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Methodological Proposal for the Analysis of Land Suitability for Corn Cultivation as an Energy Crop through the Application of Geographic Information Systems

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Abstract. The growth in energy demand and greenhouse gas emissions has intensified the search for renewable sources to decarbonize the energy system. In this context, biomass and biofuels are presented as relevant alternatives. Corn (*Zea mays L.*) is an energy crop of great interest due to its high productivity, agroclimatic adaptation, and capacity for bioethanol and biodiesel production.

This study evaluates the suitability of the territory of the Autonomous Community of Cantabria (Spain) for the application of corn as energy crop, for the production of biofuels, using a methodology based on Geographic Information Systems (GIS) and Multi-Criteria Decision Analysis (MCDA). The analysis integrates environmental, geographical, and socioeconomic criteria, weighted using the Analytic Hierarchy Process (AHP) method, classifying the territory into five levels of suitability. The results identify zones with high potential in low-altitude areas with gentle slopes and good accessibility, supporting energy planning and sustainable land management.

Key words. Energy crops, Optimal location, Bioethanol Biodiesel, Biomass.

1. Introduction

Global energy demand has experienced a continuous increase over recent decades, driven by technological and industrial development, population growth, as well as the widespread adoption of new technologies and dependence on them [1]. This increase has been accompanied by a rapid rise in greenhouse gas emissions, which has made the fight against climate change one of the main scientific and technological challenges of the contemporary world. More than 90% of the emissions associated with climate change are of anthropogenic origin [2][3], with the energy and industrial sectors being the main contributors to greenhouse gas emissions.

Addressing climate change requires development and innovation in fields such as science, technology and policy in order to meet societal commitments to reduce greenhouse gas emissions. In this regard, renewable energy sources play a key role in reducing CO_2 emissions and mitigating the use of fossil fuels.

In this context, biomass emerges as a renewable energy alternative due to its carbon-neutral emission balance. In the field of biofuels, biomass serves as a feedstock for the production of sustainable alternatives aimed at reducing dependence on conventional gasoline and diesel. There are various sources of biomass that can be classified into four general types according to their origin: energy crops, agricultural residues, forestry waste, and industrial and municipal wastes [4]. Biofuels such as bioethanol and biodiesel have been widely studied as total or partial substitutes for fossil fuels in the transport sector. Their production from energy crops can strengthen and integrate the primary sector into energy generation and help ensure supply security. However, it also presents several challenges related to land use, competition with the food sector, and environmental sustainability. The management and planning of energy resources is one of the key challenges of the energy transition. Therefore, assessing the suitability of regions with an agricultural and livestock tradition for the sustainable establishment of energy crops can create synergies with existing production systems when properly planned.

Energy crops can be defined as dense, high-yield, fast-rotation crops with low maintenance costs and high resilience, intended for the production of large amounts of biomass for processing in biorefineries. Compared to other biomass alternatives, energy crops can be utilized in situ, reducing dependence on supply chains and third parties [5]. The characteristics of the generated biomass are extremely important for defining an efficient conversion process in biorefineries. The most commonly used types, according to their chemical nature, are triglycerides, sugar and starch, and lignocellulosic feedstock. Within the second category, sugar and starch feedstock, corn or maize (*Zea mays L.*) represents a promising alternative to oil crops due to its rapid growth rate, high productivity, and ability to adapt to different agroclimatic conditions. Moreover, it allows for the integrated production of both ethanol and biodiesel. Maize can be used for bioethanol production through starch conversion and fermentation processes. Additionally, despite competition with the food sector and relatively high costs, biodiesel production is also feasible through transesterification and direct esterification of maize oil, or by using by-products such as maize germ and distillers dried grains, thereby avoiding potential conflicts [6].

In this context, the potential of the Autonomous Community of Cantabria (Spain) for the cultivation of energy maize crops is assessed based on a spatial suitability analysis. This potential application may represent an opportunity to address the risk of land abandonment and underuse in marginal areas [7]. To accomplish this, a multi-criteria analysis is proposed using an Analytic Hierarchy Process (AHP) to weigh various environmental, geographic, and socio-economic criteria, and employing a Geographic Information System (GIS) as the ideal tool for analyzing geospatial data. This study evaluates the suitability of the territory for planting corn crops for conversion into biofuel in Cantabria, to promote sustainable land use and contribute to renewable energy production. The objective is to identify optimal areas for sowing and to estimate the region's potential for generating this type of biomass based on eight criteria derived from a literature review and the authors' prior research experience.

2. Methodology

This study combines GIS and Multi-Criteria Decision Analysis (MCDA) methodologies to analyze the suitability of Cantabria for energy maize cultivation, classifying the territory into five suitability classes: suitable, very good, moderate, poor, and very poor. The applied methodology can be divided into four main phases: criteria selection, weight assignment, territorial analysis, and results assessment.

A. Geographic Information Systems and Multi-Criteria Decision Analysis

GIS are tools that integrate software and hardware, enabling the analysis, processing, and graphical visualization of georeferenced information and data in map form. When combined with MCDA, GIS allow the establishment of a structured methodology to evaluate and compare multiple alternatives based on a set of weighted criteria, using techniques such as the Analytic Hierarchy Process (AHP). This type of methodology is widely applied in optimal location and suitability studies for different energy resources, facilitating decision-making in energy management and planning. The potential of integrating GIS and MCDA has been extensively demonstrated in numerous studies, particularly in the assessment of optimal locations for wind farms [8], pumped-storage power plants [9], photovoltaic installations [10] and other applications more closely related to the case under study, such as biogas biorefineries [11].

B. Criteria selection

Numerous studies have proposed the integration of GIS and MCDA methodologies, and in all of them, criteria selection constitutes one of the most critical phases in determining territorial suitability. For the specific case of energy maize cultivation in Cantabria, a total of eight criteria are proposed, which can be grouped into three main categories: climatic-environmental, geographical, and socio-economic.

Firstly, climatic-environmental criteria aim to identify agronomically suitable areas by evaluating the conditions required for the germination and growth of the selected crop. This can be interpreted as an assessment of biological viability. This category comprises three factors: temperature, precipitation, and solar radiation. Optimal conditions for maize growth, promoting biomass production, are achieved at an average temperature range of 20–30 °C [12], as well as total accumulated precipitation ranging between 600 and 900 mm, adequately distributed throughout the growing cycle [13] and high levels of solar radiation [14]. Considering an average maize growing cycle of four months, with a sowing period between April and June, environmental factors are determined as the mean values over the corresponding months. The proposed evaluation of the aforementioned criteria according to the defined suitability ranges is presented in Table I.

Table I. – Emvironmental criteria.

	Temperature (°C) (A)	Rainfall (mm) (B)	Solar Radiation (kJ/m²· day) (C)
Totally suitable	20–30	600–900	12.6–20.33
Suitable	18–20 30–32	500–600 900–1000	11.9–12.6
Moderately suitable	18–15 32–35	400–500 1000–1200	11.3–11.9
Not Suitable	10–15 35–40	300–400 1200–1400	10.6–11.3 20.7–20.3
Not Suitable at all	<10 >40	<300 >1500	<10.68 >20.71

Secondly, geographical criteria refer to characteristic aspects related to the geomorphology and topography of the terrain, which affect the technical feasibility and biomass development. Terrain altitude or elevation influences maize production; although maize cultivation can occur at different elevations, areas at lower altitudes are generally more suitable. Additionally, terrain slope conditions the operation of agricultural equipment and machinery, whose performance becomes constrained on slopes exceeding 10%, which also increase the potential risk of soil erosion [15]. The weighting of geographical criteria according to terrain characteristics is presented in Table II.

Table II. – Geographical criteria

	Elevation (m) (D)	Slope (º) (E)
Totally suitable	<750	< 3

Suitable	750 – 1000	3-7
Moderately suitable	1000 – 1250	7-12
Not Suitable	1250 – 1500	12-15
Not Suitable at all	> 1500	> 15

The final category encompasses criteria related aspects associated with economic and regulatory/legislative feasibility. This category may include some of the most restrictive criteria, including highly relevant factors such as hydrography, which allows the assessment of water resource availability for crop supply based on the proximity to potential sources such as rivers, lakes, or groundwater aquifers. Additionally, considering the objective of maize conversion into biodiesel or bioethanol, the proximity of plantation areas to the road network is also evaluated in order to reduce the need for the construction of new transport infrastructures and to minimize transportation costs [16] as well as existing biorefineries. Finally, considering current land use and land classification, certain areas must be excluded from the analysis due to land-use incompatibilities, such as conservation areas, Special Protection Areas, urbanized zones, airports, among many other examples [17].

Table III. – Economic criteria

	Hydrography (Dist km) (F)	Transport network (Dist km) (G)	Biorefinery (Dist km) (H)	Land use
Totally suitable	<0.5	<2	<10	1
Suitable	0.5–1	2–4	10–20	–
Moderately suitable	1–1.5	4–7	20–30	–
Not Suitable	1.5–2	7–10	30–50	–
Not Suitable at all	>2	>10	>50	0

C. *Weighting Criteria*

Once the appropriate criteria for assessing the viability of energy crop cultivation in the study area have been selected, the implementation of an MCDA requires the weighting of these criteria. This involves establishing a hierarchical ranking of the different criteria by defining their relative importance, which determines the weight of each criterion in the overall suitability assessment. The weighting method proposed in this study is the Analytic Hierarchy Process (AHP), which derives criteria weights based on a pairwise comparison matrix [18].

Overall suitability is determined as the combination of the different criteria, as shown in Equation

$$\boldsymbol{Suitability = \sum(temperature + rainfall + solar\ radiation + elevation + slope + hydrography + transport\ network + biorefinery + land\ use)} \quad (1)$$

For the assignment of criteria weights, an 8 × 8 pairwise comparison matrix was established according to Saaty's fundamental scale [19]. Each element a_{ij} presents the relative importance of criterion *i* with respect to criterion *j*. These criteria are labeled from A to H, as shown in Table V. The resulting matrix is presented in Table IV.

Table IV. – Pairwise comparison matrix.

	A	B	C	D	E	F	G	H
A	1.00	1.20	0.75	1.50	2.00	2.00	6.00	3.00
B	0.83	1.00	0.67	1.11	1.67	1.67	10.00	3.33
C	1.33	1.50	1.00	1.67	2.50	2.50	10.00	5.00
D	0.67	0.90	0.60	1.00	1.25	1.25	3.33	2.00
E	0.50	0.60	0.40	0.80	1.00	1.11	2.00	2.00
F	0.50	0.60	0.40	0.80	0.90	1.00	2.00	2.00
G	0.17	0.10	0.10	0.30	0.50	0.50	1.00	1.00
H	0.33	0.30	0.20	0.50	0.50	0.50	1.00	1.00

The adopted weighting scheme prioritizes environmental criteria in order to promote appropriate biomass development over economic criteria related to transportation. The consistency of the proposed hierarchy was evaluated using the Consistency Index (CI) and the Consistency Ratio (CR), yielding a CI value of 0.02158 and a CR of 1.53%, which is considered consistent and acceptable as it is below the 10% threshold. Land use does not appear in the comparison matrix, as it is treated as an exclusion criterion and therefore leads to the removal of protected areas from the analysis. The resulting weights for each criterion are presented in Table V.

Table V. – Weighting Criteria

Criteria		Weight
A	Temperature	18.31
B	Rainfall	17.84
C	Solar radiation	24.79
D	Elevation	12.26
E	Slope	9.30
F	Hydrography	9.07
G	Transport network	3.51
H	Biorefinery	4.93

3. Results

The Autonomous Community of Cantabria, located in northern Spain, covers an approximate area of 5,321 km² and exhibits a highly diverse morphology, ranging from coastal zones to mountainous ranges, along with a strong agricultural and livestock tradition. The study area is characterized by complex topography, significant precipitation, and moderate temperatures, factors that strongly influence agricultural viability.

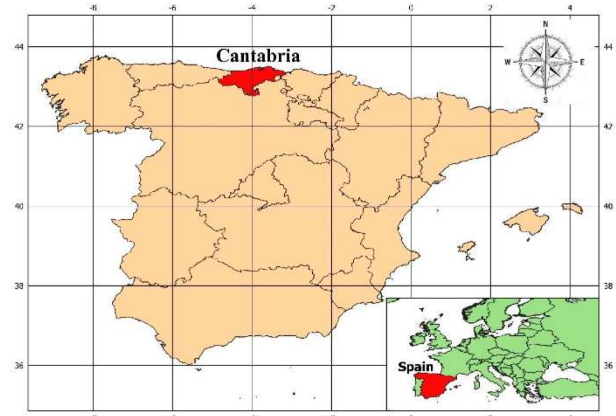

Fig. 1. Location of Cantabria in the national and European contexts.

Once the required information had been compiled, the processing and interpretation of the criteria using GIS were carried out employing the open-source software QGIS (version 3.40.8–Bratislava). The analysis of territorial suitability for each of the defined criteria was performed individually; subsequently, some examples of the partial results are presented.

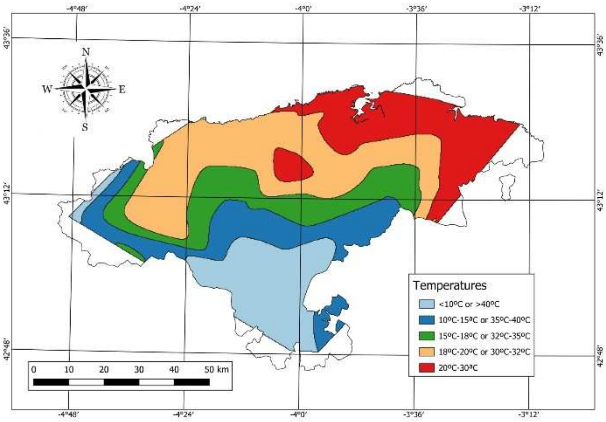

Fig. 2. Map derived from the classification of the territory based on the Temperature criteria.

For the environmental criteria, mean data from meteorological stations within the Autonomous Community of Cantabria, provided by the Spanish State Meteorological Agency (AEMET), were used. Based on these data, digital terrain models were generated for each of the studied factors, resulting in partial spatial coverage of the study area. This limitation could have been addressed by incorporating data from additional stations located in adjacent regions; however, this was not considered necessary, as the uncovered areas largely coincide with protected zones that were treated as exclusion areas in the analysis.

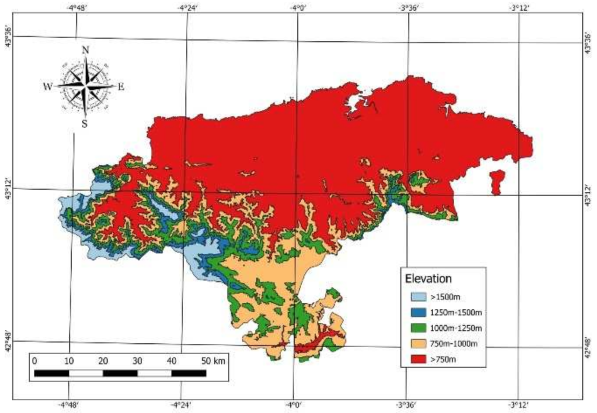

Fig. 3. Map derived from the classification of the territory based on the Elevation criteria.

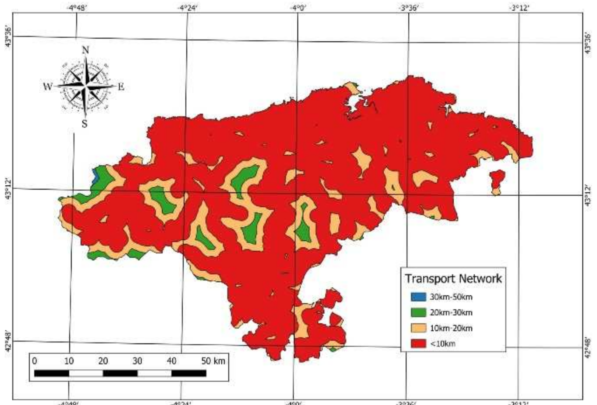

Fig. 4. Map derived from the classification of the territory based on the Transport network criteria.

Regarding the criterion related to the distance to biorefineries in the surrounding area, it should be noted that there are currently no active biorefinery facilities in Cantabria, although several project proposals for their development do exist. In light of this situation, distance to major industrial estates has been established as a proxy criterion, considering these areas as optimal locations for the potential development of future related projects and the construction of biorefineries.

Finally, land-use criteria are considered incompatible with the proposed activity. Consequently, land use is treated as an exclusion criterion, leading to the removal of these areas from the study domain. Figure 5 shows the total surface area affected by the different protection designations in Cantabria.

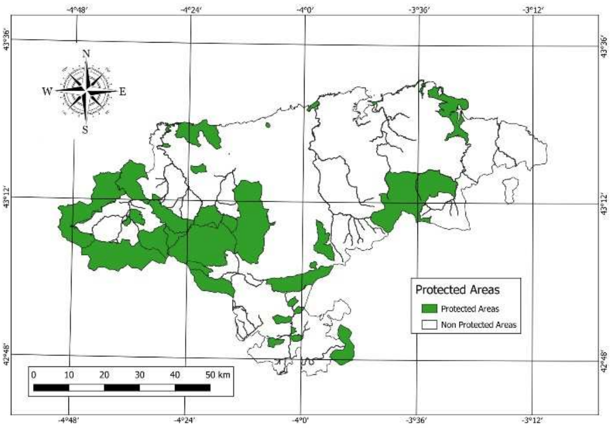

Fig. 5. Map derived from the classification of the territory based on the Land use criteria.

The combination and weighting of the full set of criteria were carried out through reclassification operations by applying the previously determined weights, resulting in the suitability map shown in the following figures.

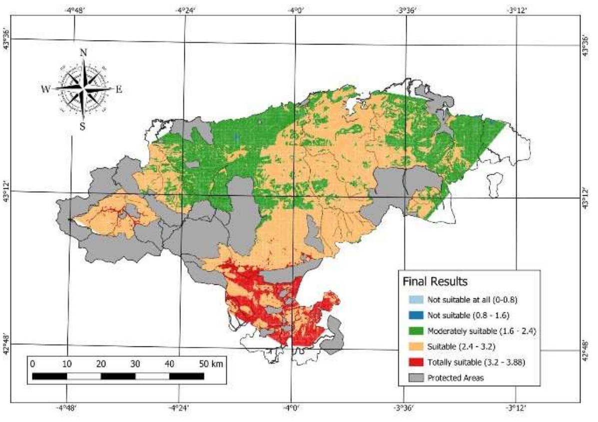

Fig. 6. Final Suitability map for corn as an energy crop in Cantabria following the weighting of criteria.

Based on the analysis of the resulting Final Suitability map, it is possible to identify and classify the territory according to its level of suitability. Accordingly, the percentage of the area classified as moderately suitable, suitable, and totally suitable can be determined. These values are expressed as a proportion of the total area of Cantabria and are presented in Table VI.

Table VI. – Division of the territory based on suitability

Suitability	Area (%)
Totally suitable	5.65
Suitable	35.89
Moderately suitable	23.25
Not Suitable	0.07
Not Suitable at all	-

The remaining 35.15% of the territory corresponds to exclusion areas and zones of land that could not be analyzed due to a lack of data.

4. Discussion

In light of the obtained results, several interpretations can be drawn regarding the research outcomes, the applied methodology and the proposed selection of criteria:

- The proposed selection of criteria can be formulated in very different ways by adding, removing, or modifying criteria, which would consequently alter the final results. In this respect, other similar studies aimed at determining land suitability for energy crops have adopted additional criteria, such as wind speed [14], soil pH, soil type, nitrogen content [20] or moisture [15], among many other examples, can be taken into account.
- The evaluation of environmental criteria is formulated based on maize (*Zea mays L.*). However, other crop varieties or species with higher oil content exist [6] that may require different parameter ranges to assess their suitability. Adapting the proposed methodology to such crops would therefore involve modifying the parameters considered for determining site suitability.
- In the present study, greater weight has been assigned to environmental criteria compared to economic or geographical ones. This weighting scheme could be modified in cases where economic costs—such as transportation costs—are, a priori, more relevant in the area where the methodology is applied, for example in sparsely populated regions with poorly developed transport networks. The same reasoning can be applied to the criterion related to proximity to biorefineries, which are not currently active in the case study area. Consequently, the weighting factors may vary slightly depending on the specific context to which the proposed methodology is applied.
- This research has been applied specifically to the region of Cantabria. Other regions of Spain with a well-developed agricultural sector may exhibit a larger suitable surface area, thereby enhancing biomass production potential.
- Unlike other similar studies, the present work incorporates a key factor affecting economic viability, namely the distance to biorefineries, as proximity to such facilities can significantly reduce transportation costs.
- Some of the areas currently identified as suitable are already exploited for other purposes; therefore, a more detailed assessment of specific locations would be required for a more precise implementation of energy crop cultivation.

5. Conclusion

This research has made it possible to establish a methodology for determining territorial suitability for the implantation of energy maize (*Zea mays L.*) crops through the combination of GIS techniques and Multi-Criteria Decision Analysis (MCDA) based on the Analytic Hierarchy Process (AHP). The results obtained from its application to the case study of the Autonomous Community of Cantabria demonstrate the potential of the proposed selection and weighting of environmental, geographical, and economic criteria.

From a quantitative perspective, the proposed case allows estimating that a total of 41.45% of the study area is classified as totally suitable or suitable, with these locations mainly concentrated in the southern part of the region. Additionally, 23.25% of the analyzed area is classified as moderately suitable, revealing significant potential within the region for the implementation of projects of this nature. These highly suitable areas are predominantly associated with low slopes, moderate elevations, and favorable solar radiation conditions. Conversely, the extent of territory classified as having low suitability is very limited, which further highlights Cantabria’s potential for the studied energy crop under the proposed framework.

Overall, the results confirm that the proposed methodology constitutes an effective tool for sustainable territorial planning in the management of energy crops. The approach enables the identification of priority areas for deployment and supports decision-making within the context of the energy transition, while also being transferable to other crop species and alternative criteria weighting schemes depending on the objectives pursued.

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