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GIS-based analytic hierarchy process model for a forest residuals biorefinery site selection

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Abstract. In general terms, renewable energy sources are characterized by their decentralized availability, ability to quickly self-regenerate, and the reduced environmental impacts resulting from their use. The conversion of forest biomass into energy will make it possible to transform waste into raw material for the energy industry while promoting forest management. Reducing the forest's fuel load will be responsible for reducing the intensity of forest fires. In this context, biorefineries significantly prevent rural fire risks by addressing two important aspects: fuel management and renewable energy generation. based on these premises, this study aims to assess the potential for implementing a biorefinery in the Centro Interior region. The amounts of available residual biomass were calculated based on data from the national forest inventory, carried out in 2015.For the municipalities with higher residual biomass production, a decision support system based on GIS and Multicriteria Decision-making was used to select sites suitable for locating a forest biorefinery and provides a valuable reference for decision-makers. The combination of MCDM and GIS methods can, therefore, be seen as a powerful tool for solving power planning problems. The most relevant areas, in terms of land occupation of the three forest species considered, are mainly found in the south of the region under study. The area under study has the potential to generate an annual flow of residual biomass of 269,024 tons per year, with maritime pine harvesting accounting for 80% of this flow. However, around 88,193 tons of the annual flow of residual biomass (33%) are found in regions that are difficult to access, and the costs may make exploration unviable in economic terms. According to the study carried out, we consider that the implementation of the biorefinery will be located in the industrial area of the municipality of Oleiros.

Key words: biorefinery location, forest biomass, spatial multicriteria analysis.

INTRODUCTION

The search for endogenous energy resources contribute significantly to the reduction of fossil energy consumption and mitigation of greenhouse gas emissions, with direct impacts on negative environmental impacts, thus allowing for the improvement of air quality, as well as the reduction/control of industrial and urban pollution (Abbasi et al., 2022; Holechek et al., 2022; EEA, 2023).

In Portugal and according to the latest forest inventory carried out (ICNF, 2015), forest space occupies an area of 6.2 million hectares, representing around two-thirds of the continental territory. This area includes forest areas (3,224.2 thousand hectares), woodland and pasture areas (2,766.2 thousand hectares) and unproductive land (191.7 thousand hectares). The most representative wood species are Eucalyptus (845 thousand hectares) and Maritime Pine (713 thousand hectares). The conversion of forest biomass into energy will make it possible to transform waste into a raw material for the energy industry, while promoting forest management. Reducing the forest's fuel load will be responsible for reducing the intensity of forest fires, replacing combustion carried out in nature, responsible for strong economic losses, with various industrial forms of thermochemical and biochemical conversion, generating added value for the economy and the environment (Casau et al., 2022; Halba et al., 2022; Pinto et al., 2022).

In this work, the residual biomass will be directed to a biorefinery in which the various components of the biomass will be used separately: extractables (essential oils, resins, and flavonoids), sugars (glucose, xylose, and arabinose) and lignin (resins and phenolic compounds) transforming them subsequently into value-added products. The process will have as its main objective the production of cellulosic ethanol from the sugars, consisting of 6 fundamental steps: (1) size reduction of material, (2) removal of extractives with solvents, (3) pre-treatment with dilute sulfuric acid, (4) enzymatic hydrolysis, (5) fermentation of sugars hydrolysates from pre-treatment and hydrolysis, (6) use of lignin from the solid residue as thermal fuel or as raw material to the production of phenolic resins.

The costs associated with biomass management can be formed by the combination of four levels of variables: (1) characteristics of the stands: forestry installation and management costs, forest species, type of stands, pure or mixed, age, density, type of undercover, costs of protection against biotic and non-biotic agents; (2) access characteristics - proximity to communication routes, terrain morphology such as slope, presence of obstacles such as rivers or swamps, presence of rocks and rocky outcrops; (3) degree of mechanization and coordination in the biomass supply chain - machines used in each of the exploitation stages, degree of planning, operational interconnectivity and storage logistics, costs of adapting the size and shape of biomass (wood chips, sawdust) and (4) fluctuation in fuel costs, operator costs per working hour, maintenance costs, fees and taxes costs and biomass sales prices (Viana et al., 2010; Karras et al., 2022; Martinez-Hernandez et al., 2021).

Multicriteria decision analysis (MCDA) deals essentially with complex decisions that involve a large amount of information, several alternative outcomes, and criteria to assess these outcomes. MCDA techniques can be used to identify a single preferred option, to rank options, to shortlist several options for further investigation, or to distinguish acceptable from unacceptable alternatives (Malczewski, 2004). Thus, multicriteria evaluation is used to solve spatial decision problems derived from multiple criteria.

The Analytic Hierarchy Process - AHP (Saaty, 1980) is a multi-criteria tool considered to be relevant to nearly any ecosystem management application that requires the evaluation of multiple participants or complex decision-making processes are involved.

Various studies were developed using GIS-MCDA techniques in the context of renewable energies (Rodríguez et al., 2017; Quinta-Nova et al., 2017; Jayarathna et al., 2022; Ma et al., 2023). A systematic review of multiple-criteria decision-making (MCDM) techniques and approaches in solving sustainable and renewable energy systems problems (Mardani et al., 2015). AHP/fuzzy AHP and integrated methods were the most used in the last years.

This study proposes a multicriteria GIS approach based on the Analytic Hierarchy Process to identify an optimal biorefinery site in the Centro Interior region, Portugal. For this purpose, criteria that will contribute to the choice of the biorefinery's location are considered, namely biomass resources availability, which was calculated in the aim of this study, different from natural and legal constraints, and accessibility.

AHP allows a comprehensive evaluation to determine the location of projects in electric energy production from plant biomass by considering multiple environmental and economic criteria, providing a holistic assessment. It also allows for the determination of criteria weights through pairwise comparisons, ensuring that the relative importance of each criterion is accurately reflected (Razak et al., 2021). However, in certain situations, the AHP for site suitability assessment may have limitations when there is a lack of data accuracy and subjectivity in criteria weighting, potentially affecting decision outcomes (Munier & Hontoria, 2021).

MATERIALS AND METHODS

The study area and data sources

The Centro Interior is a region located in eastern Portugal that includes two main administrative divisions at a subregional level: Beira Baixa and Beiras/Serra da Estrela (Fig. 1). The region covers an area of 10,919 km² and has a population of 325,086 inhabitants. Its elevations range from 103 to 1,993 m. This territory is mainly occupied by forest, agroforestry, and agricultural land.

The spatial data sets for the study were obtained from the following sources:

- Land Cover map - COS 2018 (DGT, 2024).
- Official Administrative Map of Portugal - CAOP 2022 (DGT, 2024).
- Road network (The OpenStreetMap Foundation, 2024).
- Protected Areas and Natura 2000 Network maps (ICNF, 2024).
- Copernicus Digital Elevation Model (DEM) for Europe (ESA, 2024).
- Geological map units (Monteiro-Henriques et al., 2016).
- National Ecological Structure of Continental Portugal (EPIC WEBGIS PORTUGAL, 2024).
- National Agricultural Reserve (DGADR, 2024).

Biomass estimation and exploitability potential

In this work, we considered the residual biomass flows from the main forest species that supply raw materials to the wood and pulp industry, maritime pine, and eucalyptus, respectively. We also consider the flow of biomass resulting from the elimination of the main invasive forest species in the national territory, the acacia dealbata. In the first two species, residual biomass is calculated based on the above-ground biomass excluding the trunk (branches, bark, and leaves). In the case of acacia dealbata, biomass was the total amount of biomass remaining above the ground. In the central region of Portugal, maritime pine, eucalyptus, and acacia dealbata occupy respectively 42.1%, 40.2% and 6.8% of the forest area. Together they are responsible for 89.1% of the forest cover in this region.

The determination of the residual biomass produced annually was based on data from the latest national inventory (IFN6). The national inventory estimates the average amount of biomass above ground, per hectare, and per species, and determines, for the national territory and per species, the total amounts of existing biomass per tree component: trunk, branches, bark, leaves, and roots. These last values allow determining the average value of the residual biomass fraction above ground per species deduced from the sum of the fractions corresponding to the branches, bark, and leaves commonly designated of residual canopy biomass and the amount of residual biomass available per hectare.

The estimate of the amounts of residual biomass above-ground available per species in the country was obtained by multiplying the fraction of residual biomass by the amount of above-ground biomass of the species. The annual exploitation rate of residual biomass (2.01%) was determined from the ratio between the use of residual biomass used annually, estimated at 2 million green tons annually (Ferreira et al., 2017; Avitabile et al., 2023), and the stock of biomass available in the forest stands, estimated by in 99.4 million green tons (IFN6).

The estimate of residual biomass available annually, by species, in the area under study was obtained by multiplying the extraction rate by the average amount of biomass above ground available per hectare and by the species' area of occupancy in the region. Biomass exploitation differs from the concept of availability due to the limitation imposed by land conditions on access to the resource. In this work we considered the distance to communication routes (4 classes) and the slope (3 classes) as two of the most limiting factors for the exploitation of biomass. Thus, exploitability classes were defined in each of these factors and subsequently combined as shown in Table 1.

The exploitability of biomass is expressed as a function of the distance to the road network and the slope and was classified into three classes: high exploitability (2 and 3), moderate (4 and 5) and reduced (6 and 7). The exploitability class value results from the sum of the slope class value (Vs) with the distance class value (Vd). In this way, each exploitability class integrates several combinations of slope and distance values.

Table 1. The weighting of limiting factors for biomass exploitation

Slope		Distance to roads		Exploitability classes	
(%)	Vs	(m)	Vd	Vs+Vd	Classification
< 10	1	< 50	1	< 4	High
10–30	2	50–100	2	4–5	Moderate
> 30	3	100–500	3	> 5	Reduced
		> 500	4		

Spatial Multicriteria Analysis

Selection of the criteria that will have a direct influence on the facility in question. As can be expected, many different factors can be taken into account in spatial studies and those selected will be following the required objectives, the information available, the planner’s experience, etc. In this study, all the criteria are reflected in the corresponding GIS layers (Table 2). The spatial multicriteria analysis using the Analytic Hierarchy Process (AHP) was performed for the municipalities that presented higher residual biomass production, namely Castelo Branco, Oleiros, Proença-a-Nova, Fundão, Idanha-a-Nova, Covilhã, Seia, Penamacor, Vila Velha de Ródão, and Sabugal. All are located in the southern part of the Beira Interior region.

Table 2. Factors considered in siting a biorefinery

Criteria	Description	Data source
Biomass resources	Distance to the areas with higher exploitability potential	Land Cover map - COS 2018 (DGT, 2024)
Lithology	Lithological classification to determine lithological carrying capacity	Map of soil parent material types (Monteiro-Henriques et al., 2016)
Nature conservation	Areas classified for protection of species and habitats	Protected Areas and Natura 2000 Network maps (ICNF, 2024)
Legal constraints	Legal limitations on constructing structures and equipment (national ecological reserve, national agricultural reserve, and other restrictions)	Reserva Ecológica Nacional (DGT, 2024); Reserva Agrícola Nacional (DGADR, 2024)
Access by road	Identification of buffer zones for their proximity to the road network. roads	The road network of Portugal (The OpenStreetMap Foundation, 2024)
Slope	The slope is a limiting factor for this type of installation	Copernicus Digital Elevation Model (DEM) for Europe (ESA, 2024)

First, the areas where restrictions to constructing a biorefinery exist, namely Nature Conservation areas and Legal Constraints, were identified, carrying out the Analytic Hierarchy Process (AHP) only for areas where its construction is permitted.

The AHP was performed with the criteria Biomass resources, Lithology, Access by road, and Slope (Saaty, 1980). First, a spatial database was created to include all vector and raster layers and data models. All spatial layers were prepared, and consistency of coordinates was maintained in ArcGIS 10.8 software. All criteria included in the analysis had to be standardized. Standardization keeps all spatial layers constant and in the same format of measurement units. Hence, all vector layers were converted into raster format and the reclassify tool in ArcGIS was used to standardize and assign values for each criterion.

The pairwise comparison matrix was created using a scale of 1–9 to determine the relative importance of each criterion, in which 1 had equal importance and 9 had extreme importance.

The matrix format in pairwise comparisons defines A = [cij] nxn as follows:

$$\begin{bmatrix} c_{11} & c_{12} & \cdots & c_{1n} \\ c_{21} & c_{22} & \cdots & c_{2n} \\ c_{1n} & c_{2n} & \cdots & c_{nn} \end{bmatrix}$$

After generating all pairwise comparison matrices, the vector of weights, w {w1, w2, ..., wn} is calculated according to Saaty's eigenvector method. This is followed by two steps to calculate weights: First, normalizing the pairwise comparison matrix A = [cij] nxn based on the following equation:

$$c_{ij} = \frac{c_{ij}}{\sum_{j=1}^{n} c_{ij}}$$

Then, the weight for each criterion is computed by the following equation:

$$w_{ij} = \frac{\sum_{j=1}^{n} c_{ij}}{n}$$

In the pairwise comparison matrix, n refers to numbers of elements (Mikhailov, 2003). One of the strengths of the AHP method is measuring the inconsistencies by calculating Consistency Relationship (CR) as follows:

$$CR = \frac{CI}{RI}$$

CR specifies the degree of consistency or inconsistency. It denotes the probability that the matrix judgments were made randomly. The CR depends on the Consistency Index (CI) and Random Index (RI) and can be calculated as follows:

$$\frac{\lambda_{max} - n}{n - 1}$$

Where λ_{max} is the largest eigenvalue of the matrix, n indicates the order of the matrix. RI refers to the average of the resulting consistency index, depending on the order of the matrix. The pairwise consistency is acceptable if the CR value is less than 0.10. On the contrary, if the value is higher than 0.10, this indicates inconsistencies in the evaluation, and hence the original weights should be recalculated.

In the suitability assessment stage, the weighting linear combination approach is used to produce a composite suitability map. All spatial layers were converted into raster models and the reclassify tool was employed to classify all layers to a standardized measurement suitability scale between 1 and 3, where 1 indicates less suitable while 3 denotes the most suitable. The weighted overlay technique combined all weighted spatial layers and produced the ecotourism suitability map, using the GIS-based AHP extension developed by Marinoni (2004). The technique statistically is implemented by calculating the composite suitability value (E_{ij}) for each pixel (ij) as follows:

$$E_{ij} = \sum W_k S_{ijk} \quad (1)$$

where w_k is the assigned weight for criteria k while S_{ijk} is the standardized value of pixel (ij). The values of S_{ijk} range between 1 and 3.

RESULTS AND DISCUSSION

Biomass estimation and exploitability potential

The following table presents the quantities of residual biomass existing in the area under study, considering its exploitability class.

By analyzing Table 3, we can observe that the three species considered in this study have an occupancy area of 293,744 ha. In its distribution we observed that Maritime pine is dominant, with an area of 209,959 ha (71%), followed at a great distance by Eucalyptus globulus, with an area of 81,708 ha (28%). We can also see that the invasion of the territory by the Acacia dealbata is not yet significant, with this species only occupying 2,077 ha, corresponding to around 1% of the area occupied by the three species. The dominance of maritime pine over eucalyptus in the region is opposite to the relationship between the two species in the national context, in which eucalyptus appears as the forest species with the largest area of occupation.

Table 3. Residual biomass production, in tonnes per year, in each exploitability class

	Maritime pine	Eucalyptus globulus	Acacia dealbata
Average biomass above ground per unit area (tonnes ha^{-1})	51.03	31.51	45.94
Biomass residual fraction (%)	36.79 %	32.49 %	100.00%
Average residual biomass above ground per unit area (tonnes ha^{-1})	18.77	10.24	45.94
National Area (ha)	713,300	845,000	8,400
Biomass above ground stock (tonnes)	36,399,699	26,625,950	385,896
Residual biomass above ground stock (tonnes)	13,391,449	8,650,771	385,896
Annual exploitation rate of residual biomass (%)	2.01	2.01	2.01
Residual biomass production (tonnes $year^{-1}$)	731,634	535,182	7,757
Study area (ha)	209,959	81,708	2,077
High Exploitability Area (ha)	38,790	14,717	474
Moderate Exploitability Area (ha)	102,786	38,996	1,256
Reduced Exploitability Area (ha)	68,384	27,995	347
Biomass above ground stock (tonnes) in High Exploitability Areas	1,979,435	463,719	21,772
Biomass above ground stock (tonnes) in Moderate Exploitability Areas	5,245,176	1,228,779	57,693
Biomass above ground stock (tonnes) in Reduced Exploitability Areas	3,489,620	882,120	15,949
Residual biomass above ground stock (tonnes) in High Exploitability Areas	728,234	150,662	21,772
Residual biomass above ground stock (tonnes) in Moderate Exploitability Areas	1,929,700	399,230	57,693
Residual biomass above ground stock (tonnes) in Reduced Exploitability Areas	1,283,831	286,601	15,949
Residual biomass production (tonnes $year^{-1}$) from High Exploitability Areas	39,787	9,321	438
Residual biomass production (tonnes $year^{-1}$) from ModerateExploitability Areas	105,428	24,698	1,160
Residual biomass production (tonnes $year^{-1}$) from Reduced Exploitability Areas	70,141	17,731	321

In terms of biomass stocks, we can observe that the area under study has a stock of 13.38 million tons of biomass above ground, of which 2.47 million tons (18%) are in regions of high exploitability, 6.53 million tons (49%) in regions of moderate exploitability and 4.29 million tons in regions of low exploitability (33%).

In the region under study, there are 4.87 million tons of residual biomass available, considering the sum of the three exploitability classes, allowing a flow of 269,024 tons of residual biomass annually. The residual biomass available annually comes mainly from Maritime pine stands (80%). Most of the annual flow of residual biomass comes from areas with moderate exploitability (49%). Due to the region being very mountainous and sometimes with difficult access, we can observe that 33% of the annual flow of residual biomass is found in regions of reduced exploitability, eventually calling into question the viability of the 88,193 tons of biomass in these regions. In turn, the annually available biomass located in easily accessible regions represents only 18% of the annual flow of residual biomass, corresponding to only 49,545 tons per year.

Fig. 1 presents species distribution and selected areas resulting from the analysis of the limiting factors for biomass exploitation of residues from forestry sources. The exploitability map shows that the selected forest species' occupation regions are concentrated in the southern zone of the area under study.

In this region, the southwest zone has large forest areas in mountainous areas and is frequently devastated by forest fires. In the southeast zone, outside the influence of the Serra da Estrela, Gardunha, and Açor mountain range, we have a flat area with lower levels of precipitation and humidity, dedicated to agrosilvopastoral activities, namely in the municipalities of Idanha-a-Nova and in part of Sabugal and Castelo Branco.

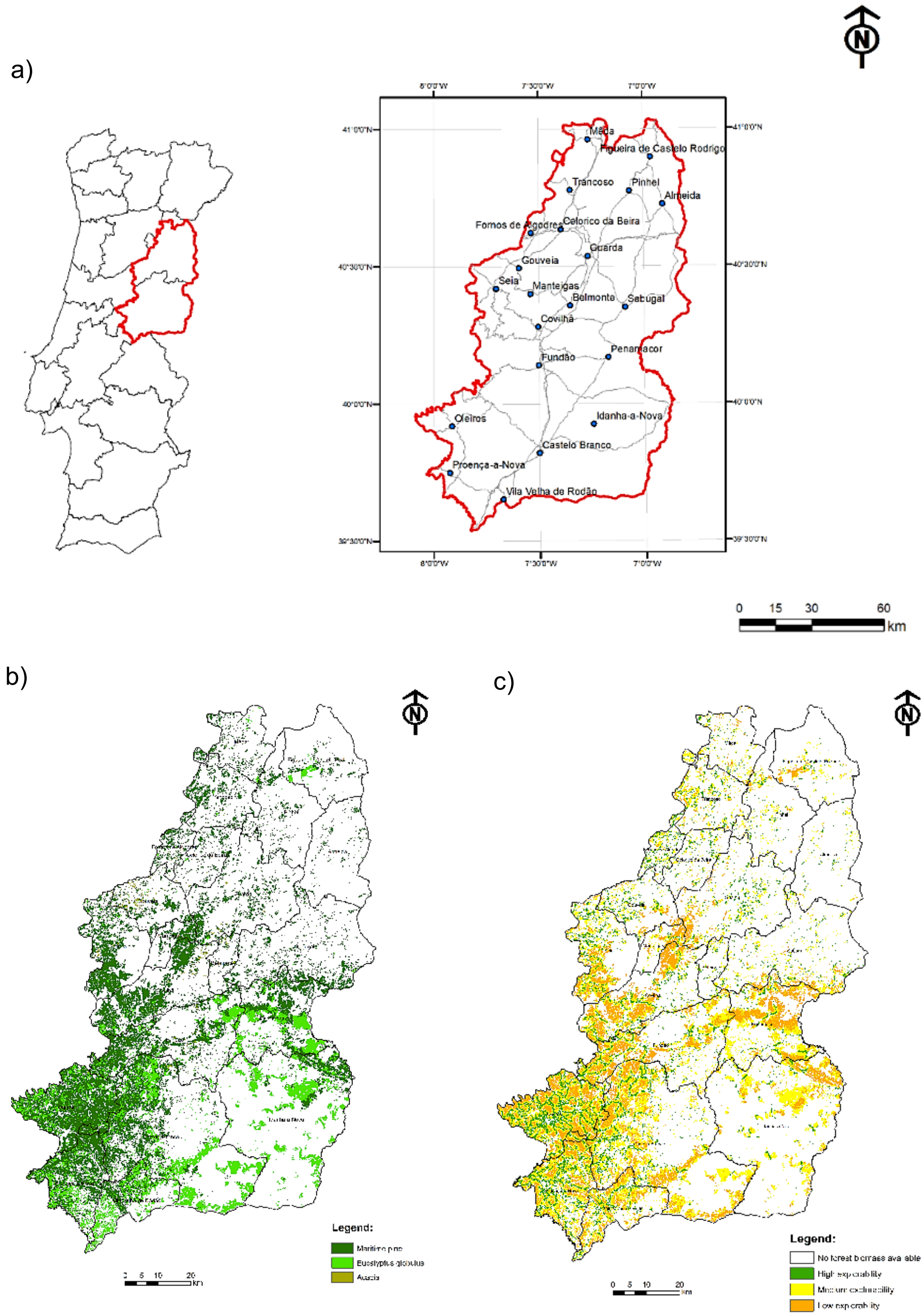

Figure 1. Study area location (a). Species distribution (b) and exploitability potential for biomass residues (c).

Spatial Multicriteria Analysis

Table 4 shows the results of the pairwise comparison matrices, where the scores and weights of each criterion calculated using the AHP method are indicated. In the analysis performed, the value of the consistency ratio (RC) obtained was 0.043 (RC < 0.1). Therefore, assuming a good consistency exists in the pairwise comparison of the matrix.

Table 4. Weights and scores of criteria

Criteria	Weight w_{ij}	Classes	Score
Distance to biomass resources	0.565	< 2.5 km	3
		≥ 2.5 km	1
Access by road	0.262	< 500 m	3
		500–1,000 m	2
		≥ 1,000 m	1
Slope	0.118	< 3%	3
		3–10%	1
		> 10%	1
Lithology	0.055	low permeability	3
		high permeability	2

As a result of the application of the Hierarchical Analytical Process, the mapping of the suitability for locating a biorefinery using the weighted linear summation technique for the municipalities with higher is presented in Fig. 2. Previously, the areas where construction is not allowed, namely areas classified for protection of species and habitats, and other legal constraints.

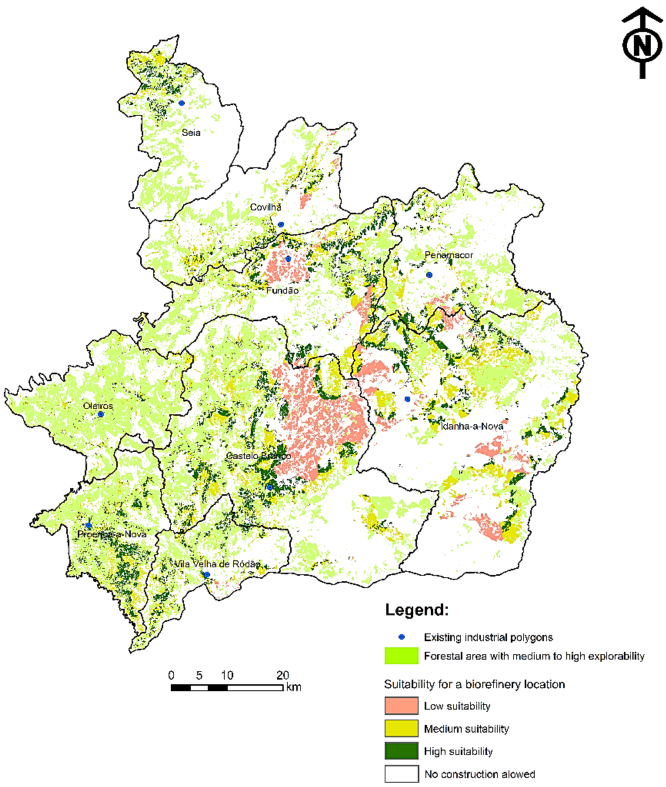

Figure 2. Suitability map of the potential for location of a biorefinery for processing forest residues.

Based on the results obtained, the surface with available biomass corresponding to a medium to high exploitability, considering a radius of 30 km around the existing industrial zones within the study area, we see that the municipality of Oleiros, with 75,988 ha, has around the largest area with medium to high exploitability, allowing an annual residual biomass flow (ARBF) of 71,440 tons per year. The remaining municipalities, Proença-a-Nova (63,092 ha; ARBF 58,367 ton per year), Castelo Branco (62,335 ha; ARBF 55 210 ton per ear, and Vila Velha de Ródão (50,251 ha; ARBF 44 628 per ton per year), have smaller areas of medium to high exploitability around them and consequently lower annual amounts of residual biomass.

To verify the availability of an area with high suitability in the Oleiros industrial polygon, an intersection operation was carried out between a layer corresponding to the Oleiros industrial polygon and the layer with the areas with high suitability according to the result of the application of the AHP. Based on the results of this operation, we verified that an area of 10 ha meets the conditions for implementing a biorefinery.

CONCLUSIONS

The most relevant areas, in terms of land occupation of the three forest species considered, are mainly found in the south of the region under study. The area under study has the potential to generate an annual flow of residual biomass of 269,024 tons per year, with maritime pine harvesting accounting for 80% of this flow. However, around 88,193 tons of the annual flow of residual biomass (33%) are found in regions that are difficult to access and the costs may make exploration not viable in economic terms.

As previously mentioned, the combination of MCDA and GIS methods is a powerful tool for solving power planning problems, such as the location of biomass plants. GIS-MCDA techniques can be used to answer a range of different questions: it can firstly be used to obtain territorial information for planning power supplies, and secondly, it can provide the necessary tools to integrate this knowledge into the development of the project to support decision-making and guarantee sustainable activities.

The forestry sector plays an important role in creating wealth and employment in Portugal's central interior region. Using residual biomass from maritime pine and eucalyptus will increase the value chain associated with these species, representing 80% of the region's forest cover. Also, using acacia biomass in a biorefinery will provide a route for material from the disposal of this invasive species, which is a threat by competing with native vegetation communities, decreasing biodiversity. As control actions involve high costs, mainly due to the necessity of several follow-up control actions, using their biomass as raw material for energy and/or bio-products may be an alternative to compensate for the eradication costs.

According to the results obtained, we consider that the biorefinery should preferably be implemented in the industrial area of the municipality of Oleiros. The production of value-added products from lignocellulosic materials in this municipality will enable the emergence of an innovative industry and the creation of qualified jobs in a rural region that has difficulty generating wealth and retaining a young population.

The work carried out also allows us to draw up specific recommendations to improve the exploitability of biomass residues in forest areas for a biorefinery plant. Specifically, (1) the use of advanced biomass estimation techniques based on the use of remote sensing and GIS technologies to accurately estimate the quantity and distribution of biomass. Such action will make it possible to identify the most viable areas for collecting biomass. (2) Optimize supply chain management by implementing advanced management tools that optimize logistics for collecting, transporting, and processing biomass waste. This capability can be achieved by optimizing transport routes and developing efficient storage solutions to reduce costs. This measure may also include identifying forest areas that require the construction of access roads to increase the exploitability of existing biomass resources. (3) The adoption of sustainable harvest guidelines. At this point, guidelines will be established for the sustainable harvesting of forest biomass to ensure ecological sustainability. This measure involves minimizing the environmental impact and maintaining the health of the forest during biomass exploitation.

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