used (AEMO (Asociación Española de Municipios de Olivo), 2012; Agriculture and Rural Development, 2012). Specifically, for young olive trees and up to the age of 50, traditional methods such as milking are used which, in this case, and bearing in mind that the operators collect 250 kg/day in a 7-hour day with rest, the cost amounts to 54.42 €/day. From the age of 50 until the end of the productive life, a branch vibrator is used with a complementary process (knock down) and collected with canvases, as long as the olive trees have a non-bifurcated trunk, a trunk height greater than 0.7 m, three or four main branches and an upright posture, the cost being 0.17 €/kg in non-irrigated crops (Navero et al., 2017; Fabbri, 2004).

Applying the procedure defined in Section 2.2.4, the evolution of the olive grove is calculated for the variables studied in order to obtain the collection cost function $F_{C.H}$. The results are shown in expression (12), Table 9 and Fig. 9.

$$F_{C.H} = a \cdot t^3 - b \cdot t^2 + c \cdot t + d \qquad (12)$$

The relationship between the pruning cost (€/ha), and the age of the olive tree (years), provides the set of parameters listed in Table 9, which represent the harvesting cost function. As Fig. 9 shows, the harvesting cost is directly proportional to productivity (kg fruit/olive tree), growing exponentially up to the maximum point of the curve, from which point it begins to decrease. The

different yields of each variety also affect harvesting costs. Finally, the cost depends on the harvesting technique used, which is more efficient according to the level of production, and the size of the crown. Picking by hand, when the specimens are young, involves a higher cost, and a branch vibrator, optimal when the olive tree is more productive, reduces harvesting time and costs.

3.3. Step 3 and 4: Definition of the benefit function and the optimum life cycle for each olive variety

With the data obtained in Step 2, and with the individual functions of the four economic variables, the benefit function $F_{B,i}$ is obtained for each olive variety. After that, the maximum benefit function is calculated and, thus, the optimal life cycle for each variety. The results are shown in expression (13). The results shown in Table 10 are obtained by maximizing this expression: the PC_{op} value corresponds to the optimum cycle of an olive grove, in years, for each variety. As can be seen from the results, the differences between varieties are small, and Picudo, with 100.31 years, and Picual and Verdial, with 97.5 years, are highlighted.

$$MAX \left[F_{B,i} \right] = F_{IP,i} + \frac{F_{IW,i}}{t} - F_{CP,i} - F_{CH,i} \qquad (13)$$
$$= -\alpha_i \cdot t^2 + \beta_i \cdot t - \frac{\gamma_i}{t} - \delta_i$$

It is possible to calculate data on the exploitation of the olive grove, by using the PC_{op}. This demonstrates the total tons of wood available in each region. As an example, the Picual variety would produce 155,590.21 tons of trunk wood per year, with respect to the optimal life cycle of 97.41 years, with an annual replanting need for 8652.51 ha.

Considering the optimum life cycle, the area occupied and the plantation density of each variety, the trunk wood mass is estimated to be obtained at the end of the productive cycle of the olive grove, with the expression (9) developed in Section 3.2.2. The results are summarized in Table 11.

The values shown in Table 11 are associated with 90% of the area occupied by the olive groves in Andalusia. Correcting this data, the Andalusian olive groves could provide a total of 266,664 tonnes/year. On the other hand, taking into account that olive wood contains 20%–25% humidity and estimating a 15% decrease, in the waste pelleting process, 159,998.50 t pellets/year would be obtained.

To analyse the influence of each of the incomes and costs that appear in the expression (13), the case is made for the Picual variety. It is possible to identify which is the determinant factor among the costs or incomes to define the optimal life cycle of the olive tree. Fig. 10 shows the income, costs and benefits over the years. The profit line will reach its maximum when the optimal life cycle of the olive tree is reached.

As can be seen in Fig. 10, the variable that has the most influence in determining the optimal time of exploitation of the olive tree is the income per production. Harvesting costs are the next
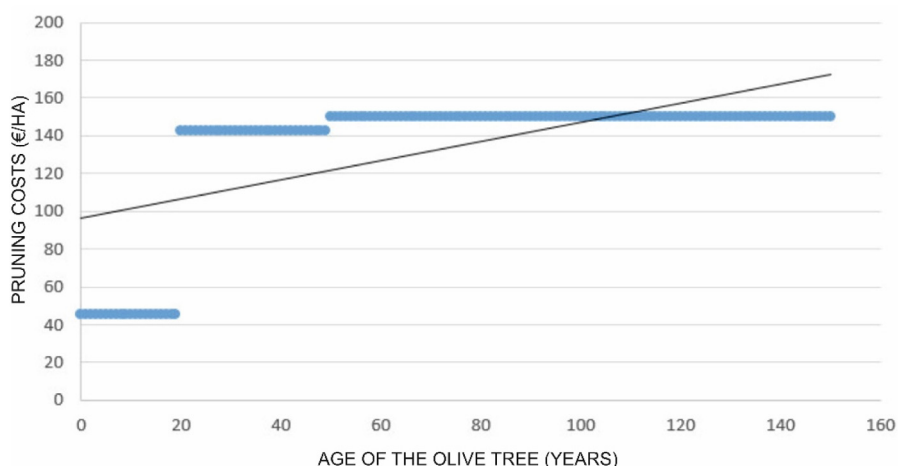
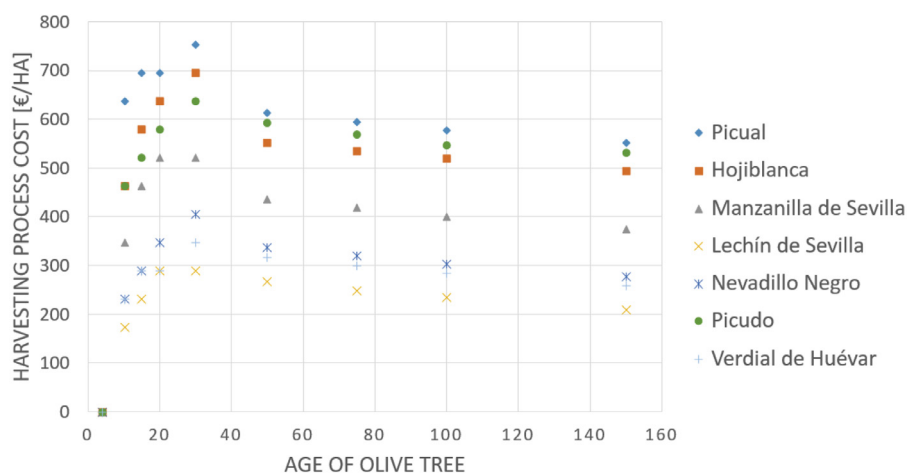Fig. 8. Distribution of values for *pruning cost function*.

Fig. 9. Distribution of values for *Harvesting cost function*.

Table 10
Optimum life cycle for each olive variety.

Variety (i)	Parameters for $MAX\left[F_{B,i}\right]$				Optimal cycle PC_{op} (years)
	α_i	β_i	γ_i	δ_i	
Picual	0.078	15.326	60.15	846.42	97.41
Hojiblanca	0.091	17.480	59.71	614.77	96.08
Manzanilla de Sevilla	0.078	14.832	50.62	402.43	94.75
Lechín de Sevilla	0.074	13.811	50.62	10.70	93.10
Nevadillo negro	0.072	13.488	50.62	188.36	93.57
Picudo	0.117	23.527	60.16	397.19	100.31
Verdial de Huévar	0.073	13.924	50.58	110.35	97.41

Table 11
Results.

| Olive variety	Optimum life cycle [yr]	Occupied area [ha]	Wood mass [kg/olive]	Total mass [t/cycle]	Annual mass [t/yr]
Picual	98	857,746	177.7	15,247,841	155,590
Hojiblanca	97	267,199	173.5	4,637,567	47,809
Manzanilla de Sevilla	95	73,766	151.6	1,119,002	11,778
Lechín de Sevilla	94	61,470	148.7	914,415	9,727
Nevadillo negro	94	40,154	148.7	597,322	6,354
Picudo	101	32,223	187.9	605,674	5,996
Verdial de Huévar	98	26,126	160.6	419,774	4,283
TOTAL (90% area)			**1,148.7**	**23,541,595**	**241,537**
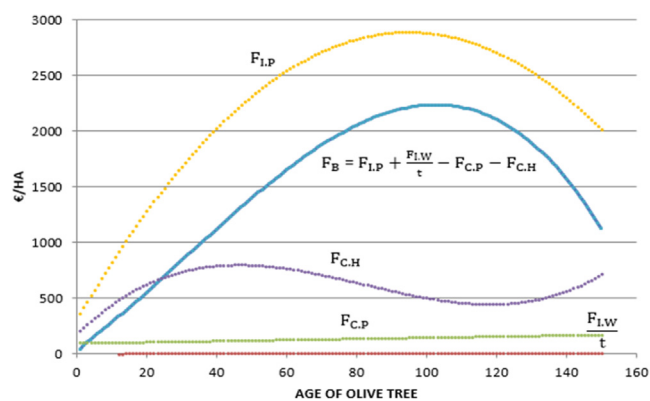
Fig. 10. Income, costs and benefits in the life of an olive tree.

Table 12
Optimum life cycle of the Picual type olive tree.

t (years)	$F_{IP,i}$ (€/ha)	$\frac{F_{IW,i}}{t}$ (€/ha)	$F_{CP,i}$ (€/ha)	$F_{CH,i}$ (€/ha)	$F_{B,i}$ (€/ha)
97.42	2889.61	5.42	145.91	516.97	2226.79

most important values, followed by income from biomass and pruning costs. With this analysis, and for the Picual variety, an optimum life cycle of the olive tree of 97.42 years is obtained. For this result, the values of each of the dimensions of the expression (13) are shown in Table 12.

In order to evaluate the profitability of the pelleting plants, all the factors which influence the investment and exploitation budget should be taken into account when analysing the potential of the existing resource. The investment will be modulated by the size of the plant, which, for a quantified resource, will depend on the choice of location (Sultana and Kumar, 2012). Once the size of the plant and the location have been defined, the average cost of transporting the biomass can be defined. The operating budget must take into account the costs of the handling and drying of the biomass, and the granulation, which has the highest energy, packaging, storage and logistics costs (Hernández et al., 2019). Profitability is uncertain because of the cost of biomass and the selling price of pellets. The influence of these variables on the profitability of the manufacturing plant can be seen with simulations carried out with the Monte Carlo method (Martinez-Hernandez et al., 2019).

The quality of the pellet will depend on the manufacturing process and, to a large extent, on the raw material used, in our case the olive tree trunk. Table 1 quantifies the properties of the pellet, the object of this work, once the tests have been carried out (García-Maraver et al., 2015; ISO, 2014b).

In order to ensure energy yields and adequate levels of emissions produced in the combustion of olive wood pellets, it will be necessary to use approved boilers (EN European Standard, 2007).

3.4. Analysis of the Mediterranean area

The results obtained can be extrapolated to evaluate the potential for the use of pellets for biomass energy in other areas and regions.

In this case, the objective is to evaluate the Mediterranean area. For this purpose, those EU countries with the largest olive grove areas were chosen (Spain with approximately 50%, Italy with 26% and Greece with 22% of the total of more than 5,000,000 ha cultivated in the EU) (European Commission, 2012; Niaounakis and Halvadakis, 2006).

The data obtained from the Spanish cultivated region were extrapolated by considering the similarity of the crops of the

Table 13
Results obtained for other European Union countries.

Study area	Occupied area [ha] (European Commission, 2012)	Wood [tn/yr]	Pellet [tn/yr]
Spain	2,500,000	444,407	266,644
Greece	1,160,000	206,205	123,723
Italy	1,350,000	239,980	143,988

three territories (Loumou and Giourga, 2003; Niaounakis and Halvadakis, 2006) as the varieties of olive trees distributed in this territory are very different, the variety parameter is not considered. This hypothesis is justified on the basis of the small difference existing between the optimal productive cycles of each olive tree variety in the Andalusian olive groves. Table 13 shows the results obtained of the potential generation of pellets from olive wood in the countries with the highest olive production in the Mediterranean area.

4. Discussion of results

The data obtained in this study are representative of the potential for using olive tree biomass as a renewable energy source in the Mediterranean area. Spain consumed a total of 400,000 tons of pellets (including domestic and industrial pellets) in 2015 (AEBIOM, 2017). Based on these data the estimated production, 266,644 t/year, would cover a large part of this demand, 66.66%. A similar situation can be expected for the other olive producing countries in the Mediterranean area.

Moreover, if the selling price of trunk wood, estimated at 30 €/t for the case under analysis, is subject to a 50% increase, the income from the sale would be increased. The sale price of the waste for pelleting is the main factor in ensuring the feasibility of the farm managing the life cycle, adjusting it to the optimal production cycle, taking into account agricultural production and biomass for energy. The process of olive grove plantation involves an important investment and adequate planning, so increased income generated by the sale of pellets could increase the feasibility of the project for the grower. However, this would not have a significant influence on the optimal energy life cycle. In addition, the price of the raw material must be in accordance with the existing market, so it does not affect the competitiveness of the final product.

The most influential of the variables that significantly affect the bioenergy life cycle of the olive grove is the selling price of the olive, which determines the income from production. The other variables, income from the sale of the trunk and the costs of pruning and harvesting, have less influence and less variability. In the specific case of the costs of harvesting and pruning, these depend on the hourly labour costs, which are stable over time and only vary by updating prices, due to inflation. For each of the olive varieties, sensitivity of the bioenergy life cycle can be seen in a low income scenario for olive sales of 0.50 €/kg, and a higher income scenario of 0.80 €/kg. The base case studied is 0.65 €/kg. Table 14 shows the values of the energy life cycle and its sensitivity to the selling price of olives.

As long periods are considered, it is important to analyse the effect of variation in the cultivation regime. The hypothesis used in the case study generalizes the dry regime for 100% of the Andalusian olive groves. With an irrigated regime, production would be increased by 25.4%, assuming a decrease in the cost, from 0.17€/kg in non-irrigated land to 0.15€/kg in irrigated land, for harvesting with a branch vibrator. On the other hand, the transformation from rain-fed to irrigated farming decreases the optimum life cycle of all olive varieties by 4 years (in this case, it would mean an average of 93 years, compared to 97 years for

Table 14
Sensitivity of the energy life cycle of the olive grove to the selling price of the Picual variety.

	Worst case. Olive sale price 0.50 €/kg	Base case. Olive sale price 0.65 €/kg	Best case. Olive sale price 0.80 €/kg
Opt. life cycle [yr]	85	98	117

dry farming). Finally, Andalusia would have a pellet generation potential of 155,225 tonnes of irrigated pellets, compared to 159,998 tonnes obtained in dry farming.

Finally, it would be interesting to reflect on the super-intensive crop, characterized by a higher density of plantation than that used in the traditional regimes (2000 olive trees/ha). In this way, the plantation layout would have a distance between olive trees of 1–1.5 m; a height of olive trees of 2.5–3 m; and, a separation between rows of 3–7 m. This type of crop brings the production cycle forward by 3 to 4 years, increases production and reduces harvesting costs, because it can be fully mechanized. The cost of harvesting is 0.03–0.05 €/kg for super-intensive, compared to 0.05–0.10 €/kg and 0.10-0.30 €/kg for milking and vibration methods, respectively.

In addition, Andalusia records a final energy consumption of 12,988,000.90 toe (Andalusian Energy Angency, 2017). The residential, service and primary sectors consume 32% of the total. With an energy supply model closely linked to fossil fuels, mainly petroleum products that cover 43.7% of total Andalusian energy demand, it is highly dependent on foreign energy, with imports representing 81% of consumption. Total residential thermal energy consumption was 5767 GWh in 2017. The thermal energy potential derived from this study for the community of Andalusia is 768 GWh.

Considering the data shown by IDAE in the Sech-Spahousec Project (IDAE, 2011), it is of interest to compare the average consumption of different energy sources in different parts of the world. For the Mediterranean area, the fuel consumption values are balanced, with a heating consumption of 27,430 TJ for petroleum products, and 27,915 TJ for natural gas. The advantages of natural gas over petroleum products are due to its ease of transport, reduced cost and lower environmental impact, however, the difficult access for residential areas reduces consumption. This is the case, for example, for the mainland area of Spain where the consumption of petroleum products is doubled for domestic heating which is estimated at 62,870 TJ of petroleum products, compared with 36,123 TJ of natural gas. In addition to the environmental benefits of using biomass instead of fossil fuel, the market study for the use of pellets, produced from olive trees, in domestic boilers, would allow those areas without access to natural gas to replace much of the consumption of petroleum products, by the consumption of biofuels. It is necessary to emphasize the benefits of the energy recovery obtained with olive tree pellets. The quality of the pellet varies, depending on the properties of the raw material used, and the pelleting processes. The pellets for non-industrial boilers, obtained from olive tree trunk wood, comply with the characteristics defined in the Standard ISO 17225-2:2014 (ISO, 2014b), being classified as type A1/A2, depending on the olive variety. These comply with the following ranges of properties: higher durability, hardness or compression strength (between 21 and 24.86 kgf), length/diameter ratio (3.5); single pellet density < 1000 kg/m3; bulk density > 600 kg/m3; ash content (1.43% ash). To achieve these characteristics, olive wood will have to undergo a pelleting process that meets the following requirements: Moisture 9%, Pelletizer Die 1, and 40 °C < T < 60 °C (García-Maraver et al., 2015). From the above, one of the important parameters to take into account is the ash content, with a higher value than other pellets from wood (with ash content < 1%). Although olive wood pellets comply with quality standards (< 3% for a

non-industrial use), their reuse should be considered. The ashes are a biodegradable material and suitable for the manufacture of different materials such as cement, ceramics, paint, plastics, uses in agriculture as fertilizers and raw material for construction (Eliche-Quesada et al., 2017).

The proposed methodology contributes, in an innovative way, to the state of the art and the best available techniques on the management and use of biomass waste in the olive grove sector. Although there are general proposals for the reuse of agricultural waste for energy production (Fernandes and Costa, 2010; Voivontas et al., 2001), and specific ones on olive residues for energy use in domestic and industrial contexts (García-Maraver et al., 2012; Rosúa and Pasadas, 2012; Spinelli and Picchi, 2010), there are no studies with the scope of this work, which includes the use of wood from the olive grove at the end of the useful life of the plantation enabling its optimal energy cycle to be calculated.

5. Conclusions

This study has estimated the optimal sustainable bioenergy life cycle of different olive groves in the Mediterranean Area, and the amount of sustainable residue available (trunk wood) at the end of the life of these groves, by optimizing the benefits through an analysis of costs and incomes of the whole life process. Specifically, the applied methodology has allowed the determination of the potential value of the trunks of olive trees to be used as biomass, in the form of pellets in domestic contexts, in a specific geographical area. The Mediterranean area has significant tracts of olive plantations and is one of the main sectors for the economy. This contributes to the generation of employment and social, territorial and cultural cohesion, as well as producing one of the main products of the Mediterranean diet. The life-cycle of the farming ends with the use of the trunk wood to produce pellets, maximizing the use of resources. In a case study applied to Andalusia, it is shown that the optimal renewable life-cycle for olive trees in this area is 97 years. If agricultural and energy sustainability laws favouring this model were adopted, this region would produce 160,000 tonnes of pellets per year, and 266,500 tonnes per year, if extended to the whole of Spain. This would represent 70.17% of current total pellet consumption. The extension of the analysis to other Mediterranean countries, such as Greece and Italy, would result in a capacity of 124,000 and 144,000 tonnes of olive tree pellets per year, respectively. According to the results obtained, use of the optimum production cycles of olive farms would increase their profitability and their economic feasibility. In order to ensure the technical viability and observance of this proposal, it would be necessary to establish long-term policies that encourage the compliance with olive grove production cycles, increasing awareness in the agri-food sector.

CRediT authorship contribution statement

Víctor M. Soltero: Conception and design of study, Acquisition of data, Analysis and/or interpretation of data, Writing - original draft, Writing - review & editing. **Lidia Román:** Conception and design of study, Acquisition of data, Analysis and/or interpretation of data, Writing - original draft. **M. Estela Peralta:** Writing - original draft, Writing - review & editing. **Ricardo Chacartegui:** Analysis and/or interpretation of data, Writing - review & editing.

Declaration of competing interest

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