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Research article

A proposal for pellet production from residual woody biomass in the island of Majorca (Spain)

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Abstract: The use of residual biomass for energy purposes is of great interest in isolated areas like Majorca for waste reduction, energy sufficiency and renewable energies development. In addition, densification processes lead to easy-to-automate solid biofuels which additionally have higher energy density. The present study aims at (i) the estimation of the potential of residual biomass from woody crops as well as from agri-food and wood industries in Majorca, and (ii) the analysis of the optimal location of potential pellet plants by means of a GIS approach (location-allocation analysis) and a cost evaluation of the pellets production chain. The residual biomass potential from woody crops in Majorca Island was estimated at 35,874 metric tons dry matter (t DM) per year, while the wood and agri-food industries produced annually 21,494 t DM and 2717 t DM, respectively. Thus, there would be enough resource available for the installation of 10 pellet plants of 6400 t·year^{-1} capacity. These plants were optimally located throughout the island of Mallorca with a maximum threshold distance of 28 km for biomass transport from the production points. Values found for the biomass cost at the pellet plant ranged between 57.1 €·t^{-1} and 63.4 €·t^{-1} for biomass transport distance of 10 and 28 km. The cost of pelleting amounted to 56.7 €·t^{-1}; adding the concepts of business fee, pellet transport and profit margin (15%), the total cost of pelleting was estimated at 116.6 €·t^{-1}. The present study provides a proposal for pellet production from residual woody biomass that would supply up to 2.8% of the primary energy consumed by the domestic and services sector in the Balearic Islands.

Keywords: pellets; residual biomass; woody crops; Geographic Information Systems; logistics; costs

1. Introduction

Energy dependency has played an important role on the EU political agenda, to a greater extent since the crisis between Ukraine and Russia. The energy supply and distribution systems to the EU require a deep reconsideration in order to reduce the 65% energy-dependency from Russian gas. Actually, efforts must be focused on thermal energy since 75% of gas in Europe is consumed for heating purposes (41% for buildings and 31% for industrial processes) and only 25% is allocated to electricity production [1].

Biomass is a very efficient and assuring source of thermal energy, especially in a longing low-carbon economy. Biomass for heating can be upwards of 85% efficient, in contrast to its use for producing electricity or transportation biofuels which involves conversion processes with higher energy losses.

Nevertheless, the low bulk and energy densities of biomass encourage operators to conduct densification processes (pelleting and briquetting) prior to its energy use, in order to take advantage of a homogeneous and easy-to-automate solid biofuel that additionally has higher energy density.

Pellet consumption in the World is expected to grow to 68–80 million tons in 2020. More specifically, the consumption of industrial pellets will grow steadily at a rate of 21% ·$year^{-1}$, whereas the increment in the consumption of domestic pellets will reach 8.5% ·$year^{-1}$ [2]. In Europe, the consumption of industrial wood pellets will be mainly absorbed by the bioelectricity plants in UK and by the medium scale heating systems in Finland and Sweden. Other significant pellet consumers in the EU are Belgium, The Netherlands and Denmark. In the production side, Portugal and Latvia are the largest exporters of industrial pellets in Europe, followed by Germany, Lithuania, Estonia, Finland and Sweden [3,4]. On the contrary, the pellet market in Spain is basically taken by the domestic pellet sector.

As a feedstock for pellet production, the use of residual biomass entails advantages such as low production costs, reduction of waste to landfill and removal of undesirable residues that otherwise would be burnt (e.g., olive tree pruning) or discarded. In addition, in the case of residual biomass of industries, the resource is concentrated on the production site, which reduces transportation costs. On the other hand, the insecurity in a stable biomass supply is the main drawback for the use of residual biomass.

The development of renewable energies and more specifically, the use of residual biomass for heating and power generation is of great interest in island regions like Majorca. The gross inland consumption of primary energy in the Majorca region ("Illes Balears") was 2.92 Mtoe in 2010, while the domestic and services sector were responsible for 32% energy consumption. In addition, this region has to import 96% of the consumed energy, which leads to a steep energy dependence of Majorca on foreign sources [5].

In order to ensure an efficient supply of residual biomass for energy applications, a resource evaluation and territory planning should be made prior to the installment of bioenergy facilities. Geographic Information Systems (GIS) are useful tools to assess biomass potential production and to plan biomass processing facilities. Thus, potential assessments of residual biomass for Spain have been largely conducted using GIS and statistical data. Some assessments have been focused on specific regions of Spain [6–10] whereas others have been addressed at the national scale [11,12]. However, to the best of our knowledge, no specific assessment of residual biomass potential in the Majorca region has been published so far.

GIS along with other tools and models have been used for the optimal location of bioenergy facilities. Most of them have been focused on liquid biofuels [13–18], bioelectricity [19–21] and biogas plants [22,23]. Studies addressed to the optimal location of pellet plants have been less widespread. For instance, Sultana and Kumar [24] developed a methodology for determining the suitable location, optimal size and number of possible pellet plants in a particular region of Canada. Mola-Yudego et al. [25] defined cluster-regions with high concentration of pellet production capacity and identified 378 potential pellet plants in Europe. Likewise, economic assessments of pellet plants considering variables like feedstock type, plant size and location, and transportation cost, among others, have also been addressed in the literature [26–28].

The aim of the present work is two-fold: (i) to estimate the potential of residual biomass from woody crops as well as from agri-food and wood industries in Majorca, and (ii) to analyze the optimal location of potential pellet plants by means of a GIS approach (location-allocation analysis) taking into account the presence of competitors plants and the maximum biomass transport distance, as calculated from the estimated costs of the pellets production chain.

2. Materials and Methods

2.1. Study area

The island of Majorca is located in the Mediterranean Sea, near of the eastern coast of the Iberian Peninsula, between 2°18'E and 3°29'E longitude and 39°15'N and 39°58'N latitude (Figure 1). It forms along with the islands *Ibiza*, *Menorca*, *Formentera* and *Cabrera* the NUTS-2 region (Nomenclature of Territorial Units for Statistics in the European Union, NUTS[1]) called "Illes Balears" (Balearic Islands). Majorca's geographical area amounts to 36,609 km^2 and its highest altitude is 1445 m.a.s.l. in 'Puig Major' peak, within the 'Sierra Tramuntana' northwestern part of the island.

According to Köppen climate classification, the climate in Majorca Island is mainly Temperate with dry or hot summer—'Csa' except for the southern coast where the climate is classified as Cold Steppe—'BSk' and in the core of "Sierra Tramuntana" where the climate class is Temperate with dry or temperate summer—'Csb' [29].

The ombrothermic diagram of 'Palma de Majorca' (capital city) is shown in Figure 2. Mean annual temperature in the Island is 16.9 °C; the annual rainfall reaches 641.5 mm on average and mean relative humidity is 71.5%. However, several weather stations in the island record precipitation values over 1000 mm (Escorca and Fornalutx). Mean global solar radiation amounts to 17.2 MJ m^{-2} day^{-1} [30] and the annual potential evapotranspiration (according to Thornthwaite equation) reaches 862.4 mm. The dry season (PP < 2 x tm) lasts four months (May to August) on average.

According to USDA soil taxonomy [31], the main types of soils in Majorca are the association Haploxeralf-Xerochrept (28.2%), followed by Rhodoxeralf (26.9%) and Xerorthent (22.9%) [32].

[1]The abbreviation NUTS means an administrative division of the territory for the elaboration of statistics at European level. According to this classification, Spain (NUTS-0) is divided into clusters of Autonomous Communities (NUTS-1), Autonomous Communities (NUTS-2), provinces (NUTS-3) and municipalities (NUTS-4).

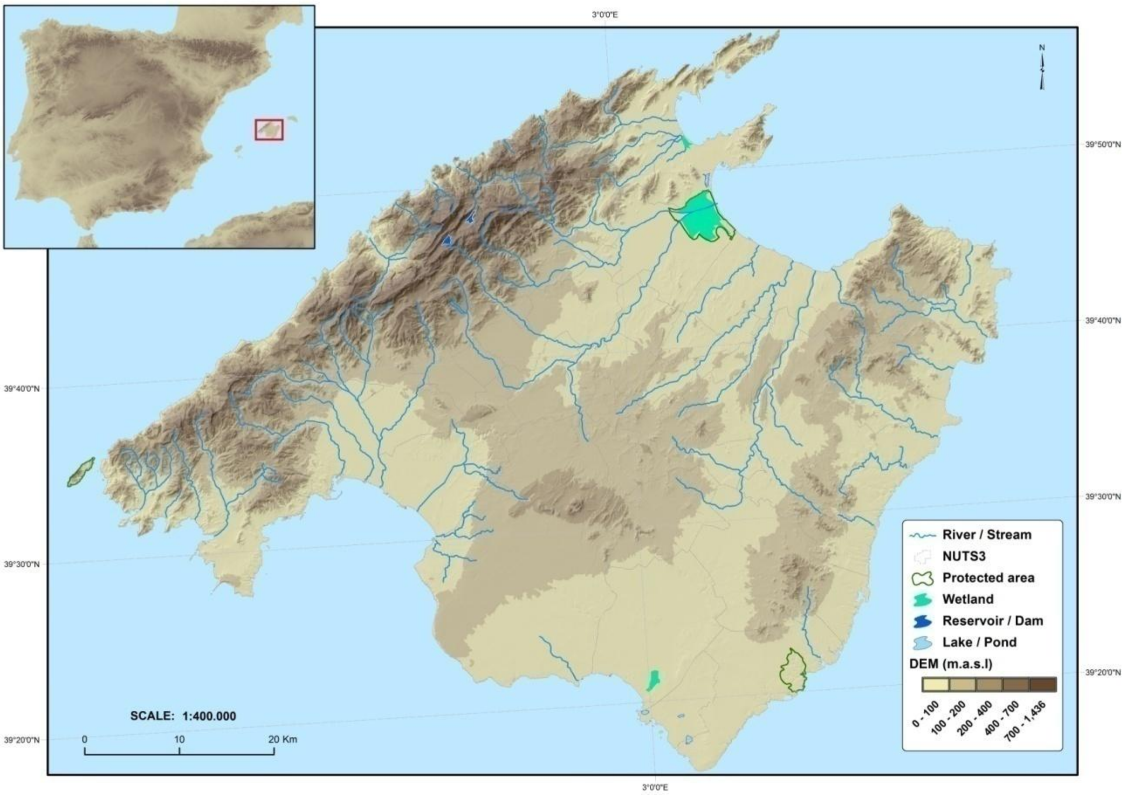

Figure 1. Location and Digital Elevation Model (DEM) of Majorca Island.

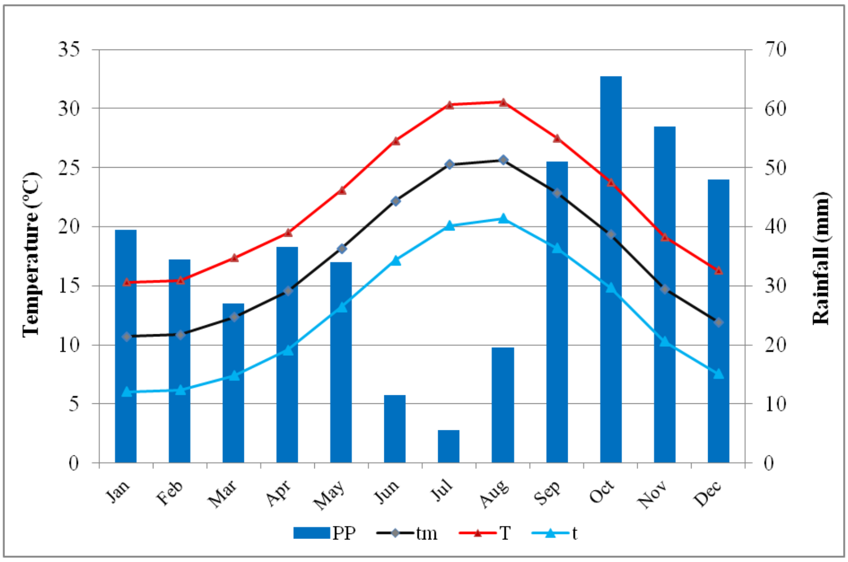

Figure 2. Ombrothermic diagram of the capital of Majorca. Mean values of two weather stations, "Palma harbour" and "Palma airport", for the period 1981–2010. tm = mean monthly temperature; T = mean maximum temperature; t = mean minimum temperature; PP = rainfall. Source: State Meteorological Agency of Spain (http://www.aemet.es/es/serviciosclimaticos/datosclimatologicos/valoresclimatologicos?k=bal).

2.2. Agricultural characterization

Statistics regarding agricultural area in 2012 at municipality scale (NUTS-4 scale in the European classification) were compiled from "*Servicio de Mejora Agraria de la Consejería de Agricultura, Medio Ambiente y territorio del Govern de les Illes Balears* (CAIB)". This database gathers the land area devoted to field crops (cereals, sunflower, maize and others), permanent crops (vineyards, olive, fruit trees) and fallow and set aside lands.

Once the database with the statistical data of agricultural land distribution at NUTS-4 scale was built, the cultivation area of woody permanent crops was selected and introduced into a GIS environment. Since the abovementioned database is not georeferenced, the "*Sistema de Información sobre Ocupación del Suelo de España (SIOSE)*" (Land use Information System of Spain) was compiled for Majorca Island. SIOSE is a geodatabase of Spain at 1:25,000 scale which gathers spatial information about land use. Disadvantages of using SIOSE are related to the time reference of the represented data (2005) and the lack of differentiation between some tree species identified as permanent crops.

Therefore, statistical data from CAIB were used to assess the residual biomass potential at NUTS-4 scale whereas SIOSE database was used to identify and locate large agricultural categories of land uses within each municipality for the GIS assessment (see sub-section 2.5).

2.3. Agricultural biomass potential

The assessment of residual biomass from agriculture conducted in this work is exclusively focused on the biomass originated from pruning operations of woody crops. Residual biomass from herbaceous crops (cereal straw and corn stover, among others) and biomass generated by the removal of tree stumps were not assessed. Therefore, issues concerning market distortion due to competitive uses of cereal straw -such as livestock feeding and bedding- or environmental services arisen from stubble left in the field (soil erosion mitigation and maintenance of organic matter, among others) did not have to be addressed.

It is well known that the amount of residual biomass from woody crops is related to several factors like crop yield, tree density or production system (rainfed/irrigated; goblet/trellis vineyards, and others). However, due to the lack of specific information at NUTS-4 scale, in our approach we used weighted means for each woody crop.

A bibliographic search was conducted for Residue Production Ratios (RPR) of woody crops in this work. Data of RPR were compiled and mean values of each crop were calculated for the subsequent assessment. In case that specific RPR values were not available, the mean RPR value of the closest woody crop (similar tree size and pruning requirements) was assigned. The compilation of RPR in metric tons dry matter per hectare and year (t DM $\cdot$ha^{-1} $\cdot$year^{-1}) is shown in Table 1.

Most RPR values compiled from the literature estimate the production of residual biomass per unit area but, for some crops, RPR is expressed on agricultural produce (t residue $\cdot$t^{-1} produce) [38]. When this was the case, values were converted to RPR per unit area from the weighted mean yield (t produce $\cdot$ha^{-1}) recorded in a ten-year period (2002–2012) by CAIB (2012). Table 2 gives the values of weighted mean yield of the main crops in Majorca Island taking the crop area (rainfed and irrigated conditions) at NUTS-2 scale as the weighting factor.

Table 1. Mean Residue Production Ratio (RPR) by unit area (t DM ·ha^{-1} ·year^{-1}) of woody crops in Majorca as classified by CAIB.

Woody crop	Mean (d.b.)	Literature values
Apricot	1.95 (0.78)	1.74[b], 1.49[d], 4.6[f], 0.7[g], 1.22[h]
Carob tree**	0.56 (0.52)	0.65[d], 0.8[f], 0.23[g]
Almond tree	0.85 (0.24)	0.9[b], 1.02[c], 0.65[d], 1.04[e], 0.8[f], 0.52[g], 1.04[h]
Hazelnut	0.58 (0.47)	0.65[d], 0.8[f], 0.28[g]
Plum tree	2.22 (0.65)	2.16[b], 1.74[c], 1.75[d], 2.8[e], 4.6[f], 0.26[g]
Citrus (Lemon)***	1.72 (0.12)	1.6[e], 1.6[f], 1.95[g]
Citrus (Mandarin)***	1.35 (0.32)	1.6[e], 1.6[f], 0.86[g]
Citrus (orange)	1.52 (0.10)	1.6[e], 1.6[f], 1.35[g]
Fig tree*	0.93 (0.38)	0.65[d], 0.8[f], 1.33[g]
Apple tree	3.04 (0.55)	5.34[b], 1.44[c], 2.86[d], 4.8[f], 1.37[g], 2.45[h]
Peach tree	2.36 (0.45)	2.16[b], 1.74[c], 1.75[d], 2.8[e], 4.6f, 1.84[g], 1.6[h]
Nectarine tree	2.61 (0.46)	2.16[b], 1.74[c], 1.75[d], 2.8[e], 4.6[f]
Olive (< 3 t ·ha^{-1} produce)	0.87 (0.40)	1.1[a], 0.85[b], 1.02[c], 1.1[d], 1.1[e], 0.7[f], 0.08[g], 1.0[h]
Olive (< 3 t ·ha^{-1} produce)	0.89 (0.46)	1.1[a], 0.85[b], 1.02[c], 1.1[d], 1.5[e], 0.7[f], 0.08[g], 1.0[h]
Other fruit trees	2.77 (0.44)	2.64[b], 1.46[c], 2.2[d], 2.8[e], 4.7[f]
Pear tree	2.84 (0.52)	1.2[c], 3.64[d], 4.8[f], 1.6[g], 2.9[h]
Vineyard	1.91 (0.49)	0.7[a], 2.3[b], 1.45[c], 1.8[d], 2.8[e], 3.5[f], 0.95[g], 1.7[h]

*Agroenergy Group. Experimental trials. Contribution to Project EURENERS, Asociación de Desarrollo del Campo de Montiel y Campo de Calatrava "TIERRAS DE LIBERTAD". Unpublished. 2008; **Assigned from hazelnut tree; *** assigned from orange tree; Literature values are reported on dry matter basis (0% moisture content). Sources: a = *; b = [33]; c = [34]; d = [35], e = [36], f = [37], g = [38], h = [8].

Table 2. Weighted mean yield in tons of fresh matter per hectare and year (t ·ha^{-1} ·year^{-1}) of woody crops in Majorca in the ten-year period 2002–2012.

Woody crop	Weighted mean yield (t crop produce ·ha^{-1} ·year^{-1})
Apricot	2.073
Carob	0.795
Almond	0.317
Hazelnut	1.021
Plum	2.700
Fig tree	0.700
Lemon	16.657
Mandarin	7.784
Apple	8.138
Peach	6.921
Orange	5.933
Olive	0.272
Pear	8.929
Vineyard	5.209

Source: "Servicio de Mejora Agraria de la Consejería de Agricultura, Medio Ambiente y territorio del Govern de les Illes Balears" (2012).

Finally, the residual biomass production of each crop was estimated at NUTS-4 scale by multiplying the assigned RPR per unit area by the actual crop area.

2.4. Residual biomass of agri-food and wood industries

Wood processing industries as well as food industries related to nuts processing are the main biomass-generating activities in Majorca Island. The former are basically cabinetmaking, sawmills and furniture-making industries whereas the latter are dedicated to almond-based products since it is the most widely woody crop in Majorca with 14,926 ha.

In order to calculate the residual biomass potential from industries in Majorca, both the location and the amount of biomass generated were compiled from the georreferenced database Bioraise [39]. This database gathers each wood industry in the Island and classifies the residual biomass into three categories: non-chemically-treated wood, bark and other byproducts. Biomass from agri-food industries in Majorca is only classified as almond shell.

Thus, data regarding the amount and type of residual biomass from industries was added to the georreferenced database of Majorca in order to determine the optimal location of pelleting facilities.

Depending on the desired pellet quality, certain issues regarding the types of biomass in this case-study should be taken into account. Residual biomass from wood-processing industries, like the bark or other byproducts, may contain compounds not suitable for producing high quality pellets (pellet quality class ENplus-A1 or ENplus-A2) [40]. This could also happen in the case of some other types of biomass like vineyards pruning, which ash content is high. On the contrary, properties of olive trees pruning are good for thermal applications as long as leaves are removed; leaves removal can be achieved by leaving the pruning drying naturally on the field. However, this practice is rarely done because it may result in the increase of plagues in olive yards (specially the olive bark beetle *Phloetribus scarabaeoides*). Consequently this biomass is usually chipped and spread on the field or just removed from it. In the case of mechanical collection, it usually gets contaminated with stones and soil particles, which would affect the quality of the processed biomass.

Nevertheless, these types of biomass could meet the quality requirements for industrial pellets (pellet quality class EN-B) [40] following UNE-EN ISO 17225 1:2014. On the other hand, in accordance with UNE 164004:2014, the properties of almond shell are usually good for its direct use in thermal applications without the need of pelleting, and this type of biomass can meet ENplus-A2 or even EN-plusA1 requirements.

In the light of the above, all types of biomass in this study were allocated to the production of industrial pellets except for almond shell, which was separately considered for domestic heating applications.

2.5. Optimal location of pellet plants - GIS assessment

Optimal location of pelleting facilities in Majorca was determined by means of a GIS approach from the results of residual biomass potential. It was based on a location-allocation analysis throughout a transport network, in this case the Majorca road infrastructure. The Network Analyst Tool from ArcGIS v.10.1 (developed by Environmental System Research Institute—ESRI™) was used for this purpose.

Firstly, the road network of Majorca was digitized using ArcGIS™ and the National Cartography

Base at 1:200,000 scale [41] as input data for building an unimodal network which differentiates between road types: motorway, dual carriageway, national road, secondary road, regional road, track and urban road (Figure 3).

Secondly, intersections in the road network of Majorca were considered as potential sites for the location of pellets production plants, on the grounds that the optimal solutions of discrete location models are always found at the vertex of a network [42]. The reason for that is that the high accessibility of the road intersections minimizes biomass transportation costs and facilitates the supply logistics to biomass processing plants. Thus, the intersections among roads (excluding motorways, tracks and urban roads) were selected as candidates for the location of pelletizers. Biomass transport in large trucks is not feasible through motorways due to speed and goods transport limitations. Similarly, biomass transport by tracks, urban roads and other narrow roads could collapse the road network in those areas.

The location of both, the residual biomass production industries and the mean centers of woody crops fields in each municipality were considered as demand points for the subsequent location-allocation analysis (Figure 4).

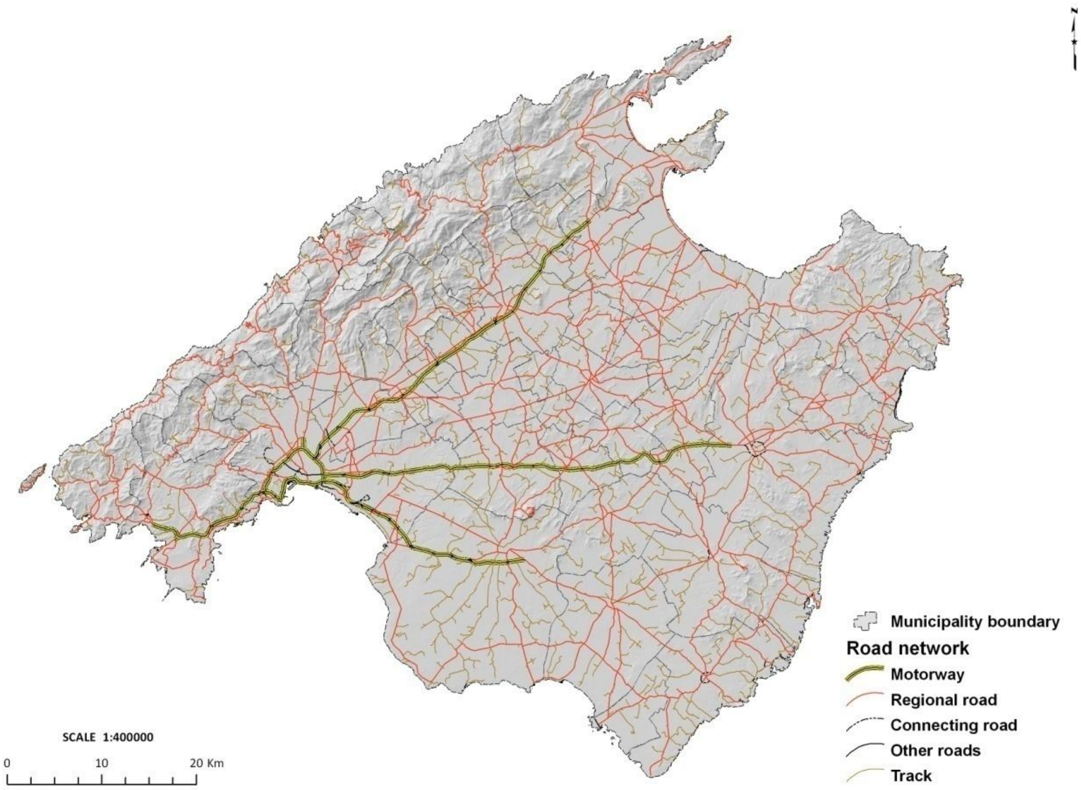

Figure 3. Road network of Majorca Island.

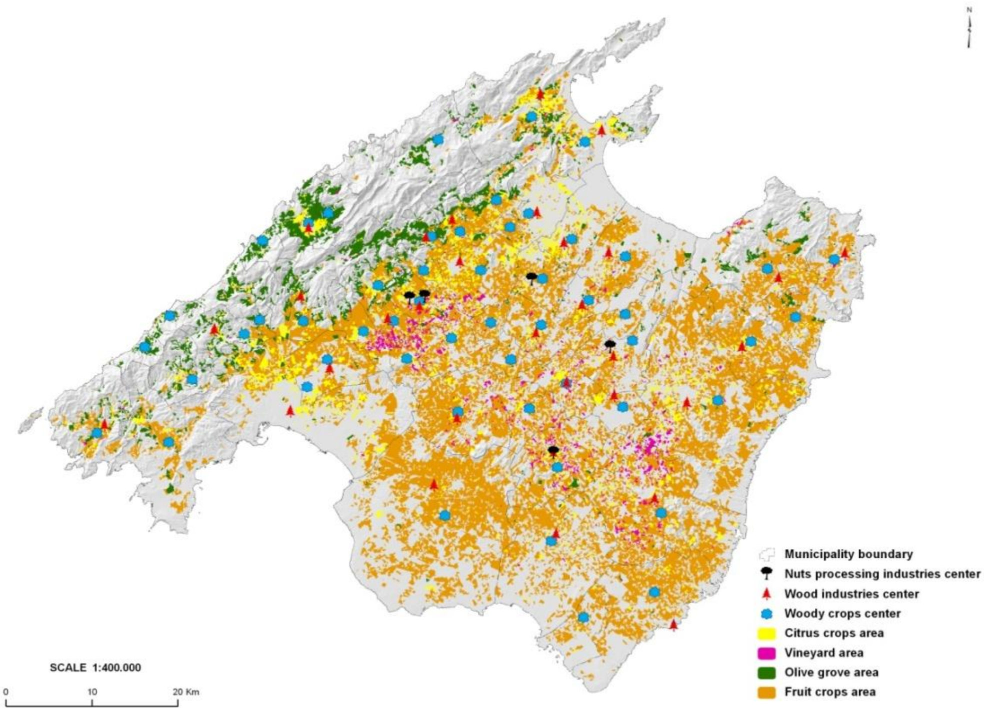

Figure 4. Residual biomass centers and woody crops area.

The location-allocation analysis was conducted by means of the 'maximize capacitated coverage' problem type. The maximizing capacitated coverage analysis chooses the location for a provided number of facilities that cover as much demand as possible within the impedance cutoff (transport distance threshold) without exceeding the maximum feedstock-processing capacity. In addition, it allows taking into account competitors for the feedstock; their capacitated-feedstock in their influence area would be allocated to the competitors facilities within the same impedance cutoff.

In our approach, the list of competitor facilities in Majorca were taken from the Spanish Association of Energy Valorization of Biomass (AVEBIOM) [43] and their location were georreferenced for the subsequent analysis. Currently, to the best of our knowledge, there are two companies in the Island related to solid biofuels. One is dedicated to pellet production (Netpellet—http://www.netpellet.com/) which produces 3000 tons of wood pellet per year; the other one (Quercus Energy—http://www.quercusenergy.es/) produces 10,000 tons of wood chips per year [43]. No details of the feedstock used were found. Therefore, in this work two scenarios were analyzed for optimal pelletizers location: (i) the pellet feedstock of abovementioned companies was residual forest biomass and therefore, they did not compete with pellets plants fed with woody crops residual biomass (ii) their feedstock was the same as the one assessed in this work and so, they represented a competitor; in this case, they should be included for the result of the optimal location.

The processing capacity of each pelleting facility to be located will essentially depend on the amount of available biomass to be processed, the capacity of pelletizer units and the number of working shifts. Consequently, these factors also influence on the number of pelletizers to be installed and located. In the current work, a production capacity of 6400 t year^{-1} for each pellet plant was chosen, assuming four pelletizer machines of 0.5 t h^{-1} (2000 t h^{-1}) and two working shifts of six hours each. Based on the results of biomass potential assessed in this work (see 3.1 section), the number of potential pellet plants was determined and subsequently they were optimally located.

In the optimal location analysis, an economic assessment of the maximum biomass transport distance was conducted as a techno-economic requirement for pellet production plants. Factors like the distance to population areas and the identification of natural protected areas, which are usually deemed to locate other types of bioenergy facilities, were not taken into account since a pellet plant do not usually produce air pollution.

Maps throughout this paper were created using ArcGIS® software by Esri. ArcGIS® and ArcMap™ are the intellectual property of Esri and are used herein under license.

2.6. Economic assessment of biomass pelleting

Production costs of pellets from residual woody biomass in Majorca Island were estimated for the whole value chain, including biomass harvest, chipping, loading, transport to processing plant, pelleting (grinding, drying and pelleting) and pellets transport.

The economic assessment aims at the comparison of the production costs of pellets made up with residual biomass with the market price of commercial pellets, in order to calculate the biomass transport distance at which biomass pelleting is not economically profitable. The resulting value for distance threshold was subsequently used in the location-allocation analysis as impedance cutoff.

The biomass logistic chain analyzed for the estimation of the production costs is shown in Figure 5. For this work, it is assumed that farmers were responsible for tree pruning and that the pruning biomass was left between rows in the field.

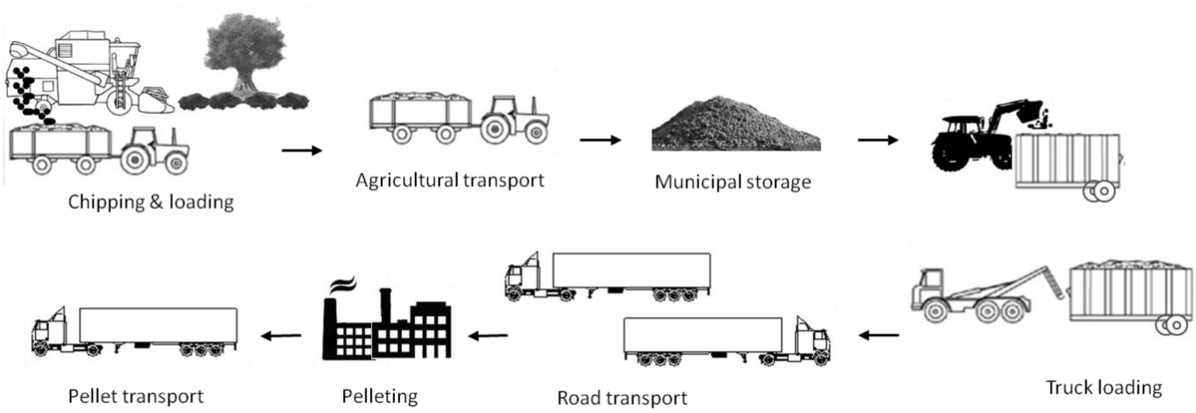

Figure 5. Considered logistic chain for pelleting residual woody biomass.

Biomass chipping and loading was assumed to be accomplished by means of a self-propelled pruning harvester equipped with a pick-up head developed by a Spanish brand [44]. For this machine, both, the effective field capacity and the working capacity of the harvester were estimated at 0.4 h ha^{-1} and 6 t h^{-1}, respectively, considering the mean values of the Spanish case from the work of Spinelli and Picchi [44] and the mean RPR by unit area in Majorca (2.4 t ha^{-1} with 30% moisture content).

The chipped product was assumed to be discharged in a 26 m^3 three-axle trailer with steering turntable towed by an 80 kW-powered tractor. Then, biomass chips were transported to a storage point (municipality mean center) from which they were loaded to a 35 m^3 trailer hitched to a 294 HP truck by means of a loader spade front-mounted on a 66 kW tractor.

Costs of agricultural and logistic operations were estimated according to the methodology established in the 'Cost calculation sheets for agricultural machinery and implements use' from the Ministry of Agriculture, Food and Environment of Spain [45]. This methodology estimates machinery costs including charges for ownership, which do not depend on the amount of machine use [46], and operation. It is based on the guidance and assumptions suggested by CEMAG [47].

Within the ownership costs a combined procedure was selected in order to estimate machine depreciation, which simultaneously includes amortization for obsolescence and wear. These costs depend on both, economic life expectancy and purchase prices of each machine. For obsolescence calculation, amortization time was assumed 15 and 10 years for tractors and implements respectively, whereas for costs associated to machine wear, the economic life expectancy was considered up to 10,000 hours for tractors and 5000 hours for implements, as suggested by authorized dealers and by MAGRAMA (2015) [45]. Dealers also provided purchase prices for every machine used in this work. Ownership costs also included the concepts of interest on investment, insurance and housing, which were calculated as a percentage of the purchase price (5%; 0.2% and 0.1% respectively).

The operating costs depend on the amount of machine use and they include labor, fuel, lubricant, repair and maintenance. Annual use was assumed as 400 h for implements and 800 h for tractors and self-propelled machines [45]. Labor costs were assumed to be 12 $€·h^{-1}$ including taxes and social security contributions.

In MAGRAMA sheets, fuel costs are based on a consumption factor (factor named "$l·h^{-1}$–kW") depending on the tractor working load and the rated engine power (kW). Values for fuel consumption factor were selected according to MAGRAMA database. The assumed diesel fuel price was 1 € l^{-1}.

Repair and maintenance costs indicated by MAGRAMA [45] were used. For implements they are established in the mentioned database in $€·h^{-1}$, whereas for tractors and self-propelled machines they are estimated from the engine power (kW), the fuel consumption factor (from 0.207 to 0.150 l h^{-1} kW^{-1}) and a rate of 0.2 € l^{-1} assumed for repair and maintenance.

Agricultural transport costs were estimated assuming 5 km transport distance to the biomass storage point, travelling at an average tractor speed of 25 km h^{-1} when loaded and 40 km h^{-1} when unloaded. Loading time depended on the chipping effective field capacity of the harvester. A required 3 minutes-time for biomass unloading from trailers was assumed. Additionally, an efficiency factor of 85% over the harvesting effective field capacity was considered in terms of traffic, downtime, trailer interchanges and different incidents.

Regarding biomass road transport, trucks were supposed to have an average speed of 70 and 80 km h^{-1} when loaded and unloaded, respectively. It was assumed 5 minutes for loading the 35 m^3 trailers with the loading-spade tractor. An efficiency factor of 85% was also applied to these operations.

Data and assumptions considered for the ownership and operation cost calculation referring to agricultural and transport machinery are shown in Table 3.

In order to assure the supply of biomass to pellet plants, an additional cost in our analysis was assumed for the biomass at the field. This cost would represent the biomass price to be paid to the supplier (farmers, industries). The assumed cost was 15 $€·t^{-1}$ biomass.

Table 3. Cost data for collecting and transport machinery (S = self-propelled; H = head; T = tractor; I = implement).

		Chipping & loading	Biomass agricultural transport		Biomass loading		Biomass road transport	
		S	T	I	T	H	T	I
Purchase price	k€	190.0	87.8	65.0	69.6	11.6	86.4	74.75
Power	kW	200.0	80.0		66.2		294.1	
Amortization time	years	15	15	15	15	10	20	15
Life expectancy	$\cdot 10^3$ h	10	10	10	10	5	12	10
Annual use	h$\cdot$year^{-1}	800	800	400	800	400	800	400
Interest rate	%	5%	5%	5%	5%	5%	5%	5%
Insurance	%	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Housing	%	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Labour	€$\cdot$h^{-1}	12	12		12		12	
Fuel consumption factor	l$\cdot$h$^{-1}\cdot$kW^{-1}	0.207	0.207		0.207		0.207	
Repair & maintenance	€$\cdot$h^{-1}	8.3	3.3	0.3	2.7	0.1	12.2	5.0

Costs of storage incurred after biomass collection were also included. They were calculated from the average amount of biomass assessed for the municipalities in Majorca, the land renting cost in Majorca [48], and the cost of the plastic tarp for covering the stored biomass, assumed as 22 €$\cdot$m^{-2}. The area covered by a chips pile was calculated considering a bulk density of 0.365 t$\cdot$m^{-3} [49].

Costs for the installation and operation of pelletizers were provided by the bioenergy company EnerAgro (http://eneragro.com/). They included capital costs (investment on the grinding mill, biomass dryer and pellet production units) and operation costs (labor, plant maintenance and power consumption). These costs depended on the number of pellet production units (pelleting machines) and working shifts as well as on the biomass moisture content, since this parameter determines the requirements for drying energy and dryer investment. The moisture content of the biomass as received at the pelletizer was assumed to be 30% [36].

Costs were calculated per ton of produced pellets considering 10 years for investments amortization. A business and office fee including communication, accountant and electricity, among others, was assumed and calculated from a 20% over the feedstock cost.

Cost related to pellet distribution was also estimated like the machinery costs explained above, considering the same 35 m^3-trailer truck, a transport distance of 50 km and a pellet bulk density of 0.600 t$\cdot$m^{-3} (UNE-EN ISO 17225 1:2014).

A 15% profit margin was also considered for logistic operations and pelleting process as if they were separated companies or economic activities, each one with its respective benefits.

The total cost was compared to the pellet selling price of 180 €$\cdot$t^{-1} [50], value taken as a reference price of marketed industrial pellets. This way, the threshold of maximum road distance for biomass transport that balanced the production total cost with the market price was calculated.

3. Results

3.1. Potential of residual woody biomass

According to CAIB statistics, there are 36,903 ha of woody crops in Majorca Island. Almond and carob tree represent the main woody crops with 40.4% and 25.9% of the permanent cropping area, respectively. Olive groves and vineyards amount to 4665 ha (12.6%) and 3895 ha (10.6%), respectively.

The potential of residual biomass from woody crops in the island of Majorca amounts to 35,874 t DM·year^{-1}, where almond (35.5%), carob tree (14.9%) and other fruit trees (26.9%) are the main sources of biomass (Figure 6).

Manacor (code 07033) and Llucmajor (code 07031) are the municipalities with the largest area of woody crops in the island with 3478 ha and 3437 ha, respectively. Consequently, they show the highest residual biomass potential from this biomass source, 3819 t DM·year^{-1} in Manacor and 2917 t DM·year^{-1} in Llucmajor (Figure 7).

Regarding the residual woody biomass from agri-food and wood industries, the potential production amounts to 24,211 t DM·year^{-1} from data of 140 industries compiled and georreferenced. A total of 135 industries are dedicated to wood processing activities producing 17,292 t DM·year^{-1}, 2074 t DM·year^{-1} and 2128 t DM·year^{-1} of non-chemically-treated wood, bark and other byproducts, respectively (Figure 8). Almond shell is produced by the other 5 industries, which generate 2717 t DM·year^{-1} of this type of biomass. The location of such industries and the biomass potential in each municipality are shown in Figure 9.

From these results, the total amount of residual woody biomass potentially available for pellet production in Majorca Island, is estimated at 57,368 t DM·year^{-1} (equivalent to 81,954 t fresh matter (FM)·year^{-1} with 30% moisture content). The number of pellet production plants that could be installed depends not only on feedstock availability but also on the pelletizer capacity and the number of working shifts. Some options identified are shown in Table 4.

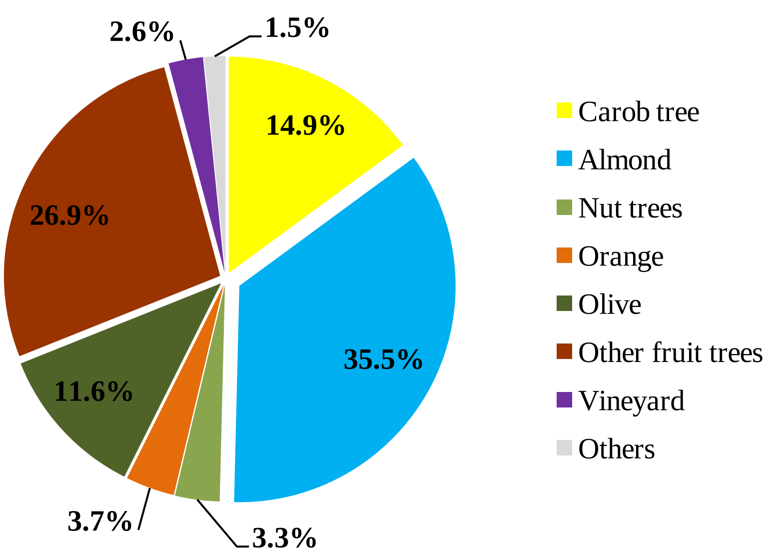

Figure 6. Sources of residual biomass from woody crops in Majorca Island.

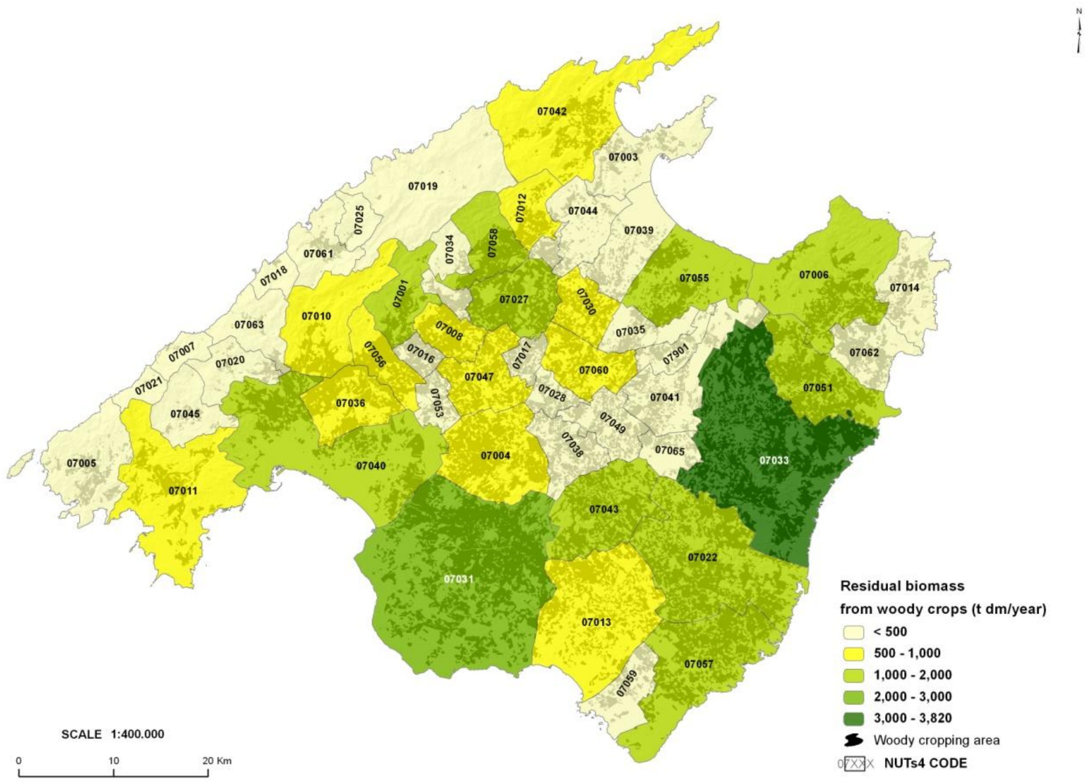

Figure 7. Map of residual biomass potential from woody crops in Majorca Island at NUTS-4 scale.

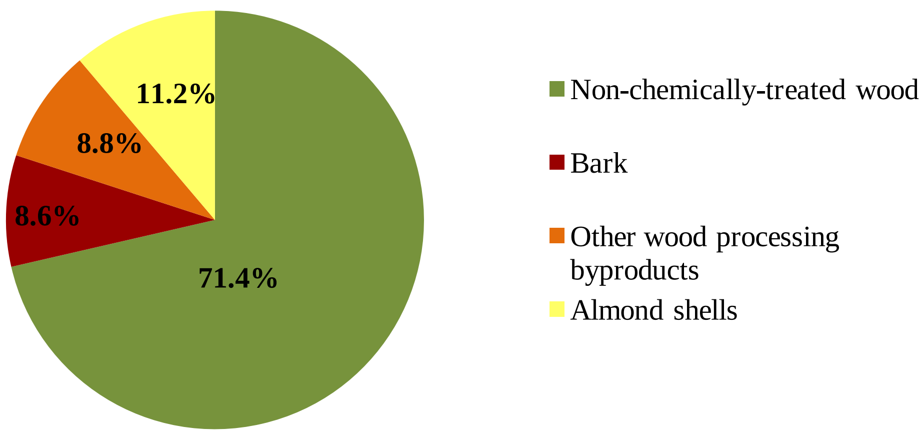

Figure 8. Sources of residual biomass from agri-food and wood industries in Majorca.

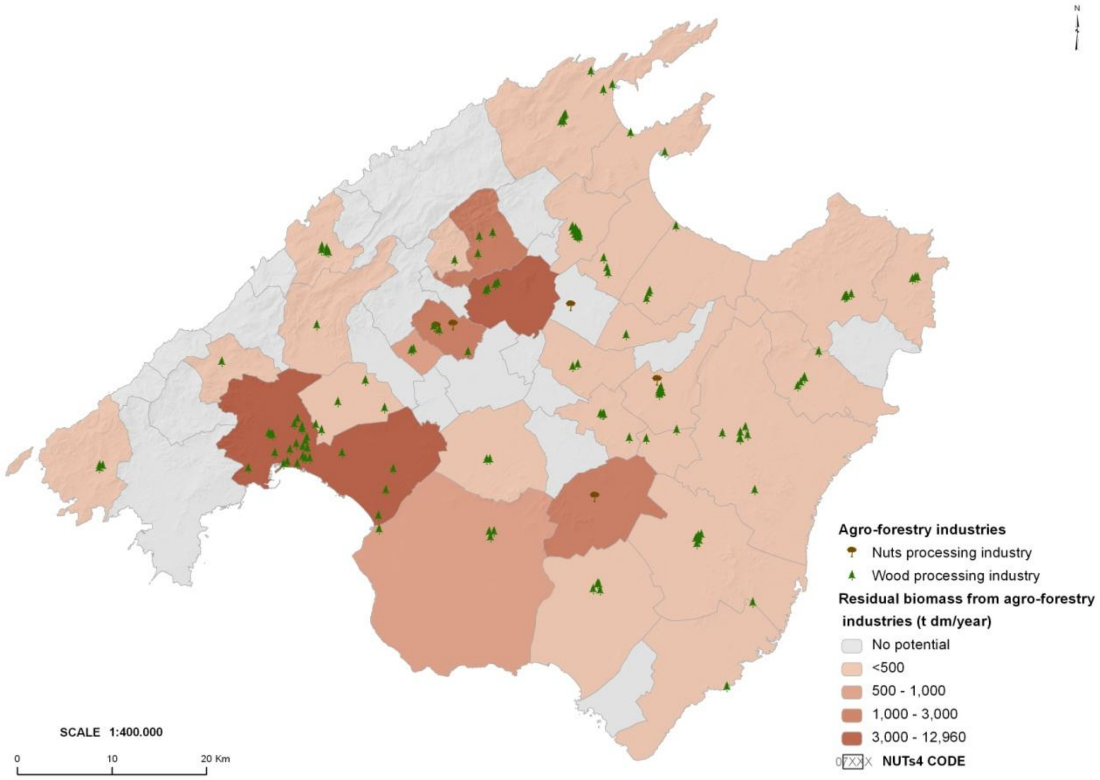

Figure 9. Map of residual biomass potential from agri-food and wood industries in Majorca at NUTS-4 scale.

Table 4. Number of pellets plants as a function of the capacity of the pelleting machines, the number of working shifts and the input of biomass.

Production capacity of a pelletizer and number of working shifts	Potential production of pellets (t year^{-1})	Biomass input (t FM year^{-1} 30% moisture)	Number of potential pellet plants
1.0 t h^{-1}, 2 shifts	3200	4023	20
1.0 t h^{-1}, 3 shifts	4800	6034	13
2.0 t h^{-1}, 2 shifts	6400	8046	10
2.0 t h^{-1}, 3 shifts	9600	12,069	6

In our approach, it was assumed that the production capacity of each pellet plant would be 6400 t year^{-1}. Therefore, ten pellets plants should have to be optimally located for a maximum biomass processing capacity of 8046 t fresh matter (t FM) year^{-1} per plant.

3.2. Economic assessment of biomass pelleting

According to the costs estimated in our work, logistic operations for collection of residual biomass from woody crops, including biomass cost at the field, biomass chipping, transport to a storage site by means of agricultural machinery, biomass loading into a truck and road transport, amounts to 55.1 €·t^{-1} FM. Assuming 15% profit margin for the logistic activities, the biomass cost at the pellet plant would be 63.4 €·t^{-1} FM (30% moisture content).

The breakdown of the logistic operation costs into fuel, labor and implement and tractor overheads is shown in Table 5. The respective costs by production unit (€·t^{-1} FM) are also given in Table 5.

The process of pelleting for 2.0 t·h^{-1} pelletizer capacity and 2 working shifts is estimated at 56.7 €·t^{-1} FM, including energy for drying, dryer amortization, electricity, labour and maintenance. Adding a 20% of business and office fee in terms of communication, accountant and electricity as well as the feedstock cost, the pellet cost at the pellet plant amounts to 144.1 €·t^{-1} (pelletizer with a working capacity of 2.0 t·h^{-1}, 2 working shifts). In addition, the costs of pellet transport result in 12.4 €·t^{-1} which raises the pellet net cost to 156.5 €·t^{-1}. Assuming 15% profit margin associated to the pelleting economic activity, the pellet production cost or threshold pellet price reaches to 180 €·t^{-1}. Table 6 shows the cost breakdown as a function of the capacity of pellet production units and working shifts, according to raw data provided by Eneragro Ltd.

The above mentioned costs are referred to the threshold transport distance which balances the total threshold pellet price to the actual market price. Such distance resulted in 28.0 km (Microsoft Excel Solver solution). As stated in section 2.5, this threshold distance was taken as impedance cutoff in the location-allocation analysis.

Table 5. Cost breakdown of logistic operations (€·h^{-1}) and total cost of the residual biomass from woody crops at the pellet plant (€·t^{-1} FM, 30% moisture).

	Cost of logistic operations (€·h^{-1})					Biomass logistic cost (€·t^{-1} FM)
	Fuel & lubricant	Labor	Implement overhead	Tractor overhead	Total	
Farmer benefit	-					15.0
Chipping	62.7	12.0	-	43.9	118.6	19.7
Chips agricultural transport (5 km)	12.0	12.0	18.1	19.8	61.9	7.9
Biomass storage	-					1.0
Chips loading	12.0	12.0	5.4	15.8	45.2	1.0
Chips road transport (28km)	60.9	12.0	25.6	25.1	123.6	10.5
				Subtotal		55.1
				Profit margin (15%)		8.3
Total cost of the residual biomass at the pellet plant						63.4

Table 6. Pellet production costs (€·t^{-1}) as a function of the capacity of the pelleting machine and the number of working shifts.

	Capacity			
	1.0 t h^{-1}		2.0 t h^{-1}	
	2 working shifts	3 working shifts	2 working shifts	3 working shifts
Feedstock (30% moisture)	63.4	63.4	63.4	63.4
Energy for drying	6.6	6.6	6.6	6.6
Dryer amortization	5.2	3.5	3.8	2.5
Electricity	15.0	15.0	15.0	15.0
Labour	12.0	12.0	9.0	9.0
Pelleting amortization	10.6	7.1	10.3	6.9
Maintenance	12.0	12.0	12.0	12.0
Pellet costs at plant	124.8	119.6	120.1	115.4
Business and office fee	25.0	23.9	24.0	23.1
Total direct cost	149.8	143.5	144.1	138.5
Pellet transport (50 km)	12.4	12.4	12.4	12.4
Pellet net cost (€·t^{-1})	162.2	155.9	156.5	150.9
Profit margin (15%)	24.3	23.4	23.5	22.6
Threshold pellet price	186.5	179.3	180.0	173.5

3.3. Optimal location of pellet production plants

The location of the potential pellet production plants was based on the "maximize capacitated coverage" problem-type, by which the chosen locations that the total sum of weighted impedance (biomass allocated to a pelletizer candidate multiplied by the transport distance) is minimized.

The location of the ten pellet plants potentially required for pelleting the amount of residual biomass of woody crops assessed in this work, is shown in Figure 10. The pellet plants were located to optimally collect the assumed biomass processing capacity of each plant (8046 t FM ·year−1, see section 3.1 and Table 4) with a threshold distance for biomass transport of 28 km and the assumption that the existing pellet plants in Majorca were supplied with forestry biomass and therefore, did not compete for the biomass assessed in this study.

If the feedstock of the currently existing pellet plants in Majorca were the same as the one assessed in this work (i.e. residual biomass from woody crops), their feedstock requirements would have to be taken into account. With this assumption, the remaining biomass -potentially available for new pellet plants- could feed eight pelletizers that would have to be located. Aiming at their optimal location, the existing pellet plants were introduced in the analysis as required facility (facilities that must be part of the solution). The optimal location of the eight new pellet plants and the location of the currently existing pellet plants are presented in Figure 11.

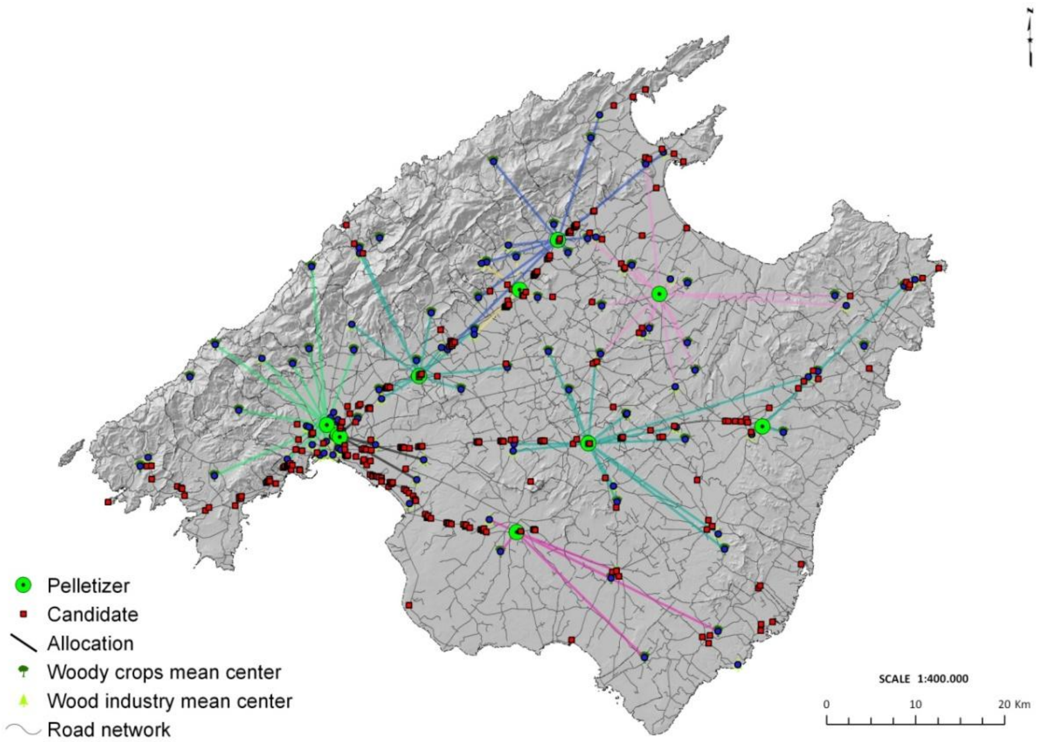

Figure 10. Optimal location of the potential pelletizers in Majorca assuming no competitor plants.

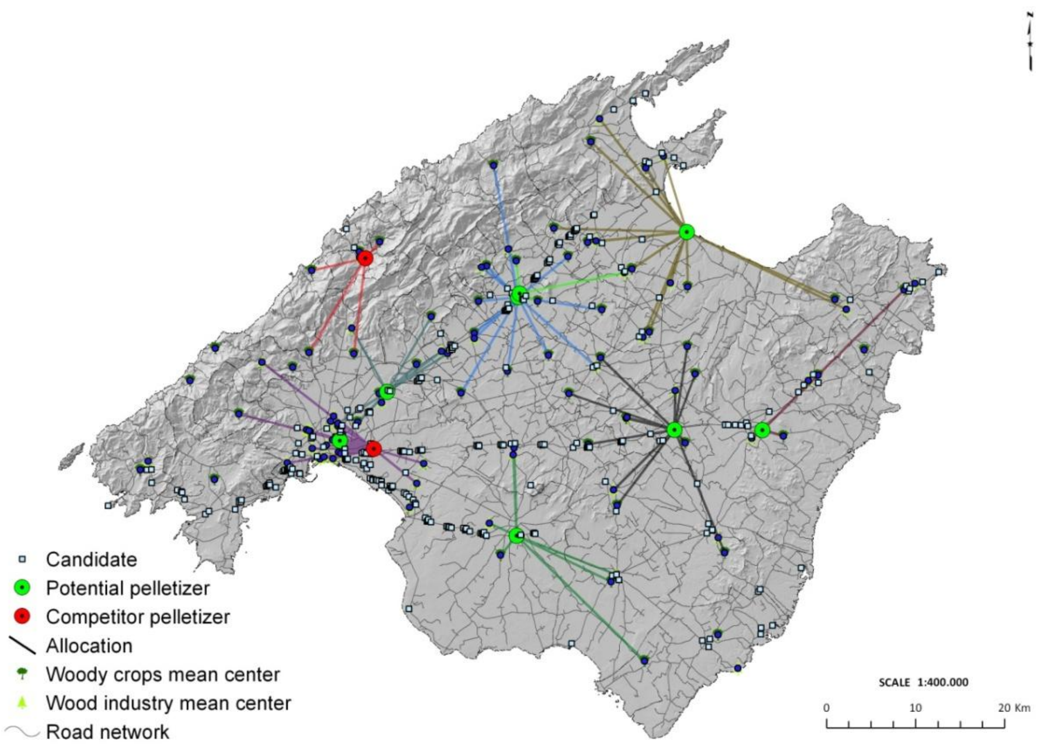

Figure 11. Optimal location of potential pellet plants in Majorca assuming that the existing pellet plants compete for the feedstock.

4. Discussion

The potential production of residual biomass from woody crops in Majorca (agricultural biomass) reaches 35,874 t DM year^{-1}, according to our approach. As stated earlier, no specific assessment of residual biomass in Majorca has been conducted so far.

The Institute for the Diversification and Energy Saving of Spain (IDAE) carried out several technical reports for the elaboration of the Renewable Energies Plan 2011–2020 for Spain. One of them aimed at the assessment of the biomass potential production at national scale [12], and reported values of biomass potential at NUTS-2 scale. According to that study, the residual biomass of woody crops in the Balearic Islands ("Illes Balears") amounted to 202,625 t DM year^{-1} (405,250 t FM year^{-1} with 50% moisture content). Assuming the breakdown of woody crops area into the Balearic Islands (89.0% in Majorca; 10.6% in Ibiza and 0.4% in Menorca), the biomass potential in Majorca would be 180,350 t DM year^{-1}. In that study, the statistical data of agricultural area were obtained at municipality scale (NUTS-4) from the land area declared for the Common Agricultural Policy (CAP) payments in 2005. Likewise, in 2005 and 2006 there was a severe decrease (−47%) in the land devoted to permanent crops in the Balearic Islands by which the total woody crops area decreased from 99,970 ha to 53,113 ha, a decrease observed mainly in the area dedicated to almond and carob tree cultivation [51]. Thus, the different time frame of the data between IDAE's study and the present work could partially explain the great difference in the assessed biomass potential of both studies.

In addition, regional results taken from national-scale assessments should be treated with caution. In fact, according to IDAE's report, orchard area were extrapolated from surveys [52] in order to obtain estimated data at NUTS-2 scale, which may differ from the data used in our study.

The use of residual biomass for energy purposes could contribute to meet the objectives of energy consumption from renewable sources in the Majorca region. Thus, assuming the minimum calorific value laid down in ISO 17225-2:2014 for industrial pellets (16,500 MJ t^{-1}) and the value found for the potential production of pellets in Majorca (6400 t year^{-1} in each of the 10 possible pellet plants), the primary energy in his biomass would be estimated at 1.056 × 10^{6} GJ year^{-1}. Regarding almond shell, the primary energy in the assessed resource (2717 t year^{-1}) would be 40,755 GJ year^{-1} (15,000 MJ t^{-1} heating value according to UNE 164004 = 2014). Therefore, the primary energy in the residual woody biomass assessed in the present study would mean 2.8% of the primary energy consumed by the domestic and services sector in 2010 in the Balearic Islands (934,282 toe).

Regarding the analysis of pellet plants optimal location, the present study took into account technical and economic parameters for the suitability assessment of potential sites: biomass availability, accessibility by the road network and threshold of maximum transport distance according to costs of the pellet production chain and pellet market price. In contrast, the analysis conducted by Sultana and Kumar [24] considered an exclusion analysis based on man-made, natural and environmental constraints—e.g. distance to rural and urban areas, airports and wetlands, among others. The exclusion analysis was followed by a preference analysis on the basis of an Analytic Hierarchy Process (AHP) [53] in order to derive a priority scale according to expert judgments through a pair-wise comparison. That methodology has also been used in the location of bioethanol plants [18,42] where the technical requirements of the processing plants are more demanding than the ones of pelletizers, like the requirements for water and power for biomass processing, water treatment facilities and remoteness from populated areas in order to avoid odors and other impacts, among others. Apparently, pellet plants do not involve so many requirements and consequently, either its location sites.

In the energy use of biomass, harvesting represents one of the key issues due to the scatter distribution of residual biomass from woody crops and the tight time window. Spinelli and Picchi [44] estimated an average harvesting cost of 28 €·t^{-1} FM (40 €·t^{-1} DM), quite high as compared to the one obtained in the present study (19.7 €·t^{-1} FM; 28.2 €·t^{-1} FM). The operative capacity assumed in both studies was similar so, differences lie in the operational cost of machinery. The hourly cost of the harvesting machinery in our work was estimated at 118.6 €·h^{-1}, whereas Spinelli and Picchi calculated 158 €·h^{-1}. Difference in service life (15 years vs. 8) and usage (800 h·$year^{-1}$ vs. 600 h·$year^{-1}$) of the machinery as well as labor cost (12 €·h^{-1} vs. 15 €·h^{-1}) explain those values.

The cost for biomass transportation is inversely proportional to transport distance. The longer the distance is, the higher the machinery utilization and amortization, and therefore, the lower the cost, even though operation costs increase through fuel and lubricant consumption. Our estimations showed a chipped biomass transport cost of 0.37 €·t^{-1}·km^{-1} by truck, value close to the one assumed by Sultana and Kumar for the variable cost related to distance traveled (0.22 $ t^{-1}·km^{-1}) [24,54]. However, no information about the type of machinery and the methodology used for the calculation of the latter was reported.

According to our approach the cost of the biomass at the plant gate ranged between 57.1 €·t^{-1} FM and 63.4 €·t^{-1} FM for a transport distance of wood chips by truck of 10 km and 28 km, respectively (including a profit margin of 15% for logistic activities).

In regards to the pelleting costs, they ranged between 52.0 and 61.4 €·t^{-1}, depending on the pelletizer capacity and the operative hours of the plant. In the case of a 2.0 t·$hour^{-1}$ pelletizer running in two working shifts, the pelleting costs were estimated at 56.7 €·t^{-1} (see Table 6). Adding the business fee, the cost of the pellet transport and the profit margin, the total costs of pelleting amounted to 116.6 €·t^{-1} (varying from 110.2 to 123.1 €·t^{-1} for different assumptions). Thus, the feedstock and the pelleting process meant the 35.2% and 64.8% of the total pellet cost, respectively (assuming the threshold of the maximum biomass transport distance). These results are in agreement with the ones obtained by Hoefnagels, et al. [27] for the SE of U.S., where the feedstock cost represented between 33.6 and 41.3% of the total pellet cost for a feedstock cost between 22 $ t^{-1} FM and 33 $ t^{-1} FM, assuming 20.2% average moisture content. At the same time, in the estimations of Usasuf and Becker [28] for Argentina, the raw material was the dominant cost factor, representing between 33 and 44% of the total specific cost.

The total pellet cost varied from 173.5 to 186.5 €·t^{-1} depending on the production capacity of the plant (Table 6) and assuming 28 km for the feedstock transport; in the case of 10 km, it ranged between 164.9 and 177.8 €·t^{-1}. Hence, the total cost of pellet production resulted more sensitive to the transportation cost than to the size of the production plant, as stated by Sultana et al. [54]. In the latter study, the cost of agri-pellets was estimated at 122.2–170.9 €·t^{-1}. Likewise, Hoefnagels et al. [27] estimated a pellet production cost of 82–100 €·t^{-1}, taken low-value wood as feedstock (forest residues from pre-merchantable thinning operations and pole mills as well as post-consumer wood wastes from discarded wooden transport pallets). On the contrary, Usasuf and Becker [28] estimated lower production costs of wood pellets (35–47 €·t^{-1}) from residual biomass of wood industries (sawdust and wood shaving).

Certainly, the effect of the economies of scale is evident in all these studies, by which an increment in the pellet production rate decreases substantially the specific pellet production costs [27,28,54]. Nevertheless, the biomass processing capacity of the pellet plants analyzed in the literature is by far larger (55,000 t·year^{-1} [27]; 6 t·h^{-1} [28]) than the ones considered in the present study. Besides, the production costs of wood pellets should be assessed in a specific basis for each region in order to avoid data extrapolation, which might lead to little representative values [28,55].

The pellet price should be compared to other energy carriers in order to provide stakeholders or government in Spain with techno-economic criteria to make a decision. In the Balearic Islands the price of heating oil is 0.859 €·l^{-1} on average (http://geoportalgasolineras.es/) which is equivalent to 8.0 c€·kWh^{-1} (assuming 10.75 kWh·l^{-1} heating value). Additionally the price of natural gas is 5.2 c€·kWh^{-1} [56] on average in Spain. Following ISO 17225-2:2014 the heating value of industrial pellets is 16,500 MJ·t^{-1} and the market price of industrial pellet is 180 €·t^{-1} [50]. Therefore, the energy pellet cost would reach 3.9 c€·kWh^{-1}, showing that industrial pellets are economically competitive. Other forms of solid biofuels can be competitors to pellets. In the context of Spain, it has been reported that bulk wood chips have a market price of 2.475 c€·kWh^{-1} while olive stone ranges between 3.62 and 4.13 c€·kWh^{-1} [50] depending on the package format of the final product. However, end-users are usually different since boilers and feeding systems are biofuel-specific.

5. Conclusion

The present study provides a proposal for pellet production based on residual biomass from woody crops and agri-food and wood industries in the island of Majorca (Spain). According to the biomass assessment here conducted, there would be enough resource for the installation of 10 pellet plants of 6400 t·year^{-1} capacity, assuming no feedstock competition with the existing biomass plants in the Island. The energy use of this potential biomass would supply up to 2.8% of the primary energy consumed by the domestic and services sector in the Balearic Islands.

The optimal location of the pellet production plants was analyzed by means of a GIS approach (location-allocation analysis) taking into account technical and economic parameters. These plants would be spread throughout the Island but always keeping 28 km transport distance to the biomass production sites at most, in order not to increase the pellet production cost over the market price (180 €·t^{-1}).

The biomass potential assessments and costs evaluation of biomass supply and logistics should be carried out taking into account regional and local conditions not to extrapolate unrepresentative production costs. Evidence of that was also provided in this work.

Further research is needed to assess the potential of other types of biomass, like forest biomass and energy crops in Majorca, in order to increase the contribution of solid biofuels to the objectives of energy consumption from renewable sources.

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Conflict of Interest

All authors declare no conflict of interest in this paper.

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