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# GIS-based multi-criteria territorial suitability assessment for insect farms: a case study for North Italy

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**RESEARCH ARTICLE**

## Abstract

Although environmental sustainability and economic feasibility frameworks have been developed to evaluate the impact of insect farms, significant studies on the development of territorial suitability methods specifically tailored to insect production have not yet been performed. This work proposes a GIS-based multi criteria decision making analysis to evaluate the suitability of a territory to the installation of insect farms. A case study developed specifically for black soldier fly *Hermetia illucens* (HI) insect farms in Emilia-Romagna region (North Italy) is presented. This is an area which, due to its agro-industrial nature and the consequent large production of related waste and by-products, is an optimal candidate for the installation of insect farms. Nine physical, environmental, and economic criteria were assessed. A raster spatial layer for each criterion was obtained, and their values were standardised. The criteria were weighted using the analytical hierarchical process, based on expert opinion recorded via an online questionnaire. The resulting weights were used to combine the single criterion maps using a weighted linear combination procedure and generate, after reclassification, the final suitability map. This map indicates the areas suitable for insect farms at the local level and provides indications for estimating suitability at regional and provincial level. The results showed that 56.2% of the study area was deemed unsuitable, and 43.8% was determined suitable for an HI insect farm; best locations were found around the main agro-industrial centres of the Po valley. The proposed methodology can be easily adapted to other breeding models, insects or study areas and adds valuable information in the development of guidelines for industrial-scale insect farms.

**Keywords:** *Hermetia illucens*, black soldier fly, insect farms, GIS, MCDM, territorial suitability

## 1. Introduction

The global concern about sustainability of the current animal industry requires replacing environmentally expensive proteins (such as fishmeal and soymeal) in feedstuff formulations with less impacting, highly digestible and nutrient-balanced protein sources (Vauterin *et al.*, 2021).

Insects are well recognised as a suitable option for environmental and economic reasons (Van Huis *et al.*, 2021) and are already bred and marketed in many countries (Niyonsaba *et al.*, 2021). Literature identifies *Hermetia illucens* (HI) as one of the most promising species for animal nutrition, both for the high biological value of its proteins (Cullere *et al.*, 2018; Fuso *et al.*, 2021), and for its capacity to reduce agri-food wastes (Barbi *et al.*, 2020; Smetana *et al.*, 2019;). HI, commonly known as 'black soldier fly', is a non-pest fly species naturally feeding on a large variety of decaying organic materials (Miranda *et al.*, 2019), and is commonly found in rotting fruits and plant remains (Čičková *et al.*, 2015). Thanks to their feeding habits, HI larvae have been extensively studied for the bioconversion of organic waste into feed for aquaculture and poultry (De Marco *et al.*, 2015). Furthermore, the obtained insect frass (residual substrate after HI rearing) could be successfully exploited as a fertiliser for crops, fulfilling a circular economy perspective (Bortolini *et al.*, 2020).

In the past, feeding farm animals with animal protein, including insects, was severely restricted in the European Union due to the prescriptions of Regulation No 999/2001 (EC, 2001) for prevention, control and eradication of transmissible spongiform encephalopathies. Regulations 2017/893 (EC, 2017) and 2021/1372 (EC, 2021) approved the use of insect-derived proteins in the EU for fish, poultry and pig feed formulation.

As of 2019, an annual insect production of 6,000 tons has been reported for the EU; it is expected to reach five million tons by 2030 due to the growing demand for alternative protein sources for animal feed (IPIFF, 2019; Niyonsaba *et al.*, 2021). This step will involve the transition from the current insect production in pilot plants to that on industrial scale, thus making it necessary to deepen our knowledge on the potential benefits and environmental impacts along the entire production chain, as well as on the economic feasibility of the insect industry (Smetana *et al.*, 2019; Van Huis *et al.*, 2021).

Environmental sustainability of insect production systems is supported by many papers. Life cycle assessment (LCA), including global warming potential and land use, was applied to assess the impact of the production of different insect species (Halloran *et al.*, 2016), both for human (Oonincx and De Boer, 2012) and for animal consumption (Smetana *et al.*, 2016). However, existing literature mainly refers to the production of proteins derived from insects in small pilot farms (0.02-1 tons of dry insect biomass processed per day); apart from land use and water depletion, their sustainability is still lower than that of the most common vegetable proteins, especially soy (Smetana *et al.,* 2019). In fact, these small-scale plants are characterised by low technological and mechanisation levels (Niyonsaba *et al.*, 2021). According to Smetana *et al.* (2019), medium- and long-term estimates show that insect-derived proteins could become more competitive from an environmental point of view if the breeding upscale will follow a virtuous industrial progress (use of renewable energy, improved processing efficiency, use of side-streams as insect feed substrate). Furthermore, most of the analyses on the economic feasibility and profitability of insect production were performed on small pilot farms. Niyonsaba *et al.* (2021) estimated a margin range for HI production from € -798 to 15,576 per ton of dried larvae. This wide range is due to the lack of reliable and accurate economic figures, especially with regard to larval sales prices, which differ by reference market and operating costs.

In contrast, to the authors' knowledge, no significant studies have been reported on the assessment of territorial suitability (TS) for insect production systems. TS evaluation allows to assess the suitability of a territory to host a production activity and to define, within it, the most suitable areas. The process requires to evaluate requisites or constraints that are often linked in a complex and interwoven or collinear way. As in traditional livestock farming, the positioning of insect farms on industrial scale must follow not only economic criteria, but also environmental, health and aesthetic requisites. For any type of feedstuff and anywhere in the world, the location of a large conversion plant should be properly chosen to ensure a constant long-term supply of raw materials and transport at sustainable costs (Kok, 2021).

TS assessment is a multiple criteria decision making (MCDM) process. TS parameters (criteria) must be derived from spatial and non-spatial, qualitative and quantitative information under different conditions. Geographic information systems (GIS) are best suited to manage a wide range of data from various sources for time-efficient and cost-effective assessment (Chen *et al.*, 2010a). The integration of MCDM tools in GIS for TS assessment has been reported in previous specific reviews on the topic (Cegan *et al.*, 2017; Greene *et al.*, 2011; Huang *et al.*, 2011; Malczewski, 2004, 2006a; Zavadskas *et al.*, 2014;). Therefore, TS assessment mapping and modelling is one of the most useful applications of GIS for spatial planning and management (Malczewski, 2006b). Territorial suitability evaluation is already widely used for identification of optimal land area to host conventional animal farms to optimise regional land use planning, to maximise economic gain for farms, and to minimise their impact on the environment and on the population (Qiu *et al.,* 2017).

From the circular economy perspective, it is also strategic, particularly for insects feeding on decaying organic matter such as HI, to identify suitable production sites taking into account the distance from the agro-industry establishments plants that supply these organic by-products. This is substantial both for economic reasons (lower transport costs, time savings, etc.) and for the reduction of $CO_2$ emissions deriving from the transport of large quantities of substrates to feed the larvae. Furthermore, large-scale insect production is also expected to lead to environmental and social problems, such as unpleasant odour, public health concern and social issues (for instance, acceptance of insect farms by neighbouring residents).

In the present study, an original MCDM methodology was developed to assess territorial suitability for the installation of HI farms. The procedure was applied using Emilia-Romagna region (Italy) as case study. The proposed multi-step MCDM approach incorporates two well-known methods, namely analytic hierarchy process (AHP) and weighted linear combination (WLC). AHP is a technique for evaluating the weight (i.e. importance) of the criteria involved in the MCDM process. WLC is one of the commonly used MCDM aggregation operators due to its simplicity and efficiency (Qiu *et al.,* 2017). The criteria used in the analysis involve physical, environmental and economic aspects. The analysis aims to assess suitability at regional and province level, highlighting both optimal and unsuitable locations. This study investigates and identifies the legislative and practical bottlenecks that hinder the setting up of insect farming facilities in Italy and may be useful in developing guidelines for industrial-scale insect farming.

## 2. Materials and methods

### Study area

The study was conducted in the Emilia-Romagna (ER) region (Figure 1), which is located in northern Italy and measures around 22,500 km$^2$. Elevation in the area ranges from 0 to 2,165 m above sea level. Emilia-Romagna occupies the south-eastern portion of the Po valley and most of the regional territory is level; alluvial plan and low mountain (below 800 m) account for 89% of the surface. The mountain area, a strip 230 km long and 60-70 km wide, is the northern side of the Apennines and reaches 2,165 above sea level. (Ambrosini *et al.,* 1992). The area is a sequence of deep NE-SW oriented valleys oriented with no plateaus or highlands. The region is bordered on the eastern side by the Adriatic Sea. From an administrative point of view, the region is made up of 10 provinces divided into 330 municipalities.

Emilia-Romagna is one of the most developed and richest regions of Italy; the agri-food production is a key sector of the region's economy. The size of the agri-food companies is mostly small-medium, but there are also large multinationals, especially in the food processing chain. This leads to an enormous availability of agro-industrial production waste and by-products; Rossi and Piccinini (2007) estimated 233,500 t/year of agro-industrial waste for the period 2004-2005, of which over 50% due to industrial tomato processing. The region is home to companies that produce energy from biomass derived from agricultural processing residues and food industry waste. However, the surplus of this production waste remains high and new disposal and/or recycling systems are strongly urged by stakeholders and planners.

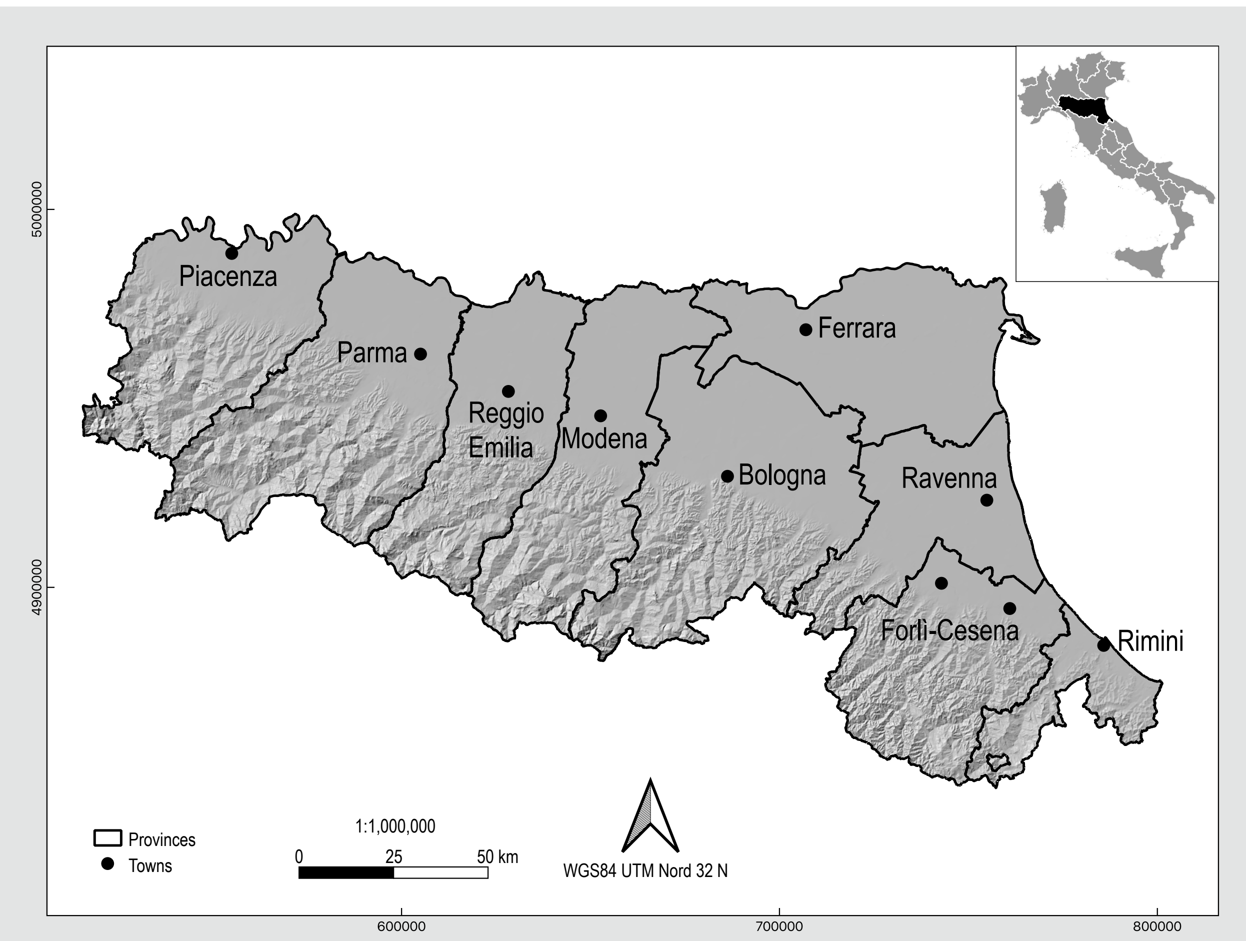


**Figure 1. Map of the study area.**

## Methods

The study workflow is shown in Figure 2 and the methodological steps are fully described in the following sections. The method was developed by involving a panel of national and international insect farming experts, including researchers, specific stakeholders, decision makers and industrialists.

### Criteria selection and criterion maps processing

Evaluation criteria objectives and attributes need to be identified with respect to the situation under consideration. The set of selected criteria should adequately represent the decision-making environment and contribute to the achievement of the final goal (Prakash, 2003).

As this is the first time that MCDM approach has been applied to insect farm suitability evaluation, previous guidelines for selecting and processing appropriate parameters were not available in literature. In the present study, a novel criteria selection was developed based on: (1) expert knowledge; (2) requirements from involved stakeholders; (3) data availability; (4) selected rearing substrates for HI diet and potential ER customers of HI derived protein flours. With regard to this last point, which essentially concerned economic criteria, their evaluation was based on the results of the Flies4Value Project (https://flies4value.it/en), founded by ER region and aimed at enhancing the main regional agro-industrial by-products through insect farming. As part of the project, four types of by-products (bran, tomato peels and seeds, whey and legume waste) were selected as main components of HI diet. At the same time, the project identified laying hen farms as the main potential ER customers of insect-derived proteins (L. Maistrello, personal communication; available at: https://www.youtube.com/watch?v=MtvQCl85ebU). Therefore, the procedures developed in this study for economic criteria evaluation are based on these results. Moreover, the methodology has been targeted to the installation of industrial-scale insect farms (with a production of around 1000 t of dry flour), therefore taking advantage of the huge and stable availability of agro-industrial waste of ER region.

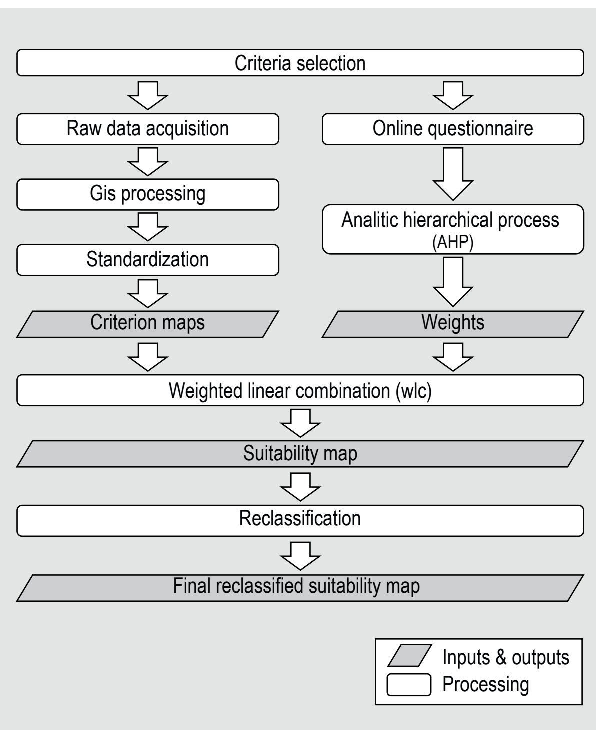


**Figure 2. Flowchart of the implemented methodology.**

Overall, nine criteria were selected in the suitability assessment process (Table 1), which were clustered into three main categories, namely physical, environmental, and economic aspects. They have been derived from existing public data sets and their data sources are listed in Table 1. Most of the GIS data were publicly available and downloaded from the ER Geoportal (https://geoportale.regione.emilia-romagna.it/). These criteria can be distinguished as constraints and factors. Constraints are non-compensatory exclusionary criteria expressed in the form of a Boolean (logical) map; areas are categorised into two classes, suitable (value = 1) and unsuitable (value = 0). Areas not eligible for a constraint are automatically deemed unsuitable in final TS evaluation; moreover, constraints do not participate in the weighting process. Factors are compensatory non-exclusionary criteria that contribute to some extent to the output (suitability) and have values between 0 and 1, where 0 represents the least suitable areas and 1 represents the most suitable area for that criterion. They can contribute positively to the output (the higher the values, the better) or negatively (the lower the values, the better). Contrary to constraints, which cannot be compensated, poor performance of one factor can be compensated by good performance of another factor (Ferretti, 2011).

In TS analysis, each evaluation criterion is represented by a separate map in which a 'degree of suitability' with respect to that particular criterion is ascribed to each map unit (Prakash, 2003). Selected criteria were processed through GIS tools (conversion from vector to raster where necessary, map overlay, buffering, reclassification, cost distance mapping, spatial queries, standardisation) using open-source R (R Core Team, 2021) and QGIS (QGIS Development Team, 2022) software. Each criterion map was resampled to get a raster grid with a spatial resolution of 25 m projected into UTM Zone 32N WGS84.

Finally, maps were standardised. In this step, impact scores for each criterion are made dimensionless and mutually comparable through the identification of the relevant transformation functions that convert the data related to each criterion to a value judgement on a 0-1 scale (Ferretti,

**Table 1. Criteria used in the implemented multi criteria decision making analysis.**

| Category | Criterion | Code | Type | Data source |
|---|---|---|---|---|
| Physical aspects | elevation | EL | factor | Tinitaly DEM (Tarquini *et al.*, 2007) |
| | grade | GR | factor | Tinitaly DEM (Tarquini *et al.*, 2007) |
| | morphological constraint | MC | constraint | Tinitaly DEM (Tarquini *et al.*, 2007) |
| | hydrogeological risk | HGR | constraint | Emilia-Romagna Geoportal |
| Environmental aspects | land cover | LC | factor | Emilia-Romagna Geoportal |
| | forbidden areas | FA | constraint | Emilia-Romagna Geoportal |
| | protected areas | PA | constraint | Emilia-Romagna Geoportal |
| Economic aspects | substrate providers' proximity | SPP | factor | Road network = Emilia-Romagna Geoportal<br>Substrate Providers = WEB |
| | customers' proximity | CP | factor | Road network = Emilia-Romagna Geoportal<br>Laying hens farms = Italian National Livestock Register |

2011). Thus, the criterion maps are directly comparable and ready to be used in the following steps of the MCDM analysis.

The appropriate standardisation technique for each criterion was based on recommendations by the experts involved in the methodology development. A detailed description of the constraints and factors used in this study is included below.

*Constraints (exclusion criteria)*

The morphological constraint (MC) concerns areas with grade greater than 30%, therefore unsuitable (value = 0) for the installation of any type of plant, due to the high excavation and construction costs. The grade was calculated starting from Tinitaly DEM (Tarquini *et al.*, 2007), a digital terrain model with a 10 meters resolution, available for free at: https://tinitaly.pi.ingv.it/.

The hydrogeological risk (HGR) constraint concerns areas with high hydrological and landslide risk, not suitable (value = 0) for the installation of any type of plant. The GIS layers used to compute this constraint were downloaded from the ER Geoportal and are listed in Supplementary Table S1; they were reclassified to 0 in risk-prone areas, and 1 elsewhere.

The forbidden areas (FA) constraint concerns areas prohibited for the installation of an insect farm for health and environmental reasons, similarly to what happens for production activities such as livestock farms or production facilities hazardous for human health. Currently Italy has no specific law or regulation from which could be inferred or derived a list of land cover classes deemed as suitable (or not) for insect farming, and the same holds for any conceivable buffer distance: it is anyway likely that in the future ad hoc regulations will be issued. Considering this regulatory gap, the land cover classes and distances from them (Table 2) commonly used in Italy for animal husbandry were used to calculate FA constraint. Land cover classes were extracted from 2017 land cover classification available on ER Geoportal (see below for more details) and buffer areas were calculated in GIS environment.

The protected areas (PA) constraint concerns ER natural areas subject to environmental protection regulations (national and regional parks and reserves). These areas were deemed unsuitable as they are subject to specific restrictions on the authorised production activities. The GIS layer of the protected areas (dataset ID: 5d9f109f-77b6-4eec-872f-9c72e3e65ed9) was downloaded from the ER Geoportal and reclassified to 0, while remaining areas to 1.

*Factors (non-exclusion criteria)*

For the land cover (LC) factor, the 2017 land cover classification (dataset ID: r_emiro:2020-04-06T135319) available on ER Geo-portal was used. The 1:10,000 original land cover classification was performed through photointerpretation of 2017 airborne 20 cm spatial resolution real colours and near infrared imagery. In this study, the 90 original land cover classes have been standardised by reclassifying them with values from 0 to 1 (Supplementary Table S2); anthropized areas (with the exception of production plants and livestock farms that were reclassified to 1), wetlands and water bodies have been reclassified to 0, while agricultural areas to 1 and wooded areas to 0.5.

**Table 2. Buffer distances (m) used to calculate the forbidden areas constraint.**

| Land cover class | Buffer (m) |
|---|---|
| Urban areas | 250 |
| Isolated residential structures | 50 |
| Water areas | 50 |

The elevation (EL) factor was derived from Tinitaly DEM (Tarquini *et al.*, 2007). According to expert opinion, the higher the elevation, the lower the suitability. Therefore, the related criterion map was obtained by standardising the DEM by means of a linear monotone function with decreasing suitability.

The grade (GR) was calculated starting from Tinitaly DEM (Tarquini *et al.*, 2007) and was further reclassified. Grade between 0 and 10% is considered optimal and has been reclassified to 1. Between 10 and 30% suitability decreases as grade increases; therefore, grade was reclassified and standardised using a decreasing linear monotone function. Grade values above 30% are considered unsuitable (value = 0) and included in MC constraint.

The substrate providers' proximity (SPP) factor, together with the customers' proximity (CP) factor, evaluates the economic suitability of the installation of HI farms. It evaluates the proximity to the plants that supply the agro-industrial by-products selected for HI diet within the Flies4Value Project, measured as the time required to reach the insect farm. Although the criterion is not calculated in purely economic terms, it implicitly includes an assessment on this aspect, since the closer the supplier, the more economically sustainable the area for the installation of the HI farm is, due to the lower transport costs. Figure 3 shows the methodology implemented to determine this factor. First, potential suppliers and their addresses for each type of substrate were surveyed on internet (Table 3) using ParseHub software, a free downloadable web scraper, and imported in GIS environment to determine their spatial coordinates. Considering that the proposed methodology is targeted to industrial-scale insect farms, only the main agro-industrial plants able to provide big quantities of by-products were selected excluding small direct producer markets.

Subsequently, a cost-distance analysis was carried out for each type of plant using the 'gdistance' package (Van Etten, 2017) of R software. This allowed to calculate distances as function of time, i.e. as travel times calculated in minutes. For the analysis, the GIS road network layer available on the ER Geoportal (dataset ID: r_emiro:DBTR:STR_GLI) was used applying the average travel speeds shown in Table 4.

Since the results of this step concern only grid cells corresponding to the road network (the others have NA values), the data was spatialised for the entire regional territory by means of a moving window median filter. The

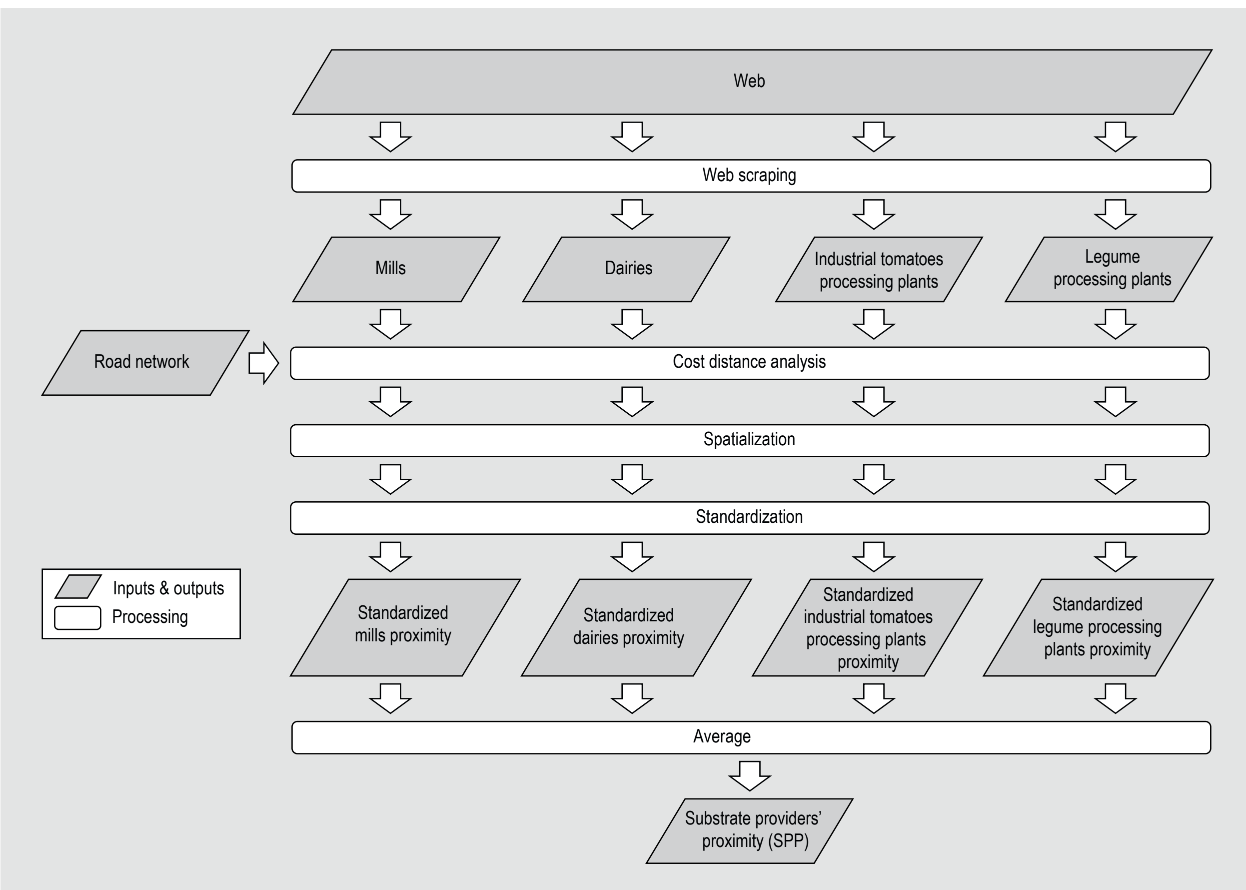


**Figure 3. Flowchart of implemented methodology to determine substrate providers' proximity factor.**

**Table 3. Plants surveyed for the determination of the substrate providers' proximity factor.**

| Substrate | Type of plant | Surveyed plants |
|---|---|---|
| Bran | Mills | 83 |
| Whey | Dairies | 319 |
| Tomato peels and seeds | Industrial tomato processing plants | 26 |
| Legume waste | Legume processing plants | 21 |

next step consisted in standardisation as a function of time according to the values indicated in Table 5. This led to the creation of 4 intermediate standardised proximity maps (one for each type of substrate) which were averaged to derive the final SPP criterion map.

The customers' proximity (CP) factor evaluates the proximity of laying hen farms, identified by the Flies4Value Project as potential customers for HI-derived protein meal. For its determination, a process similar to that implemented for PFS factor was used, with the exception of the last step (averaging) as it was not necessary.

Data on laying hen farms located in ER was downloaded from the website of the Italian National Zootechnical Registry (https://www.vetinfo.it/j6_statistiche/index.html#/). In the Region there are 200 laying hen farms for a total of over 10,000,000 heads distributed over 77 municipalities. The website provided the municipality for each laying hen farm, but no names and addresses were available, thus preventing a precise geolocation. Considering the small average size of the ER municipalities (68.4 $km^2$), the centroid of the municipalities in which laying hen farms are located was used for calculations.

**Table 4. Average travel speeds by road type applied for the cost-distance analysis.**

| Road type | Average speed (km/h) |
|---|---|
| Highway | 100 |
| National road | 70 |
| Provincial road | 60 |
| Municipal road | 40 |
| Military road | 40 |
| Private road | 30 |
| Forest road | 20 |

**Table 5. Thresholds applied for the standardisation of the proximity maps of each *Hermetia illucens* diet substrate supplier.**

| Proximity (minutes) | Value |
|---|---|
| 0-15 | 1 |
| 15-30 | 0.8 |
| 30-45 | 0.6 |
| 45-60 | 0.4 |
| 60-75 | 0.2 |
| <75 | 0 |

### Estimating criterion weights

The weight assigned to each criterion is one of the key steps in the development of MCDMs, as it determines the influence of each individual criterion in the final criterion map overlaying. In this study, weights were assessed using the Analytical Hierarchy Process (AHP) method (Saaty, 1988), a well-known procedure that has been incorporated into several GIS-based suitability evaluations (Carver, 1991; Jankowski and Richard, 1994; Makropoulos *et al.*, 2003; Malczewski 1999a,b, 2004; Marinoni, 2004). The AHP method calculates the weights associated with the respective criterion using preference matrices, in which all the identified criteria are compared to each other by competent subjects based on preference factors. The weights of the individual comparisons are then aggregated. The AHP has gained popularity both due to its ability to integrate heterogeneous data and because the calculation of the required weights is relatively simple, even for a large number of criteria (Chen *et al.*, 2010a).

Two hundred participants were recruited via mail on a national and international basis and invited to fill anonymously a questionnaire designed using Google Forms, which was accessible online from 7 to 16 April 2021. The participants to the panel were selected to form groups of homogeneous size representing the main categories of stakeholders (researchers, specific stakeholders, decision makers, industrialists) involved in the insect farms development process, thus favouring independency and normality of the results. The questionnaire consisted of 10 sections in which the 5 selected factors (constraints were not included) were pairwise compared using the scale of preference (Saaty scale) indicated in Table 6.

The results were processed to derive the preference matrices and, according to Saaty's methodology, to derive the relative weights for each criterion.

**Table 6. Saaty scale used for pairwise comparison.**

| Intensity of importance | Description |
|---|---|
| 1 | Equal importance |
| 3 | Moderate importance |
| 5 | Strong or essential importance |
| 7 | Very strong or demonstrated importance |
| 9 | Extreme importance |
| 2,4,6,8 | Intermediate values |
| Reciprocals | Values for inverse comparison |

**Table 7. Ranges used for the final reclassification of the suitability classes.**

| Range | Suitability class |
|---|---|
| 0-0.25 | Unsuitable |
| 0.25-0.5 | Poorly suitable |
| 0.5-0.75 | Suitable |
| 0.75-0.99 | Very suitable |
| 1 | Optimal |

Since human judgment can violate the transitivity rule and thus cause inconsistencies, the consistency of the overall set of pairwise comparison results was assessed using the consistency ratio (CR) (Saaty, 1977). CR has already been widely used as a measure of consistency in numerous applications of the AHP methodology (Chen *et al.*, 2010b). A CR value ≤0.10 indicates a reasonable level of consistency and therefore the calculated weight values are valid and usable (Park *et al.*, 2011; Saaty, 1977). On the other hand, if CR>0.10, pairwise comparisons lack consistency. Several methods have been developed to correct these inconsistencies, including the one developed by Harker (1987), available in the 'ahpsurvey' package (Cho, 2019) of R software and implemented in this investigation. In short, the method consists of a reiterative process of detecting the most inconsistent judgements and replacing them with consistent values until a CR value ≤0.10 is reached.

### Overlaying map layers and reclassified final suitability map

Once the criteria weights were established, criterion maps were aggregated using the weighted linear combination (WLC) method to produce the suitability map. WLC is one of the most common GIS approaches for carrying out MCDMs (Malczewski, 2000); it combines the criterion maps of both factors and constraints according to the following formula (Gemitzi, 2007; Ferretti, 2011):

$$\mathrm{SI} = \sum_{i=1}^{N} w_i x_i \prod_{j=1}^{K} b_j \tag{1}$$

where: SI = overall suitability index value; $w_i$ = weight of factor *i*; $x_i$ = criterion score of factor *i*; $b_j$ = criterion score of constraint *j*; *N* = number of factors; *K* = number of constraining criteria. The obtained suitability map gave values between 0 and 1, where high values correspond to areas suitable for HI farms installation, while low values correspond to areas unsuitable for this purpose. This output was furtherly reclassified according to the ranges of Table 7, defined on expert opinion. The final suitability classes were: 'unsuitable', 'poorly suitable', 'suitable', 'very suitable', 'optimal'. The range 0-0.25 mainly includes areas that are unsuitable due to one or more constraints. The range 0.25-0.5 includes poorly suited areas, while for values from 0.5 upwards the area is considered suitable. Specifically, the area is considered 'very suitable' for values between 0.75 and 0.99, while the last class ('optimal') includes all those areas that have obtained a maximum score for both overall suitability and for each criterion evaluated.

## 3. Results

### Criterion maps

Criterion maps for each implemented criterion are shown in Figure 4. After standardisation, criteria values ranged from zero to one, where a value of zero meant that suitability for that criterion was null, while a value of one meant optimal suitability.

It is worth noting that SPP and CP criteria maps have most values in the range 0.4-1. This aspect, considering the relative criteria weights (see next section), had a crucial impact in the final suitability map.

### Criterion weights

The questionnaire to assess criterion weights was compiled by 42 participants. The independency and normality of the results, with respect to the background of the involved stakeholders, is assumed considering that all the different types of stakeholders involved in the insect farms development process were homogeneously represented in the panel and that the questionnaire was compiled by a substantial number of participants. The resulting CR value was 0.298, higher than the 0.1 threshold which indicates the acceptability of the test. Therefore, the method developed by Harker (1987) was applied, leading to a CR value of 0.097. The resulting criterion weights are shown in Table 8. The highest weights were attributed to the economic criteria (SPP and CP), which together achieve about 70% of the suitability. LC factor accounts for 18%, while little importance was assigned to physical criteria (EL and GR) which together account for 9%.

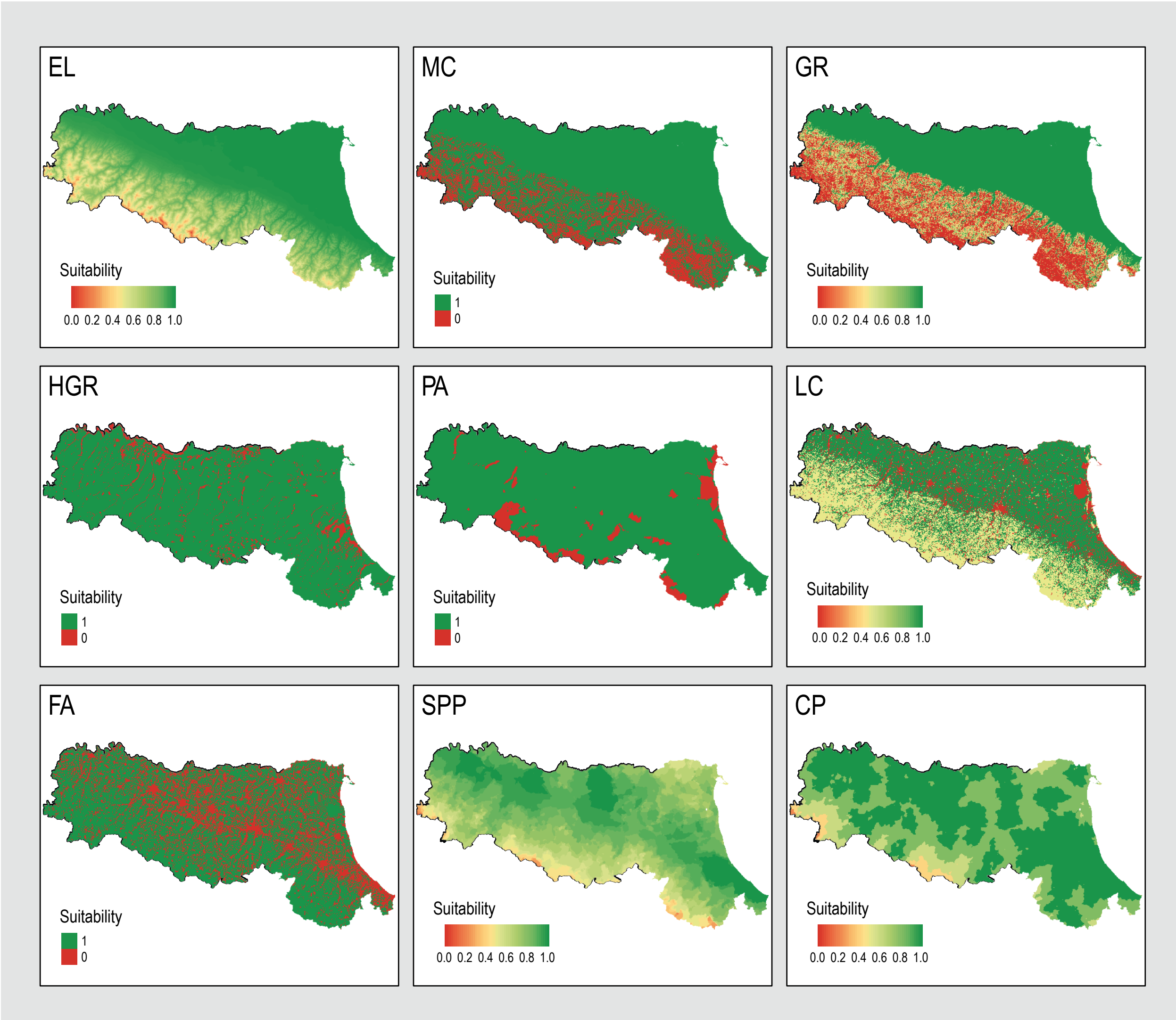


**Figure 4. Criterion maps. CP = customers' proximity; EL = elevation; FA = forbidden areas; GR = grade; HGR = hydrogeological risk; LC = land cover; MC= morphological constraint; PA = protected areas; SPP = substrate providers' proximity.**

### Suitability map

The final reclassified suitability map for HI farm installation in ER is shown in Figure 5; surfaces (km$^2$) and percentages of each suitability class are provided in Figure 6. About 11.6% of the regional territory falls into the 'optimal' class, located exclusively in the Po Valley area. The 'highly suitable' and 'suitable' classes account for 23.1 and 9% of the total regional surface, respectively, bringing overall the areas suitable for the establishment of HI farms to a total of 43.8% of the regional territory. Most of the remaining area of the regional territory is in the 'unsuitable' class (56.2%) due to one or more constraints, while only a very low percentage (0.1%) falls into the 'poorly suitable' class.

Figure 7 shows the extent of unsuitable areas for each constraint considered in the analysis. Most of the unsuitable areas are due to FA constraint, covering more than 7,000 km$^2$, followed by MC (4,337 km$^2$); HGR and PA constraints have a lower impact, counting for 1,810 and 1,737 km$^2$, respectively.

**Table 8. Criterion weights and percentage contribution obtained through analytical hierarchical process procedure.**

| Criterion | Weight | Percentage contribution |
|---|---|---|
| Elevation (EL) | 0.059 | 5.9% |
| Grade (GR) | 0.044 | 4.4% |
| Land cover (LC) | 0.180 | 18% |
| Substrate providers' proximity (SPP) | 0.450 | 45% |
| Customers' proximity (CP) | 0.264 | 26.4% |

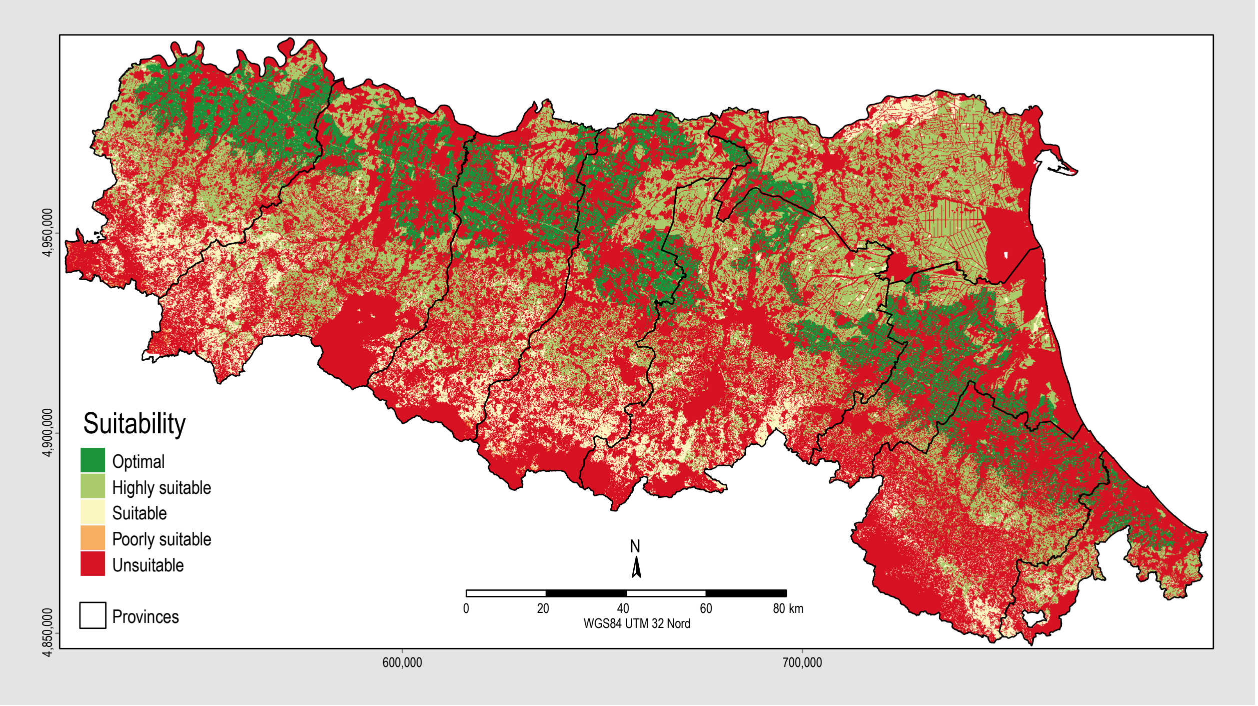


**Figure 5. Classified suitability map for *Hermetia illucens* farms.**

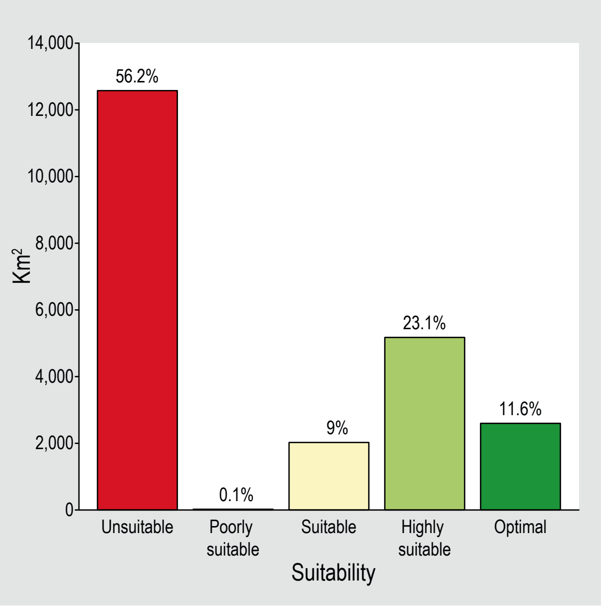


**Figure 6. Extent (km$^2$ and percentages) of the suitability classes for Emilia-Romagna region (Italy).**

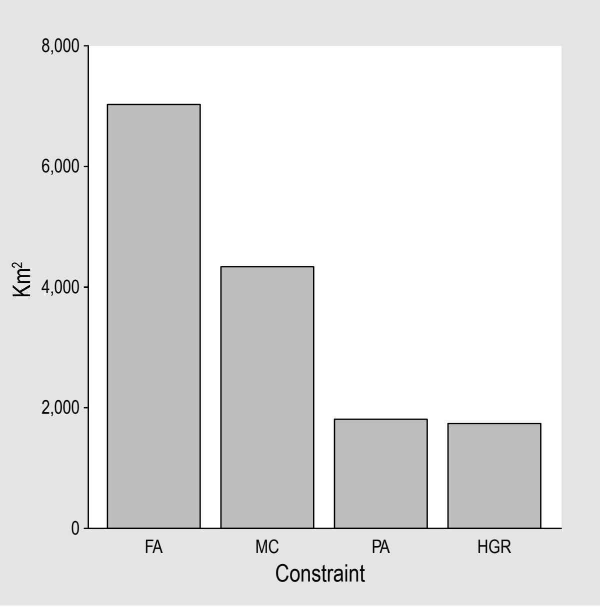


**Figure 7. Extent of unsuitable areas to the installation of *Hermetia illucens* farms for each constraint considered in the analysis. FA = forbidden areas; HGR = hydrogeological risk; MC = morphological constraint; PA = protected areas.**

Figure 8 provides the extent (km$^2$ and percentages) of each suitability class at province level. Unsuitable areas vary from a minimum of 46.3% for Piacenza to a maximum of 69.5% for Forlì-Cesena. Areas at least suitable (i.e. areas falling into the 'suitable', 'highly suitable' and 'optimal' classes) range between 30.6% (Forlì-Cesena) and 53.4% (Piacenza). Forlì-Cesena is the province with the highest percentage of 'unsuitable' areas (69.5%) and the lowest percentage of at least suitable areas (30.5%), of which only 8.3% is in the 'optimal' class. Similar results emerged for Rimini province.

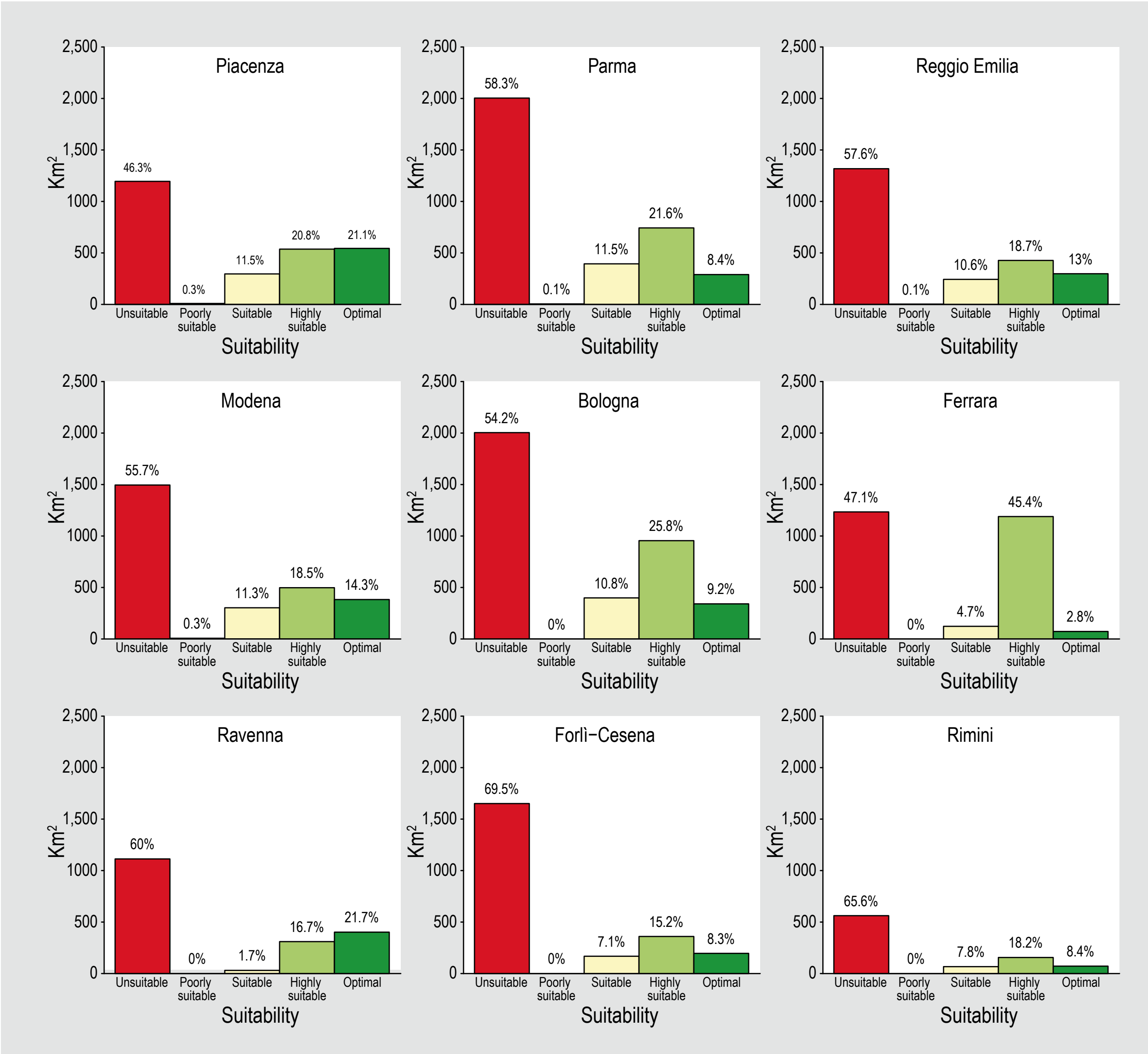


**Figure 8. Extent (km$^2$ and percentages) of the suitability classes for the provinces of Emilia-Romagna region.**

## 4. Discussion and conclusions

In the present study a methodology for assessing territorial suitability to host HI farms in ER Region (Italy) was developed; it considered both exclusionary (constraints) and non-exclusionary (factors) criteria coupling GIS with MCDM techniques. To the authors' knowledge, this is the first time that the MCDM process is applied to insect production.

The case study showed that the analysed region is characterised by a marked suitability for the installation of HI farms: although a large percentage of its area was found 'unsuitable' due to one or more constraints, the remaining part of the territory was substantially suitable and about 11% was classified as 'optimal'. This high overall suitability is mainly due to the marked agro-industrial nature of the region, which implies a large availability of by-products for HI feeding and a high accessibility to the plants that supply them, as they are widely distributed over a large part of the territory. Only a very low percentage of the region ER was found to be 'poorly suitable' (0.1%), thus indicating that, apart from the areas that are not suitable for one or more constraints, the ER territory is substantially suitable for HI plants.

Most suitable areas for the establishment of HI farms are located in the Po Valley near the main agro-industrial centres, both for the ideal physical characteristics and for the large presence of substrate suppliers and laying hen farms, with consequent high PFS and PC values. In fact, the AHP process led to the weight definition (Table 8) which gave a strong relevance to economic factors. As regards the Appennines, large areas are unsuitable due to

MC, PA and HGR constraints; in the remaining surfaces suitability falls into the 'suitable' and 'very suitable' classes, even if the presence of both substrate suppliers (especially industrial tomato and legume processing plants) and laying hen farms is less.

The study revealed a great variability of suitability between the provinces, which mainly depends on the physical characteristics of the territory and the peculiarities of the local production systems. The high suitability found for Piacenza is mainly due to the marked agro-industrial production vocation of the province with a consequent high presence of plants capable of supplying substrates for HI feeding. On the contrary, the south-eastern provinces bordering the Adriatic Sea (Forlì-Cesena, Rimini and Ravenna) are those with the lowest percentages of suitability, despite the flat nature of large portions of their territory. This is due to the strong predominance of the tertiary sector (mainly tourism) and the consequent lower presence of agro-industrial processing plants and laying hen farms compared to other provinces.

The final suitability map constitutes an important decision support tool for spatially identifying the optimal location for future HI farms installation in the region, highlighting, at the same time, the critical areas unsuitable for this activity due to one or more constraints.

It should be emphasised that this study has limitations, mainly related to the availability of data. The list of selected criteria included only data available for the entire study area and in spatial format (i.e. georeferenced); additional parameters that could enrich the analysis were omitted because not available in this format. Table 8 clearly indicated that economic criteria (PFS and PC) were considered the most influential by the experts involved in the criterion weights definition process. Therefore, it might have been useful to include other economic factors, such as the average cost of the land and/or funds where to install HI farms, as this is usually a discriminating factor in choosing the optimal location. However, these data were not available in spatial format for large areas of ER region and could not be included in the analysis. Furthermore, regarding SPP and CP economic factors, they were evaluated based on the time needed to reach them, that is in the form of accessibility. This choice was made because, in the development phase of the methodology, information or estimates were not yet available about the quantity of substrates required annually and/or the need to replenish during the year (for example due to impossibility of stabilising the substrates) or only in certain periods (for example due to seasonality). Such information could make it possible to explicitly evaluate these factors as a function of the cost of sourcing substrates and not only as a function of the time required to reach substrate suppliers. Moreover, the methodology could be integrated in the future also considering the presence of competitors to insect farms. This criterion has not been implemented in the present work since there are currently no other production activities comparable to insect breeding, i.e. capable both to dispose and valorise waste with little or no value and to transform it into proteins and other products of high added value, in a sustainable way alternative to traditional methods.

Another criticality that emerged during the analysis is the lack of regulations about the areas where to install HI farms and the minimum distances to be respected. While it is more than likely that it will not be possible to install insect farms in urban areas, it is difficult to predict the minimum distances (buffer) that shall be respected. However, these distances have a strong impact on the extent of the surfaces which will consequently be prohibited (i.e. FA constraint). In this study, it was decided, after confrontation with various regional administrative parties, to use the values indicated in Table 2. However, to demonstrate how much the extent of FA constraint can vary according to the buffer distances adopted, Table 9 shows the extent of forbidden areas according to scenarios based on different buffer distances (scenario 1 corresponds to the distances used in this study); prohibited surfaces vary considerably as a function of distances apparently similar to each other. Furthermore, higher buffer distances would greatly reduce suitability in highly suitable areas (i.e. flat areas near the main agro-industrial centres) as they are among the most populated in ER.

Finally, a critical aspect that emerged is a difficulty to apply the AHP method to a panel of participants not familiar

**Table 9. Extent of forbidden areas according to scenarios based on different buffer distances.**

| Scenario | Buffer (m) | | | Forbidden areas (km$^2$) |
|---|---|---|---|---|
| | Urban areas | Isolated residential structures | Water areas | |
| 1 | 250 | 50 | 50 | 7,028 |
| 2 | 500 | 100 | 100 | 11,269 |
| 3 | 750 | 150 | 150 | 14,577 |

with the pairwise comparison process. The initial CR value equal to 0.32, further improved using the method developed by Harker (1987) leading to an acceptable value <0.1, testified to this difficulty and highlighted inconsistencies in the answers provided by participants. This drawback has already been showed in previous works (Deng, 1999; Macharis *et al.*, 2004) and the results of this investigation suggest that participants should be helped by a facilitator or that more intuitive methods could be implemented.

Despite these limitations, the methodological framework presented in this study is proposed as a solid decision support method for assessing suitability and identifying the optimal areas for HI farms installation, and it can be improved in the future as key production and legislative aspects regarding industrial-scale insect farming are defined. The tool can integrate other existing analyses on economic feasibility and environmental sustainability in the regional and local planning phase and provide a comprehensive assessment for virtuous insect production on industrial scale. Furthermore, the method was developed using only open-source data and software, an aspect that increases its replicability. Finally, the criteria chosen in this analysis and the related parametrisations were based on the specificities of ER region and HI business model identified within the Flies4Value Project; however, the evaluation framework could be easily adapted to other insects, diets and study areas according to their peculiarities. The results of the present investigation show that MCDM represents a valuable decision support tool by providing a platform for the integration of information and methods necessary to assess the environmental and economic sustainability of HI farms.

## Supplementary material

Supplementary material can be found online at https://doi.org/10.3920/JIFF2022.0085

**Table S1.** GIS layers used to compute hydrogeological risk constraint.

**Table S2.** Reclassified values used to compute land cover factor.

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## Conflicts of interest

The authors declare no conflict of interest.

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