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A holistic approach for tourism carrying capacity estimation in sensitive ecological areas

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Abstract

Mediterranean ecosystems are in the spotlight of tourism activities, with the local populations trying to make the most of them, while in parallel, the stress signs, such as habitat and biodiversity degradation, increased pollution, or beach erosion, have begun to emerge. Furthermore, this combination of exotic and delicate qualities accompanied by excessive tourist flows leads to the imperative need for sustainable tourism development studies in these areas. In the current study, aiming to develop a new holistic framework for assessing Carrying Capacity in sensitive coastal ecosystems, a combined methodology was created and tested in Balos Lagoon, a Natura 2000 area in Western Crete. The method encompasses calculating different Carrying Capacity indicators, environmental quality measurements, visitors' perceptions identification, and finally, a multicriteria analysis to capture the stakeholders' and local community's viewpoints. The combined methodologies identified vital issues, including overcrowding—Effective Carrying Capacity is exceeded by 1000 people per day during the peak season—tar residue pollution, microplastics, insufficient road infrastructure and excessive car numbers exceeding capacity. Stakeholder involvement was pivotal, prioritizing twelve proposed actions to address those issues. Notably, "frequent beach clean-ups," targeting visual impacts, emerged as the most critical action, while parking reallocation and setting a maximum daily ferry limit were also highly ranked, promising solutions to alleviate overcrowding issues. The paper offers valuable insights for future research, emphasizing the need for continuous environmental monitoring, implementation of high-priority measures, and economic valuation of natural capital. Ultimately, this research contributes to the literature by presenting a pioneering methodology for holistic assessment and sustainable tourism development in Mediterranean sensitive coastal ecosystems.

Keywords Carrying capacity · Sustainable tourism · Natura 2000 · Multicriteria decision method

Abbreviations

CC	Carrying capacity
ECC	Effective carrying capacity
ETCC	EcoTourism carrying capacity

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GIS	Geographic information systems
PCC	Physical carrying capacity
RCC	Real carrying capacity
TCCI	Tourism carrying capacity index
TOC	Total organic carbon

1 Introduction

Mediterranean regions' relief has unique morphological characteristics that collectively form a plethora of special places of scenic beauty, which most of the time host sensitive ecosystems of rich biodiversity. Hence, those ecosystems are in the spotlight of tourism activities, with the local populations trying to make the most of them, while in parallel, stress signs have emerged (ISMAR-CNR, 2018). Furthermore, this combination of exotic and delicate qualities and excessive touristic flows leads to the imperative need for sustainable tourism development studies in these areas (UNWTO).

The predominant issues emerging from excessive tourism in coastal eco-sensitive zones are mainly addressed by the grave concerns of habitat degradation and destruction, which negatively affect delicate ecosystems such as coral reefs, mangroves, and sand dunes. It is also highlighted that the alarming levels of beach and marine pollution attributed to inadequate waste management and unchecked tourist influx further endanger marine life and ecosystem health. Additionally, there are implications on the socio-economic factor, including water scarcity due to increased demands, cultural identity erosion from inauthentic experiences, and infrastructure strain affecting local communities. Hence, gaining a holistic comprehension of the diverse array of issues presented by the surplus of coastal tourism underscores the importance of promoting sustainable approaches that harmonize economic advancement with the preservation of the environment (Mejjad et al., 2022).

Over the years, several studies have explored sustainable tourism in coastal regions, shedding light on diverse aspects crucial to the interaction between the three pillars of sustainability (nature, society, and economy-tourism). Research conducted in Emilia-Romagna, Italy, analyzes the interplay between geomorphological evolution, carrying capacity, and the perceptions of users and explores how the evolving coastal landscape affects the region's capacity to support tourism while considering visitors' perceptions of these changes (Rodella et al., 2017). Moving to Asinara Island, where a dual approach encompassing carrying capacity assessments and web-based evaluations has been recently implemented. This combination optimizes the management of two distinct pocket beaches, aligning tourism activities with the ecological sensitivities inherent to the island (Corbau et al., 2019). Shifting to the Costa Brava in Spain, older research has focused on public perceptions of beach quality based on users' profiles, providing insights for tailored beach management strategies (Roca et al., 2009). Another study conducted in Baisha Beach, Taiwan, offers a deep understanding regarding management priorities and carrying capacity for maintaining a delicate balance between tourism and nature (Chen and Teng 2016). Collectively, these papers underscore the nature of sustainable coastal tourism, encompassing geomorphology, social considerations, ecological evaluations, public perceptions, and management strategies.

The phenomenon of over-tourism (Vagena, 2021) was effectively described by the European Parliament in 2018 as the condition under which tourism, in a specific place and time, exceeds its multilevel capacity threshold (physical, ecological, social, economic, psychological, or/and political). It could also be expressed as a dependent variable on unstable parameters, such as the touristic destination's number of visitors, seasonality, or carrying capacity.

Overtourism and seasonal characteristics, in conjunction with the current crises concerning energy, biodiversity, water, food, and health (Searchinger et al., 2018), have an accumulative negative impact on tourism destinations, making the realization of sustainable development actions inevitable (Lange, 2015). Thus, environmental impact assessments and planning processes are essential to define an area's Carrying Capacity (CC) (Cifuentes, 1992) to build the foundations for sustainable tourist growth.

The aim of studying the CC of sensitive coastal ecosystems (Jurado et al., 2012; Lange, 2015) is to determine the maximum number of individuals, species, or activities an ecosystem can support without experiencing significant degradation. Much more than a balance concept or a number inherent to the area examined, CC is a dynamic, multidimensional management concept, and estimating it enables policymakers to determine the maximum number of individuals or activities that can be developed without causing permanent damage to the ecosystem (Cifuentes, 1992). Ultimately, it provides valuable information to develop management plans that aim to protect the ecosystem and promote its healthy function in the long run (Paskova et al., 2021).

The CC assessment in sensitive coastal regions has already been studied through various research and methodologies. As mentioned in a recent and extensive literature review (Ajuhari et al., 2023) of over 80 studies and their methods used for assessing CC in tourism and recreation destinations, there is yet progress to be made for a systematic or even standardized approach to CC assessment.

The main contributions of this study are:

1. The emphasis on stakeholder engagement in CC assessment is essential to ensure that CC assessments reflect local perspectives, values, and knowledge.
2. The importance of ongoing monitoring and adaptive management in CC assessment to account for changing conditions and emerging threats.

The survey methodology through questionnaires and interviews is traditionally used to identify the local community's perceptions of tourism development. A study conducted by the University of Kashmir, India (Wani et al., 2022), makes an essential contribution by focusing on the perspectives of indigenous communities, whose attitudes and perceptions are critical for developing sustainable tourism practices that respect and preserve local values and traditions and ensure that tourism's benefits are distributed equitably. The study's findings indicate that local communities have a mixed perception of tourism development, which can cause plenty of impacts (positive and negative) on the local economy, culture, and environment. It also emphasizes the importance of community involvement and participation in tourism development to ensure that tourism practices align with local culture and values. One limitation and a critical factor in such studies is the representative sample size.

A more quantitative approach is the estimation of the EcoTourism carrying capacity (ETCC), Physical (PCC), Real (RCC), and Effective Carrying Capacity (ECC) (Sobhani et al., 2022). The nature of this method has constraints as it does not consider qualitative factors, such as cultural values and perceptions. Visitors' behavior, infrastructure development, and natural resource availability all limit the CC of ecotourism in these protected areas. The study emphasizes the importance of efficient management approaches to control the number and behavior of visitors while minimizing the negative environmental impacts of tourism. Also, the importance of balancing the economic benefits of tourism with the conservation of natural and cultural resources was emphasized.

In another research, a new tourism carrying capacity index (TCCI) was created to measure the capacity of tourism activities in coastal areas of Mediterranean islands. The TCCI was developed by considering several factors, including environmental quality, socio-economic factors, and the number of tourists (Leka et al., 2022). One of the study's significant contributions is its comprehensive approach to measuring the TCCI by considering multiple factors that affect the CC of tourism activities and a complete framework to measure it. Similarly, system dynamics modeling is another standard methodology used in the field of CC identification, usually preferred to capture the dynamic relationships among various factors and simulate the impacts of different management strategies (Olumide et al., 2022; Wang et al., 2022). Due to the lack of qualitative inquiry, the last two methodologies usually export similar findings. At the same time, it is vital to comprehend that emphasis on quantitative methods may overlook the role of qualitative factors, such as cultural values and perceptions, when shaping the relationship between environmental pollution and coastal tourism.

In the current study, aiming to develop a new holistic framework for assessing CC in sensitive coastal ecosystems, a combined methodology—of all the abovementioned approaches—was created and tested. The method encompasses the calculation of PCC, RCC, and ECC, a multicriteria analysis to capture the stakeholders and the local community's perception, and finally, environmental quality measurements. The carrying capacity estimation methods enable us to quantify the maximum visitor load the beach can sustain while considering various limiting factors. The multicriteria decision analysis engages diverse stakeholder perspectives to prioritize sustainable management actions, ensuring that cocreation and cooperation are achieved in the decision-making procedures, and the physicochemical analyses shed light on the environmental quality, plastic pollution, and potential anthropogenic threats in the ecosystem. By combining these methodologies, the study addresses the immediate challenges facing Balos Beach, also fosters a comprehensive approach that informs effective management strategies, policy formulation, and conservation efforts for the long-term well-being of such unique coastal environments.

2 Methodology

This study sought to design and perform a holistic approach that would investigate all three sustainability components, i.e., environment, society, and economy, of a single site, proposing a three-level methodology for calculating its CC:

(1) Estimation of the physical, real, and effective CC (Nilsen, 2010),
(2) Obtaining the stakeholders' views (Turker et al., 2016) and
(3) Quantification of the ecosystem's quality (Naeem et al., 1999).

The methodology is tested in one key region, which was purposefully selected to answer in five characteristics: (a) insular, (b) coastal, (c) sensitive, (d) economic pole, and (e) tourist attraction.

The three-scaled methodology was constructed to achieve the maximum insight into the ecosystem's current condition and propose tailor-made solutions for sustainable development. Concretely, all possible issues and weaknesses were recorded through CC calculation and environmental quality measurements, each of which actions were proposed to address them. The actions were the result of:

- Carrying Capacity calculation (CC), analytically described in Section i
- Biological measurements (BM), analytically described in Sect. 0 and
- TripAdvisor analysis (TA): To quantify and evaluate the given issues of the area (intensity, seasonality), data were gathered from the 120 users' reviews found on Balos' TripAdvisor page for the period June 2020 to October 2021 (which are the total reviews of 2020–2021). The comments were then analyzed via statistical analysis of frequencies to extract the most highly mentioned issues over the two years (Skiniti et al., 2022).

This integrated approach helps to promote social and environmental sustainability and to ensure that decisions are effective over the long term.

Calculating the physical, real, and effective CC, understanding the stakeholders' views, and quantifying the ecosystem's biological quality help ensure that decisions are inclusive, transparent, and based on sound scientific data. By considering all three CCs of the ecosystem, the perspectives and interests of different stakeholders, and the current state of the environment, informed decisions that consider a range of crucial factors can be made. This comprehensive approach ensures that decisions are made with a complete understanding of the state of the ecosystem, the potential impacts of human activities, and the needs and interests of different stakeholders.

Each methodology is presented in detail, beginning with how all CCs are calculated, then the scientific method used to determine tourist demand, and finally, the chosen methods' goals. The third section presents the multicriteria method PROMETHEE, which was deemed more appropriate for investigating the perspectives of local stakeholders.

2.1 The study area

The study area selected was Balos Lagoon, located in Crete, Greece, 17 km northwest of Kissamos. The lagoon is formed by an uncovered, narrow strand of land between the Gramvousa Cape and the peninsula of Tigani. The area is declared protected under the institutional framework of N2K (code GR4340001) and Corine biotopes, owing to its ecological, social, cultural, and aesthetic value (FILOTIS—Database for the Natural Environment of Greece) covering 31,08 km^2 of land (Natura 2000-Standard Data Form).

Balos Lagoon is known for its unique geomorphological features, i.e., the plethora of sand dunes and the rocky and calcareous landscapes featuring steep slopes and rugged, sea-inaccessible coastlines alongside the enriched ecosystems of Posidonia in the sea. Vegetation is predominantly phryganic, led by shrubby perennials like *Sarcopoterium spinosum*, *Coridothymus capitatus*, and *Callicotome villosa*.

The area harbors endemic plants, rare reptiles, invertebrates, and migratory birds. Species like *Centaurea pumilio* are rare IUCN-listed and protected under the Greek law, *Filago aegaea ssp. aristata*, *Cynara cornigera*, *Silene fabaria*—restricted species, or endangered birds like *Gyps fulvus* and *Gypaetus barbatus*, as well as monk seals, add to its ecological value (Natura 2000-Standard Data Form).

The definition of the study area started with a more detailed and accurate survey of the area of Balos and reached up to the level of the Municipality of Kissamos (Fig. 1). In several cases, the influence of the lagoon is highlighted at the level of the Regional Unit, as it is not only a place of unique natural heritage but also one of the most significant points

Fig. 1 Levels of the Balos Lagoon Study Area

of tourist interest on a global scale. Thus, some parts of the holistic approach, such as the biological measurements and the tourist demand, were held on a strictly local level, Balos' lagoon. In contrast, the multicriteria method was held on a regional level, as stakeholders in the whole region of Crete are affected by this critical Natura area.

2.2 The holistic methodology

2.2.1 Estimation of the physical, real, and effective carrying capacity

CC is defined as "the maximum number, density or biomass of a population that a specific area can sustainably support" (Cifuentes, 1992; Hartvigsen, 2022; UNWTO, 1981). To preserve and develop a sensitive ecosystem feasibly, the CC definition can provide an approach to analogize the area's current state with the optimum 'one.

Calculating physical, real, and effective carrying capacities (Suwarno et al., 2018) in sensitive coastal ecosystems is crucial in understanding these ecosystems' limits, actual state, and sustainable use.

The CC of a sensitive coastal tourist destination is determined by factors such as the availability of natural resources, the ability of the ecosystem to absorb waste and recover from disturbances, and the impact of tourism activities on the local community and culture. For example, suppose the number of tourists exceeds the CC of the area. In that case, it can result in the overuse of resources, increased pollution, and degradation of the natural and cultural heritage of the area. On the other hand, poor visitation could severely lessen development opportunities and benefits for stakeholders (Mihalic, 2020). Consequently, if the CC is appropriately managed, tourism can contribute to the conservation of the ecosystem, the promotion of sustainable economic growth, and the preservation of local culture and heritage.

Thus, determining the CC of a sensitive coastal touristic destination is essential for making informed decisions about the development and management of tourism activities. By balancing the needs and interests of different stakeholders and considering the impact of tourism on the ecosystem and the local community, decision-makers can ensure that tourism activities are sustainable and that the long-term health and integrity of the ecosystem are protected.

It is often done using mathematical models and simulations, which take into consideration the available data on resource availability, climate, terrain, biotic factors, and human activities. However, it is worth mentioning that CC is a dynamic concept that can change over time due to environmental and human activities.

Physical carrying capacity (PCC) is given by the following equation (Suwarno et al., 2018):

$$PCC = A \times \frac{V}{A_p} \times R_f \left[\frac{visitors}{day} \right] \quad (1)$$

where,

A: the available space for use (m^2),

$D = \frac{V}{A_p}$: users' density as the area required per user to move freely (person/m^2),

R_f: rotation factor (number of visits/day): The ratio of the open period to the average duration of a single visit. This number expresses the daily number of visits possible for a user.

Real carrying capacity (RCC)is described as (Suwarno et al., 2018):

$$RCC = PCC \times C_{f1} \times C_{f2} \times C_{f3} \times C_{f4} \left[\frac{visitors}{day} \right] \quad (2)$$

where,

C_f: corrective factor (rainfall days, days with strong winds, cold days, and heatwave days), expressing the negative impact on tourist activity and is calculated by:

$$C_f = 1 - \frac{M_1}{M_t} \quad (3)$$

where,

M_1: limiting magnitude of the variable.

M_t: total magnitude of the variable.

Then Effective Carrying Capacity (ECC) (Suwarno et al., 2018):

$$ECC = RCC \times MC \quad (4)$$

where,

Management Capacity (MC) is an index number based on the number of tourism employees and the budget for the conservation and protection of the site. The current number of employees was estimated by observations in the field survey and information by the local authorities, as well as assumptions made based on the literature review. The existing workforce is distributed in the cafeterias, parking areas, toilets, the guardhouse, lifeguards, and the ships that operate the services.

Estimating the ideal number of workers needed on the site was based on the baseline scenario, the legal guidelines for lifeguarding, and the adequate number of shifts.

$$MC = \frac{amc}{imc} \times 100\% \tag{5}$$

where,

amc: The current number of employees for the maintenance of the site,

imc: The ideal number of employees for the sustainable development of tourism at the site.

2.2.2 Multicriteria method for key stakeholders

The definition of stakeholders' views in decision-making procedures for protecting sensitive coastal ecosystems is essential for ensuring that decisions are inclusive, transparent, and effective. By considering the perspectives and interests of different stakeholders, including local communities, government agencies, and businesses, decision-makers can build trust, promote innovative solutions, and promote social and environmental sustainability. Including stakeholders in the decision-making process helps ensure that decisions are accountable and meet the needs of both the ecosystem and the people who depend on it.

In the following figure, the steps of the multicriteria method are described in detail, from the problem description to the final stage of the analysis's results with the ranking of sustainable tourism policy measures (Fig. 2).

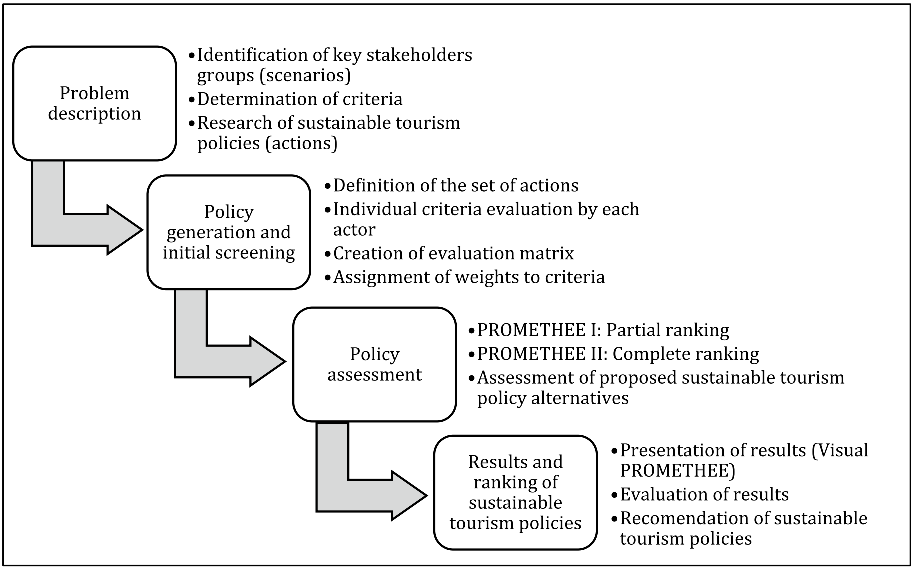

Fig. 2 Description of the multi-criteria method for the evaluation of sustainable tourism development policies (Farmaki et al., 2018)

The multicriteria method (Online Annex C) PROMETHEE (Farmaki et al., 2018; Stamatakis et al., 2016; Tsoutsos et al., 2009) studies the views of all stakeholders involved (by filling out the questionnaire of Online Annex B, developed for this study) (Table 1) in the management of the ecosystem (Natura 2000). This method hierarchies a set of n alternatives $a_i(i = 1, 2, ..., n)$ based on k criteria $g_j(j = 1, 2, ..., k)$. The evaluation $g_j(a_i)$ of each alternative a_i for every criterion g_j should be maximized or minimized, depending on the criterion (Argyriou et al., 2022).

The initial hierarchy is obtained via the PROMETHEE I method for partial ranking, followed by the PROMETHEE II method for the automatic complete ranking of the alternatives produced by the program after the partial ranking. Subsequently, the Geometrical Analysis for Interactive Aid (GAIA) tool can be utilized to present the examined actions concerning all criteria. The fifth and final step involves a sensitivity analysis of the weights assigned to different actions, which is applied to assess the robustness of the complete ranking.

Net flows (phi) in PROMETHEE are calculated for each alternative by considering both positive and negative flows. These flows represent the degree to which an alternative outranks or is outranked by other alternatives for each criterion. The positive flow (phi+) measures the preference an alternative has over others, while the negative flow (phi−) quantifies how much an alternative is outranked by others. The net flow for an alternative is the difference between its positive and negative flows.

A higher net flow value suggests that the alternative has a more substantial overall advantage over others. In comparison, a lower or negative net flow value indicates a weaker position relative to other options.

Twelve measures were selected to be evaluated by eight criteria (Tables 2 and 3). As shown in the following table, actions were the result of 3 methods used to address the issues in the area (CC: Carrying Capacity calculation, BM: Biological Measurements, and TA: TripAdvisor analysis, alongside an extensive literature study which provided the actual actions, a.k.a. the measures used in other similar case studies to solve such issues in the past. For example, Carrying Capacity calculation identified issues related to the overcrowded beach, which, according to the literature, are addressed via the definition of a maximum number of visitors or ferries per day or a more organized implementation of an admission fee, actions 8, 9 and 11 suggested in the current study.

Generally, Table 2 includes each measure selected to address one or more issues identified, as well as the method from which each issue was identified, while the 7th and last column of the table, the reference used to find the appropriate solution for each problem, appears.

The criteria selection needed to be related to the issues tracked in the area and the actions proposed to address them. At the same time, they were based on the three

Table 1 Questionnaires' target group

Category	n. of respondents
Local authorities	3
Tourism factors—Financial investors	4
Non-governmental organizations—Local initiatives	2
Academia—research sectors	3
Regional—National government	3

Table 2 Actions—Sustainable Ball Management Measures

N. of Action	Measure	Issue	CC	BM	TA	Reference
A1	Oil boom installation across the sea	Marine tar residues		✓	✓	Asif et al., (2022)
A2	More frequent beach clean-ups	Presence of microplastics at the beach		✓		Testa (2018); Zielinski et al., (2019)
A3	Transport by electric bus till the beginning of the pathway to the beach	Road conditions unsuitable for most cars			✓	Nikiforiadis et al., (2022)
A4	Eco-friendly improvement of the main road	Road conditions unsuitable for most cars			✓	European_Commision (2013)
A5	Parking lot reallocation outside of the NATURA area	The number of cars exceeds the parking space			✓	European_Commision, (2013)
A6	Open space information boards about the protected area	Littering/lack of awareness			✓	Marschall et al., (2016)
A7	Observatory for the environmental quality monitoring of the area	Marine tar residues/Presence of microplastics at the beach		✓		Glaviano et al., (2022)
A8	Definition of a maximum number of visitors/day	Overcrowded beach	✓			Suwarno et al. (2018)
A9	Definition of a maximum number of ferries/day	Overcrowded ferries	✓			Suwarno et al. (2018)
A10	Dispersion of tourist boat itineraries	Overcrowded beach	✓			Suwarno et al. (2018)
A11	Organized implementation of an admission fee	Overcrowded beach	✓			Reynisdottir et al., (2008)
A12	Online pre-booked tickets	Overcrowded beach/ferries	✓			Zielinski et al., (2020)

*CC: Carrying Capacity calculation (CC), Biological measurements (BM) and TripAdvisor analysis (TA)

Table 3 Criteria

Category	Code	Criterion	Description
Environment	C1	Energy saving	Decrease fuel consumption
	C2	Pollution	Decrease pollution due to tourist activity and shipping
Society	C3	Safety	Sense of safety accessing the area and during the stay
	C4	Visitors' satisfaction	Level of satisfaction with visitors' experience
	C5	Residents' satisfaction	Level of satisfaction with tourist activity and acceptance due to tourism
	C6	Job opportunities	Sustaining or increasing the number of working positions due to tourism
Economy	C7	Tourist flows	Number of tourists visiting
	C8	Tourist income	Financial benefits due to tourism

pillars of sustainability and an extensive literature review of similar studies (Chen and Bau 2016; Pesce et al., 2018). Firstly, the inclusion of "Energy saving" (C1) and "Pollution" (C2) is justified by the imperative to minimize the environmental footprint and pollution from tourism-related activities, waste, and transportation emissions.

The following criteria are emphasised in the social sector: "Safety" (C3) is an important parameter, as a safe environment fosters positive experiences and encourages repeat visits, ultimately contributing to the long-term sustainability of the tourism industry. At the same time, "Visitors' satisfaction" (C4) and "Residents' satisfaction" (C5) are pertinent criteria, reflecting a balanced approach that acknowledges that tourism development should not only enhance visitor experiences but also respect the quality of life and cultural integrity of the host community.

Furthermore, the "Job opportunities" (C6) criterion recognise tourism's potential for local employment, fostering economic stability and reducing unemployment. At the same time, " Tourist flows" (C7) ensure sustainable visitor levels, preventing overcrowding, resource strain, and environmental degradation, and "Tourist income" (C8) evaluates how tourism revenue can boost local economies, supporting businesses and infrastructure development for long-term resilience.

While the selected criteria are well-considered and collectively encompass ecological, social, and economic dimensions, local stakeholders, experts, and community members need to be engaged in the decision-making process to ensure the relevance of those criteria. Additionally, ongoing monitoring and evaluation can refine and adjust the criteria as the region's dynamics evolve, providing a robust framework for sustainable tourism development.

The questionnaire was distributed via email, including guidelines to fill it, to a contact list of 30 stakeholders related to the survey's target group (Table 1), which was then reached by phone calls to provide further information on the questionnaire. Finally, 15 valid questionnaires were collected for further analysis. However, this number is limited for statistically solid analysis; it is estimated as satisfactory following global research practice in the multicriteria analysis since the selected group of respondents was very well targeted (Dean, 2022).

2.2.3 Physicochemical analyses in Balos Lagoon

The quantification of the ecosystem's biological quality is vital to designing a conservation plan, which will be followed by extensive monitoring and evaluation procedures to upgrade this plan, target its flows, and adjust and improve conservation strategies in response to changes in the ecosystem.

In Balos Lagoon, ten samplings were carried out (June–October 2021 and May–September 2022) (Lilli et al., 2022), from which 60 samples in total were analysed. The sample was planned in two cross sections (A and B) (Fig. 3) in the lagoon's most heavily touristic location. Two "composite" samples (from each cross-section) of saltwater (hereinafter referred to as Aw & Bw respectively), sediment (hereafter referred to as Ai & Bi respectively), and beach (sand) (hereafter referred to as As & Bs respectively) were taken in each sampling.

To gather samples of sand and sediment, a 40cm x 40cm frame was placed into the substrate of each transect, and 500 g of the material was collected from the frame for all analyses except microplastics. In the case of microplastics, all of the sand or sediment from the frame was retrieved and sorted through 2 mm and 53 mm sieves after being placed in a metal container with water. Seawater samples were analyzed for nitrate, sulfate, phosphate, ammonia ions, and total organic carbon (TOC) in the laboratory using spectrophotometry (HACH—DR 2800) and the thermocatalytic oxidation method (multi N/C® 2100S Analyzer, AnalyticJena). The total metal concentration (B, Na, Mg, Al, Si, K, Ca, Cr, Mn, Fe, Co, Ni, Cu, Zn, As, Cd, Ba, Hg, Pb) of the samples (Online Annex D) was determined using inductively coupled plasma mass spectrometry (ICP-MS, 7500cx, Agilent Technologies). Microbiological testing was performed by cultivating seawater samples or leachates (sand-sediment) in particular nutrients at 37oC for *E. Coli* (*Hicrome E. Coli Agar*), *Enterococci* (*Slanetz & Bartley Medium, Membrane Enterococcus Agar*), and total coliforms (*Membrane Lauryl Sulfate Broth & Agar*). Total petroleum hydrbons (TPH) were detected using gas chromatography (GC-FID, Shimatzu) of pentane extracts of the samples, and microplastics were manually separated by hand; each subcategory was counted

Fig. 3 Sampling design. Cross sections (A and B) were used for sand, sediment, and seawater sampling

and weighed. Finally, 50 L of seawater was collected using sieves for microplastics, which is consistent with international literature (Karkanorachaki et al., 2018).

3 Results

3.1 Carrying capacity estimation

(a) PCC Estimation

The assessment of the available area visitors can occupy at Balos Beach was performed with the assistance of maps provided by the Hellenic Cadastral Survey using the "area measurement with polygon definition graphics" tool.

The areas where bathers can be present both in standing and lying positions, i.e., sandy and with a minimum slope (at low altitude from sea level) (Elliniko Ktimatologio). The marked boundaries of the continuous surface can be found in Online Annex A.

$$The\,total\,surface, A_{tot} = 33,033\text{m}^2$$

To estimate the space occupied by a single bather, the dimensions of a sunbed were measured as $1.90\text{m} \times 0,60$ m. and an extension of one meter was added in both directions in each dimension, making it possible to move freely between them. (≈ 4.7 m^2/bather).

The rotation factor is defined as the ratio of the time the site is open to the public, i.e., 24 h, to the average length of a visitor's stay at the beach, taking into account the time needed to get there and return to the starting point (place of stay). The average time for all visitors was extracted from a tourist survey conducted between September 13–23, 2023. However, 51% of visitors arrive by boat, which is not available 24 h per day, and due to the difficulty of accessing Balos at night, the time that the beach is open to the public was considered 12 h.

Hence,

$R_f \approx 2.08$ and finally,

$$PCC = 6,776\left[\frac{visitors}{day}\right]$$

(b) RCC Estimation

The RCC of Balos Beach was estimated considering the following limiting factors on PCC.

C_{f1}: rainfall days.

C_{f2}: days with solid winds above 5 Beaufort or 29 km/h.

C_{f3}: cold days, where the temperature was less than or equal to 10 °C

C_{f4}: heatwave days, where the temperature exceeds 35 °C C_{f5}: days of 'low season, from 1 November to 28 February.

The meteorological data were obtained from the nearest station of the National Observatory of Athens, located in Falassarna, covering a period from 1 January 2011 to 31 October 2021. The number of off-season days was estimated as 119. The limiting factors are illustrated in Online Annex D. Considering that the limitation factors vary, as shown in the Online Online Annex, the RCC for different scenarios occur where each factor is separately minimized, while the values of the total available area for bathers, the area required per user, the rotation factor and the number off-season days ($\boldsymbol{C_{f5}}$) served as a baseline scenario. This led to

Table 4 The limitation factors C_{fi}

	C_{f1}	C_{f2}	C_{f3}	C_{f4}
Min	0.85	0.97	0.99	0.99
Max	0.72	0.86	0.88	0.95

Table 5 Estimation of the existing and necessary staff for the sustainable development of the Balos

	Canteens	Parking lot	Toilets	Umbrellas	Shelter	Boat amenities	Lifeguards
Current number of employees (amc)	5	5	2	2	1	62	1
The ideal number of employees (imc)	6	6	3	3	2	62	5

an average minimum RCC. The exact process was followed for an average maximum value (Table 4).

Ultimately, the RCC of Balos Beach is $RCC = 2,695 - 3,039\left[\frac{visitors}{day}\right]$

(c) ECC Estimation

The workforce of 78 people/day is distributed in the cafeterias, parking areas, toilets, the guardhouse, lifeguards, and the ships that operate the services.

The assumptions for the estimation of the ideal number of workers needed on the site are as follows:

- An extra person should be employed in the refreshment rooms, parking areas, toilets, and guard posts so that two shifts are easily carried out during the day.

- There should be five lifeguards (General Secretariat of Safety-Navigation, 2010), each supervising a 600 m radius of the beach in 2 shifts per day. The calculation made using the maps of the Hellenic Cadastral Survey (Online Annex A, Fig. 6) showed that the coastline is 1408 m.

- The number of people employed on board may remain unchanged (Tables 5, 6).

The *amc* and *imc* numbers are summarized below:

Thus, the manpower capacity, FM, is calculated as $FM = \frac{78}{87} \times 100\%$ and the ECC of Balos Beach is estimated as:

$$ECC = RCC \times FM$$

The exact process for estimating RCC was followed here. FM was considered, ranging from 90% to an optimum 95%, corresponding to the ideal number of employees for all posts, apart from lifeguards. This is due to the fact that the presence of 5 lifeguards requires an equal number of lifeguard chairs, which is thought to be a heavy human intervention. Hence, in Table 7, the range of all the above-head calculations appears.

or

$$ECC = 2,425 - 2,888\left[\frac{visitors}{day}\right]$$

Table 6 Quantitative Parameters and Carrying Capacity Metrics. Results are based on the baseline, the minimum, and the maximum scenarios

Parameters	baseline	min	max	RCCmin	RCCmax	ECCmin	ECCmax
Total available Area for Bathers (m^2)	33,032						
Area required per user (190×60 cm) (m^2)	10.14						
Rotation Factor	2.00						
C_{f1}	0.79	0.85	0.72	2,633	3,101	2,369	2,946
C_{f2}	0.91	0.97	0.86	2,695	3,039	2,425	2,887
C_{f3}	0.93	0.99	0.88	2,694	3,040	2,425	2,888
C_{f4}	0.97	0.99	0.95	2,807	2,927	2,526	2,781
C_{f5}	0.67						
MC	90%	90%	95%				
Average				2,695	3,039	2,425	2,888

Table 7 Average Relative weight % for each stakeholder group

Criteria	Local authorities	Economic and Tourism	NGOs and Local communities	Regional and National Government	Academic-research bodies
C1	9.3	17.40	15.30	16.70	15.30
C2	22.2	16.00	22.20	22.20	19.00
C3	14.8	17.40	18.00	18.50	17.10
C4	16.7	12.50	12.50	13.00	14.30
C5	8.3	6.30	12.50	7.40	13.20
C6	10.2	9.00	11.10	5.60	8.80
C7	8.3	9.70	4.20	11.10	7.10
C8	10.2	11.80	4.20	5.60	5.20

The tourist flows during the peak season (August) for 2017–2021 (Skiniti et al., 2022) have exceeded Balos's ECC by approximately 1,000 people.

3.2 Results of the multicriteria decision analysis

The responses of each stakeholder group provided the necessary information to create the average evaluation matrix for each group and calculate the average assigned weights (Table 7). The detailed results of the evaluation matrices and an example of the weight calculations per sector are presented in Online Annex E.

The above data were imported into the PROMETHEE program, from which the overall results were obtained. From the partial ranking presented in Table 8, the hierarchy of the actions proposed for the sustainable development of Balos Lagoon per stakeholder

Table 8 Partial ranking of actions by all stakeholder groups

Ranking	Local Authorities	Social and tourist bodies	NGO and local communities	Regional and national governance	Academy
1	A1	A1	A1, A5	A9	A5
2	A4	A2	A2	A8	A3
3	A5	A9	A4	A11	A8
4	A3	A10	A9	A1	A2
5	A7	A4	A8	A2	A12
6	A10	A5	A3	A5	A4
7	A6	A8	A10	A10	A6
8	A8	A11	A6	A12	A9
9	A9	A7	A7	A3	A7
10	A12	A3	A11	A7	A10
11	A11	A6	A12	A4	A1
12	A1	A12		A6	A11

group involved in the survey is presented. It is concluded that for local government, priority is given to actions related to regular beach cleaning and road improvements, while oil booms and implementation of an entrance fee are of minor importance. For the economic and tourism sectors, priority is given to actions concerning regular beach cleaning and oil booms. At the same time, information signs and an online pre-booked ticket system seem insignificant. For NGOs and local communities, regular beach clean-ups and oil booms are the most important, with the last two measures relating to implementation and online booking of tickets coming last. For regional and national governance, setting maximum numbers of people and boats are key actions, while road improvement and information signs are not considered priorities. For academic and research bodies, actions on parking reform and access to the electric bus are prioritized, while oil booms and ticketing appear to be less critical.

It is observed that in the overall "complete" ranking of measures in descending order, the main priority is the action related to the regular cleaning of the beach (Phi = 0.379), while the action associated with the online pre-booked tickets comes last (Phi = – 0.332) (Table 9).

Figure 4 shows the profile of the actions in relation to the three categories of criteria (environment—green, economy -red, and society-blue), where according to the stakeholders' responses, measure A2—Regular beach clean-ups seem to be the most balanced among the three pillars of sustainability, but with an emphasis on the society. This does not seem to be the case for action 9—The definition of a maximum number of boats arriving per day, which, while important from the environmental aspect, does not seem to be satisfying concerning society and even more so to the economy.

In the same diagram, the hierarchy described in the upper table is also shown, with the most essential measure being A2 on the left side, while the last is on the right side. It is interesting to observe that measures of high priority can be of low satisfaction for one or more sustainability pillars, for example, the second measure, about the Parking lot reallocation outside of the NATURA, or the one about the definition of a maximum number of ferries/days seem to have no significant effect on the economy.

Table 9 Prioritization of sustainable management actions

Ranking	Action	Phi
1	A2: More frequent beach clean-ups	0.379
2	A5: Parking lot reallocation outside of the NATURA area	0.287
3	A9: Definition of a maximum number of ferries/day	0.205
4	A4: Eco-friendly improvement of the main road	0.134
5	A8: Definition of a maximum number of visitors/day	0.090
6	A1: Oil booms installation across the sea	0.083
7	A3: Transport by electric bus till the beginning of the pathway to the beach	–0.021
8	A10: Dispersion of tourist boat itineraries	–0.059
9	A7: Observatory for the environmental quality monitoring of the area	–0.192
10	A6: Open space information boards about the protected area	–0.285
11	A11: Organized implementation of an admission fee	–0.288
12	A12: Online pre-booked tickets	–0.332

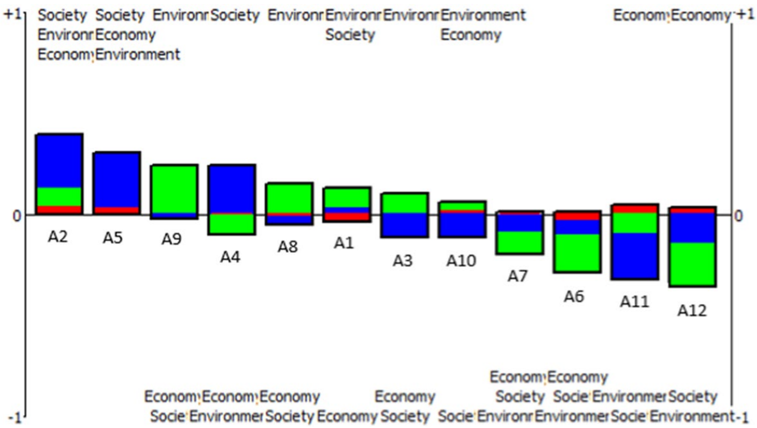

Fig. 4 Profile of each action, where green refers to the environment, red refers to the economy, and blue refers to the social category

Reading the same figure with emphasis on the vertical axis, it is possible to observe that measures may have a positive effect on one sector and a negative on another. More specifically, A3: Transport by electric bus till the beginning of the pathway to the beach is an environmentally friendly and effective measure, but for society, it is certainly not a priority, leaning to the negative part of the diagram below the horizontal axis.

3.3 Results of physicochemical analyses

Physicochemical analyses of the samples taken in the ten samplings are presented in Online Appendix. The samples' physicochemical characterization (Table 10) showed that the values are typical of a coastline (Lilli et al., 2022), and there are no significant differences between the A and B cross-sections. There are also no significant differences between the

Table 10 Average value of physicochemical parameters. Results are reported for both cross-sections (A and B). Parentheses show standard deviations

	Water	Sand	Sediment
pH	6.6–8.19	–	–
DO	9.5 (0.95) mg/L	–	–
$N–NO_3$	3.4 (1.98) mg/L	12.3 (9.7) mg/kg	10.9 (6.7) mg/kg
$P–PO_4$	< 0.01 mg/L	0.08 (0.07) mg/kg	0.09 (0.07) mg/kg
TPH	< DL	< DL	< DL
TOC	61.85 (78.14) mg/L	7.6 (16.63) g/kg	4.0 (0.96) g/kg
SO_4	3668 (1192) mg/L	1266 (756) mg/kg	1285 (355) mg/kg

sand and sediment samples. For all samples taken in the various samplings, As, Cd, Cs, Hg, and U were tested below the detection limit. Co, Pb, Ni, Cr, Ti, Zn, and Sn concentrations showed shallow values or were below the detection limit for all samples as well. No total petroleum hydrbons were detected in the samples; however, tar pellets were observed in some water and sand samples, resulting in increased TOC amounts in these samples (Table 10).

The density of plastic fragments and pellets determined in the ten samplings is demonstrated in Table 11. The results showed that microplastics of > 2 mm and > 53 m size were discovered in an average of 19 n/m^2 of sand samples, while microplastics of the same size have been identified in sediment samples at a rate of 5 n/m^2 and 8 n/m^2, and in seawater samples at a rate of 0.002 n/m^2 and 0.007 n/m^2, respectively. Findings that are consistent with the literature, and especially with samplings in Greek beaches of the Aegean, where there have been revealed microplastics (2–4 mm) densities in the top 3cm of the subsurface ranging between 10 and 602 items/m^2 (Kaberi et al., 2013; Karkanorachaki et al., 2018).

Higher values of *Escherichia coli* (> 500cu/100 g) were observed in the sand samples of the B cross-section and *enterococci* (> 2500cu/100 g) of the A cross-section compared to the other samplings in July 2021. More elevated values of total coliforms in the water, sand, and sediment samples and *Escherichia coli* in the water sample of transect B were observed in August 2021 compared to the other samplings. Higher values of enterococci in water and sediment samples, and *Escherichia coli* in sediment samples were observed in July 2022 compared to other samplings. More elevated values of *enterococci* in the samples of the sand as well as of the sediment of the A cross-section were observed in September 2022, about the rest of the samplings. It is worth noting that, according to the legislation for water quality (European (European Union, 2006) and Greek (Ministry of Interior—Finance—the Environment and Energy—Health, 2009) legislation), the seawater of the Balos lagoon can be characterized as "excellent" quality, since the values of *enterococci* and *Escherichia coli* were below 100 and 250 cu/ml respectively, in all samplings

Table 11 Absence of microplastics in the samples

		> 2 mm		> 53 µm	
Type of sample	Units	Values range	Average	Values range	Average
Sand	n/m^2	0–80	19	0–47	10
Sediment	n/m^2	0–20	5	0–27	8
Sea water	n/L	0–0.02	0.002	0–0.06	0.007

(Fig. 5). It is imperative to remain cognizant that during the peak of the tourist season, concentrations of *Escherichia coli* and *enterococci* reach their zenith, approaching regulatory thresholds. Consequently, tourism activities over successive years engender apprehension regarding the potential to surpass these established thresholds by such microbial indicators.

The most crucial indicator is the presence of tremendous quantities of tar balls or residues on all the samples that originated from both human-caused and natural oil leaks in the ocean environment. Marine tar residues are formed by the transformation of liquid petroleum under specific conditions like weathering, sedimentation, and other processes (Warnock et al., 2015). This issue is essential not only from the environmental perspective but from the social as well, as it is mentioned by visitors and stakeholders as a crucial issue faced in the field that needs to be addressed.

Throughout the tourist seasons of 2021 and 2022, extensive monitoring was conducted to assess the environmental quality of the Balos Lagoon, with the aim of identifying critical indicators that require attention to promote sustainable development in the area. However, further research is imperative to determine the root cause of tar residue in the lagoon and to devise effective remedies for this pressing issue.

Also, it is of particular importance that the area has extensive Poseidonia meadows, which are a priority habitat with code 1120*, an endemic species at risk from climate change and other anthropogenic threats.

4 Discussion and recommendations

Traditional Carrying Capacity assessments typically focus on one dimension, such as Physical carrying capacity (PCC), often neglecting the integration of environmental data or a multicriteria approach. Additionally, single-factor environmental studies are also usual, focusing solely on water quality or biodiversity indices, while sustainable tourism frameworks, although valuable, often lack the specificity needed to address over-tourism in sensitive coastal ecosystems, mainly investigating stakeholders' views.

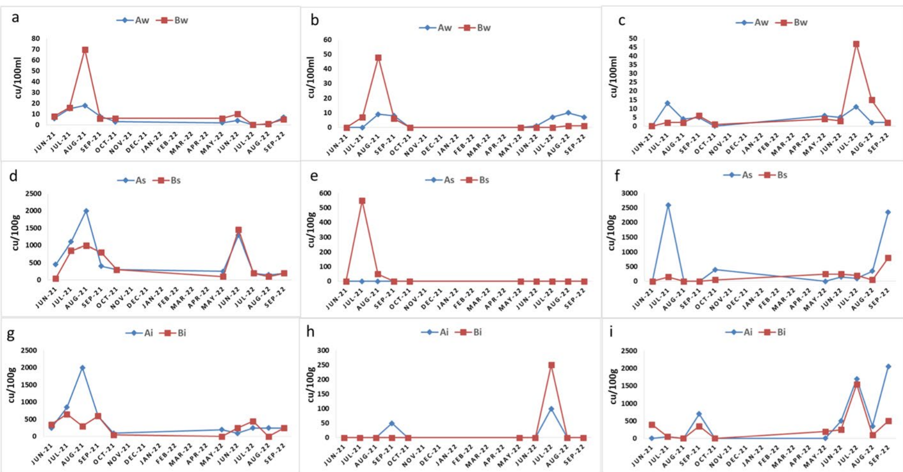

Fig. 5 Temporal variability, in seawater, sand, and sediment samples, of total coliforms ((**a**), (**d**), (**g**)) *Escherichia coli* ((**b**), (**e**), (**h**)) and *enterococci* ((**c**), (**f**), (**i**))

Against this background, the proposed methodology stands out for its innovation, offering a more comprehensive and dynamic assessment that combines capacity calculations with a protocol for environmental measurements, followed by a multicriteria decision-making framework that engages stakeholders from multiple sectors. This holistic approach directly targets the issue of over-tourism, providing adaptability and a participatory character, making it a cutting-edge solution for sustainable coastal tourism management.

Firstly, by calculating the ECC through a series of mathematical functions that associate its determinants, we found that 2888 people/day is the case study's upper visitation threshold. Meanwhile, it is derived from the existing data that during the peak season, up to 3200 people per day are accepted on the site (Skiniti et al., 2022) (1st issue, Table 12), exceeding by far its CC. Our findings align with those of other coastal areas, such as Cala dei Ponzesi and Cala Giordano in Asinara (Corbau et al., 2019), where at first sight, the ECC (175 and 34 visitors per day, respectively) seem to exceed, proportional to the beaches' respective surfaces (916 m^2 and 180 m^2), compared to what we propose for Balos Beach, but this can be attributed to fact that Balos Lagoon is not as accessible as these beaches. Additionally, the coastline of Lido di Comacchio in the northern Adriatic Sea, 16 km long, revealed an ECC of approximately 25 thousand visitors per day (Rodella et al., 2017), fully compatible with what we would suggest.

Having identified this first significant issue, from a sustainable spatial management point of view, it was necessary to integrate into the methodology three other factors: society, economy, and environment. Therefore, to cover the environmental aspect, biological measurements were collected both in the waters of Balos and in the sediment and sand, from which it appears that most indicators are compatible with those of coastlines, with the main problem being the existence of large quantities of tar balls or tar residues in all three sampling points and secondarily the presence of microplastics (but not in alarming quantities) (Issues 2 and 3, Table 12).

Furthermore, to integrate the social dimension into the study, an analysis of the reviews and ratings on the TripAdvisor platform of Balos from June 2020 to October 2021 was carried out, which brought to light issues 4–8, Table 12.

The above complications are interdependent in various ways. For instance, overloaded boats, alongside the number of cars exceeding the parking area's CC, are a combination that leads to an overcrowded beach, which quickly affects the amount of litter or microplastics at the beach.

One or more measures were proposed to address each of the abovementioned issues. Then, these twelve actions were hierarchised by the stakeholders (local authorities,

Table 12 Sum of the issues arrived from the study of Balos

N. of Issue	description
1	Overcrowding on the beach—Overtourism
2	Tar as waste in water, sediment, and sand
3	Microplastics in the aquatic environment
4	Waste/Litter
5	Uncontrolled grazing
6	Insufficient road conditions for most cars
7	The number of cars is more significant than the capacity of the parking area
8	Overcrowding on the tourist boats

tourism factors and financial investors, non-governmental organizations, academia and regional–national government) via a multicriteria analysis. The most crucial action for the sustainable tourism development of the area was the “most frequent beach clean-ups” which addressed not only environmental degradation but aesthetics as well. Following, the parking lot reallocation and the definition of a maximum number of ferries per day are also high in the ranking as two promising measures to solve the problem of overcrowding spaces (beach, boats, and parking) and, consequently, all of its derivatives. A major part of this study’s innovation is this multicriteria method, which has highly safe results; as for all the different stakeholder groups with different interests, at least the high priority in preference measures were similar.

Notably, further initiatives, such as the online pre-booked tickets or the operation of an observatory, have received lower rankings from stakeholders and local authorities than actions already in progress. The lower prioritization of novel sustainable tourism measures by stakeholders and local authorities can be attributed to factors such as a preference for proven, less risky actions, a lack of awareness about the long-term benefits of their implementation, and external pressures for immediate economic results. Dealing with this situation requires proactive efforts, including raising awareness to illustrate the value of innovative approaches through data and case studies and involving stakeholders in the decision-making process. These steps are essential to shift perceptions, mitigate risk aversion, and foster a more comprehensive and sustainable approach to tourism development.

Several gaps can be covered in future studies, such as:

- Continuous environmental monitoring. Continuous measurements and data are needed for the physicochemical evaluation to be more accurate.
- The mathematical models and combined methodology should be proven in action. The measures highest in the stakeholders’ ranking list should be implemented to test their positive trajectory and social consensus.
- Visitors’ demand. It is essential to identify the target group, in this case, for a touristic coastal area, which will be determined through an extended survey targeting Balos’s visitors.
- Willingness-to-pay. The economic valuation of the benefits gained from the natural capital should be incorporated into the future management plan of Balos. In this way, the long-term development and conservation of the ecosystem can be ensured.
- Upgraded local specialisation. Local characteristics such as species risks, climate change impact, cultural traditions, and social characteristics need to be added.
- Enhanced accuracy in the analysis. Additional responses from targeted stakeholders in the multicriteria method could also give more accurate results, even though the plethora of answers is valid according to the literature (Dean, 2022).

5 Conclusions

In conclusion, this study has introduced an innovative holistic methodology for assessing the Carrying Capacity and addressing the sustainability challenges of sensitive coastal ecosystems tested in Balos Lagoon. The findings emphasize the urgent need for sustainable tourism management in the area, particularly given the discrepancy between the current visitation levels and the calculated upper visitation threshold.

Our study underscores the importance of stakeholder involvement in decision-making and prioritizing actions that address environmental concerns. It is worth noting that while newly proposed measures received lower rankings, this may be attributed to risk aversion and a lack of awareness, emphasizing the need for proactive stakeholder education and communication.

This paper contributes significantly to the existing literature by presenting a novel methodology that combines multiple approaches for assessing sustainable tourism development in sensitive coastal ecosystems. The proposed framework serves as a valuable reference for similar case studies in the future, offering a structured approach to analyze complex issues and engage stakeholders effectively. Moreover, future studies should focus on continuous environmental monitoring, testing the practical implementation of high-priority measures, understanding visitor demand and willingness to pay, and incorporating economic valuations to ensure such natural assets' long-term conservation and development. Overall, this research provides a foundation for fostering sustainability in Mediterranean ecosystems and beyond, safeguarding their ecological integrity while enhancing the quality of tourism experiences for both visitors and local communities.

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