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GIS-based land suitability analysis for the optimal location of integrated multi-trophic aquaponic systems

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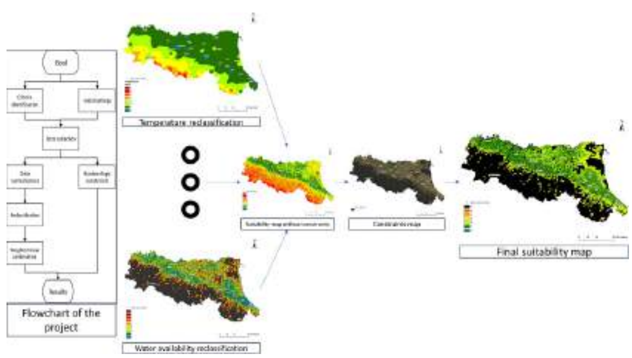
HIGHLIGHTS

- A GIS-MCDA model has been developed to investigate the best location for an aquaponic system.
- Decisions and criteria have been selected via a participatory mechanism involving experts in the field.
- The GIS-model has allowed to exclude the unsuitable areas in the Emilia-Romagna region.
- The most suitable areas in the region have been identified based on multiple criteria selection.
- The most suitable areas are located nearby most populated cities in Po Valley and near the sea.

GRAPHICAL ABSTRACT



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ABSTRACT

Aquaponics has witnessed global proliferation and a notable enhancement in sustainability in recent years. Consequently, it assumes paramount importance to delineate optimal locations for its implementation, in fact, the success of an aquaponic facility also depends on its geographical placement, necessitating consideration of many variables encompassing natural resources, socioeconomic factors, infrastructural availability and environmental constraints, whether natural or artificial. This paper focuses on the definition and test in the Emilia-Romagna region (Italy) of a GIS-based multi-criteria land suitability assessment model aimed at allowing the diffusion and environmental integration of innovative integrated multi-trophic aquaponic systems. The process has been implemented with a Weighted Linear Combination (WLC) model, where decisions and criteria were selected via a participatory mechanism involving experts in various fields. The region has been subdivided into 50 × 50 m grid cells, with each grid cell being associated with a value ranging from 0 to 8. In this context, a rating of 0 means unsuitability, while a rating of 1 denotes minimal suitability, and the highest rating of 8 designates maximal suitability. Notably, a substantial portion of the surveyed territory has been found to be completely unsuitable for the establishment of aquaponic facilities. More than 86.4% of the remaining suitable areas were rated 6, 7, or 8, affirming the overall favourability of the Emilia-Romagna region for aquaponic installations. Finally, the veracity and robustness of the results have been tested through a one-at-a-time sensitivity analysis, that has proven the appropriateness of the proposed model.

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1. Introduction

In 2000, the members of the United Nations signed the Millennium Declaration with which they undertook to respect the so-called Millennium Development Goals (United Nations, 2000b). These statements had the objective of enhancing the lives of every person in the world within 2015 based on eight goals. The first and most urgent of these was the eradication of extreme poverty and hunger (United Nations, 2000a).

The document has been updated in 2015 with new goals to be achieved within 2030. The new objectives, the so-called Sustainable Development Goals, have the intent of "achieving a better and more sustainable future for all". They present a list of seventeen goals. The second one is "End hunger, achieve food security and improved nutrition and promote sustainable agriculture" (United Nations, 2015). It is clear that the elimination of hunger is a major topic and a subject that is being considered and analysed by many institutions, from local to international levels.

In this context, demand for marine products for food has increased in the past years (Naylor et al., 2021) and the global request for seafood is continuing to rise sharply, both because of population growth and because of the increased per capita consumption (Charles et al., 2010). Therefore, there's been an increasing pressure on natural resources and, consequently, a rising interest in models for sustainable production. For these reasons, aquaculture has progressively gained popularity over recent years (Morro et al., 2022), even thanks to the fact that it has become progressively more sustainable over the past two decades (Naylor et al., 2021).

In this framework, an aquaculture approach that can play an important role and is growing in popularity is IMTA (Integrated Multi-Trophic Aquaculture) where aquatic species from different trophic levels are raised together. This generates many positive effects such as the improvement of the efficiency of the system and the reduction of waste. Species at the lower trophic level like plants or invertebrates feed on waste products such as faecal matter or uneaten food from the higher trophic species, generally composed of fish (FAO Fisheries and Aquaculture Department, 2009).

A variant of the IMTA approach is aquaponics, which is a food production closed system coupling aquaculture with hydroponics (cultivating plants in water, without soil). The principles are the same as in the IMTA approach: the waste products of the aquaculture waste accumulate in the water. This wastewater, full of nutrients, is then used as a fertiliser for the plants (Rakocy et al., 2006). The difference is that the process is enclosed in an inland system where parameters such as air temperature or water oxygenation can be monitored and modified if unsuitable. Nowadays, aquaponics is an important implementation because it is a sustainable solution for food production, as IMTA approaches in general (Kloas et al., 2015).

To facilitate the diffusion of these sustainable systems, it is important to identify the most suitable areas for their realisation. The success of an aquaponic project depends especially on the proper selection of a site where the system would be built. To maximise the performance of production of an aquaponic system, it is essential that it is placed in the most proper location, not only taking into consideration the natural variables and resources in need for the system to work adequately (such as water supply) but also the social, economic and infrastructural factors as well as natural or human limitations to the construction of the new plant.

In this field, GIS-MCDA approaches are methodologies that have been increasingly used. This technique, a methodology that couples Multi-Criteria Decision Analysis with GIS system, has been applied in many sectors, in the field of agri-food structures and infrastructure, it has been used to analyse the suitability of land use for agriculture such as in Kazemi and Akinci (2018) where they analysed the land use suitability for the hosting of rainfed farming in a province of Northern Iran, taking into consideration simultaneously meteorological (temperature, rainfall and sunshine hours), physical (altitude, slope, and land uses among others) and chemical factors (organic matter, pH and texture classes). The authors found out that these factors may also become constraints if they reach a certain threshold: rain must be superior to 200 mm/year, soil erosion is also a limiting factor, as well as inadequate soil depth and high slope. GIS-MCDA techniques are also applied to Saltuk and Artun (2019) who investigated a model to select the most suitable location for greenhouses in the four provinces of the Lower Euphrates Basin, Turkey, an area where these kinds of agricultural facilities are not common. To do so, the study examines the climate conditions of the Antalya province, which has the highest quantity of greenhouses in Turkey, in terms of paragon, taking into account climate, soil, wind, altitude, slope, aspect and distance to water sources data. The approach is especially popular nowadays for the suitability analysis of renewable energy planning, such as solar farms as in Mensour et al. (2019) where they investigate the most suitable sites to host a photovoltaic system in Southern Morocco, considering various criteria, like solar irradiation, the closeness to existing facilities (roads and electricity cabins) and restriction factors such as the terrain slope, the protected areas and considering natural disaster risks. The approach has been used also for the evaluation of biomass energy facilities as in Jeong and Ramírez-Gómez (2018). Their study is about the selection of the proper location of a biomass plant in Extremadura, Spain. The analysis has been led using three criteria groups, namely the environmental one, the socio-economic one and the geophysical one. This work has been finalised with an F-DEMATEL (Fuzzy-DEcision-MAking Trial and Evaluation Laboratory) technique to form a structural arrangement among the criteria and their weights. GIS-MCDA has been also implemented to select the best areas for aquaculture locations. An example of GIS-MCDA applied to the identification of the best localisations of offshore aquaculture farms is in the works by Dapueto et al. (2015). They applied the technique to an area in the Ligurian Sea, Italy, considering factors concerning the environmental quality, the optimal conditions for fish and social-economical evaluation. Moreover, they took into account constraints such as the proximity to beaches, ports and diving sites. Many other authors dealt with GIS-MCDA applied to aquaculture, mostly for applications in the sea. Jean-Baptiste E. Thomas and Gröndahl (2019) conducted a study to determine the optimal location for macroalgae production along the West Coast of Sweden. Their analysis incorporated 13 criteria, among which some of the most notable are of environmental factors such as sea depth and chlorophyll concentration. Economic considerations, including fishing areas, were also given importance. Manca Zeichen et al. (2022)presented a paper that outlies the methodology for identifying the ideal site for a fish farm along the Tyrrhenian coast in Tuscany, Italy. Their study relied on a spatial model developed through the collection and analysis of Earth Observation (EO) data, encompassing parameters such as water temperature, turbidity, in situ oceanography measurements (e.g., pH values), and considerations related to infrastructure and environmental constraints, such as military easements and protected areas. The application of GIS-MCDA was also highlighted for selecting suitable areas for inland aquaculture locations. Shunmugapriya et al. (2021) identified suitable land for inland aquaculture in the coastal region of Thiruvarur, India. Their study aimed to suggest sustainable practices for increasing the number of aquaculture farms in the area, considering various parameters, especially topographic aspects such as hydrology, land use, and elevation. Bandira et al. (2021) identified suitable areas for a potential inland aquaculture site in the George Town Conurbation, Malaysia. Their approach incorporated diverse criteria, including soil characteristics (e.g., pH), topography (elevation and slope), and infrastructure and facilities (e.g., distance to water bodies and roads). Similar to other examples, the study considered constraints, notably protected areas and built-up zones. Calle Yunis et al. (2020) explored the optimal location for constructing an inland fish farm for rainbow trout in the Amazonian district of Molinopampa, Peru. Their work, like other examples, organized criteria into categories, encompassing environmental factors such as slope, land use, and pH; economic criteria such as distances to roads, markets, and inputs; and social constraints, including populated and protected areas.

As it is evident, all these studies consider similar factors for their analyses. The most recurrent ones are the meteorological condition, the land uses, the distance from the existing facilities, topographic indicators and the economic feasibility.

Moreover, all these works are characterised by three common elements: the reclassification of the criteria, the weighting of the criteria and the aggregation of the criteria. The first one is essential to make data comparable, they are, in fact, of many different types and they could not be used without this refinement. The weighting is utilised to give different importance to the criteria applied in the model. Most of the times, the choice of weight importance is determined by asking opinions from experts. Finally, the aggregation of the criteria is useful to create a final suitability map that can be later delivered to stakeholders and policymakers.

In this context, the GIS-MCDA methodology can play a significant role as a decision support tool regarding best location for an aquaponic system. To the authors' knowledge, to this moment, an implementation on aquaponics has not been analysed yet, therefore it deserves further analyses.

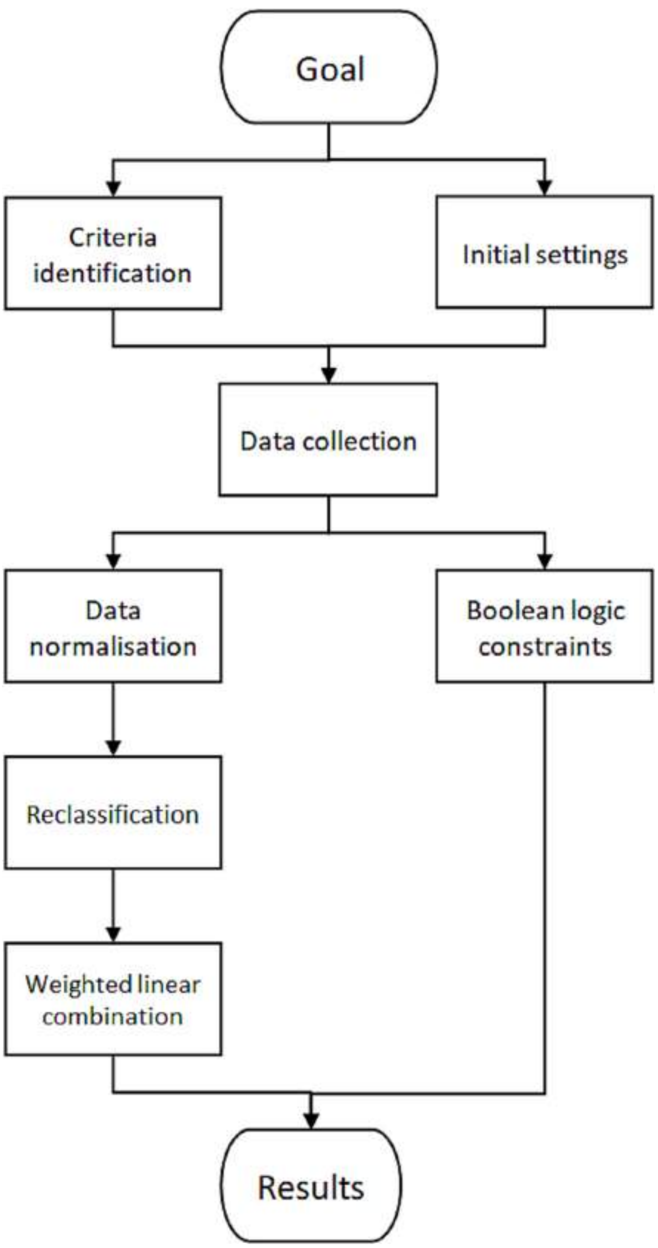

Fig. 1. Flowchart of the GIS-MCDA process.

This paper focuses on the definition and test of a GIS-based multi-criteria land suitability assessment model allowing the diffusion and environmental integration of an innovative integrated multi-trophic aquaponic system for environmentally friendly marine fish and halophytic plants production, developed and demonstrated within the international project SIMTAP (Self-sufficient Integrated Multi-Trophic AquaPonic systems for improving food production sustainability and brackish water use and recycling, UniPI et al., 2019). The specific goals of this work are both to conceive a model integrating environmental factors, availability of resources and infrastructure, potential access to market and labour, and potential interferences with other land-uses and activities, and to implement the model on a case-study at the regional scale in the Mediterranean area, also paving the way for extension and application of the model to other contexts.

The study area is the Emilia-Romagna region, located in Northern Italy and facing the Mediterranean Sea. Thanks to its climatic and environmental qualities, the Emilia-Romagna weather is suitable to host an aquaponic plant and, moreover, it has been proved that it is economically feasible to build aquaponic systems in a Mediterranean region (Asciuto et al., 2019).

The paper will be articulated in 3 sections. Section 2 is about the materials and methods, subdivided into five subparagraphs (study area, structure of the proposed GIS-MCDA model, criteria and constraints identification, definition of the weights, reclassification procedure); Section 3 is about the results and the sensitivity analysis, Section 4 reports the conclusions.

2. Materials and methods

2.1. Study area

The study area is the Italian region of Emilia-Romagna, located in Northern Italy between 45°07′ N and 43°43′ N and between 9°12′ E and 12°45′ E. It has approximately an area of 22,500 km^2 and a population of roughly 4.5 million inhabitants. The region is one of the wealthiest in Italy and in the European Union.

The most populated cities are placed on the ancient Roman way called Via *Aemilia*, from which the region takes the first of its name, Emilia. This road divides the territory into two almost equivalent areas: the north-east consists of the plains of the Po valley, while the other half, almost equally subdivided into hilly and mountainous territory, is composed of the Northern section of the Apennine Mountains.

Political and natural boundaries match, in fact, the northern limit is the Po River, the eastern border is the Adriatic Sea and the southern-western boundary is defined by the Apennines.

The coastline measures about 135 km and it is mostly flat and sandy. The northernmost part of the Emilia territory is occupied by the Po Delta and by the shallow brackish lagoons of Comacchio. Besides the Po River, the region has a developed hydrographic network. Most of the rivers have their sources in the mountains in the south, they follow the valleys and travel the plains until they flow into the Po River. Hence, the majority of the rivers have a south-north direction. Emilia-Romagna has also an evolved system of artificial canals used for civil, industrial and agricultural purposes.

The predominant climate of Emilia-Romagna is the temperate one, especially in the Po Valley. It is characterised by hot and humid summers and cold and rainy winters. On the Apennines, the climate is oceanic with cooler winters and temperate summers and common rainfalls also during summers, while, along the coastline, it becomes more similar to the Mediterranean climate, with milder winters.

Thanks to the plains and fertile of the Po Valley, agriculture, especially cereals and wine is a leading sector of the region, as well as livestock, in particular cattle and pig breeding.

Table 1
Factors and related submodels.

Water availability	Atmospheric conditions	Topographic conditions	Infrastructures and facilities	Access to market	Land use
Proximity to the nearest water source (sea, freshwater, brackish water)	Average annual temperature	Elevation	Proximity to electricity network	Income	Current land use type (CORINE land cover)
		Slope	Proximity to road network	Proximity to settlements and urban areas	
			Proximity to sewage network	Unemployment rate	
			Proximity to fish hatcheries / fishfarms	Potential consumers (proxy: population density)	
			Proximity to gas network	Proximity to logistic platforms (harbour, etc.)	
			Proximity to plant nurseries	Potential organic products consumers (proxy: age groups and education level)	
			Proximity to industrial activities		

As it will be demonstrated later in the text, access to water, meteorological conditions, resource availability facilitated by fertile soil, and proximity to potential customers driven by high population density in the Po Valley area are all crucial factors for determining the optimal locations of an aquaponic plant. Consequently, Emilia-Romagna presents itself as a promising region for conducting a thorough investigation towards the establishment of an aquaponic system.

2.2. The structure of the proposed GIS-MCDA model

The methodology proposed for this work is a GIS-MCDA process: a combination of a GIS analysis and a decision support system. Specifically, GIS (Geographic Information Systems) technologies allow the determination and evaluation of factors and the collection in a spatial database. GIS software is a notoriously good tool to solve many spatial problems, such as spatial optimisation, land suitability, site selection, etc. (Church, 2002; Tassinari and Torreggiani, 2006). Consequently, GIS has to be integrated with a tool that allows the simultaneous analysis of many criteria at the same time, namely, the Multi-Criteria Decision Analysis (MCDA) technique (Malczewski, 2006). MCDA is a decision-making analysis that can be used to solve problems that are characterised by a consistent number of choices among alternatives. MCDA helps the decision-makers choose the best solution. Integrated GIS and MCDA, or GIS-MCDA, is a common and prolific approach to solve many types of spatial problems thanks to its capacity to convert and merge geographic data together with the decision makers' preferences into a decision map that can later be used by land use planners (Malczewski and Rinner, 2015).

The GIS-MCDA method is then combined with the WLC (Weighted Linear Combination) method, which can be implemented in the GIS software thanks to the map algebra operations (Dana Tomlin, 1990). This methodology is characterised by the assignment of a weight to every criterion of the analysis based on its importance. The selection of the attributes that affect the suitability level and the definition of their weights, depending on their relative importance, are crucial phases in the implementation of a GIS-MCDA methodology (Malczewski and Rinner, 2015). In this study, they have been carried out through a participatory process, with the involvement of a panel of experts, as described in the following section.

In this study, this process has been applied together with a Boolean logic, used to exclude the areas that are unsuitable for the system and that cannot consequently be taken into consideration in the analysis. The following scheme (Fig. 1) represents the flowchart of the GIS-MCDA process.

Even though WLC methods can be implemented both with vector and raster format, the last one is often considered to be more effective to implement and supported in a better way by the GIS software (Dapueto et al., 2015). For this work, the initial data were in vector format (points, lines or polygons), therefore, they were first converted into raster before the analysis. Moreover, all raster layers must have the same extent and their pixels must be perfectly overlapped.

Since an area corresponding to 0.25 ha has been designed as an appropriate surface for hosting an aquaponic system, it has been decided by the experts that the cell size for the study is 50 × 50 m.

The management and processing of spatial data have been carried out via ArcMap 10.8.1 and ArcGIS Pro 3.0.0 with their plug-ins and tools.

2.3. Criteria and constraints identification

As in Pérez et al. (2005), the structure of the model has been built hierarchically. The relevant criteria have been selecting starting from an in-depth study of the scientific literature (Dapueto et al., 2015; Jeong and Ramírez-Gómez, 2018; Kazemi and Akinci, 2018; Mensour et al., 2019; Saltuk and Artun, 2019; Shunmugapriya et al., 2021), with the support of a panel of experts, using focus groups, panel workshops and questionnaires. The people involved in these processes were members of the research teams of the above-mentioned SIMTAP project, from various Mediterranean countries (Italy, France, Turkey and Malta), all experts in various disciplines including biology, environmental engineering, horticulture, aquaponics, agricultural science and agricultural and biosystems engineering.

As already pointed out, the criteria chosen for this analysis have been selected taking into account both experts' opinions and previous research works, derived from the above-summarized state of the art. All the criteria have been divided into three main categories: factors, constraints and contextual factors. Factors are criteria that have been considered important for the selection of a suitable aquaponic system site and that may alter the suitability of an area to host an aquaponic system. Constraints are criteria that forbid the construction of an aquaponic system. Contextual factors are criteria that may allow the construction of the system under specific circumstances.

The factors designated for this case study are:

- water availability,
- atmospheric conditions,
- topographic conditions,
- infrastructure and facilities,
- access to market,
- land use.

Each of these has been subdivided into subcategories, called submodels. Factors and their related submodels are shown in Table 1.

In the next paragraph, all the submodels will be presented and their presence in the study will be justified.

1) Proximity to the nearest water source: the presence of water is essential for the lifecycle of all organisms involved in the aquaponic mechanism.
2) Average annual temperature: maintaining an optimal atmospheric temperature is essential for the well-being of the organisms. Extreme temperatures, whether excessively low or high, could cause excessive expenses for air and water temperature control, and negatively impact the economic feasibility and environmental sustainability of the project.
3) Elevation: elevation can influence numerous factors, including temperature variation and accessibility. Excessive elevation may impede accessibility and increase the risk of flooding.
4) Slope: in cases where the terrain shows excessive steepness, the construction of an aquaponic system may be challenging and too expensive, potentially undermining the economic feasibility of the project.
5) Proximity to the electricity network: adequate access to electricity is essential for fundamental requirements such as lighting and powering all the equipment of the system (pumps, water and air heating and cooling, etc.).
6) Proximity to the road network: the system should ideally be situated in proximity to the road network to ease the access for both workers and customers, and to allow transportation of both input and products.
7) Proximity to the sewage network: the location should be reasonably close to a sewage network to facilitate the drainage of wastewater.
8) Proximity to fish hatcheries: proximity to fish hatcheries is necessary for providing the juveniles to the integrated aquaponic system.
9) Proximity to gas network: the availability of gas for basic needs like heating is crucial within the aquaponic system.
10) Proximity to plant nurseries: the presence of nutrient-rich water runoff from plant nurseries can be utilised to feed the organisms within the aquaponic system, hence proximity to such facilities is preferable, to reduce water consumption and increase environmental sustainability.
11) Proximity to industrial activities: the use of thermal waste generated by industrial activities is a good reason to consider proximity to industrial areas, since it allows to reduce the fossil energy consumption and increase environmental sustainability.
12) Income: based on the scientific literature, individuals with higher income are more likely to buy food produced within the aquaponic system.
13) Proximity to settlements and urban areas: strategic placement within populated areas can increase potential customers, and proximity to final consumers would reduce food transportation needs and costs, thus also reducing the environmental footprint of the food chain.
14) Unemployment rate: a higher unemployment rate would ease the recruitment of potential workers for the aquaponic system and facilitate a positive contribution of the integrated aquaponic system to increase the employment levels.
15) Potential consumers: the economic feasibility of the project depends on the potential customer base, with population density serving as a reliable proxy.
16) Proximity to logistic platforms: the aquaponic system may necessitate storage facilities and food logistic platforms for the distribution of crops and fish produced, thus proximity to logistic platforms is desirable.
17) Potential organic products consumers: demographic segments such as individuals aged 25–40 and those with higher levels of education are more inclined to purchase organic food (Gundala Raghava and Singh, 2021), which can be considered a proxy of potential customers of sustainable and short-food-chain products coming from the integrated aquaponic system under study.
18) Current land use type: only specific land use types are suitable for the establishment of aquaponic systems, to avoid or limit land-use interference of competition.

Data were collected mostly from the official geodata repository of the Emilia-Romagna region (https://geoportale.regione.emilia-romagna.it/), others were pre-processed after the 2011 Italian census (last available one), or collected or provided by the Emilia-Romagna regional environmental protection agency (https://geoportale.regione.emilia-romagna.it/), or downloaded through the OpenStreetMap data mining tool Overpass turbo (https://overpass-turbo.eu/). Finally, land use data have been collected from the CORINE Land Cover (CLC), the European Union's Earth observation programme database, providing an inventory of land cover in Europe according to 44 land use classes. CLC data for 2018 (the last available year) were collected via Sentinel-2 and Landsat-8 with a geometric accuracy of ≤10 m, a spatial resolution of 100 m and with the same methodology for all the European countries (https://land.copernicus.eu/). These characteristics are perfectly suitable for the replicability purpose of the analysis. Data source, original data format and pre-processing operations are show in in Table a in the supplementary materials.

The panel of experts has been asked to select which of the 44 land cover types were suitable for hosting an integrated aquaponic plant. Only the land use types that have been chosen at least by half of the participants have been incorporated in the analysis, as follows:

- Continuous urban fabric;
- Discontinuous urban fabric;
- Industrial or commercial units;
- Road and rail networks and associated land;
- Port areas;
- Dump sites;
- Construction sites;
- Non-irrigated arable land;
- Permanently irrigated land;
- Rice fields;
- Pastures;
- Annual crops associated with permanent crops;
- Complex cultivation patterns;
- Land principally occupied by agriculture, with significant areas of natural vegetation;
- Salt marshes;
- Salines.

The constraints identified are:

- archaeological areas,
- protected areas,
- Natura 2000 areas,
- water availability (sites where proximity to the nearest water source is higher than the threshold indicated by the experts),
- military zones,
- active mining areas.

Finally, the contextual factors are:

- Touristic places such as viewpoints, swimming shores, beach resorts, etc.
- Water quality (acidity, nitrates, nitrites, salinity, etc.)

The meaning of these contextual factors is that an aquaponic system could be built in places where tourist attractions exist, but its structure should be designed to fit some specific requests for potential visitors. For example, the system could be established near the swimming shores, but

Table 2
Factors, submodels and their weights.

Factors	Submodels	Factor weights	Subweights	Final submodel weights
Water availability		0.208		
	Proximity to the nearest water source (sea, freshwater, brackish water)		1	0.208
Atmospheric conditions		0.142		
	Average annual temperature		1	0.147
Topographic conditions		0.120		
	Elevation		0.534	0.066
	Slope		0.466	0.057
Infrastructures and facilities		0.177		
	Proximity to electricity network		0.181	0.030
	Proximity to road network		0.181	0.030
	Proximity to sewage network		0.148	0.028
	Proximity to fish hatcheries		0.140	0.025
	Proximity to gas network		0.132	0.024
	Proximity to plant nurseries		0.124	0.022
	Proximity to industrial activities		0.093	0.017
Access to market		0.188		
	Income		0.208	0.0332
	Proximity to settlements and urban areas		0.181	0.029
	Consumers (proxy: population density)		0.169	0.028
	Proximity to logistic platforms (harbour, etc.)		0.169	0.028
	Unemployment rate		0.142	0.023
	Organic products consumers (proxy: age groups and education level)		0.132	0.022
Land use		0.176		
	Current land use type (CORINE land cover)		1	0.176

it should also have a touristic purpose such as showing an eco-friendly way to cultivate plants and breed fish in a step-by-step trail. The second type of contextual factor is the quality of water. Water is a fundamental element for an aquaponic system for all the organisms of the cycle (Farhan Mohd Pu'Ad et al., 2020). It is, therefore, important that chemicals dissolved in it are present in an appropriate quantity. Nevertheless, this is not considered as a constraint since water quality can be controlled using specific techniques and systems. However, it cannot be considered as a full factor since the costs for these processes may be extremely high and might undermine the economic feasibility of the project. For this reason, it is always important to monitor the quality of the water used as a supply for the system and to perform some assessment operations before.

2.4. Definition of weights

As previously mentioned, one of the most crucial steps of a WLC method is the weighting phase. Generally, weights can be decided via many processes, requiring different levels of complexity and with different advantages and limitations. One of the most common and comprehensive methodologies is the AHP (Analytical Hierarchy Process), theorised by Saaty in 1980 (Saaty, 2005). It is suitable to solve problems where the factors can be organized in a hierarchical way into submodels, as in this case. The AHP method employs pairwise comparison matrices to determinate global weights, wherein each submodel is evaluated for its relative importance in comparison to every other one (Malczewski and Rinner, 2015).

Various papers about GIS-MCDA employ the AHP as a methodology to indagate the weights for their analyses (Taherdoost and Madanchian, 2023). For instance, Ruiz et al. (2020)applied it for the analysis of the optimal location of solar energy plants in West Kalimantan Province, Indonesia. Mora and Peláez (2020) used it for examining the landfill site selection in Azuay province, Ecuador. In Ali et al. (2017) AHP was applied to indagate the most optimal onshore windfarm site location in South Korea. Bakirman and Gumusay (2020) utilised it for the optimal location of habitat of *Posidonia oceanica* in Gulluk Bay, Turkey.

Nevertheless, considering the participatory approach of the study and the aim to facilitate its implementation in the real world, we have carefully considered alternative approaches to define the weights, based on evidence from the literature, in order to allow a sound analysis, whilst reducing the burden for the experts involved in the process. In fact, the use of AHP would have required a total of 153 pairwise comparisons to investigate the eighteen submodels. This would have been too time-consuming for the decision-makers, also considering that weigh-estimation is only a part of the process. Therefore, another approach commonly used in the MCDA field has been used (Mohammadi and Tamburri, 2023): the normalised arithmetic mean. Experts have been asked to define the importance of every submodel on a scale from 1 (least important) to 7 (most important). The same has been done for the six factors (water availability, atmospheric conditions, topographic conditions, infrastructures and facilities, access to market and land use). The results have then been averaged via an arithmetic mean and then normalised. Finally, also the submodels were given a value through an arithmetic mean, not only based on the result of the survey but also on the values previously computed of the factors. Later, they have been normalised. Thanks to this methodology, it has been possible to consider all criteria and submodels, without the need to reduce the complexity of the model. This has proved to be a sound and robust methodology, leading to positive results. In fact, the experts have always discussed together about the decisions to be made. Consequently, most of their answers to the weighting survey denoted similarity or minor deviations. Evidence of the validation of this coherence can be found in the sensitivity analysis (Section 3.2), whose results clearly state that the importance of the submodels and the factors have been addressed soundly.

The weights for all the factors and submodels are shown in Table 2.

2.5. Reclassification procedures

The reclassification phase is another important step of the GIS-MCDA method. Each factor and submodel is, in fact, calculated with different units of measurement (distance, percentage, temperature, ratio). Therefore, reclassification is necessary to make the data comparable (Diti et al., 2015). All the submodels have been reclassified thanks to the experts' opinion. The majority of them have been reclassified according to a range decided by the experts for each variable (see Table b in the supplementary material for further information). Later, they have been and divided into eight equal intervals with class 8 corresponding to the most suitable level, while class 1 representing the less favourable class. A table summarising all the values for all the submodels is presented in the supplementary materials.

Three submodels, namely the proximity to the nearest water sources, the average annual temperature and the current land use types have been reclassified with a specific methodology which will be presented in the following paragraphs.

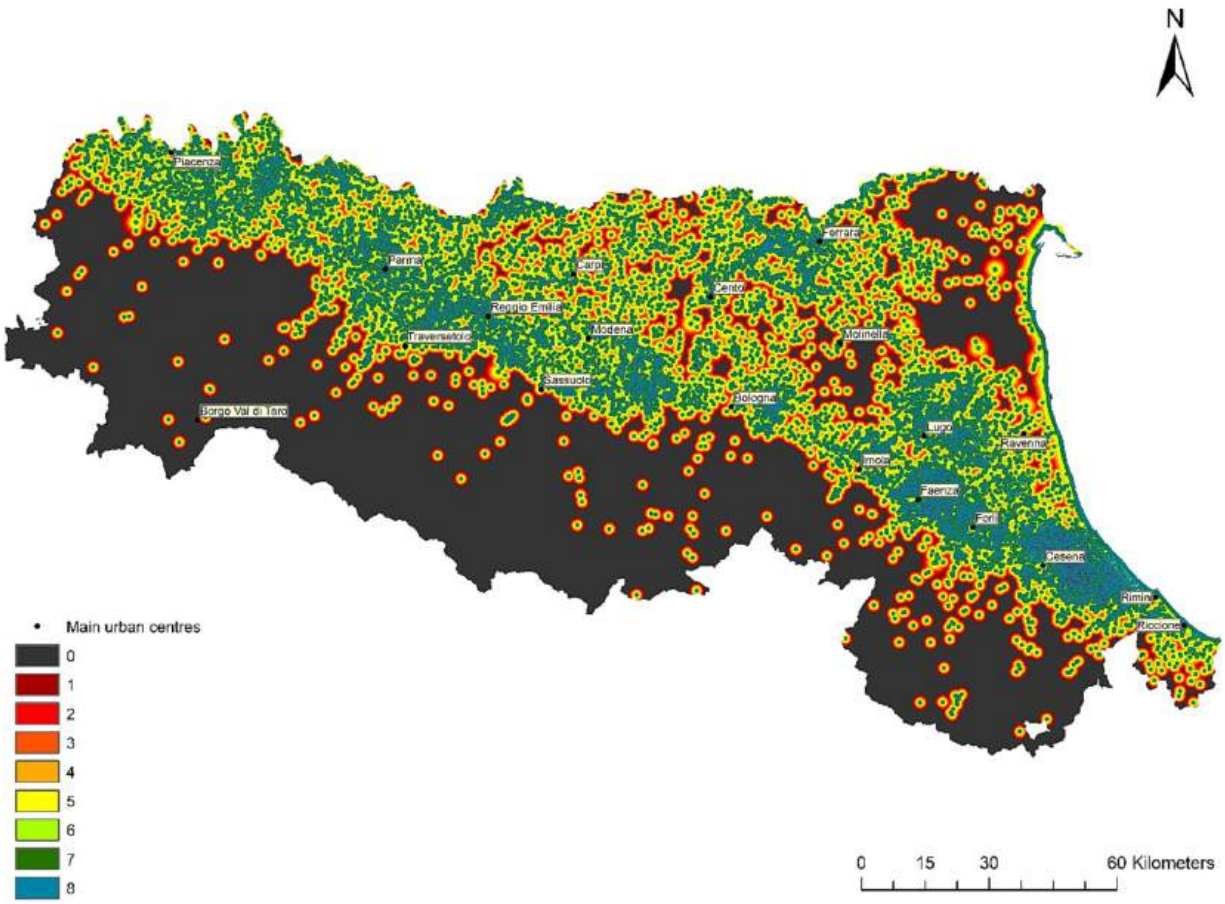

Fig. 2. Suitability map of the submodel "Proximity to the nearest water source".

Fig. 3. Suitability map of the submodel of the criterion "Temperature".

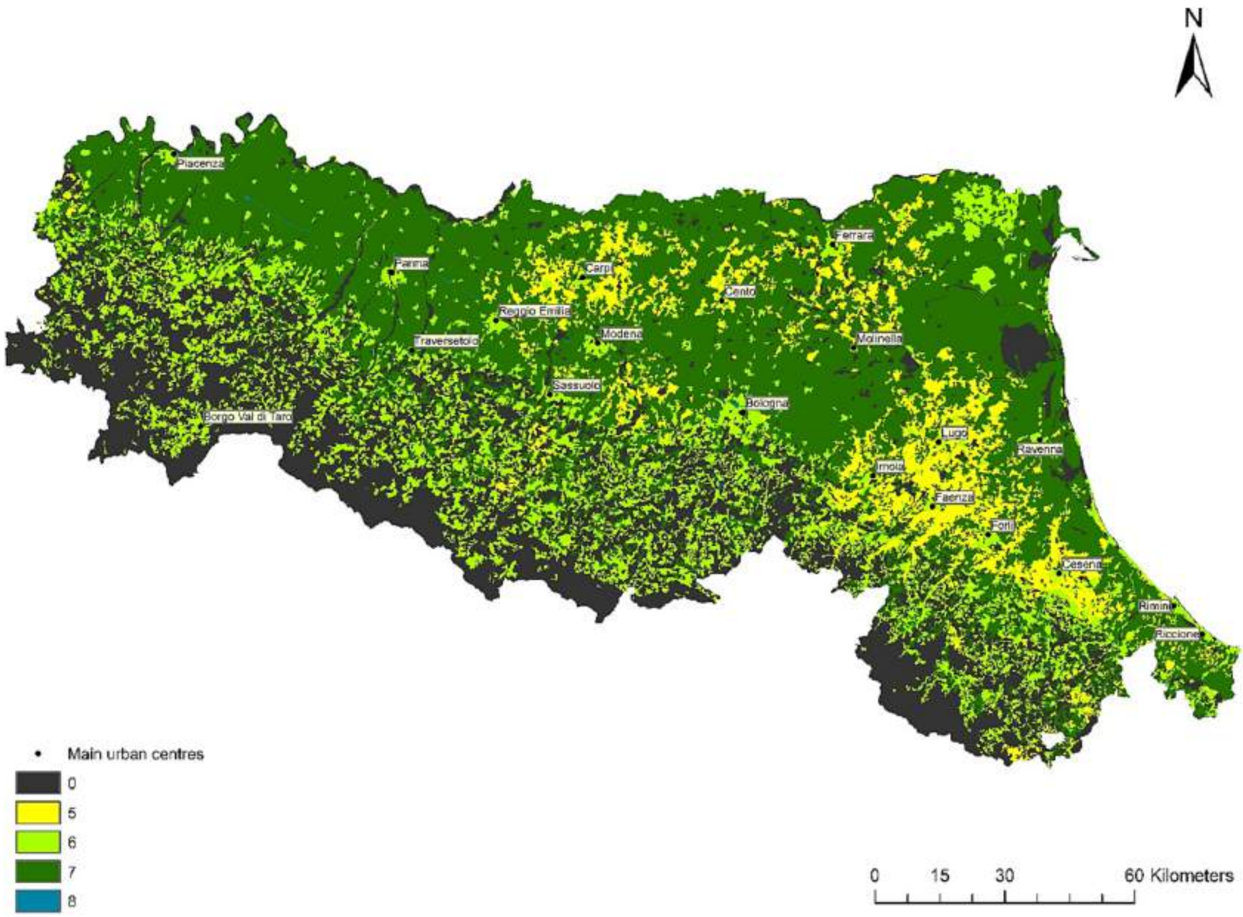

Fig. 4. Suitability map of the submodel "Current land use type".

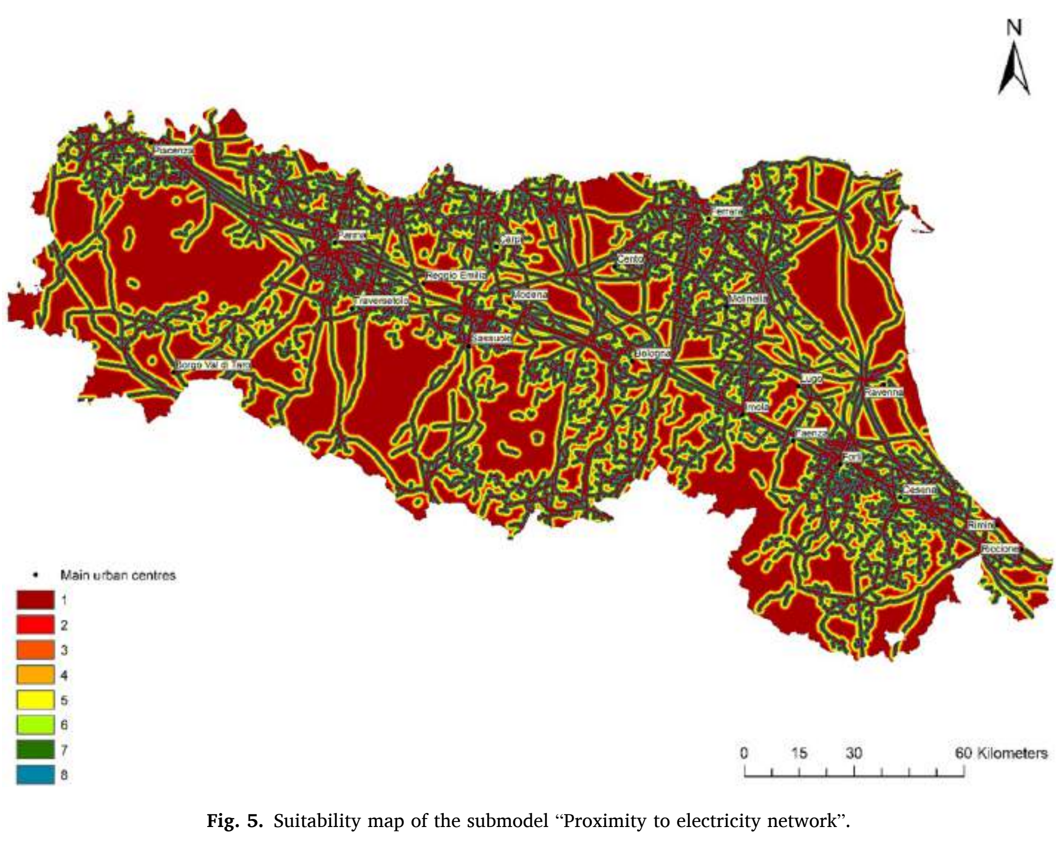

Fig. 5. Suitability map of the submodel "Proximity to electricity network".

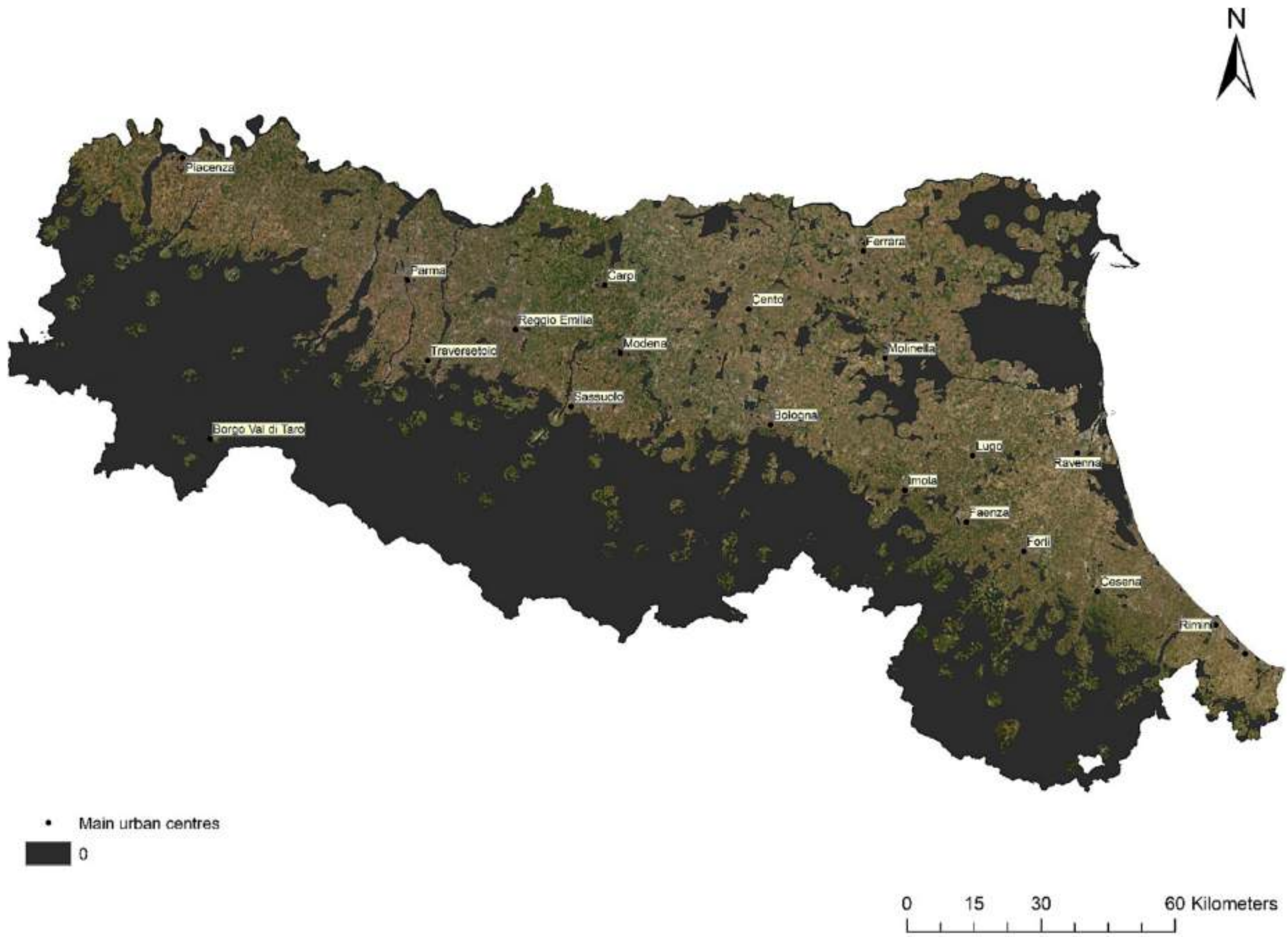

Fig. 6. Constraints map. Restricted areas are depicted in black.

1) Proximity to the nearest water sources

Water source data for this analysis may be of three different types (sea, freshwater and brackish underground water). This element is so important for the aquaponic system that beyond a certain distance from the sources, it must be considered as a constraint. Nevertheless, it is not necessary that the plant is located in an area close to all these three kinds of water sources simultaneously, just one is satisfactory. Since the three different sources have been classified with different importance (the relative importance for water sources is 0.361, for sea is 0.332 and for brackish underground water is 0.307) by the experts, a reclassification method considering this importance and the distance from the three sources altogether has been applied. First, distance raster maps for all the three water types have been created and, after, reclassified according to experts' opinions. The reclassified raster maps have then been multiplied by the normalised values, namely 1 for the freshwater sources, 0.918 for the sea and 0.849 for the brackish underground water sources.

Finally, every pixel of the raster map has been assigned the result of the best performing water source (highest result of the three related to the different water sources) using the raster calculator GIS tool.

2) Temperature

Based on the literature, experts specified the optimal temperature for an aquaponic system, should be 22.2 °C. The average temperature of the Emilia-Romagna ranges from 5.7 °C to 16.1 °C, Consequently, the above-mentioned interval has been divided into 8 classes and the closer to the optimal temperature has been reclassified as 8, while the furthest one has been reclassified as 1. All the other classes were reclassified proportionally.

3) Current land uses

After the process of selection of the appropriate land uses, the experts were asked to evaluate the importance of each of them. The land uses have been later reclassified according to the importance questionnaire assigning classes according to the normalised values (see supplementary materials for further information).

3. Results

After the reclassification process, a thematic map is generated from each submodel. For the sake of brevity, only some of the maps will be displayed, namely the three ones just presented in the previous paragraph with a specific methodology and the "Proximity to electricity network" to give an example of the other submodels. All the maps are shown in Figs. 2 to 5. All the other submodel maps are presented in the Supplementary materials (Figs. 16–30).

3.1. Application of Boolean logic

After the data rasterization of every submodel into 50 × 50 m pixel layers, the Boolean logic tool has been applied.

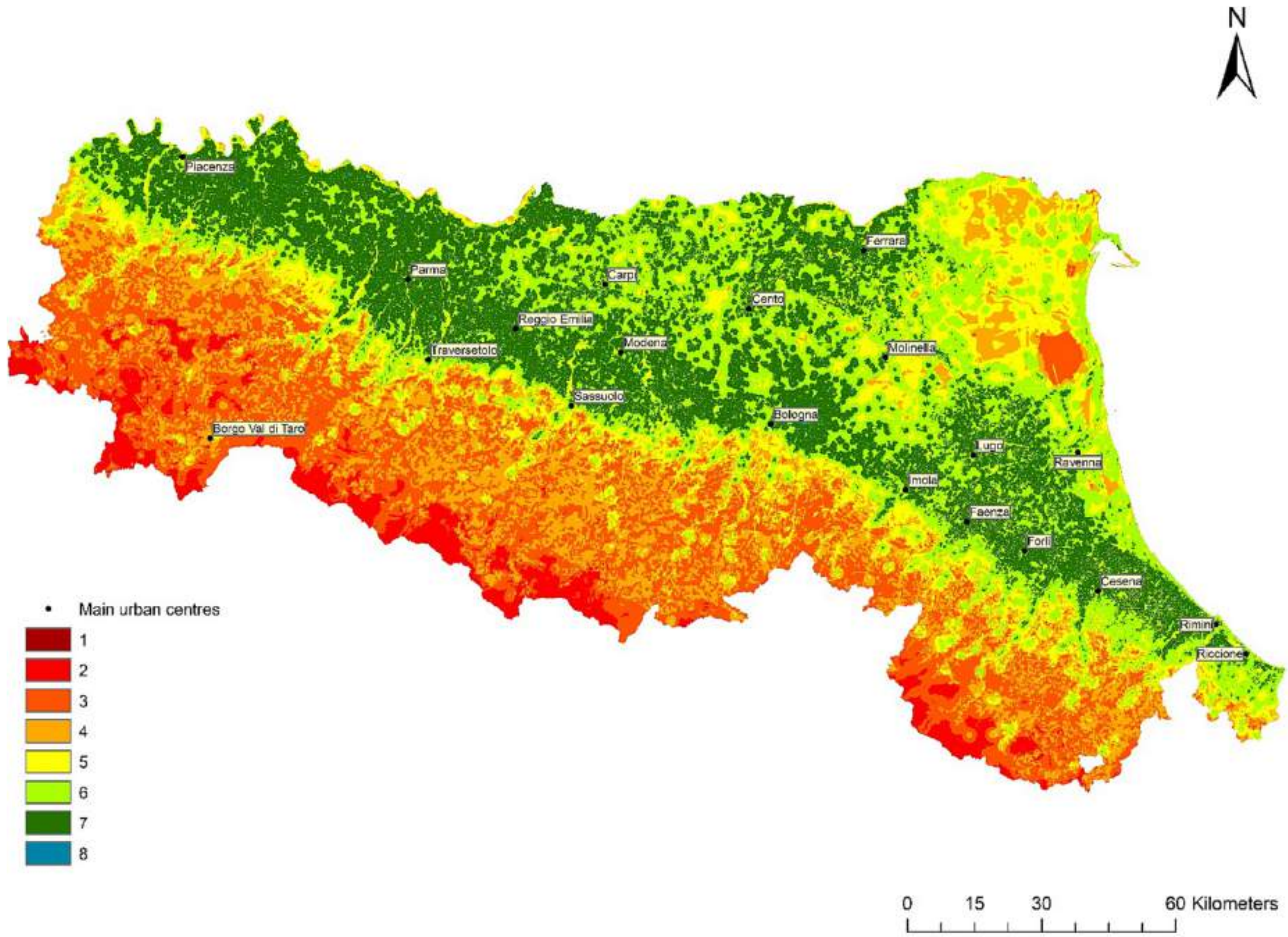

Fig. 7. Suitability map without constraints.

The Boolean logic transforms related information from each input map into binary form (True or False or 0 and 1, in the case of GIS) (Shahabi et al., 2014). In this study, it has been used as a mask to exclude the unsuitable areas, namely the ones that have been designated as constraints (archaeological areas, protected areas, Natura 2000 areas, water availability, military zones and active mining areas). The presence of a single one of these constraints implies the complete exclusion of that cell from further analyses. All the pixels with constraints are identified in the maps with the black colour to which was assigned the numeric class 0, meaning a lack of suitability. The choice of the numeric class 0 has been made to simplify the final step of the process, which involves merging the constraint-free final map (Fig. 7) with the constraints map (Fig. 6). This numerical assignment of 0 is therefore advantageous during the merging operation, which can be calculated by multiplying the two raster datasets. To clarify, where a constraint is present (depicted in back in Fig. 6 and labelled with 0), the resultant merged value remains 0, excluding that pixel from further analysis.

Once all the submodel raster maps have been created, they can be merged together considering the weights previously calculated. The result is presented in Fig. 7.

This map is not enough because it does not include the constraints introduced in the previous paragraph. The following step has been the merging of this resulting map with the constraint map. The final map is shown in Fig. 8.

Table 3 shows the pixel values, their count, the surface occupied in hectares and the percentage for the suitability map without constraints (represented in Fig. 7). Then, in the adjacent columns on the right, the count, the surface occupied in hectares and the percentage for the final suitability map with all the constraints is depicted in bold (represented in Fig. 8). This allows a quick comparison between the two results. Finally, the last column shows the percentage of pixels in the final suitability map without considering the constrained pixels.

Some interesting information can might be inferred from these data. Specifically, for the suitability map without constraints:

- there are only very few pixels scoring 1 and few with class 2, meaning that the Emilia-Romagna region is generally a good area for the construction of an aquaponic system;
- the 8-class pixels, are the second less common after class 1 pixels (only ~0.032 % of the region territory), but pixels with 7-class are the most common ones, meaning that the majority of Emilia-Romagna soil is very suitable for an aquaponic system.

While, for the final suitability map:

- more than half of the pixels are constrained with class 0;
- the majority of the pixels that became constrained were taken from the lowest class pixels: all 1-class and 2-class pixels converged into the 0-class ones, while 3-class, 4-class and 5-class pixels were strongly reduced in count and percentage;
- 6-class, 7-class and 8-class pixel amounts (considering the percentage without constrained pixels) were slightly affected by the constraints, while their percentage deeply increased, especially for the 6-

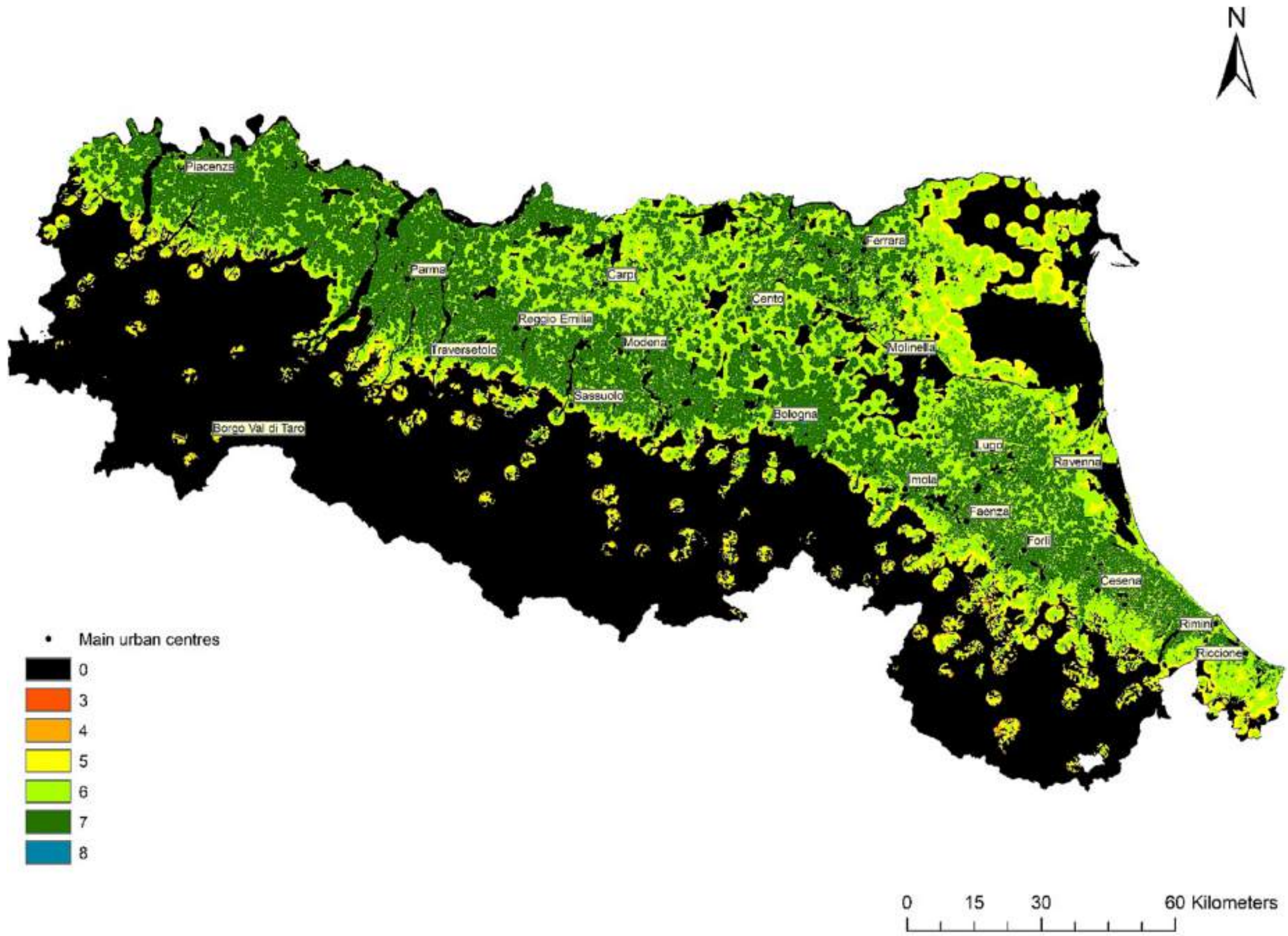

Fig. 8. Final suitability map.

Table 3
Suitability map without constraints pixel values and relative count, surface and percentage. Suitability map pixel values and relative count, surface, percentage and percentage without constrained pixels.

Value	Count of suitability map without constraints	Count of suitability map	Surface of suitability map without constraint (ha)	Surface of suitability map (ha)	Percentage of suitability map without constraints (%)	Percentage of suitability map (%)	Percentage without constrained pixels (%)
0	0	4,561,188	0	1,140,297	0	50.805	//
1	243	0	60.75	0	0.002	0	0
2	392,248	0	98,062	0	4.369	0	0
3	1,641,978	2007	410,494.5	501.75	18.289	0.022	0.045
4	1,531,021	51,479	382,755.3	12,869.75	17.053	0.573	1.165
5	1,274,038	559,595	318,509.5	139,898.7	14.191	6.233	12.670
6	1,989,176	1,769,441	497,294	442,360.2	22.156	19.709	40.063
7	2,145,629	2,031,432	536,407.3	507,858	23.899	22.627	45.995
8	3435	2626	858.75	656.5	0.038	0.029	0.059

class pixels, (from ~22.16 % to ~39.42 %) and for the 7-class pixels (from ~23.9 % to ~46.96 %).

This means that the majority of the constraints influences the lowest class pixels, keeping the highest-class pixels mostly untouched, underling the accuracy in the choice of the constraints.

The optimal areas for the establishment of an aquaponic system are located in the countryside surrounding the major cities situated in the Po Valley plain, where the absence of mountains and steep terrain make the morphologic features more favourable. The facilities are more easily met thanks to the proximity to the major cities and the number of potential customers is higher due to the fact that the population is concentrated nearby. Other positive factors positively contributing to the localisation of the most suitable area in the plain zone of the region is the temperature mildness of the Po Valley and the appropriate land uses, which are generally more common in the plain than in the mountainous and hilly areas of Apennines.

For the abovementioned reasons, the southern seacoast also emerges as a feasible candidate for aquaponic system installation. However, the northern coastal region faces constraints primarily due to its proximity to the Po Delta and the associated marshy terrain.

Table 4
Changes in quantity of pixels belonging to a class (columns) in "Proximity to water sources" criterion after every percentage increase (rows). Suitability analysis row represents the values after the sensitivity analysis. It is noteworthy that class 0 quantity remains always the same because it represents constrained pixels.

	0 (constraints)	1	2	3	4	5	6	7	8
Suitability analysis	4,561,188	0	0	2007	51,479	559,595	1,769,441	2,031,432	2626
1 %	4,561,188	0	0	2089	57,347	574,657	1,731,151	2,048,217	3119
2 %	4,561,188	0	1	2160	63,854	588,336	1,694,140	2,064,169	3920
3 %	4,561,188	0	1	2246	71,464	601,519	1,658,254	2,078,274	4822
4 %	4,561,188	0	2	2342	79,238	613,002	1,624,218	2,091,944	5834
5 %	4,561,188	0	2	2485	88,301	622,672	1,591,338	2,104,655	7127
6 %	4,561,188	0	3	2620	98,401	631,720	1,559,309	2,115,774	8753
7 %	4,561,188	0	4	2809	108,515	638,400	1,529,384	2,127,094	10,374
8 %	4,561,188	0	4	2983	119,499	643,385	1,500,606	2,137,374	12,729
9 %	4,561,188	0	5	3179	131,661	645,238	1,473,950	2,146,942	15,605
10 %	4,561,188	0	6	3403	144,326	646,197	1,448,254	2,155,206	19,188
11 %	4,561,188	0	11	3655	156,513	647,286	1,422,990	2,162,677	23,448
12 %	4,561,188	0	11	3941	168,679	647,781	1,398,165	2,169,393	28,610
13 %	4,561,188	0	15	4297	182,366	647,078	1,373,698	2,173,975	35,151
14 %	4,561,188	0	21	4802	196,733	646,025	1,348,065	2,178,226	42,708
15 %	4,561,188	0	26	5363	212,158	643,459	1,323,445	2,178,915	53,214
16 %	4,561,188	0	32	6140	229,646	637,580	1,300,208	2,178,381	64,593
17 %	4,561,188	0	41	7226	248,023	629,500	1,278,331	2,174,410	79,049
18 %	4,561,188	0	57	8598	267,130	619,958	1,256,202	2,169,223	95,412
19 %	4,561,188	0	65	10,177	286,899	608,699	1,236,205	2,160,387	114,148
20 %	4,561,188	0	69	12,237	306,859	595,871	1,217,596	2,148,870	135,078

3.2. Sensitivity analysis

Results of an MCDM-analysis might be jeopardised due to the high number of experts and their different opinions on the criteria selection and the determination of the importance of the criteria through their weights. This could be due to the fact that decision makers are not completely aware of their preferences regarding the criteria or because the nature and the scale of the criteria is not known (Chen et al., 2010). The validation of the results is therefore an important part of the analysis. To do so, a final sensitivity analysis has been conducted (Watson and Hudson, 2015; Aghmashhadi et al., 2022; Zhao et al., 2023). Sensitivity analysis is crucial to the validation and calibration of numerical models. It can be used to check the robustness of the final outcome (Zoras et al., 2007).

Sensitivity analysis has been carried out using a one-at-a-time approach, which consists in slowly increasing the weights of every criterion (proportionally decreasing all the other criteria). This allows the evaluation of the importance of a factor at a time (Malczewski and Rinner, 2015). In this case, the weights of each criterion have been increased by 1 % at a time, until 20 %. A total of 360 cases have been studied. For every run, changes in quantity for every pixel class were tracked, as it is shown in Table 4, an example of the 18 tables created (one for each criterion) showing the modifications of criterion "proximity to water sources". The full list of the results can be found in the supplementary materials (tables d-t).

The following example is presented to enhance comprehension of the table. The row labelled "Suitability Analysis" represents the outcomes of the suitability analysis, having the same values found in Table 3 in the column denoted as "Count of Suitability Map." Subsequently, the row marked as "1 %" signifies an incremental augmentation of 1 % in the weight attributed to the criterion "Proximity to Water Sources." The ensuing cells elucidate the resultant alterations in outcomes consequent to this marginal increment. Notably, within certain classes, there is an augmentation in count, while in others, a reduction is observed. It is imperative to underscore that the cumulative sum remains invariant, a pattern consistent across all scenarios involving percentage increments, as observed in analogous instances.

In Fig. 9, the changes in quantity of pixels belonging to the class 8 are shown for the three kinds of trends: growing since the first increment in weight (proximity to the nearest water source), decreasing at the beginning and increasing after some increments in weight (proximity to gas network), decreasing since the first increment in weight (organic products consumers). The remaining graphs are shown in the supplementary materials (fig. a-o). X-axes display the percentage changes of the weights after every run; Y-axes display the total amount of value 8 pixels after every run.

Table 5 shows the difference between quantity of pixels belonging to class 8 after increasing a criterion weight by 20 % and the initial quantity of pixels in class 8 after the suitability analysis (2626 pixels). Criteria has been ranked on the base of their sensitivity.

The result shows that 'proximity to the nearest water sources' criterion is the most sensitive one, meaning that increases in its weights cause the most significant changes. It is also the most important criterion indicated by the experts. Other sensitive criteria are 'slope' and 'elevation', both high in the weight importance rank.

'Potential consumers' and 'potential organic products consumers' criteria are the less important ones: increasing their importance, the pixels belonging to class 8 decrease compared to the initial result. 'Potential organic products consumers' criterion has been classified by experts as the least important one, while the 'density' criterion has been classified as the 9th most important one.

Finally, the least sensitive criteria, meaning the ones that produce less changes, are 'proximity to plant nurseries' and 'proximity to industrial activities' criteria, both classified as non-important criteria (15th and 16th out of 18).

In conclusion, since the prioritization of most of the criteria remained the same, experts have predicted their sensitivity, meaning that their opinion was, even before the results, reliable and well-grounded. Therefore, that the proposed model was appropriate for the study.

4. Conclusions

The primary objective of this paper was to formulate and empirically validate a GIS-based multi-criteria land suitability assessment model tailored for the integration of multi-trophic aquaponic systems. While the GIS-MCDA methodology has found several applications across various sectors linked to agri-food structures and infrastructure, its implementation in the context of aquaponic systems remained a notable lack, hence necessitating this investigation.

The outcomes of this study have shown that the most favourable locations for the establishment of aquaponic systems, predominantly are centred around the principal cities and along the seacoast of the Emilia-Romagna region. These areas offer the confluence of ideal

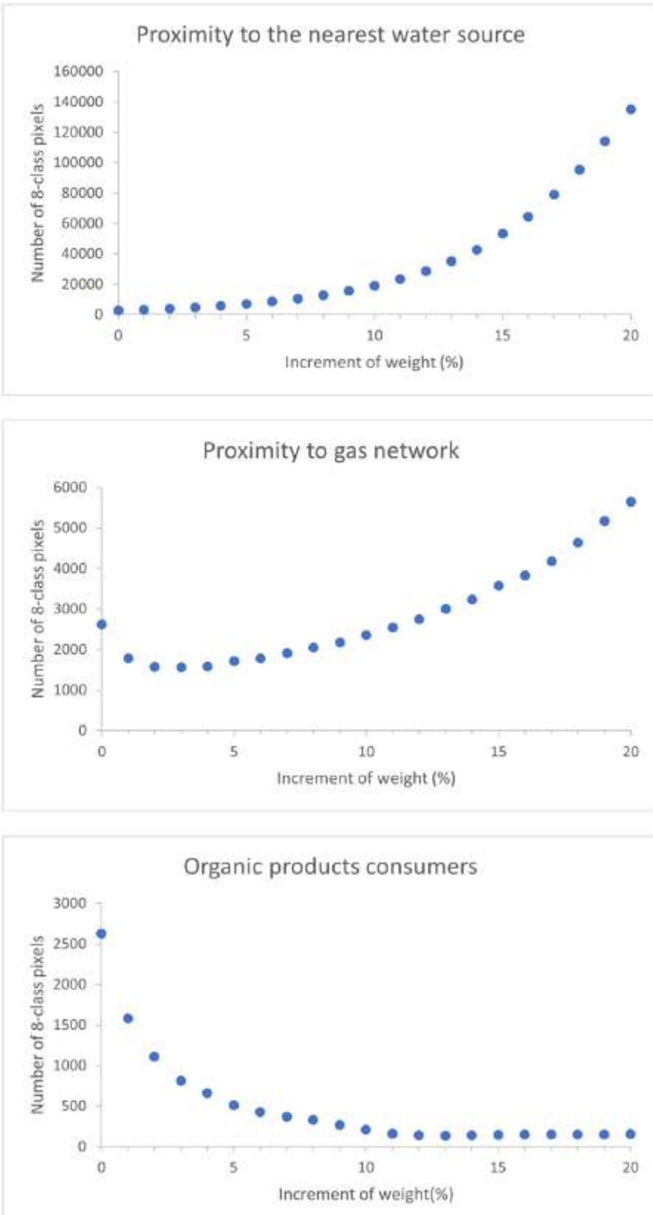

Fig. 9. Most representative graphs of the changes in 8-value pixels after every increment of weights.

morphological characteristics, ready access to essential facilities, and a good potential customer base.

Although only 0.029 % of the area of the Emilia-Romagna region has been designated as absolutely suitable for the implementation of multi-trophic aquaponic systems, equivalent to 656.5 ha, a substantial proportion of the total area remains highly suitable, with a classification of either class 7 (22.627 %) or class 6 (19.709 %), corresponding to a combined total of 950,218.2 ha. These two classes represent the most prevalent categories, excluding constrained areas. In fact, a noteworthy result is that 50.805 % of the Emilia-Romagna region surface is completely unsuitable for hosting an aquaponic system.

Furthermore, the application of the model within the Emilia-Rmagna region has served as a foundational study for other investigations encompassing other regions and countries. To the authors' knowledge, to this moment, this is the first example of an application of GIS-MCDA methodology on aquaponics. The whole process was deeply based on a participatory approach, for the determination of the factors, the sub-models, their respective importance and the classifications. This was a core feature of the study, since it is conceived to be applicable in the real world, to support decision makers, and to be extended and transferrable to other geographic and environmental contexts. Considering the critical issues related to the application of AHP, in particular complexity and onerousness for the panel of experts involved in the study, further developments of the study may be addressed to explore other alternative methodologies for the weighting phase, considering the specific challenges that apply and the need to combine accuracy and feasibility.

Table 5
Difference between quantity of pixels belonging to class 8.

Criteria	0 %	20 %	Difference (20 % - 0 %)
Proximity to the nearest water sources	2626	135,078	132,452
Slope	2626	82,614	79,988
Elevation	2626	81,032	78,406
Proximity to the road network	2626	46,164	43,538
Proximity to the electricity network	2626	41,067	38,441
Proximity to industrial activities	2626	38,233	35,607
Proximity to settlements and urban areas	2626	30,100	27,474
Proximity to the sewage network	2626	29,955	27,329
Income	2626	23,139	20,513
Average temperature	2626	15,865	13,239
Unemployment rate	2626	7976	5350
Proximity to the gas network	2626	5648	3022
Current land use type	2626	3563	937
Proximity to fish hatcheries / fishfarms	2626	3472	846
Proximity to plant nurseries	2626	3353	727
Proximity to industrial activities	2626	3005	379
Potential organic products consumers	2626	155	−2471
Potential consumers	2626	9	−2617

Future developments could be also directed towards the refinement of the model and its submodels and criteria, based on the specific characteristics of aquaponic systems and landscape features. This optimisation would make the GIS-MCDA methodology more user-friendly, with the final objective of extending its applicability to encompass other Mediterranean regions. The overarching aim remains the identification of optimal zones within the entire Mediterranean Basin that are suitable to the establishment of aquaponic systems, thereby contributing to the sustainable development of aquaculture and agriculture in general.

Another possible further development would be the creation of a web interactive decision tool for stakeholders or all the possible audience to ameliorate and facilitate possible operations of spatial planning. This tool will allow changing factors, conditions and weights one at a time allowing the exploration of multiple possibilities.

CRediT authorship contribution statement

Andrea Zaniboni: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft. **Patrizia Tassinari:** Funding acquisition, Project administration, Resources, Supervision, Writing – review & editing. **Daniele Torreggiani:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Software, Supervision, Validation, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Daniele Torreggiani reports financial support was provided by PRIMA program (Partnership for research and innovation in the Mediterranean area).

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2023.169790.

References

Aghmashhadi, A.H., Azizi, A., Hoseinkhani, M., Zahedi, S., Cirella, G.T., 2022. Aquaculture site selection of Oncorhynchus Mykiss (rainbow trout) in Markazi Province using GIS-based MCDM. ISPRS Int. J. Geo Inf. 11 (3) https://doi.org/10.3390/ijgi11030157.

Ali, S., Lee, S.-M., Jang, C.-M., 2017. Determination of the most optimal on-shore wind farm site location using a GIS-MCDM methodology: evaluating the case of South Korea. Energies 10 (12). https://doi.org/10.3390/en10122072.

Asciuto, A., Schimmenti, E., Cottone, C., Borsellino, V., 2019. A financial feasibility study of an aquaponic system in a Mediterranean urban context. Urban For. Urban Green 38 (2), 397–402.

Bakirman, T., Gumusay, M.U., 2020. A novel GIS-MCDA-based spatial habitat suitability model for Posidonia oceanica in the Mediterranean. Environ. Monit. Assess. 192 (4), 231. https://doi.org/10.1007/s10661-020-8198-1.

Bandira, P.N.A., Mahamud, M.A., Samat, N., Tan, M.L., Chan, N.W., 2021. GIS-based multi-criteria evaluation for potential inland aquaculture site selection in the George Town conurbation, Malaysia. Land 10 (11). https://doi.org/10.3390/land10111174.

Calle Yunis, C.R., Salas López, R., Cruz, S.M.O., Barboza Castillo, E., Silva López, J.O., Iliquín Trigoso, D., Briceño, N.B.R., 2020. Land suitability for sustainable aquaculture of rainbow trout (Oncorhynchus mykiss) in Molinopampa (Peru) based on RS, GIS, and AHP. ISPRS Int. J. Geo Inf. 9 (1) https://doi.org/10.3390/ijgi9010028.

Charles, H., Godfray, J., Beddington, J.R., Crute, I.R., Haddad, L., Lawrence, D., Muir, J.F., Pretty, J., Robinson, S., Thomas, S.M., Toulmin, C., 2010. Food Security: The Challenge of Feeding 9 Billion People.

Chen, Y., Yu, J., Khan, S., 2010. Spatial sensitivity analysis of multi-criteria weights in GIS-based land suitability evaluation. Environ. Model Softw. 25 (12), 1582–1591. https://doi.org/10.1016/j.envsoft.2010.06.001.

Church, R.L., 2002. Geographical information systems and location science. Comput. Oper. Res. 29 (6), 541–562. https://doi.org/10.1016/S0305-0548(99)00104-5.

Dana Tomlin, C., 1990. Geographic Information Systems and Cartographic Modeling.

Dapueto, G., Massa, F., Costa, S., Cimoli, L., Olivari, E., Chiantore, M., Federici, B., Povero, P., 2015. A spatial multi-criteria evaluation for site selection of offshore marine fish farm in the Ligurian Sea, Italy. Ocean Coast. Manag. 116, 64–77. https://doi.org/10.1016/j.ocecoaman.2015.06.030.

Diti, I., Tassinari, P., Torreggiani, D., 2015. The agri-environmental footprint: a method for the identification and classification of peri-urban areas. J. Environ. Manag. 162, 250–262. https://doi.org/10.1016/j.jenvman.2015.07.058.

FAO Fisheries and Aquaculture Department, 2009. Integrated Mariculture A Global Review.

Farhan Mohd Pu'Ad, M., Azami Sidek, K., Mel, M., 2020. IoT based water quality monitoring system for aquaponics. J. Phys. Conf. Ser. 1502 (1) https://doi.org/10.1088/1742-6596/1502/1/012020.

Gundala Raghava, R., Singh, A., 2021. What motivates consumers to buy organic foods? Results of an empirical study in the United States. PLoS One 16 (9), 1–17. https://doi.org/10.1371/journal.pone.0257288.

Jean-Baptiste E. Thomas, F.S.R., Gröndahl, F., 2019. Identifying suitable sites for macroalgae cultivation on the Swedish west coast. Coast. Manag. 47 (1), 88–106. https://doi.org/10.1080/08920753.2019.1540906.

Jeong, J.S., Ramírez-Gómez, Á., 2018. Optimizing the location of a biomass plant with a fuzzy-DEcision-MAking Trial and Evaluation Laboratory (F-DEMATEL) and multi-criteria spatial decision assessment for renewable energy management and long-term sustainability. J. Clean. Prod. 182, 509–520. https://doi.org/10.1016/j.jclepro.2017.12.072.

Kazemi, H., Akinci, H., 2018. A land use suitability model for rainfed farming by multi-criteria decision-making analysis (MCDA) and geographic information system (GIS). Ecol. Eng. 116, 1–6. https://doi.org/10.1016/j.ecoleng.2018.02.021.

Kloas, W., Groß, R., Baganz, D., Graupner, J., Monsees, H., Schmidt, U., Staaks, G., Suhl, J., Tschirner, M., Wittstock, B., Wuertz, S., Zikova, A., Rennert, B., 2015. A new concept for aquaponic systems to improve sustainability, increase productivity, and reduce environmental impacts. Aquac. Environ. Interact. 7 (2), 179–192. https://doi.org/10.3354/aei00146.

Malczewski, J., 2006. GIS-based multicriteria decision analysis: a survey of the literature. Int. J. Geogr. Inf. Sci. 20 (7), 703–726. https://doi.org/10.1080/13658810600661508.

Malczewski, J., Rinner, C., 2015. Multicriteria Decision Analysis in Geographic Information Science. https://doi.org/10.1007/978-3-540-74757-4.

Manca Zeichen, M., Ciotoli, G., Archina, M., 2022. Geospatial analysis for fish farming across Tyrrhenian coast (Tuscany, central Italy). Ocean Coast. Manag. 226, 106261 https://doi.org/10.1016/j.ocecoaman.2022.106261.

Mensour, O.N., El Ghazzani, B., Hlimi, B., Ihlal, A., 2019. A geographical information system-based multi-criteria method for the evaluation of solar farms locations: a case study in Souss-Massa area, southern Morocco. Energy 182, 900–919. https://doi.org/10.1016/j.energy.2019.06.063.

Mohammadi, M., Tamburri, D., 2023. Unveiling and Unraveling Aggregation and Dispersion Fallacies in Group MCDM.

Mora, S.L.C., Peláez, J.L.S., 2020. Sanitary landfill site selection using multi-criteria decision analysis and analytical hierarchy process: a case study in Azuay province, Ecuador. Waste Manag. Res. 38 (10), 1129–1141. https://doi.org/10.1177/0734242X20932213.

Morro, B., Davidson, K., Adams, T.P., Falconer, L., Holloway, M., Dale, A., Aleynik, D., Thies, P.R., Khalid, F., Hardwick, J., Smith, H., Gillibrand, P.A., Rey-Planellas, S., 2022. Offshore aquaculture of finfish: Big expectations at sea. In: Reviews in Aquaculture, vol. 14, issue 2. John Wiley and Sons Inc., pp. 791–815. https://doi.org/10.1111/raq.12625

Naylor, R.L., Kishore, A., Sumaila, U.R., Issifu, I., Hunter, B.P., Belton, B., Bush, S.R., Cao, L., Gelcich, S., Gephart, J.A., Golden, C.D., Jonell, M., Koehn, J.Z., Little, D.C., Thilsted, S.H., Tigchelaar, M., Crona, B., 2021. Blue food demand across geographic and temporal scales. Nat. Commun. 12 (1) https://doi.org/10.1038/s41467-021-25516-4.

Pérez, O.M., Telfer, T.C., Ross, L.G., 2005. Geographical information systems-based models for offshore floating marine fish cage aquaculture site selection in Tenerife, Canary Islands. Aquac. Res. 36, 946–961.

Rakocy, J.E., Masser, M.P., Losordo, T.M., 2006. Recirculating Aquaculture Tank Production Systems: Aquaponics-Integrating Fish and Plant Culture.

Ruiz, H.S., Sunarso, A., Ibrahim-Bathis, K., Murti, S.A., Budiarto, I., 2020. GIS-AHP Multi Criteria Decision Analysis for the optimal location of solar energy plants at Indonesia. Energy Rep. 6, 3249–3263. https://doi.org/10.1016/j.egyr.2020.11.198.

Saaty, T., 2005. Analytic Hierarchy Process. https://doi.org/10.1002/0470011815.b2a4a002.

Saltuk, B., Artun, O., 2019. Multi-criteria Decision System for Greenhouse Site Selection in Gediz Basin, Turkey Using Geographic Information Systems (GIS). https://www.researchgate.net/publication/334824318.

Shahabi, H., Keihanfard, S., Ahmad, B. Bin, Amiri, M.J.T., 2014. Evaluating Boolean, AHP and WLC methods for the selection of waste landfill sites using GIS and satellite images. Environ. Earth Sci. 71 (9), 4221–4233. https://doi.org/10.1007/s12665-013-2816-y.

Shunmugapriya, K., Panneerselvam, B., Muniraj, K., Ravichandran, N., Prasath, P., Thomas, M., Duraisamy, K., 2021. Integration of multi criteria decision analysis and GIS for evaluating the site suitability for aquaculture in southern coastal region, India. Mar. Pollut. Bull. 172 https://doi.org/10.1016/j.marpolbul.2021.112907.

Taherdoost, H., Madanchian, M., 2023. Multi-criteria decision making (MCDM) methods and concepts. Encyclopedia 3 (1), 77–87. https://doi.org/10.3390/encyclopedia3010006.

Tassinari, P., Torreggiani, D., 2006. Location planning: a methodological approach for agro-industrial buildings in rural territory. Trans. ASABE 49, 505–516. https://doi.org/10.13031/2013.20405.

UniPI, UniBo, U. K. I. L. M. L. M. M, 2019. SIMTAP (Self-sufficient integrated multi-trophic AquaPonic).

United Nations, 2000a. The Millennium Development Goals. www.un.org/millenniumgoals.

United Nations, 2000b. United Nations Millennium Declaration.

United Nations, 2015. Transforming our World: The 2030 Agenda for Sustainable Development.

Watson, J.J.W., Hudson, M.D., 2015. Regional Scale wind farm and solar farm suitability assessment using GIS-assisted multi-criteria evaluation. Landsc. Urban Plan. 138, 20–31. https://doi.org/10.1016/j.landurbplan.2015.02.001.

Zhao, H., Gao, J., Cheng, X., 2023. Electric vehicle solar charging station siting study based on GIS and multi-criteria decision-making: a case study of China. Sustainability 15 (14). https://doi.org/10.3390/su151410967.

Zoras, S., Triantafyllou, A.G., Hurley, P.J., 2007. Grid sensitivity analysis for the calibration of a prognostic meteorological model in complex terrain by a screening experiment. Environ. Model Softw. 22 (1), 33–39. https://doi.org/10.1016/j.envsoft.2005.09.010.