Earth Systems and Environment (2026) 10:4199–4218
https://doi.org/10.1007/s41748-025-00860-3

ORIGINAL ARTICLE

Integrating Multicriteria Decision Analysis for Beekeeping Suitability: Insights from a Portuguese Honey PDO Landscape

Carlos Silveira[1] · Natália Roque[2] · Bruno Leitão[3] · Paulo Fernandez[2,4] · Ofélia Anjos[2,5] · Miguel Vilas-Boas[1]

Received: 19 June 2025 / Revised: 2 September 2025 / Accepted: 25 September 2025 / Published online: 9 October 2025

Abstract

Beekeeping plays a vital role in biodiversity conservation and local economy development, as bees are key pollinators of numerous wild plant species and agricultural crops. Accordingly, understanding the suitability of rural territories is essential to provide an overview on bee activity and support the development of more sustainable beekeeping practices. This study presents an enhanced multicriteria approach for mapping beekeeping suitability, applied to a Portuguese region renowned for its honey with Protected Designation of Origin (PDO). The methodology integrates topographic, environmental and climatic criteria closely linked to bee ecology, whose relevance was prioritised in each category following expert perceptions and the Analytic Hierarchy Process (AHP). For these criteria, high-quality spatial data were compiled and processed using Geographic Information Systems (GIS) to evaluate landscape favourable conditions and limiting factors for beekeeping. Results indicate a comparable and significant influence of environmental and climatic criteria (43% each) relative to topographic ones (14%). Within each category, hillside exposure (63%), flora (53%) and rainfall (50%) contributions are particularly remarkable in defining the beekeeping suitability. When crossing the final suitability map with the apiary influence range, most apiaries were found in areas classified as very high suitability. This information provides valuable insights for beekeepers and policymakers, helping to optimize the beekeeping management and enhance the honey quality, particularly in PDO areas. Moreover, the proposed approach offers a scalable and adaptable framework that can be applied to other regions with beekeeping potential.

✉ Carlos Silveira
carlos.silveira@ipb.pt

[1] CIMO, LA SusTEC, Instituto Politécnico de Bragança, Campus de Santa Apolónia, 5300-253 Bragança, Portugal

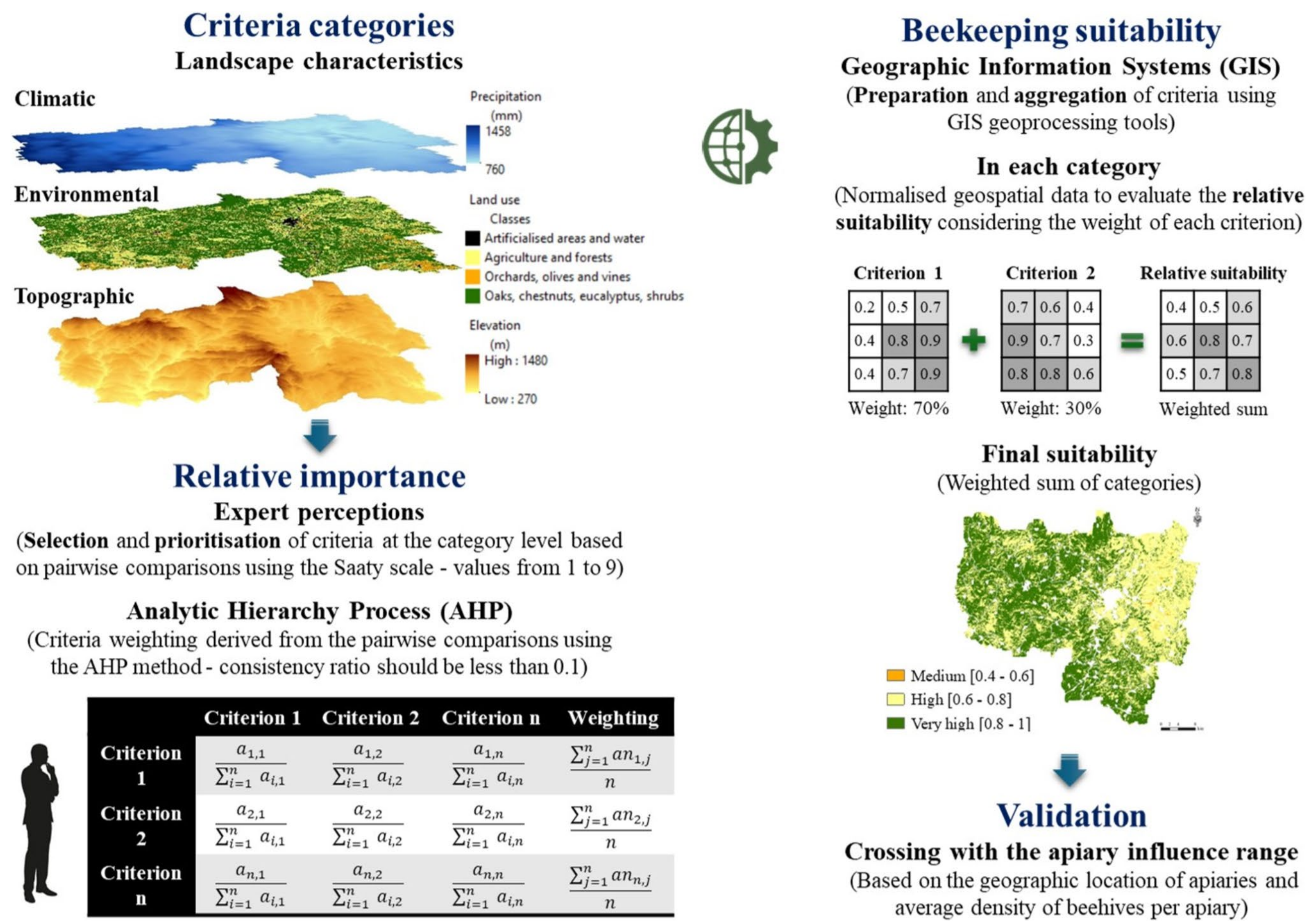
[2] CERNAS-IPCB, Research Centre for Natural Resources, Environment and Society, Polytechnic University of Castelo Branco, Castelo Branco, Portugal

[3] Comissão de Coordenação de Desenvolvimento Regional do Norte, I.P., Porto, Portugal

[4] MED – Mediterranean Institute for Agriculture, Environment and Development & CHANGE – Global Change and Sustainability Institute, Universidade de Évora, Évora, Portugal

[5] Forest Research Centre, TERRA Associate Laboratory, School of Agriculture, University of Lisbon, Lisbon, Portugal

Graphical Abstract



This diagram provides a concise overview of the study's core components and methodologies focused on evaluating land suitability for beekeeping. It presents a multicriteria framework developed using analytical and geoprocessing tools (AHP and GIS) and expert perceptions orientated towards mapping beekeeping suitability in a Portuguese region with PDO-certified honey production. To that end, high-quality spatial datasets covering landscape characteristics (i.e., topographic, environmental and climatic criteria) were selected, compiled and analysed for their relative importance in each category. When assigning weightings to each spatially normalised criterion (common scale with values between 0 and 1), the weighted sum result expresses the relative beekeeping suitability within and across the criteria categories. The final suitability map, which represents the weighted sum of the categories, shows a territory of excellence for the development of beekeeping activity, as it almost entirely falls into the high and very high classes. For this output, environmental and climatic categories had a significant and comparable contribution (43% each), whereas hillside exposure (63%), flora (53%) and rainfall (50%) were individually the most influential criteria. By spatially overlaying the final beekeeping suitability with the apiary influence range, it was found that most apiaries are located in areas classified as very high suitability. This integrated approach is therefore a scalable and adaptable decision-support tool to enhance apiary planning and landscape management, helping stakeholders to align ecological potential with sustainable beekeeping practices.

Highlights

- Integrated analysis of biophysical and human criteria provides a solid basis for beekeeping policy and land use planning.
- Criteria prioritisation at the category level reduces subjectivity in decision-making.
- Reliable and detailed spatial data are vital for identifying most suitable areas for beekeeping.
- AHP and GIS coupling proved to be a powerful analytical and geoprocessing approach.
- Findings contribute to boost the beekeeping management and honey quality in PDO areas.

Keywords Honey PDO region · Bee ecology · Analytic Hierarchy Process (AHP) · Geographic Information Systems (GIS) · High-quality spatial data · Sustainable beekeeping

1 Introduction

In rural areas, beekeeping is often regarded as a low-investment but highly rewarding activity, offering a sustainable pathway for the economic development. Besides generating direct income through honey production and other beehive products, it provides numerous ecosystem services, including: (a) ecological balance maintenance; (b) landscape preservation, as healthy bees rely on diverse and well-managed habitats; and (c) pollination, a cornerstone of biodiversity and agricultural productivity (Gilioli et al. 2018; Novelli et al. 2021; Ojija et al. 2023; Cotrina-Sanchez et al. 2023). However, the importance of beekeeping extends beyond economics and ecology. It is a cultural and traditional practice in many regions, deeply rooted their history and local identity. In areas where honey has Protected Designation of Origin (PDO) certification, beekeeping plays a pivotal role in preserving natural and cultural heritage and maintaining high-quality honey production (Flinzberger et al. 2022).

Despite its recognized significance, beekeeping faces increasing challenges due a variety of threats that have contributed to the global decline in honeybee populations, such as climate change, habitat degradation, pesticide exposure, and pests and diseases (Abou-Shaara et al. 2013; Switanek et al. 2017; Hosni et al. 2022; Gebremedhn et al. 2024). These pressures highlight the urgent need of management and conservation strategies that ensure the beekeeping sustainability (De La Rúa et al. 2009). As a starting point, it is imperative to identify and optimise suitable areas for apiaries, enabling a better allocation of resources, and an improvement in bee health and honey production (Sari et al. 2020b; Tennakoon et al. 2023). In this context, mapping beekeeping suitability is a powerful means for making progress in this field, integrating various criteria, such as floral availability, climatic conditions and topographic features, which researchers and sector experts can work together to support both bee populations and the communities that depend on them (Abou-Shaara 2019; Kotovs and Zacepins 2023). When incorporating floral resources of beekeeping interest, the idea is to verify whether these nectar and pollen producing species are available throughout the foraging season, thus ensuring continuous nutrition and productivity of bee colonies (Beekman and Ratnieks 2000; Decourtye et al. 2010). From the climatic point of view, the air temperature is an important factor to regulate bee forage and thermal activities. Honeybees, as the European race *Apis mellifera* L., have a forage activity between 14 ºC and 38 ºC, although the richness and abundance of interesting plant species are more evident at higher temperatures. Values above this threshold can negatively affect the bee biology and even their survival (Ludewig et al. 2023; Stabentheiner and Kovac 2023), especially during severe drought periods, where plants struggle to flower due to the scarcity of water (Sarvia et al. 2023; Şengül et al. 2023). Therefore, climate is one of the main drivers related to vegetation´s spatial and temporal dynamics, implying changes in the type of existing plant species and flowering calendars and, consequently, in the physiology and distribution pattern for a wide range of pollinators (Mahankuda and Tiwari 2024; Tennakoon et al. 2024). Negative climatic impacts can be minimised when the beekeeping territory is endowed with a good hydrographic network or a suitable rainfall regime, as the availability of nearby water sources favours the beehive thermoregulation and reduces the energetic effort expended by the pollinators (Kovac et al. 2018). Beyond flora and climate, the inclusion of topographic features (elevation, slope and aspect) is pivotal to better understand their close relationship with vegetation distribution patterns and the microclimatic variability, incisively contributing to the scheduling beekeeping activities. Studies have shown that gentle terrain relief, high melliferous flora availability, proximity to water, and moderate climatic conditions are crucial for maintaining healthy bee populations and optimizing honey production (Estoque and Murayama 2010; Triantomo et al. 2016; Elmastaş et al. 2022; Fotso Kamga et al. 2024).

On this multicriteria basis, advanced technological tools like the Analytic Hierarchy Process (AHP) and Geographic Information Systems (GIS), provide a robust and effective approach for systematic assessing the beekeeping suitability. Their coupling allows to integrate diverse criteria, prioritise them according to their importance, and generate spatially explicit suitability maps using appropriate geoprocessing and normalisation techniques (e.g., reclassification, fuzzy logic) (Zoccali et al. 2017; Kumar and Prasad 2018; Tennakoon et al. 2023). Such tools not only aid in identifying the best locations for apiaries, but also contribute to a sustainable management of resources and preservation of pollinator habitats. This way, stakeholders can better understand the complex interaction between environmental and socioeconomic aspects that influence beekeeping practices (Cotrina-Sanchez et al. 2023). On the other hand, the ability to combine techno-scientific knowledge with practical applicability makes AHP and GIS indispensable for modern beekeeping planning, as it enables more informed decisions regarding the optimal beehive placement, resource allocation and risk management (Widiatmaka et al. 2016; Pantoja et al. 2017; Sari et al. 2020a). In other fields, the combined use of AHP and GIS geospatial technologies has

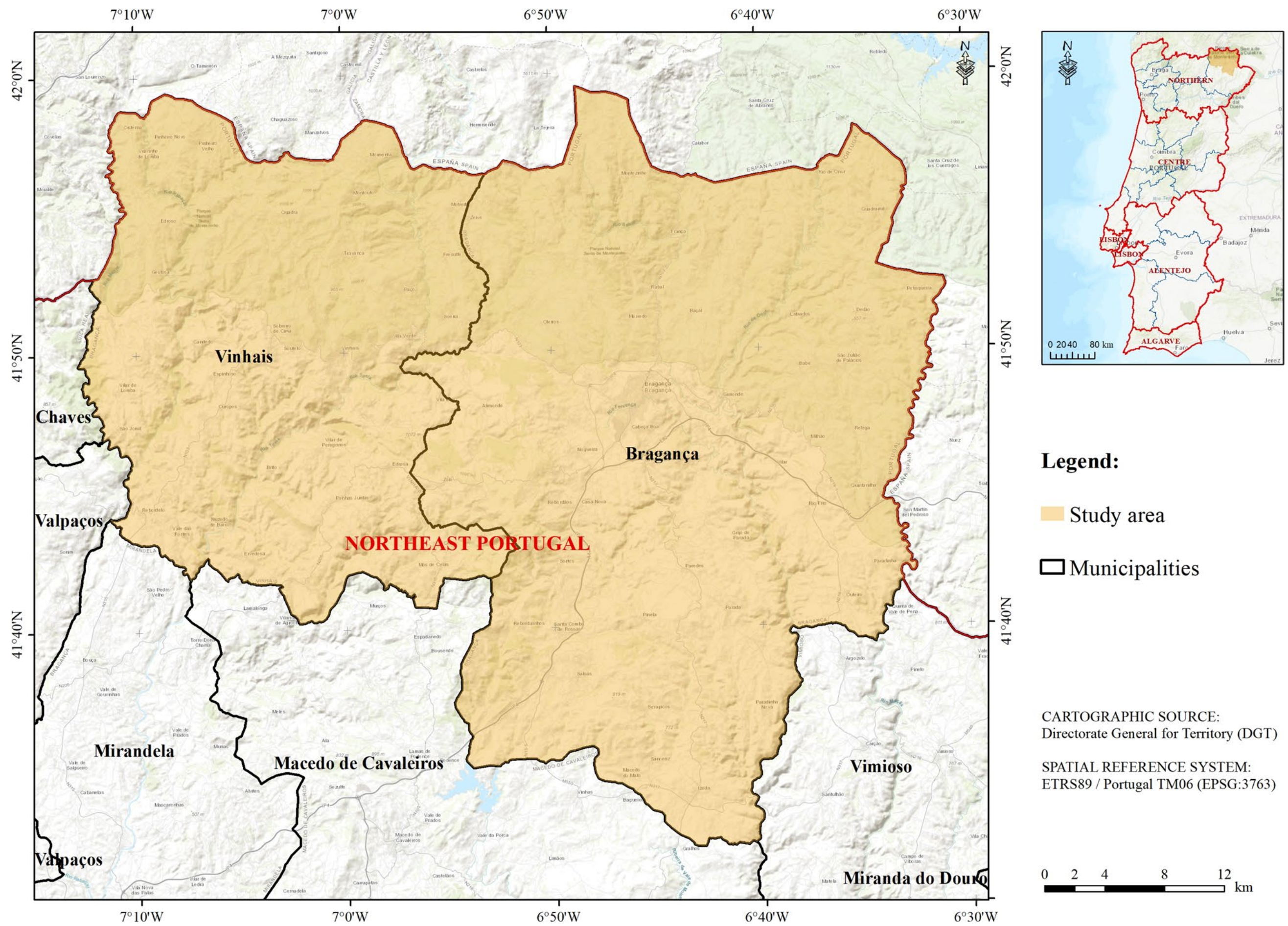


Fig. 1 Geographic location of the study area

also proven to be highly effective in decision-making and planning contexts across different regions. For instance, to assess the multi-hazard susceptibility and earthquake risk in mountainous cities from the Northwestern Himalayas (Rehman et al. 2022, 2025), and to map local scale geotechnical microzonation in a city located in the active tectonic Himalayan region, aimed at analysing the site suitability for settlements (Rehman et al. 2021). This integrated approach becomes even more impactful when high-quality input data are used, allowing a detailed analysis of critical factors. In beekeeping, Marnasidis et al (2021) and Antonopoulos et al (2023) focused on incorporating melliferous flora classes that are not included in classic land cover maps, but are of paramount importance for knowing the real beekeeping suitability. However, there is limited consensus on the relative importance of the targeted criteria across different regions, and gaps remain in integrating expert knowledge with high-quality spatial data to generate meaningful insights. Also, diverging opinions on the bee adaptability to extreme conditions (e.g., heatwaves, water scarcity) and the comparison of paired criteria from different categories make these assessments even more complex.

The objective and novelty of the present study focuses on the aforementioned challenges and opportunities to develop an enhanced multicriteria approach orientated towards assessing beekeeping suitability. Firstly, a group of experts from the beekeeping sector with in-depth knowledge of the case study was assembled in order to select and prioritise the important criteria within thematic categories. Secondly, refined and locally calibrated spatial data were incorporated to increase the accuracy of geospatial modelling. Thirdly, a two-tier aggregation method was applied, combining criteria within each category before generating the final suitability map, thereby reflecting the hierarchical structure of decision-making. Finally, the model was validated by comparing its outputs with actual apiary locations and average beehive densities. For this purpose, the following activities were carried out:

- A Portuguese region recognised for its honey with PDO status was selected as a case study;
- A set of topographic, environmental and climatic criteria was selected and prioritised by beekeeping sector

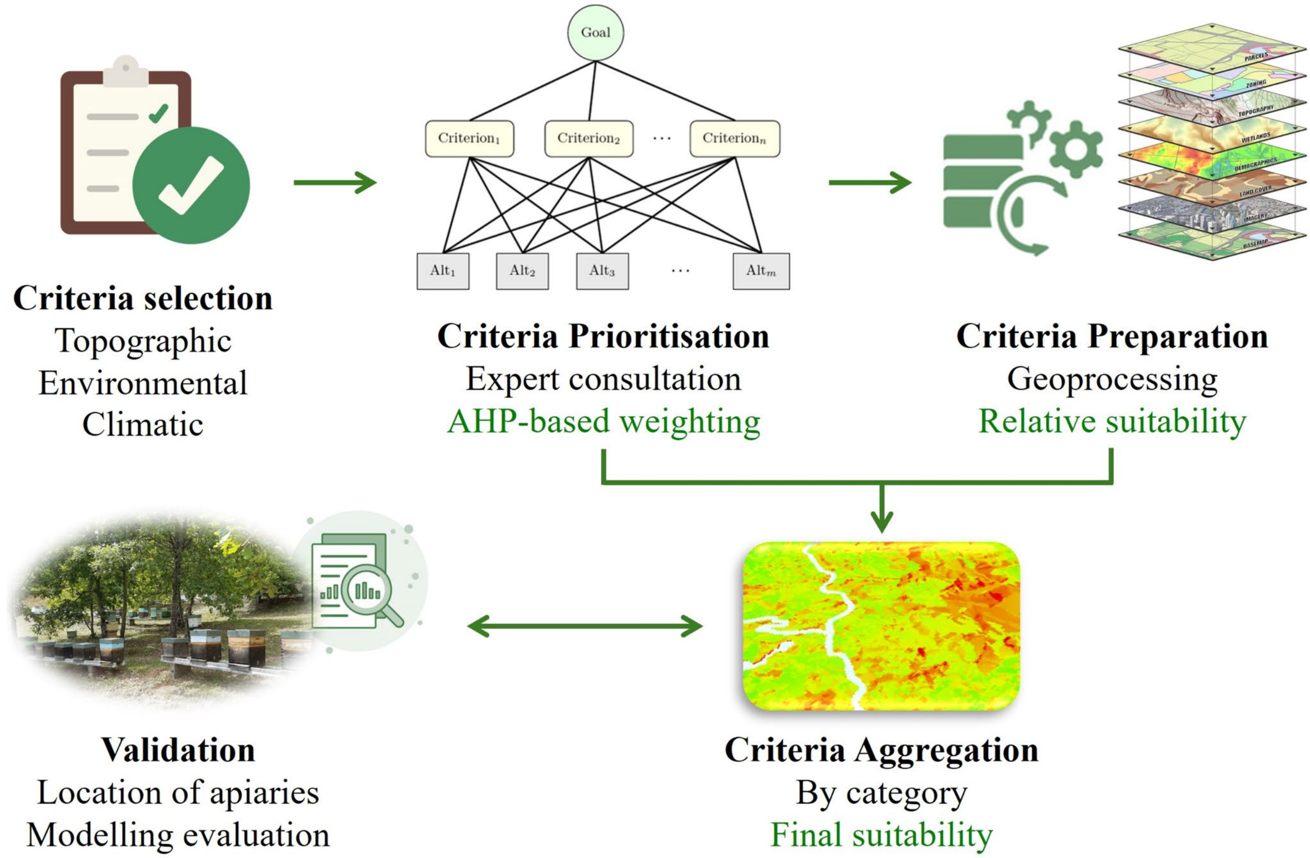


Fig. 2 Methodological scheme designed for assessing the beekeeping suitability

experts, combining pairs of criteria within each category using the AHP method;

- For each criterion, high-quality and resolution data were sought in order to spatially and accurately assess its relative importance. Appropriate geoprocessing tools were used;
- Geospatially processed and AHP-weighted criteria were initially aggregated by category, and their results were then used to produce the final beekeeping suitability map;
- Modelling results were evaluated in line with the actual geographic location of apiaries and the average density of beehives per apiary, extracting prohibited areas for beekeeping according to legal constraints.

2 Materials and Methods

2.1 Case Study

The study area, which comprises the municipalities of Bragança and Vinhais in northeast Portugal (Fig. 1), is part of the Iberian Plateau and stands out for its harmonious combination of topographic, environmental and climatic features, offering ideal conditions for traditional agriculture, beekeeping activities and biodiversity conservation.

The landscape of Bragança and Vinhais, marked by rolling hills, steep slopes and plateaus, varies in altitude from 270 to 1480 m, with the highest peaks located in the Montesinho Natural Park. This diverse topography fosters a range of microclimates that support the melliferous flora and bee colonies. The higher altitudes, often cooler and less disturbed by human activity, serve as important refuges for pollinators, while the flat areas at lower altitudes provide accessible and ecologically rich sites for apiaries. The region's geology, dominated by schist and granite, shapes the shallow and acidic soils which, despite their limitations, support a wide range of native vegetation essential for pollination and biodiversity. The vegetation is dominated by a mosaic of oak woodlands (*Quercus pyrenaica* and *Quercus rotundifolia*), chestnut groves (*Castanea sativa*) and scrublands (e.g., *Erica* spp., *Lavandula* spp., *Rosmarinus officinalis*), interspersed with agricultural fields and pastures, thus contributing to the distinctive flavour and quality of local honey with PDO.

In climatic terms, the region is characterised by a Mediterranean climate with continental influences. This climate is often marked by hot and dry summers and cold winters with frequent frosts and occasional snowfall at higher altitudes. Annual precipitation, ranging from 780 to 1458 mm and concentrated mainly in autumn and winter, boosts the growth of diverse melliferous flora, ensuring a continuous supply of floral resources throughout the year. Nonetheless, extreme conditions, such as summer droughts and notable diurnal temperature variations, require careful beekeeping management to safeguard the bee health and productivity.

This region benefits from an extensive network of rivers, streams and natural springs, ensuring essential water resources for honeybees, particularly during dry periods, while also influencing the strategic placement of apiaries. In addition, the abundance of rural roads and trails that cross the target municipalities facilitates the access to these sites, enabling beekeepers to efficiently monitor and manage their beehives. This synergy between water availability and good accessibility supports the adoption of sustainable beekeeping practices orientated towards the production of high-quality honey.

Further information on the region's biophysical characterisation, particularly with regard to the criteria addressed in this study, is presented in Sect. 2.2 and Figs. 8, 9 and 10 in Appendix A.

2.2 Multicriteria Analysis Approach for Beekeeping

This research expands on the work carried out by Roque et al (2024), by enhancing the AHP and GIS based-multi-criteria decision analysis (MCDA) framework as follows: (i) new criteria were added; (ii) their relative importance for beekeeping was initially assessed at the category level; and (iii) the validation of the final suitability map involved, along with the geographic location of the actual apiaries, the average density of beehives per apiary. The AHP facilitates the prioritisation of criteria that influence beekeeping suitability by breaking down complex decisions into a structured hierarchy. It involves pairwise comparisons following expert opinions and weights to appropriately determine the relative importance of each criterion for the overall analysis. In turn, GIS serves as a powerful geoprocessing platform for spatial analysis, enabling the combination, visualisation and mapping of georeferenced data. When integrated, the weightings derived from AHP are applied in GIS to spatially model the beekeeping suitability. The MCDA methodology to assess beekeeping potential in study area encompasses five key stages (Fig. 2):

1. **Criteria selection—**Bee-relevant criteria of topographic, environmental and climatic nature were identified;
2. **Criteria prioritisation—**Expert insights were gathered through a structured questionnaire, and the AHP method was employed to derive weights for each criterion;
3. **Criteria preparation—**High-quality spatial datasets were compiled and processed using advanced GIS techniques to evaluate the relative suitability of the targeted criteria;
4. **Criteria aggregation—**Criteria were initially aggregated by category based on their relative suitability and AHP weights. Categorised outcomes were then combined considering AHP weights to compute the final beekeeping suitability map;
5. **Validation—**Quantitative analyses based on both geographic location of apiaries and average density of beehives per apiary were conducted to evaluate modelling results.

2.2.1 Criteria selection

The careful selection of criteria is a crucial step in the MCDA process, as it defines the factors that can influence the suitability of specific locations for beekeeping. This stage focused on identifying criteria that are directly relevant to the success and sustainability of beekeeping, considering three primary categories:

- **Topographic criteria—**including elevation, slope and aspect, can affect the seasonality of beekeeping activities by shaping vegetation cover and local meteorological conditions. These are closely linked to the availability of floral resources and the foraging behaviour of pollinators;

Table 1 Normalisation and weighting of the targeted criteria using the AHP method

	Criterion 1	Criterion 2	…	Criterion n	Weighting (W_i) *
Criterion 1	$an_{1,1} = \frac{a_{1,1}}{\sum_{i=1}^{n} a_{i,1}}$	$an_{1,2} = \frac{a_{1,2}}{\sum_{i=1}^{n} a_{i,2}}$	…	$an_{1,n} = \frac{a_{1,n}}{\sum_{i=1}^{n} a_{i,n}}$	$W_1 = \frac{\sum_{j=1}^{n} an_{1,j}}{n}$
Criterion 2	$an_{2,1} = \frac{a_{2,1}}{\sum_{i=1}^{n} a_{i,1}}$	$an_{2,2} = \frac{a_{2,2}}{\sum_{i=1}^{n} a_{i,2}}$	…	$an_{2,n} = \frac{a_{2,n}}{\sum_{i=1}^{n} a_{i,n}}$	$W_2 = \frac{\sum_{j=1}^{n} an_{2,j}}{n}$
…	…	…	…	…	…
Criterion n	$an_{n,1} = \frac{a_{n,1}}{\sum_{i=1}^{n} a_{i,1}}$	$an_{n,2} = \frac{a_{n,2}}{\sum_{i=1}^{n} a_{i,2}}$		$an_{n,n} = \frac{a_{n,n}}{\sum_{i=1}^{n} a_{i,n}}$	$W_n = \frac{\sum_{j=1}^{n} an_{n,j}}{n}$

*Each weight in the pairwise comparison matrix is the average of the normalised values (*an*) in row *i*, where *n* represents the number of criteria. When comparing pairs of criteria using the Saaty scale (Saaty 2008), $a_{i,j}$ shows the relative importance of criterion *i* compared to *j*

Table 2 Overview of the selected criteria, data sources, scale or resolution, and geoprocessing techniques (GIS tools and settings) used for harmonising the spatial datasets

Categories	Criteria and units	Scale or resolution	Geoprocessing tools and settings	Data sources
Topo-graphic **[Topo]**	Elevation (m) **[Elev]**	1/10000	Create TIN | TIN to Raster (output: DEM) Small FM (Midpoint of the range of raster values; Spread = 5)	Municipalities of Bragança and Vinhais (10 m elevation contours)
	Slope (%) **[Slope]**	1/10000	Slope (DEM) MSSmall FM (Mean and SD Multiplier = 1)	
	Aspect **[Asp]**	1/10000	Aspect (DEM) Reclassify (Flat, E, SE, S = 1; NE, SW = 0.75; W = 0.50; NW = 0.25; N = 0.1)	
Environ-mental **[Env]**	Land use / Flora **[Flora]**	10,000 m^2	Union (COS2018 + iSIP) – 80% Kernel Density (GBIF) – 20% Reclassify COS2018 + iSIP (Artificialised areas and water = 0; Agriculture, forests and agro-forestry = 0.5; Orchards, olives and vines = 0.75; Oaks, chestnuts, eucalyptus, grassland and shrubs = 1) GBIF was used to extract occurrence densities of shrub species of beekeeping interest	COS2018 (DGT 2019) iSIP (IFAP 2024a) GBIF (GBIF 2024)
	Proximity to water (m) **[Water]**	1/25000	Euclidean Distance (for the line and point layers) Cell Statistics (minimum value of the line and point outputs) MSSmall FM (Mean and SD Multiplier = 1)	Municipalities of Bragança and Vinhais (rivers and streams) ICNF (water points) (ICNF 2024)
	Proximity to rural roads (m) **[Roads]**	1/25000	Euclidean Distance MSSmall FM (Mean and SD Multiplier = 1)	OSM (secondary and pedestrian roads) (OSM 2024a)
	Distance to ionizing radiation sources (m) **[Ion]**	1/25000	Euclidean Distance (for the line and point layers) Cell Statistics (minimum value of the line and point outputs) Linear FM (Minimum and maximum of the range of raster values)	E-REDES (medium and high voltage electricity network) (E-REDES 2024) OSM (mobile communication antennas) (OSM 2024b)
	Risk of rural fires **[Fire]**	25 m × 25 m	Reclassify by risk classes (Very low = 1; Low = 0.75; Medium = 0.5; High = 0.25; Very high = 0.1)	ICNF (ICNF 2024)
Climatic **[Clim]**	Solar radiation ($Wday^{-1}/m^2$) **[Rad]**	1/10000	Area Solar Radiation (calculated from the DEM for 21 March; Latitude = raster's centre point; Atmospheric transmittivity = 0.7) Linear FM (Minimum = raster´s minimum value; Maximum = raster´s mean value – suitability is 1 above this record)	Municipalities of Bragança and Vinhais (10 m elevation contours)
	Maximum temperature of the warmest month (ºC) **[Temp]**	1000 m × 1000 m	Resample (Bilinear; Cell size = 10 m) Inverse of Linear FM (Minimum = raster´s maximum value; Maximum = raster´s mean value – suitability is 1 below this record)	WorldClim (WorldClim 2024)
	Wind speed (m/s) **[Wind]**	1000 m × 1000 m	Resample (Bilinear; Cell size = 10 m) Inverse of Linear FM (Minimum = raster´s maximum value; Maximum = raster´s mean value – suitability is 1 below this record)	
	Annual precipitation (mm) **[Prec]**	1000 m × 1000 m	Resample (Bilinear; Cell size = 10 m) Linear FM (Minimum = raster´s minimum value; Maximum = raster´s mean value – suitability is 1 above this record)	

TIN Triangulated Irregular Network, *DEM* Digital Elevation Model, *FM* Fuzzy Membership (set of tools used for normalising the criteria), *COS2018* A Land Cover/Use Map of Mainland Portugal for 2018, *iSIP* Online Parcel Identification System, *GBIF* Global Biodiversity Information Facility, *ICNF* Institute for Nature Conservation and Forests, *OSM* OpenStreetMap, *E-REDES* Electricity Distribution in Portugal, *WorldClim* Global Climate Data

- **Environmental criteria**—the presence of melliferous flora and proximity to water and rural roads are factors that positively interfere with the bee ecology and the development of the beekeeping activity, while proximity to ionizing radiation sources and high fire risk are dissuasive aspects for apiary placement;
- **Climatic criteria**—variables like solar radiation, annual precipitation, wind speed and maximum temperature of the warmest month were selected, given their connection with the flowering season and the health and productivity of bee colonies.

For these categories, the identified criteria were selected for assessing beekeeping suitability (Table 2).

2.2.2 Criteria Prioritisation

The prioritisation of criteria is a pivotal step in the MCDA, aimed at assigning relative importance to the selected criteria based on their influence on beekeeping suitability. This analysis reflects the practical and ecological requirements for an effective apiary management. For this purpose, the criteria ranking was established at the category level through expert consultation and AHP-based weighting.

Expert consultation A structured questionnaire was distributed to beekeeping experts in order to relate pairs of criteria using the Saaty scale (Saaty 2008), which assigns numerical values to judgments about the relative importance or preference of each criterion in a decision-making process. This scale ranges positive values from 1 to 9 when one criterion is preferred over another, taking negative values if that criterion is penalised or considered less desirable than another. If both criteria contribute equally to the objective, the scale is set to 1. Based on their reasoned assessments, pairwise comparison matrices are produced.

AHP-based weighting The AHP was employed to systematically compare the criteria in a pairwise manner. This approach allowed the calculation of weights corresponding to the influence of each criterion, ensuring consistency and reducing subjective bias. To this end, the pairwise comparison matrices derived from the expert consultation were normalised to determine the priority vector, which represents the weights of the targeted criteria (Table 1). To evaluate the consistency degree of the expert judgments, the Consistency Index (CI) and Consistency Ratio (CR) were calculated for each pairwise comparison matrix (Eqs. 1–3). If CR exceeds 0.1, a revision of the values for the respective matrices is recommended. Further details on the AHP method can be found in Saaty (2008).

By integrating expert knowledge with a systematic criteria weighting framework, the prioritisation process balances the complexity of beekeeping requirements with analytical precision to produce reliable and specific suitability models.

$$\lambda_{max} = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{\sum_{j=1}^{n} a_{i,j}W_i}{W_i}\right) \tag{1}$$

$$CI = \frac{\lambda_{max} - n}{n-1} \tag{2}$$

$$CR = \frac{CI}{RI} \tag{3}$$

where, n is the number of criteria; $a_{i,j}$ expresses the relative importance of criterion i compared to j; W_i reflects the weight (priority) of criterion i; λ_{max} is the maximum eigenvalue of the pairwise comparison matrix; RI is a random index (tabulated values that depend on the n).

Table 3 Pairwise comparison matrices resulting from expert judgements by: (a) criteria categories; (b) topographic criteria; (c) environmental criteria; and (d) climatic criteria

Categories	Topo	Env	Clim
Topo	**1**	-3	-3
Env	3	**1**	1
Clim	3	1	**1**

(a)

Criteria	Elev	Slope	Asp
Elev	**1**	3	-3
Slope	-3	**1**	-5
Asp	3	5	**1**

(b)

Criteria	Flora	Water	Roads	Ion	Fire
Flora	**1**	5	7	7	5
Water	-5	**1**	3	7	5
Roads	-7	-3	**1**	3	3
Ion	-7	-7	-3	**1**	1
Fire	-5	-5	-3	1	**1**

(c)

Criteria	Rad	Temp	Wind	Prec
Rad	**1**	3	3	-3
Temp	-3	**1**	-3	-5
Wind	-3	3	**1**	-3
Prec	3	5	3	**1**

(d)

2.2.3 Criteria Preparation

The preparation of criteria involves transforming raw spatial data into operational information, ensuring that each selected criterion is accurately represented and ready to be integrated into the suitability model. This step focuses on refining and normalising data to enhance their relevance and spatial precision, considering:

High-quality geospatial data acquisition and processing High-quality geospatial datasets were compiled to effectively represent the selected criteria, providing detailed topographic, environmental and climatic information essential for the overall analysis. Afterwards, advanced geospatial techniques using GIS software were applied to process and standardise the data, including interpolation, reclassification, fuzzy logic operations (Fuzzy Membership) and the generation of raster layers to ensure consistency in scale and resolution across all criteria. The Fuzzy Membership tool reclassifies or transforms values on a continuous scale, where criteria can have a degree of membership between 0 and 1.

Relative suitability assessment Each criterion was spatially normalised from 0 (no suitability) to 1 (maximum suitability) to create relative suitability scores on a comparable scale, enabling a meaningful aggregation in subsequent stages. This systematic preparation ensures that all criteria are reliably represented and spatially harmonised, allowing a robust and precise evaluation of beekeeping suitability.

Table 2 summarizes the selected criteria, the sources where the raw data were collected, their scale or resolution, and the geoprocessing techniques applied to harmonise all criteria.

2.2.4 Criteria aggregation

Criteria aggregation is the process of combining individual criteria into a unified suitability model, reflecting the overall potential of locations for beekeeping. This step integrates the weighted and spatially normalised criteria, taking into

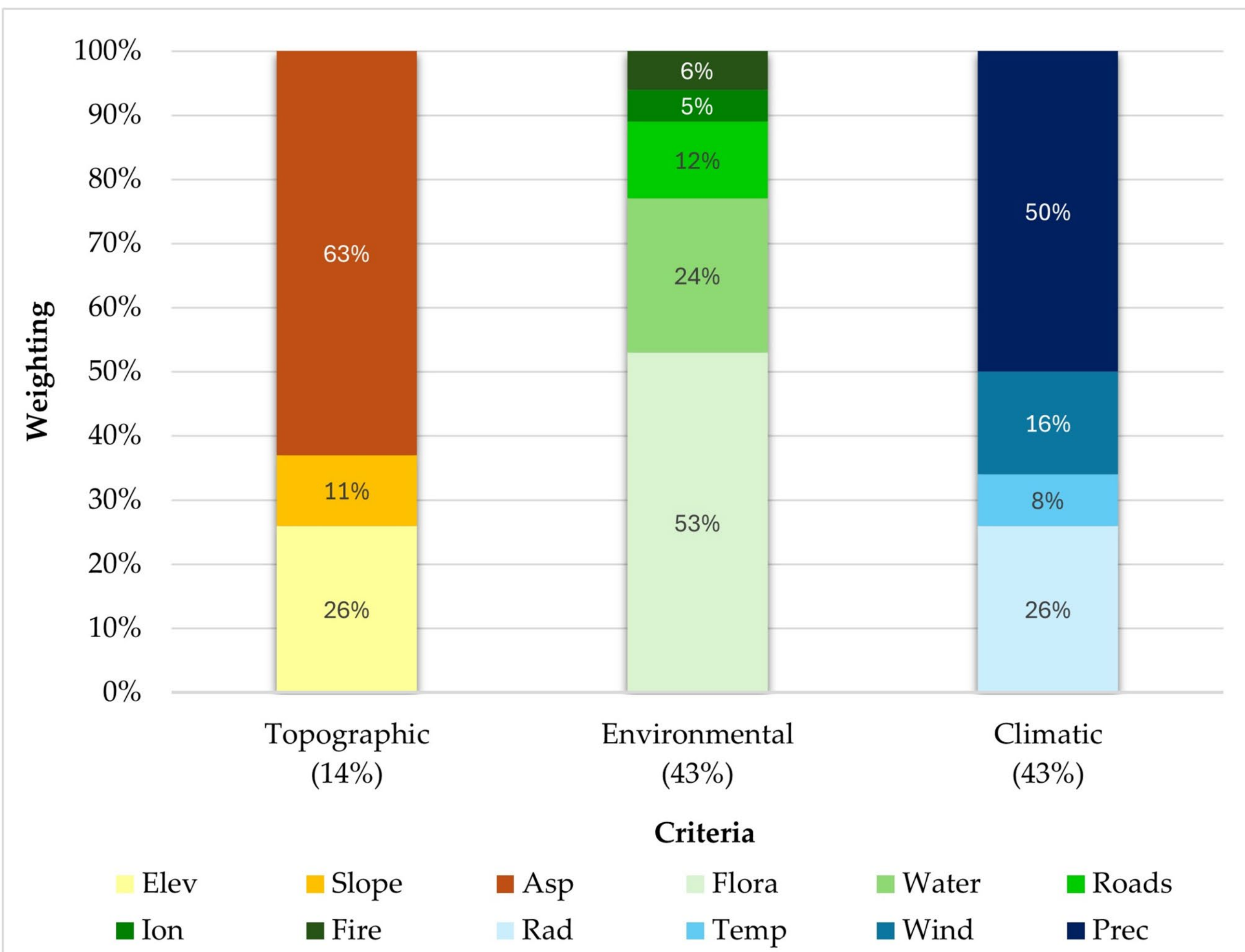


Fig. 3 Criteria weighting derived from the pairwise comparisons using the AHP method

account their relative contribution to a broad assessment at the category level and subsequent mapping of the final beekeeping suitability (Eq. 4).

Aggregation by category Criteria were grouped into the respective categories to evaluate specific dimensions of suitability, enabling a structured analysis involving factors of different natures that influence the overall beekeeping potential.

Final suitability mapping Once the suitability maps by category have been created, their results were aggregated according to the Eq. 4 to produce a composite suitability score for the study area.

This approach safeguards that the diverse criteria influencing the beekeeping success are holistically evaluated, leading to a detailed and reliable suitability assessment.

$$Suitability = \sum_{i=1}^{n} w_i X_i \tag{4}$$

where, n is the number of criteria in each category, or the number of criteria categories when the purpose is to map the final suitability; w_i denotes the weight assigned to each criterion or category i; X_i corresponds to the spatially normalised grid for each criterion or category i (values between 0 and 1).

2.2.5 Validation

The validation process aims to assess whether the predicted results are aligned with the real-world conditions and test the model's robustness for practical applications in beekeeping. To that end, modelling outcomes, arranged by beekeeping suitability classes, were confronted with the geographic location of apiaries and the average density of beehives per apiary at the parish level. To verify the agreement between the estimated suitability scores and the existing beekeeping records, a comprehensive quantitative analysis was performed. This analysis offers a solid foundation for managing beekeeping activities and supporting informed decision-making.

3 Results

3.1 Pairwise Comparisons and Weights

The pairwise comparisons and derived weights provide a systematic representation of the criteria's relative importance. This approach combines expert insights with analytical precision using the AHP method, so that the resulting suitability model effectively reflects the key factors impacting the beekeeping potential.

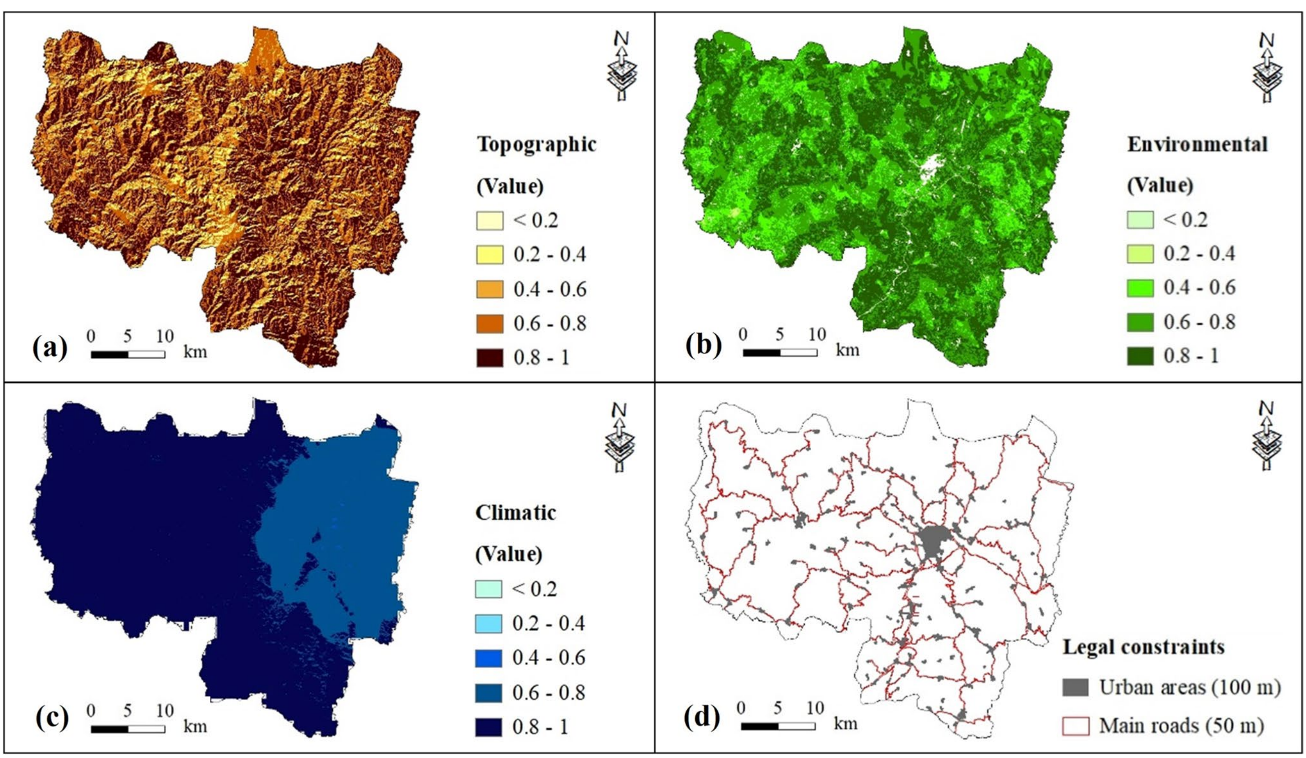


Fig. 4 Mapping of beekeeping suitability by category of criteria: **a** topographic, **b** environmental, and **c** climatic, as well as **d** legal constraints on the activity's development

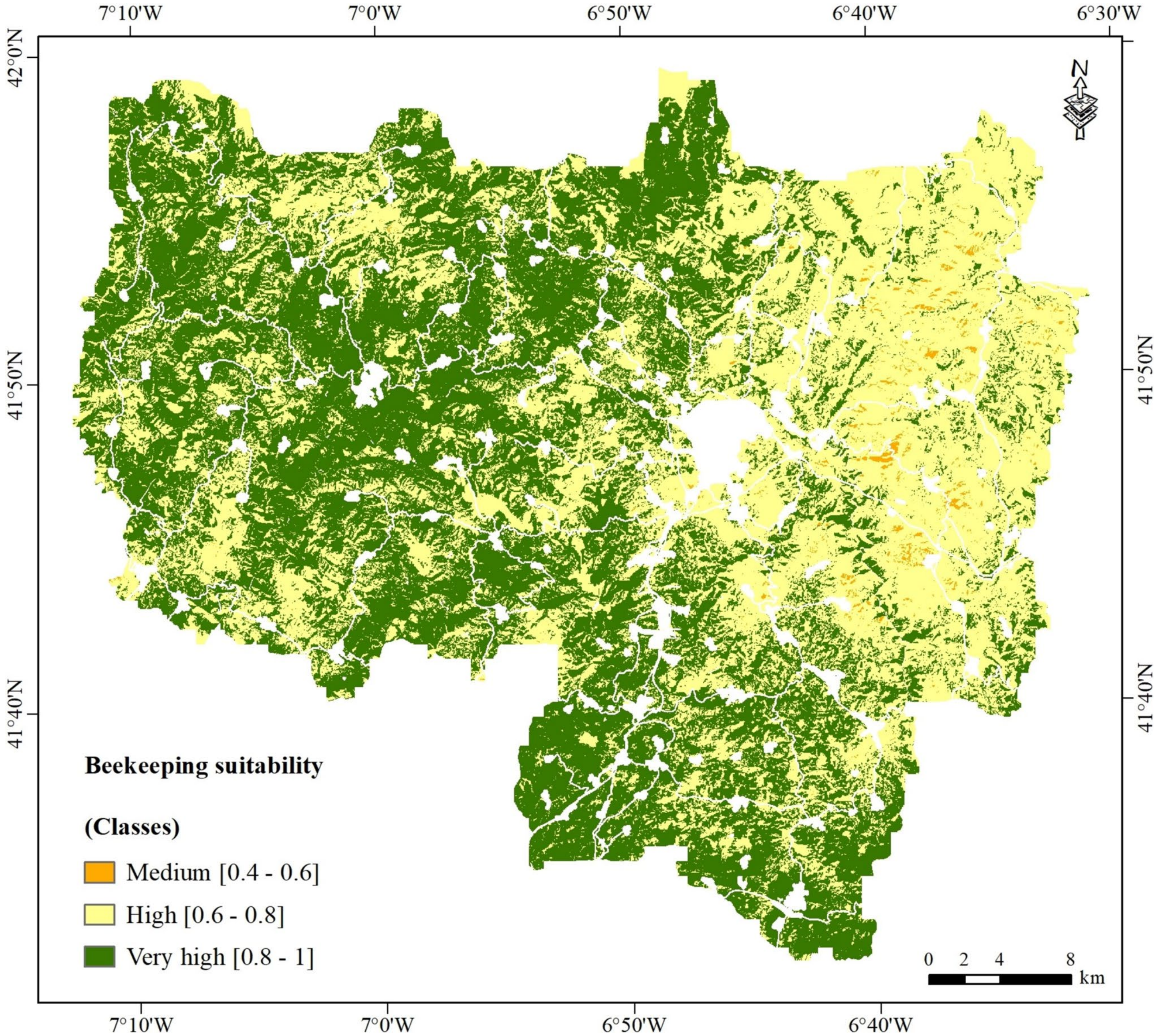
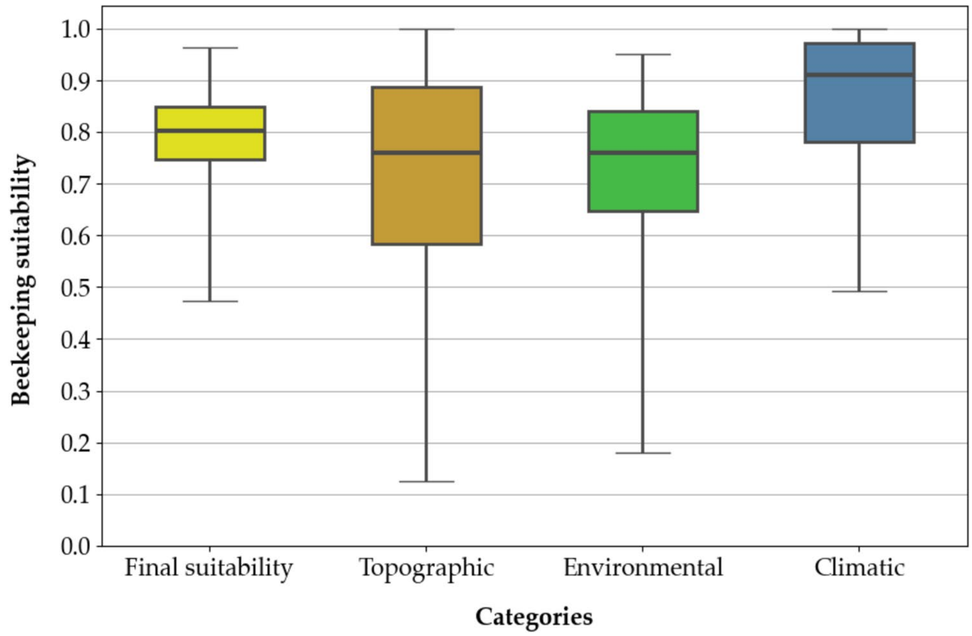


Fig. 5 Mapping of final beekeeping suitability for the study area

Comparisons were carried out separately at the category level and the criteria comprising them (Table 3). In a first analysis, it is worth noting the equal preponderance assigned to the environmental (Env) and climatic (Clim) categories (scalar value is 1). Within each category, greater importance was attributed to hillside exposure (Asp), land use/flora (Flora) and annual precipitation (Prec), as these criteria have higher positive values compared to the other ones. This expert judgement is based on the premise that rainfall and solar exposure are fundamental drivers for the vegetation's seasonality and distribution, particularly flora of beekeeping interest. In turn, it has a direct influence on the bee ecology by modulating the spatiotemporal availability of key resources (pollen and nectar) that sustain bee foraging activity, colony development, and ecosystem interactions involving pollinators. Nevertheless, other analysed criteria, such as proximity to water and rural roads, along with the remaining topographic and climatic variables, should also be taken into account given their interconnection to shape microclimatic conditions, habitat suitability and accessibility, which are crucial aspects for successful beekeeping.

Translating the matrix results into weights, the obtained percentage coefficients mirror the integrated multicriteria analysis carried out by the beekeeping experts (Fig. 3). Therefore, for beekeeping suitability mapping, a higher weighting was allocated to the environmental and climatic categories (43% each). Analysing each criteria category,

Fig. 6 Variability of beekeeping suitability in the study area considering criteria aggregated by category and the final suitability map. For each column, suitability values for the minimum, 25th, 50th (median) and 75th percentiles, and maximum, are displayed



priority was assigned to hillside exposure (Asp, 63%), land use/flora (Flora, 53%) and annual precipitation (Prec, 50%).

It should be noted that the intramatricial evaluations resulting from expert judgments are in agreement with the consistency degree recommended (CR < 0.1): (a) criteria categories, CR = 0.000; (b) topographic criteria, CR = 0.033; (c) environmental criteria, CR = 0.090; and (d) climatic criteria, CR = 0.074.

3.2 Beekeeping Suitability

Once the relative importance (weighting) of each category and criterion has been determined, the targeted criteria were prepared and aggregated to map the beekeeping suitability.

The criteria preparation involved the acquisition, geoprocessing and normalisation of high-quality spatial data, so that these are on a common and comparable scale (values between 0 and 1). As a result of these operations, described in Table 2, the spatial representation and relative beekeeping suitability (i.e., normalised grid data) for each criterion were mapped (Figs. 8, 9 and 10 in Appendix A).

After weighting and normalising the criteria, these were aggregated by category according to the Eq. 4. Concerning the topographic criteria, higher suitability is linked to low-elevation areas with gentle to moderate slopes and east to south-facing exposures. This association could be due to the occurrence of favourable microclimatic conditions for diverse flowering plant and pollinator communities and their relationships, along with a reduction in soil erosion risk, helping to maintain stable habitats and healthy and resilient bee populations (Fig. 4a). In environmental terms, the presence of flora with beekeeping interest (e.g., oaks and chestnuts) and the proximity to water and rural roads are the most contributed factors to increased suitability values, by offering forage and hydration for bee colonies, while good accessibility is essential for supporting beekeeping practices (Fig. 4b). Lastly, the annual precipitation, followed by the solar radiation and wind speed, were the most influential climatic criteria in determining the land suitability. Higher suitability areas are associated with increasing precipitation and radiation records, as these variables are vital for ensuring plant´s growth and flowering, thus contributing to the bee foraging success and improved colony productivity. In contrast, strong winds and high maximum temperatures (for the warmest month) produce a harmful effect on the bee's behaviour and health, hence the lower estimated suitability values under these conditions (Fig. 4c). Prohibited areas for beekeeping in accordance with legal constraints (Ministry of Agriculture 2005), namely 50 m from main roads and 100 m from any building in use (Fig. 4d), were extracted (9% of the study area) when mapping the final suitability (Fig. 5).

The final version of the beekeeping suitability map represents the sum of the normalised score (i.e., aggregated criteria) per category multiplied by the weighting assigned to the respective criteria categories (Eq. 4). The result expresses the territory's potential to meet the beekeeper needs and the bee biological requirements, by establishing suitability classes that relate the normalised values with qualitative assessments. Taking into account the scores obtained, three suitability classes were defined: Medium [0.4–0.6], High [0.6–0.8], and Very high [0.8–1]. Looking at the Fig. 5, it is perfectly clear that the study area has a strong potential for beekeeping, as it falls almost entirely into the high and

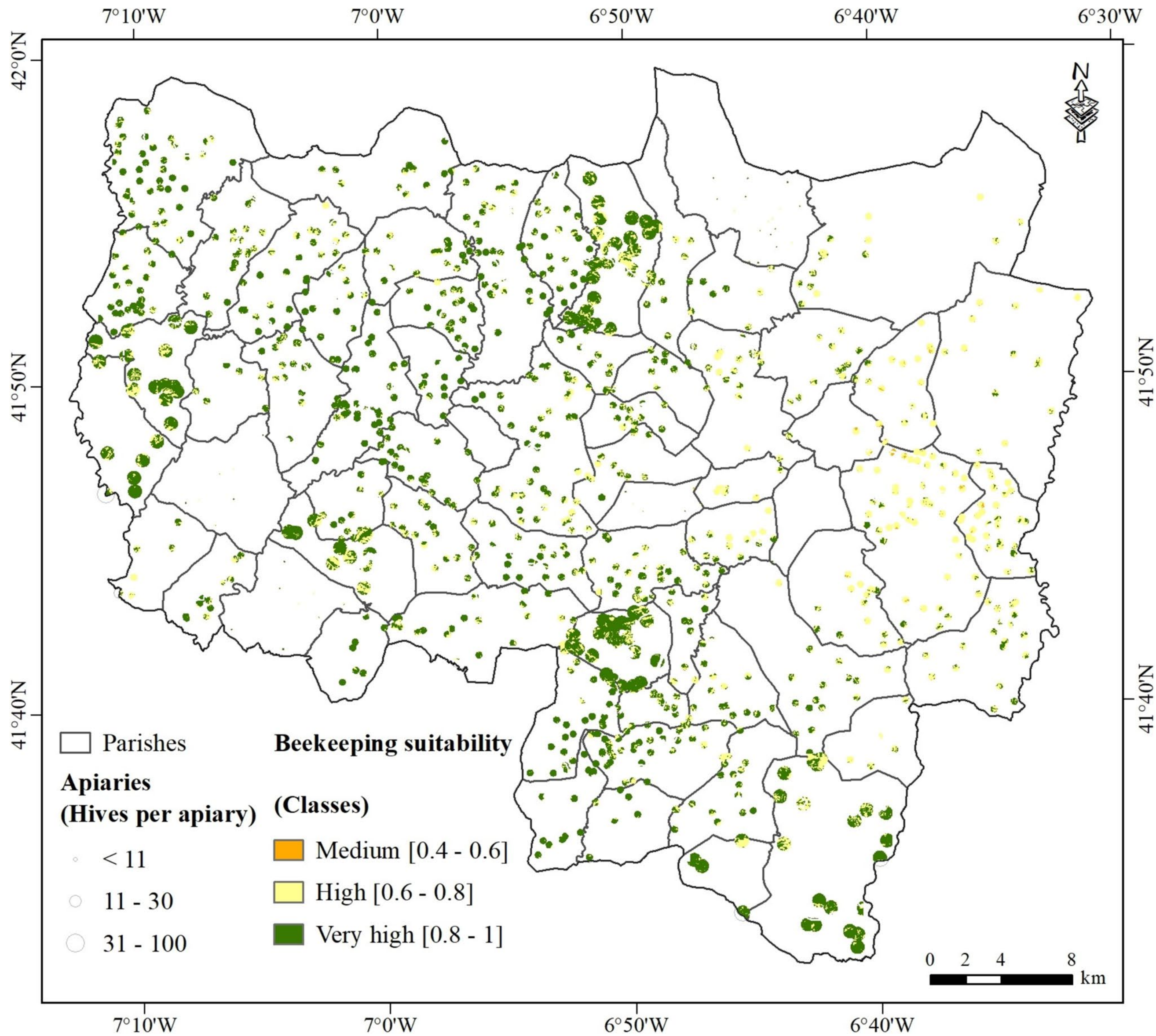


Fig. 7 Geographic location of the apiaries and their beekeeping suitability considering the average density of hives per apiary to set the influence range

Table 4 Total study area and apiary influence range (in ha and %) per beekeeping suitability class

Beekeeping suitability classes	Study area		Apiary influence range *					
			50 m		200 m		400 m	
	(ha)	(%)	(ha)	(%)	(ha)	(%)	(ha)	(%)
Medium [0.4 – 0.6]	945	0.6	–	–	41	0.4	–	–
High [0.6 – 0.8]	80,472	48.1	2	66.7	4145	40.3	1179	26.8
Very high [0.8—1]	86,029	51.3	1	33.3	6110	59.3	3213	73.2
Total	167,446	100	3	100	10,296	100	4392	100

*The apiary influence range was based on the average density of beehives per apiary and its minimum distance from the nearest one (under the national decree-law 203/2005 of 25 November [Ministry of Agriculture 2005)]: 50 m radius—Beehive density less than or equal to 10 (40 apiaries); 200 m radius—Beehive density between 11 and 30 (926 apiaries); 400 m radius—Beehive density between 31 and 100 (111 apiaries).

very high classes. This assessment reflects the recognized excellence of this PDO territory, reinforcing its value for developing successful and high-standard beekeeping activities. For that appreciation, a combination of favourable biophysical conditions, i.e. among the analysed criteria, much contributed.

By crossing the spatial variability of final beekeeping suitability with the relative suitability of each criteria category (Figs. 4 and 5), the statistics show a greater dispersion of values in the topographic data. This could be due to the complex terrain morphology and the finer scale (10 m × 10 m horizontal resolution), leading to a wider range of suitability values. In turn, environmental criteria also contributed to a high dispersion of values, particularly at the minima, which correspond to areas poor in melliferous flora, whose suitability values are highly correlated with the degree of proximity to the existing hydrographic and rural road networks (positive correlation). In the climatic variables, the range of values is lower due to the more homogeneous spatial pattern, as a result of the coarser resolution underlying the raw data and the scale at which meteorological variations occur. Regarding the final suitability map, that variability is smoothed out by combining the weighted and spatially normalised data per category (Fig. 6).

3.3 Modelling Evaluation

Modelled results of final beekeeping suitability were assessed against the geographic location of the apiaries (IFAP 2024b) and the average density of beehives per apiary at the parish level (FNAP 2024). In total, 1077 apiaries are identified in the study area. Overall, most of these apiaries and beehives are located in highly suitable sites for beekeeping (Fig. 7). However, there are some areas classified with very high suitability that exhibit minimal or no beekeeping activity, especially in the northern part of the study area (Figs. 5 and 7). This happens because these areas are located at high altitudes, far from villages, with limited or poorly maintained access, and vegetation of little interest to beekeepers.

Ultimately, for each beekeeping suitability class, the whole study area and the apiary influence range, which depends on the density of beehives, were quantified (Table 4). This class-level numerical analysis emphasises the spatial relationship between the land suitability for beekeeping and its extension to the existing apiaries. As main considerations, it is worth noting that the majority of the study area falls within the very high suitability class (51.3%), while the medium classification has only a residual spatial presence (0.6%). Focusing on the apiary influence range, whose distances were defined by law based on the density of beehives (Ministry of Agriculture 2005), it is clear that beekeeping suitability in areas with 200 m and 400 m radiuses (i.e., with a stronger beekeeping activity) is predominantly classified as very high. This finding is particularly evident in the 400 m range (73.2% within the very high class), demonstrating that the beekeepers, especially those managing many beehives, have a deep knowledge of the activity and the territory where they operate.

4 Discussion

The results presented in this study provide valuable insights on the spatial distribution of beekeeping suitability in a honey PDO region, highlighting the importance of biophysical and human factors in determining ideal locations for the successful establishment of apiaries. The integration of expert knowledge with the AHP method allowed the construction of a robust suitability model that reflects the relative importance of various topographic, environmental and climatic criteria. By combining this MCDA process with GIS geoprocessing tools applied to high-quality spatial data, the approach produces detailed suitability maps that can assist stakeholders, such as beekeepers, land planners and policymakers, in identifying areas where beekeeping could be promoted or expanded, particularly in locations with lower activity levels. In other words, these suitability maps offer a powerful tool for beekeeping planning and management, providing a comprehensive view of the land potential for honey production. Thereby, sustainable beekeeping practices aimed at natural heritage and biodiversity conservation should be encouraged, particularly with regard to the health and foraging behaviour of bee colonies. Thus, by integrating bee ecology into spatial modelling, it is hoped a more accurate and meaningful evaluation of landscape suitability for beekeeping. Furthermore, certain particularities inherent to the study area, such as the local climate, orography and vegetation have also contributed to the honey PDO labelling, ensuring high quality and authenticity standards and an enhanced market value. To evaluate the performance of this integrated modelling approach, a comparison between the final beekeeping suitability and the influence range of the actual apiaries revealed that most of these are in sites classified as highly suitable, thus confirming the alignment of expert judgments and beekeeper decisions. This evidence reinforces the importance of integrating specialised knowledge and geospatial tools to support the sustainable development of beekeeping activities.

Despite the valuable insights provided by this study, some limitations must be recognised. The model primarily considered biophysical and expert-derived criteria, without directly addressing socioeconomic or logistical factors that can significantly influence the beekeeping viability, such as market access, infrastructures, land tenure or technical support. In addition, some spatial datasets (e.g., melliferous shrub species and climatic variables) could benefit from further refinement to enhance the modelling accuracy. The reliance on a limited group of experts can also introduce subjectivity, emphasising the need for a greater stakeholder involvement in future assessments. On the other hand, factors related to bee health, which were not integrated into the model, such as pesticide exposure, disease prevalence and ecological competition, could substantially affect the long-term suitability. Therefore, future studies should aim to incorporate these dimensions and assess how suitability patterns may shift under climate change and land use dynamics. Addressing these limitations will support the development of more comprehensive, realistic and actionable planning tools for sustainable beekeeping.

In a broader geographic context, research on beekeeping suitability has emphasised the methodological scheme and various criteria adopted in this study. In Konya, Turkey, Sari et al (2020b) tested two MCDA methods (AHP and PROMETHEE—Preference Ranking Organization Method for Enrichment of Evaluations) to determine suitable locations for apiaries. Both methods reached similar results, highlighting flora, proximity to water, and hillside exposure as the most influential criteria. In another MCDA study involving AHP and GIS techniques, conducted in the northwest region of Amazonas, Peru, Cotrina-Sanchez et al (2023) showed that highly suitable areas for beekeeping were primarily determined by the combination of three biophysical criteria: land cover/land use (forest), proximity to water (within 500 m), and air temperature (20–25 °C). Using an MCDA based solely on GIS, applied to Mediterranean lands (Calabria, Southern Italy), Zoccali et al (2017) demonstrated that an innovative GIS approach for assessing beekeeping suitability can overcome methodological constraints and reduce the subjective influence of decision makers. Under harsh environmental conditions in Saudi Arabia, Abou-Shaara et al (2013) identified a set of criteria affecting honeybee colonies during summer, in order to map the beekeeping suitability based on uncontrolled (maximum temperature and relative humidity) and controlled (land use, summer crops and water resources) factors. This approach proved to be relevant for identifying the most suitable areas for beekeeping, providing a scientific basis to guide decision-making in management of beekeeping activities in the face of weather extremes.

5 Conclusions

This research highlights the significant role of beekeeping suitability mapping in a Portuguese honey producing region with PDO certification. By adopting an enhanced multicriteria approach, it assesses the suitability of rural landscapes for beekeeping activities and the fulfilment of the bee ecological requirements, considering topographic, environmental and climatic criteria. This integrated assessment methodology, which combines expert perceptions with analytical and geoprocessing tools (AHP and GIS), not only provides practical guidance for sustainable beekeeping, but also offers a scalable framework applicable to other regions with similar ecological and biophysical characteristics.

The findings indicate that environmental and climatic criteria categories had a greater impact (43% each) on overall beekeeping suitability. Within each target category, hillside exposure, land use/flora and annual precipitation were the main contributing criteria, significantly influencing the landscape potential for honey production and maintaining bee health. Moreover, a comparison between the final suitability map and the geographic location of the existing apiaries, revealed that the influence range of most apiaries is located in very high suitability areas, thus validating the accuracy and effectiveness of this beekeeping mapping approach.

In conclusion, this study reinforces the importance of beekeeping suitability mapping and the potential of the proposed methodology for improving beekeeping practices and supporting the sector´s sustainability, ensuring the economic viability and the environment conservation. In addition, this appeal has a special meaning for the rural development, given the honey PDO status attributed to the study area, which confers recognized quality and subsequent higher profitability, as the entire production chain is based on traditional and sustainable beekeeping activities.

Appendix A

Mapping the selected criteria considering their spatial representation and relative beekeeping suitability (see Figs. 8, 9 and 10).

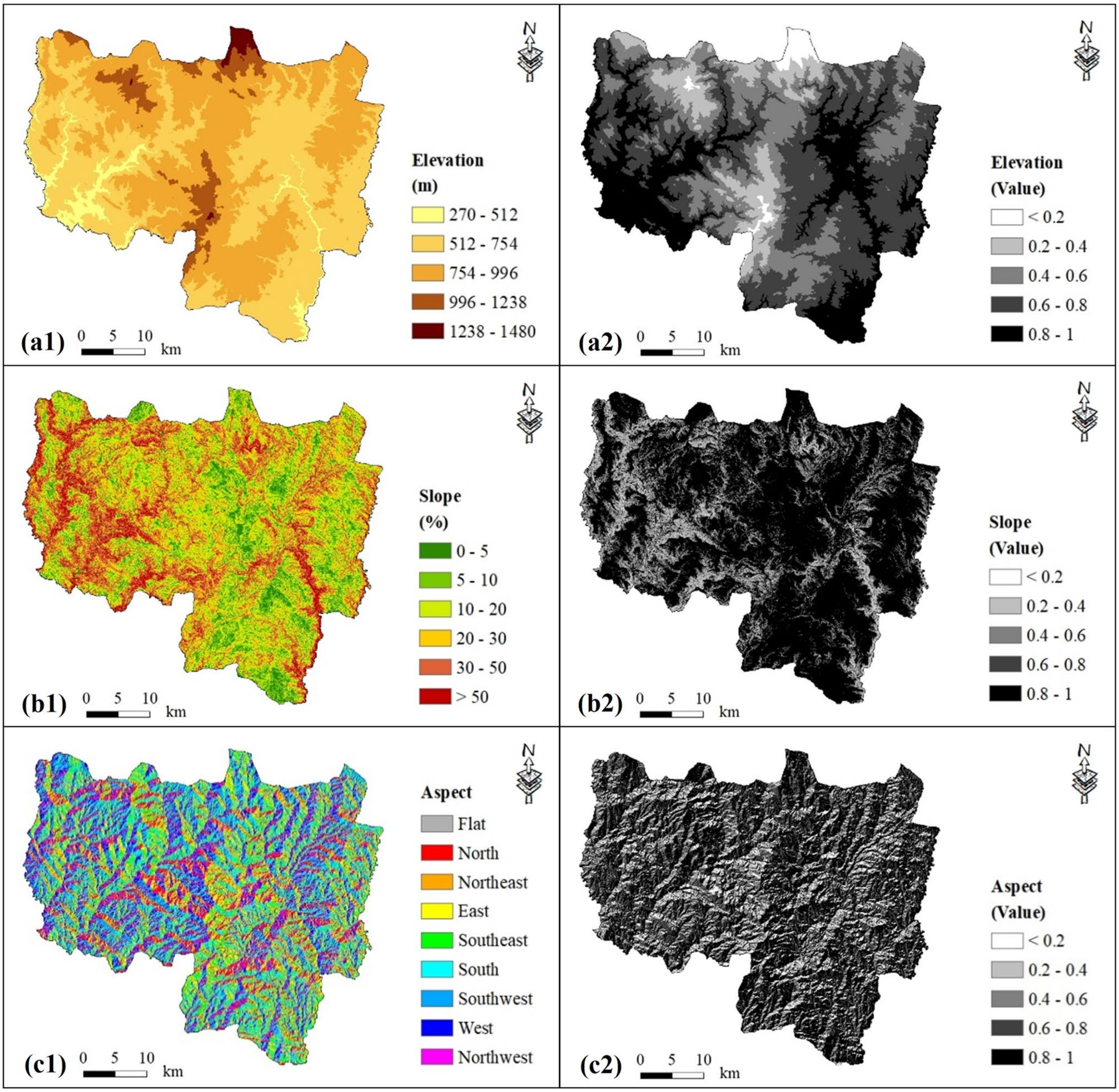


Fig. 8 Mapping the topographic criteria considering their spatial representation (**a1**–**c1**) and relative beekeeping suitability (**a2**–**c2**)

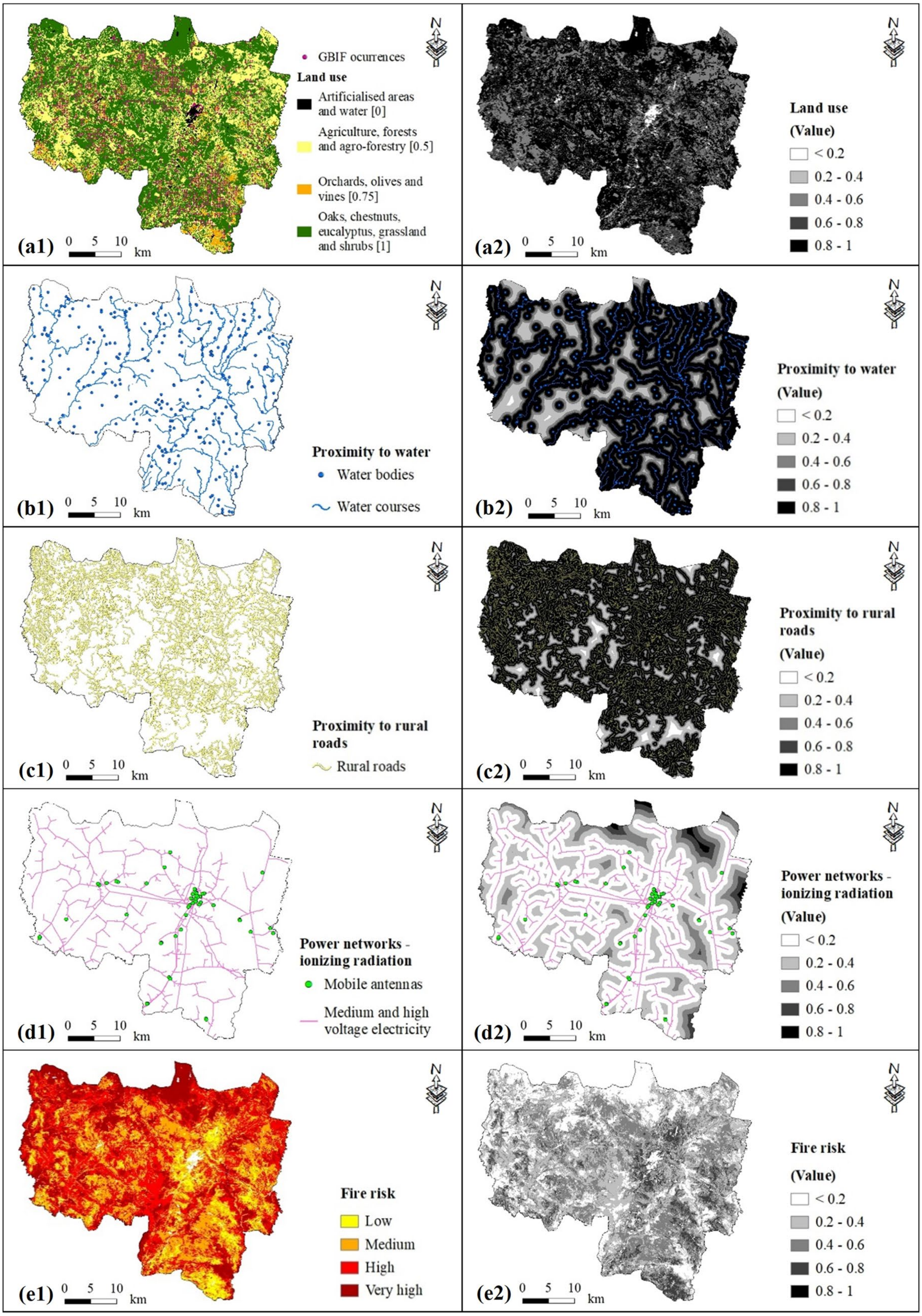


Fig. 9 Mapping the environmental criteria considering their spatial representation (a1–**e1**) and relative beekeeping suitability (**a2**–**e2**)

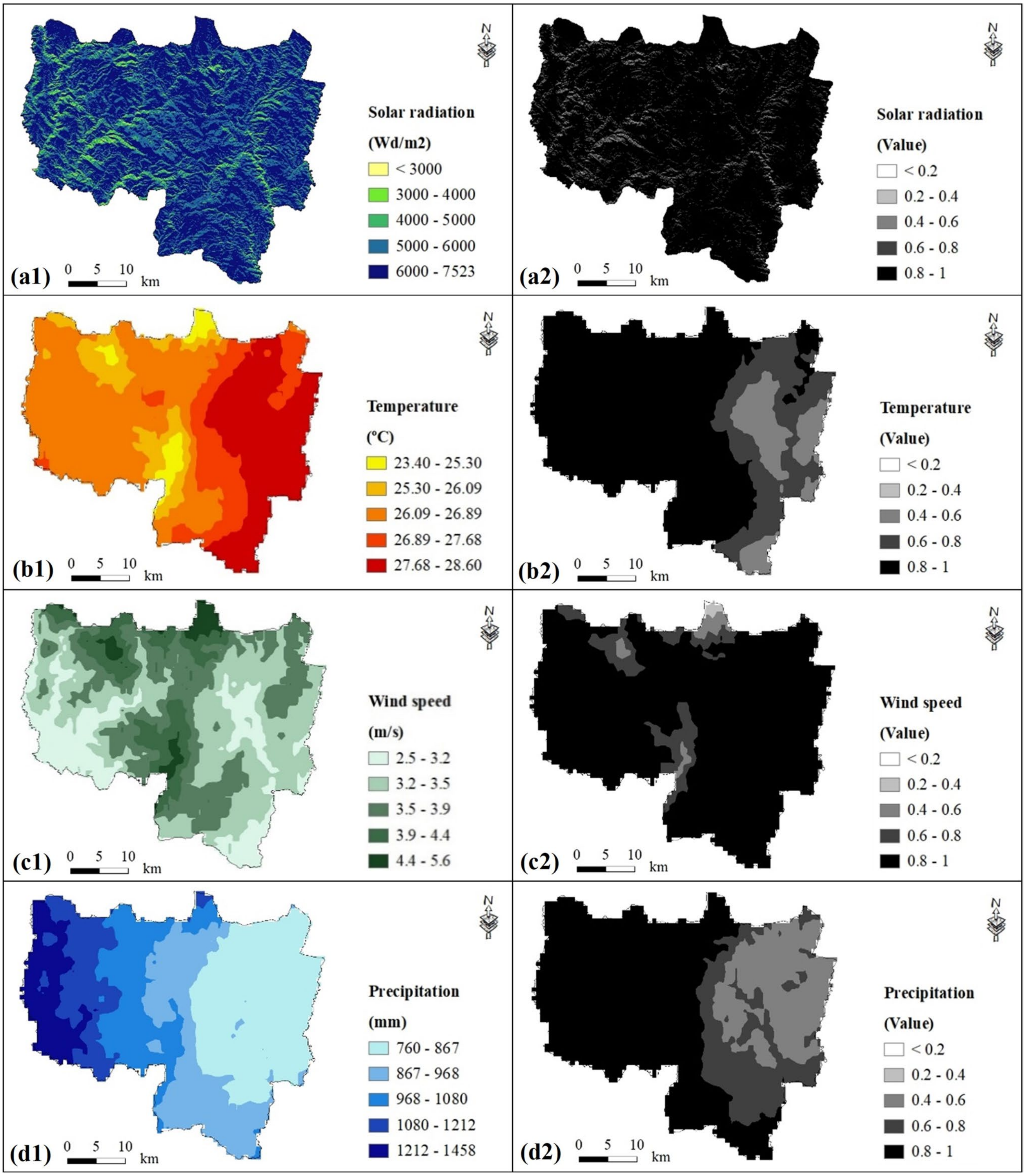


Fig. 10 Mapping the climatic criteria considering their spatial representation (**a1**–**d1**) and relative beekeeping suitability (**a2**–**d2**)

Acknowledgements The authors are grateful to the beekeeping sector experts for their participation in the questionnaire for criteria prioritisation, and the municipalities of Bragança and Vinhais, National Federation of Beekeepers of Portugal (FNAP), and Institute for Financing Agriculture and Fisheries (IFAP) for kindly providing the datasets that supported this research.

Author Contributions All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Carlos Silveira, Natália Roque and Bruno Leitão. The first draft of the manuscript was written by Carlos Silveira and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding This research was supported by the NextGenerationEU recovery funds through the Project BeeLand PRR-C05-i03-I-000081, and by national funds through FCT/MCTES (PIDDAC): CIMO, UIDB/00690/2020 (https://doi.org/10.54499/UIDB/00690/2020) and UIDP/00690/2020 (https://doi.org/10.54499/UIDP/00690/2020); SusTEC, LA/P/0007/2020 (https://doi.org/10.54499/LA/P/0007/2020); CERNAS (UIDB/00681; https://doi.org/10.54499/UIDP/00681/2020); UIDB/00239/2020 (DOI https://doi.org/10.54499/UIDB/00239/2020) and UIDP/00239/2020 (DOI https://doi.org/10.54499/UIDP/00239/2020); and MED, UIDB/05183/2020.

Data availability The authors confirm that the data supporting the findings of this study are available within the article.

Declarations

Conflict of Interest The authors have no relevant financial or non-financial interests to disclose.

References

Abou-Shaara HF (2019) Geographical information system for beekeeping development. J Apic Sci 63(1):5–16. https://doi.org/10.2478/JAS-2019-0015

Abou-Shaara HF, Al-Ghamdi AA, Mohamed AA (2013) A suitability map for keeping honey bees under harsh environmental conditions using geographical information system. World Appl Sci J 22(8):1099–1105. https://doi.org/10.5829/IDOSI.WASJ.2013.22.08.7384

Antonopoulos A, Gounari O, Falagas A, Tsagkarakis A, Karantzalos K (2023) Mapping bee-keeping forest plants from medium spatial resolution multispectral satellite data. Int Arch Photogramm Remote Sens Spat Inf Sci XLVIII-1-W2-2023(1/W2-2023):1839–1845. https://doi.org/10.5194/ISPRS-ARCHIVES-XLVIII-1-W2-2023-1839-2023

Beekman M, Ratnieks FLW (2000) Long-range foraging by the honeybee, *Apis mellifera* L. Funct Ecol 14(4):490–496. https://doi.org/10.1046/J.1365-2435.2000.00443.X

Cotrina-Sanchez A, García L, Calle C, Sari F, Bandopadhyay S, Rojas-Briceño NB, Meza-Mori G, Torres Guzmán C, Auquiñivín-Silva E, Arellanos E, Oliva M (2023) Multicriteria analysis in apiculture: a sustainable tool for rural development in communities and conservation areas of northwest Peru. Land 12(10):1900. https://doi.org/10.3390/LAND12101900/S1

De La Rúa P, Jaffé R, Dall'Olio R, Muñoz I, Serrano J (2009) Biodiversity, conservation and current threats to European honeybees. Apidologie 40(3):263–284. https://doi.org/10.1051/APIDO/2009027

Decourtye A, Mader E, Desneux N (2010) Landscape enhancement of floral resources for honey bees in agro-ecosystems. Apidologie 41(3):264–277. https://doi.org/10.1051/APIDO/2010024

DGT (2019) A land cover/use map of mainland Portugal for 2018. Directorate-General for Territory, Lisbon

Elmastaş N, Ölmez İ, Vural E (2022) Suitability analysis of apiculture (beekeeping) activity areas with multi-criteria method: a case study of Adıyaman. J Geog 0(44):19–30. https://doi.org/10.26650/JGEOG2022-894419

E-REDES (2024) Medium and high voltage electricity network (data not publicly available). In: Electr. Distrib. Port. https://e-redes.opendatasoft.com/pages/homepage/. Accessed 3 Jan 2024

Estoque RC, Murayama RCE (2010) Suitability analysis for beekeeping sites in La Union, Philippines, using GIS and multi-criteria evaluation techniques. Res J Appl Sci 5(3):242–253. https://doi.org/10.3923/RJASCI.2010.242.253

Flinzberger L, Zinngrebe Y, Bugalho MN, Plieninger T (2022) EU-wide mapping of 'Protected Designations of Origin' food products (PDOs) reveals correlations with social-ecological landscape values. Agron Sustain Dev 42(3):1–14. https://doi.org/10.1007/S13593-022-00778-4/TABLES/3

FNAP (2024) Survey of the average density of beehives per apiary at the parish level (data not publicly available)

Fotso Kamga GA, Bouroubi Y, Germain M, Mbom AM, Chagnon M (2024) Expert knowledge-based modelling approach for mapping beekeeping suitability area. Ecol Inform 80:102530. https://doi.org/10.1016/J.ECOINF.2024.102530

GBIF (2024) The Global Biodiversity Information Facility. https://www.gbif.org/. Accessed 3 Oct 2024

Gebremedhn H, Gebrewahid Y, Haile GG, Hadgu G, Atsbha T, Hailu TG, Bezabih G (2024) Projecting the impact of climate change on honey bee plant habitat distribution in Northern Ethiopia. Sci Rep 14(1):1–16. https://doi.org/10.1038/s41598-024-66949-3

Gilioli G, Simonetto A, Hatjina F, Sperandio G (2018) Multi-dimensional modelling tools supporting decision-making for the beekeeping sector. IFAC-PapersOnLine 51(5):144–149. https://doi.org/10.1016/J.IFACOL.2018.06.225

Hosni EM, Al-Khalaf AA, Nasser MG, Abou-Shaara HF, Radwan MH (2022) Modeling the potential global distribution of honeybee pest, *Galleria mellonella* under changing climate. InSects. https://doi.org/10.3390/INSECTS13050484

ICNF (2024) Geographic Information: Theme 5-Risks and Threats. In: Inst. Nat. Conserv. For. https://geocatalogo.icnf.pt/catalogo_tema5.html. Accessed 3 Oct 2024

IFAP (2024a) iSIP-Online Parcel Identification System. In: Inst. Financ. Agric. Fish. https://www.ifap.pt/portal/sip-informacao-basica. Accessed 15 Sep 2024

IFAP (2024b) Geographical survey of existing apiaries in the study area (data not publicly available)

Kotovs D, Zacepins A (2023) Importance of GIS solutions for beekeepers: a review. Agron Res 21(2):799–813. https://doi.org/10.15159/AR.23.049

Kovac H, Käfer H, Stabentheiner A (2018) The energetics and thermoregulation of water collecting honeybees. J Comp Physiol A Neuroethol Sens Neural Behav Physiol 204(9–10):783–790. https://doi.org/10.1007/S00359-018-1278-9

Kumar PB, Prasad TK (2018) Application of multicriteria decision analysis (MCDA) to apiculture potential assessment: A case study of Thiruvananthapuram Corporation, Kerala, India. GeoEye 7(2):25–31. https://doi.org/10.53989/BU.GE.V7I2.7

Ludewig MJ, Landaverde-González P, Götz KP, Chmielewski FM (2023) Initial assessment to understand the effect of air temperature on bees as floral visitors in urban orchards. J Insect Conserv 27(6):1013–1022. https://doi.org/10.1007/S10841-023-00516-5/TABLES/3

Mahankuda B, Tiwari R (2024) Impact of climate change on honeybees and crop production. In: Adapt to Clim Chang Agric Pract :211–224. https://doi.org/10.1007/978-3-031-28142-6_8

Marnasidis S, Kantartzis A, Malesios C, Hatjina F, Arabatzis G, Verikouki E (2021) Mapping priority areas for apiculture development with the use of geographical information systems. Agriculture 11(2):182. https://doi.org/10.3390/AGRICULTURE11020182

Ministry of Agriculture RDF (2005) Decree Law No. 203/2005. In: Repub. Diary No. 227/2005, Ser. 1 2005–11–25. https://diariodarepublica.pt/dr/en/detail/decree-law/203-2005-481729. Accessed 8 Jan 2025

Novelli S, Vercelli M, Ferracini C (2021) An easy mixed-method analysis tool to support rural development strategy decision-making for beekeeping. Land 10(7):675. https://doi.org/10.3390/LAND10070675

Ojija F, Adam LS, Nicholaus R, Mwakalapa EB (2023) Insect-pollinators and their interactions with plants differ in disturbed and semi-natural areas: Tanzania's Southern Highlands case study. Sci Prog 106(2):1–17. https://doi.org/10.1177/00368504231184035/ASSET/IMAGES/LARGE/10.1177_00368504231184035-FIG3.JPEG

OSM (2024a) Download OpenStreetMap data for this region: Portugal. In: OpenStreetMap. https://download.geofabrik.de/europe/portugal.html. Accessed 13 Sep 2024

OSM (2024b) Antenas Mobile V2.1. In: OpenStreetMap. https://umap.openstreetmap.fr/pt-pt/map/antenas-mobile-v21_724717. Accessed 13 Sep 2024

Pantoja G, Gómez M, Contreras C, Grimau L, Montenegro G (2017) Determination of suitable zones for apitourism using multi-criteria evaluation in geographic information systems: a case study in the O'Higgins Region. Chile Cienc e Investig Agrar 44(2):139–153. https://doi.org/10.7764/RCIA.V44I2.1712

Rehman A, Song J, Haq F, Ahamad MI, Sajid M, Zahid Z (2021) Geo-physical hazards microzonation and suitable site selection through multicriteria analysis using geographical information system. Appl Geogr 135:102550. https://doi.org/10.1016/J.APGEOG.2021.102550

Rehman A, Song J, Haq F, Mahmood S, Ahamad MI, Basharat M, Sajid M, Mehmood MS (2022) Multi-hazard susceptibility assessment using the analytical hierarchy process and frequency ratio techniques in the Northwest Himalayas, Pakistan. Remote Sens 14(3):554. https://doi.org/10.3390/RS14030554

Rehman A, Sajjad M, Song J, Riaz MT, Mehmood MS, Ahamad MI (2025) Integrated frequency ratio-analytical hierarchy and geospatial techniques-based earthquake risk assessment in mountainous cities: a case from the Northwestern Himalayas. Georisk Assess Manag Risk Eng Syst Geohazards 19(2):389–409. https://doi.org/10.1080/17499518.2024.2378285

Roque N, Fernandez P, Silveira C, Vilas-Boas M, Anjos O (2024) Using analytic hierarchy process to assess beekeeping suitability in portuguese controlled areas: a first approach. InSects 15(2):91. https://doi.org/10.3390/INSECTS15020091/S1

Saaty TL (2008) Decision making with the analytic hierarchy process. Int J Serv Sci 1(1):83–98. https://doi.org/10.1504/IJSSCI.2008.017590

Sari F, Ceylan DA, Ozcan MM, Ozcan MM (2020a) A comparison of multicriteria decision analysis techniques for determining beekeeping suitability. Apidologie 51(4):481–498. https://doi.org/10.1007/s13592-020-00736-7

Sari F, Kandemir İ, Ceylan DA, Gül A (2020b) Using AHP and PROMETHEE multi-criteria decision making methods to define suitable apiary locations. J Apic Res 59(4):546–557. https://doi.org/10.1080/00218839.2020.1718341

Sarvia F, De Petris S, Borgogno-Mondino E (2023) Mapping melliferous potential in productive honey areas through spatial tools: towards a rationalization of beekeeping. Ecol Inform 78:102362. https://doi.org/10.1016/J.ECOINF.2023.102362

Şengül Z, Yücel B, Saner G, Takma Ç (2023) Investigating the impact of climate parameters on honey yield under migratory beekeeping conditions through decision tree analysis: the case of İzmir Province. ANADOLU Ege Tarımsal Araştırma Enstitüsü Derg 33(2):268–280. https://doi.org/10.18615/anadolu.1394787

Stabentheiner A, Kovac H (2023) A mixed model of heat exchange in stationary honeybee foragers. Sci Rep 13(1):1–11. https://doi.org/10.1038/S41598-023-31320-5

Switanek M, Crailsheim K, Truhetz H, Brodschneider R (2017) Modelling seasonal effects of temperature and precipitation on honey bee winter mortality in a temperate climate. Sci Total Environ 579:1581–1587. https://doi.org/10.1016/J.SCITOTENV.2016.11.178

Tennakoon S, Apan A, Maraseni T, Altarez RDD (2023) Decoding the impacts of space and time on honey bees: GIS based fuzzy AHP and fuzzy overlay to assess land suitability for apiary sites in Queensland, Australia. Appl Geogr 155:102951. https://doi.org/10.1016/J.APGEOG.2023.102951

Tennakoon S, Apan A, Maraseni T (2024) Unravelling the impact of climate change on honey bees: an ensemble modelling approach to predict shifts in habitat suitability in Queensland, Australia. Ecol Evol 14(4):e11300. https://doi.org/10.1002/ECE3.11300

Triantomo V, Widiatmaka W, Fuah AM (2016) Land use planning for beekeeping using geographic information system in Sukabumi Regency, West Java. J Nat Resour 6(2):168–177. https://doi.org/10.19081/JPSL.2016.6.2.168

Widiatmaka WA, Sjamsudin CE, Syaufina L (2016) Geographic information system and analytical hierarchy process for land use planning of beekeeping in forest margin of Bogor Regency, Indonesia. J Trop Silvic 7(3):S50–S57. https://doi.org/10.29244/J-SILTROP.7.3.S50-S57

WorldClim (2024) Bioclimatic variables. In: WorldClim. https://www.worldclim.org/data/bioclim.html. Accessed 3 Oct 2024

Zoccali P, Malacrinò A, Campolo O, Laudani F, Algeri GM, Giunti G, Strano CP, Benelli G, Palmeri V (2017) A novel GIS-based approach to assess beekeeping suitability of Mediterranean lands. Saudi J Biol Sci 24(5):1045–1050. https://doi.org/10.1016/j.sjbs.2017.01.062

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.