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A proxy for carrying capacity of Mediterranean aquaculture

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ABSTRACT

In developing a holistic and innovative approach to determining the carrying capacity in marine finfish aquaculture, we carried out a modified Delphi exercise in which we asked industry experts to identify the factors influencing the production levels of the activity under different scenarios. We disseminated and discussed three rounds of questionnaires in sectoral roundtables and workshops with experts, culminating in the development of a simple formula that adapts production levels to the physical, ecological, social and economic conditions of the activity on the Spanish Mediterranean coast. We used this formula to approach the carrying capacity of the system. Based on the developed model and its theoretical application, we estimated the carrying capacity for floating cages on the Spanish Mediterranean coast at 117,162 t—about 1.5 times the current granted production level of 79,440 t. We therefore concluded that, subject to the execution of an in-situ validation of the model, the production level of floating nurseries on the Spanish Mediterranean coast could be increased by up to 47.5%.

1. Introduction

Over the last decades, worldwide, open sea fish farming has experienced an almost exponential growth (FAO, 2020) due to the high demand for fish products for human consumption (Ruiz-Zarzuela et al., 2009) and the decline of natural fish communities due to overfishing (FAO, 2020). The evolution and development of European Union fish farming, however, has not followed the same trend, with production stagnating since 2000 (APROMAR, 2022). This may be attributed mainly to the limited availability of suitable areas for aquaculture (Sanchez-Jerez et al., 2016) due to the confluence of uses of maritime space (UICN (Unión Internacional para la Conservación de la Naturaleza y de los Recursos Naturales), 2009) and the consequent conflicts for space with other sectors—such as fisheries and tourism (Neofitou et al., 2019). The planning and management of aquaculture sites will therefore play a key role in their successful sustainable development (Borg et al., 2011). Aquaculture management should thus consider the selection of allowable zones for aquaculture development (AZAs; Sanchez-Jerez et al., 2016), considering simultaneously their carrying capacity (FOESA (Fundación Observatorio Español de Acuicultura), 2013; Macias et al., 2019; Weitzman and Filgueira, 2020; Weitzman et al., 2021;). Evaluation of the carrying capacity will facilitate the establishment of upper limits of aquaculture production, environmental limits and social acceptability of aquaculture (Ross et al., 2013).

Surprisingly, carrying capacity has not, to date, been used as one of the most relevant concepts—environmentally, socially and economically—in decision-making on the location of facilities (OESA (Observatorio español de acuicultura), 2019) or in their subsequent environmental management (Cranford et al., 2012; OESA (Observatorio español de acuicultura), 2019; Fernández-Ávila et al., 2020; Weitzman and Filgueira, 2020). In fact, only the Greek fish farming industry has implemented a new regulatory system based on the physical and ecological carrying capacity of the activity on the eastern Mediterranean coast (Karakassis et al., 2013). The regulation describes how to calculate the total production (starting from 150 t/ha) that should be allowed in different scenarios (Karakassis et al., 2013). Thus, it is an intuitive estimation model that calculates a proxy for the maximum allowable production level based on several factors (Macias et al., 2019; Yigit et al., 2021).

Despite this interesting methodological approach as a proxy for the calculation of carrying capacity on the eastern Mediterranean coast, the regulation does not take into account social and economic aspects of the

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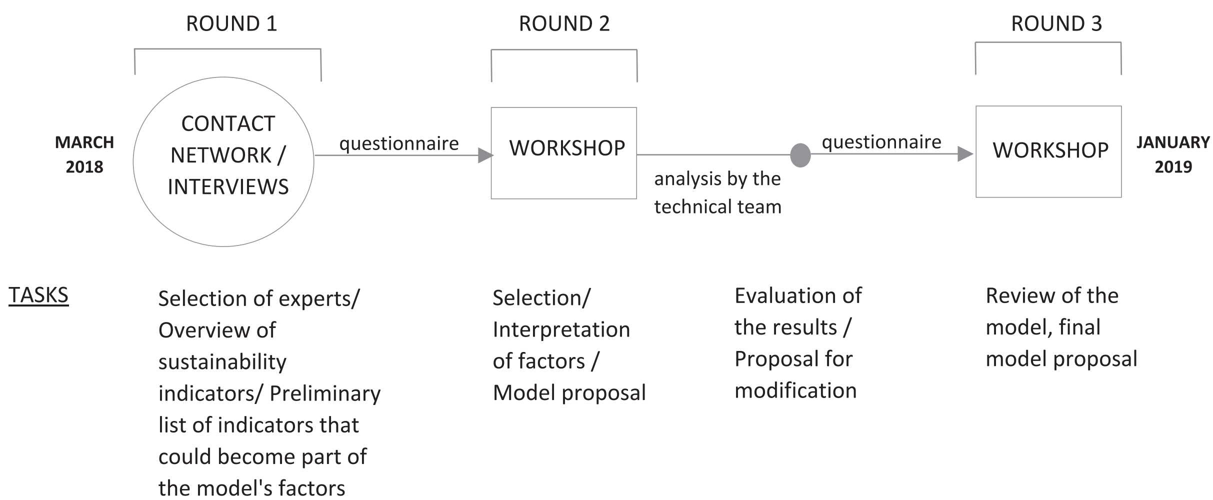

Fig. 1. Structure of the modified Delphi study.

activity, both of which have been identified as major challenges for the sustainable development of aquaculture (Weitzman and Filgueira, 2020). Here, we aim to bolster a framework for the estimation of carrying capacity in marine finfish aquaculture in a more holistic and innovative way, following the proposed concept of carrying capacity (McKindsey et al., 2006), and offering the possibility of incorporating new environmental factors that may be of interest on the other side of the Mediterranean. We therefore developed a methodology for adapting production levels of fish farming to the physical, ecological, social and economic conditions of the aquaculture sector in the western Mediterranean, specifically off the Spanish Mediterranean coast.

2. Material and methods

2.1. Study approach

Achieving consensus among several experts or practioners is challenging, and current techniques have been developed to seek agreements and establish criteria that facilitate decision-making (Fernández-Ávila et al., 2020). One of these techniques is the Delphi study (Dalkey and Helmer, 1963) which has been used not only in aquatic environmental impact assessments (Zuboy, 1981; Green et al., 1990; Mohorjy and Aburizaiza, 1997; Clark and Richards, 2002; Taylor and Ryder, 2003) but also in aquaculture planning and management (Karakassis et al., 2013; Díaz et al., 2015; Weitzman et al., 2021). A systematic and interactive survey technique, it is based on independent input from a group of experts on a specific problem which they address based on general group agreement (Mohorjy and Aburizaiza, 1997; Fernández-Ávila et al., 2020). Here, we used a modification of the traditional Delphi methodology to find a consensus on the estimation of carrying capacity based on basal production and certain other factors. Main differences with the traditional Delphi methodology were the inclusion of a prospective round (Round 1; Fig. 1) of interviews/questionnaires to identify most suitable sustainability indicators that may be further discussed for inclusion in subsequent rounds (Rounds 2 and 3; Fig. 1). These latter were face-to-face workshops rather than traditional individual questionnaires that avoid direct contact between experts (Dalkey and Helmer, 1963). Given the wide range of knowledge that is needed to build up a holistic carrying capacity model, the in-person consensus workshops allowed different stakeholders to give a more informed response to questions on technical–productive, environmental, social and economic factors ranges and weights to be included in the model.

2.1.1. Selection of expert participants

We first formed a network of contacts to elaborate a preliminary list of the potential Delphi expert panel. We used a mixed scanning method of identification which included word-of-mouth communications with existing contacts, bibliographical references from 62 studies and 10 face-to-face and virtual/telephonic meetings with producers, research centres and public administration. To ensure a balance of interests, the final contacts network included 21 experts distributed between the private, academic and government sectors. Private sector experts were professionals involved in the offshore fish farming sector, comprising mainly producers on the Spanish Mediterranean coast. We included both key personnel from relevant government ministries and agencies working for, or with, governance and/or public administration agencies and the academic community from both universities and research institutions.

2.1.2. Delphi exercise

This study used a modified Delphi approach (Hasson and Keeney, 2011) where the wording of the questions evolved over three rounds in response to the results and expert comments (Fig. 1).

In the first round, we conducted semi-structured interviews where experts were asked to show the most representative sustainability indicators in the carrying capacity models and their degree of importance on a scale of 1 to 10, with 1 being unrepresentative and 10 being highly representative. We divided these indicators into categories of carrying capacity for which the indicator was useful (technical–productive, environmental, social and economic). During this first round we developed a preliminary questionnaire of sustainability indicators that could be included the model. The second round had two clear objectives: $_{i}$ to reach a consensus on the value of basal production and the factors to be considered in the model for estimating carrying capacity, and $_{ii}$ to establish their corresponding ranges and weighting values. To this end, we held three face-to-face working groups with different representatives from each sector. At each of the roundtables, these representatives discussed the preliminary questionnaire, reassessing the degree of importance of the sustainability indicators and determining the value of the baseline production. Each working group presented its results and the Delphi panel of experts—after a consensus analysis looking at the average score of the rounds—selected the value of the basal production and the factors involved in an increase or decrease in basal production. In addition, we also proposed five ranges and five weighting values for each of the factors and they were discussed at each of the tables after their selection. Thus, the second round ended with a model proposal for an estimating carrying capacity. The need for testing the model led us to carry out 29 simulations in real activity environments. Because we detected inconsistencies and difficulties in the data collection, the technical team of the project convened the Delphi expert panel in a third

Table 1
Preliminary sustainability indicators subjected to consensus.

Sustainability indicator	Mean level of importance Round 1	Mean level of importance Round 2	$\overline{X}$ Rounds	Possible factors to include in the model
Technical and Production				
Food Conversion Rate	7.5	8.5	8	Food Conversion Rate
Percentage of space used (%)	New	10	8.25	Space arrangement of the concession
Volume of water occupied per kg of product (Kg/ m^3)	6.5			
Distance between facilities	New	8.5	8.5	Distance between facilities
Environmental				
Distance to priority habitats	New	10	10	Distance to priority habitats
Depth	8.5	9	8.75	Depth
Microbiological indicators	5.67	8	6.5	Granulometry
Oxygen saturation	5.83			
Existence of common criteria for site selection	7.33	7	7.67	Current velocity
Current velocity	8.67			
Social				
Sustainability or staff turnover rate	6.67	10	7.95	Employment provided
Quantity and quality of employment	7.17			
Communication strategy	7.17	7.11	7.11	Social acceptability
Employee-management relations	7.33			
Number of professional associations	6.83			
Economic				
Market-oriented aquaculture (in-company market strategy)	7	8	6.46	Investment in R&D
Diversification of goods and services	6.66			
Selling price development	5.83			
Evolution of total aquaculture production value	6.0			
Existence of quality certification systems	6.33			
Cost of feed /kg of fish produced (and % of total cost)	6.17			
Cost of fry /kg (and % of total cost/kg)	5.83			
Investment in aquaculture R&D	6.33			
Legal security of the concession	7.33	9	7.72	Legal certainty
Duration of an authorisation/ concession	6.83			

Table 2
Preliminary model for the estimation of the carrying capacity for floating cages.

Carrying capacity = BP * V_{T1} * V_{T2} * V_{T3} * V_{A1} * V_{A2} * V_{A3} * V_{S1} * V_{E1}

Basal production allowed (BP) = 50 t/ha

Factor of the model	Description	Calculation	Range	Weighting value (V)
Technical and production				
** Food Conversion Rate	Feed provided (kg) / biomass gained (kg)	<1.60*	1.38	1.38
		1.6–2*	1.18	1.18
		2–2.5*	1	1
		2.5–3*	0.87	0.87
		>3*	0.5	0.5
Space arrangement of the concession	Average clear area between two system of floating cages / average area of system of floating cages	>4*	1.33	1.33
		4–3*	1.14	1.14
		3–2*	1	1
		2–1*	0.86	0.86
		<1*	0.66	0.66
Distance between facilities	Distance (nm) between one installation and the next nearest installation	>20 nm	1.47	1.47
		10–20 nm	1.27	1.27
		2–10 nm	1.05	1.05
		1–2 nm	0.82	0.82
		<1 nm	0.62	0.62
Environmental				
Distance to priority habitats	Distance (nm) from the installation to marine phanerogams, maërl and gorgonian beds	5–6 nm	1.48	1.48
		4–5 nm	1.32	1.32
		3–4 nm	1.1	1.1
		2–3 nm	0.97	0.97
		1–2 nm	0.72	0.72
Depth	Average depth (m) of the installation	>60 m	1.57	1.57
		50–60 m	1.32	1.32
		40–50 m	1.08	1.08
		30–40 m	0.83	0.83
		<30 m	0.42	0.42
Current velocity	Annual average current velocity (cm/s) in the installation at a depth of 15 m	>10 cm/s	1.35	1.35
		10–6 cm/s	1.18	1.18
		6–4 cm/s	1.02	1.02
		4–2 cm/s	0.8	0.8
		<2 cm/s	0.37	0.37
Social				
Employment provided	Annual Work Units / number of inhabitants of the coastal province (mil.)	> 800	1.1	1.1
		600–800	1.05	1.05
		400–600	1	1
		200–400	0.95	0.95
		0–200	0.9	0.9
Economic				
Investment in R&D	Three-year average annual return excluding investments and amortisation	>10 M€	1.09	1.09
		10–5 M€	1.04	1.04
		5–1 M€	1	1
		1–0.5 M€	0.98	0.98
		>0.5 M€	0.93	0.93

* This factor is a dimensionless index and lacks unit of measurement.
** The values of this factor are valid for sea bream/bass farming, and the ranges and values must be adjusted for different species.

Table 3
Results of the preliminary model for validation, carried out by the technical team of the project where BP is the basal production in t/ha and V is the weighting value for each of the factors.

Farm	Hectares	BP	V_{T1}	V_{T2}	V_{T3}	V_{A1}	V_{A2}	V_{A3}	V_{S1}	V_{E1}	Capacity estimated (t)	Production granted (t)
1	48.75	50	1	1.33	1.47	0.72	0.83	0.8	1.1	1	2506	2500
2	1.60	50	1	0.66	1.47	0.72	0.42	1.02	1.1	1	26	300*
3	178.25	50	1	1.33	1.05	0.72	1.32	1.18	1.1	1	15,354	4500
4	51.97	50	1	1.33	1.05	0.72	0.83	1.18	0.95	1	2431	1000
5	95.01	50	1	0.86	1.47	0.72	1.08	1.35	0.95	1	5989	4000
6	28.44	50	1	1	1.47	0.72	0.83	1.18	0.95	1	1400	2000*
7	30.39	50	1	1.14	0.62	0.72	0.83	0.8	0.95	1	488	1000*
8	71.68	50	1	1.33	0.62	0.72	0.83	0.8	0.95	1	1342	1500
9	29.50	50	1	1	0.82	0.72	0.83	0.37	0.95	1	254	1085*
10	64.00	50	1	0.86	0.82	0.72	1.08	0.37	0.95	1	617	1500*
11	140.77	50	1	1.33	0.82	0.72	1.08	0.37	0.95	1	2098	1500
12	64.00	50	1	0.86	0.82	0.72	1.08	0.8	0.95	1	1334	1500
13	90.00	50	1	1	0.82	0.97	1.08	0.8	0.95	1	2783	3000
14	45.00	50	1	1	0.82	0.72	0.83	0.37	0.95	1	388	3000*
15	221.87	50	1	1.33	1.05	0.72	1.08	0.8	0.95	1	9155	8000
16	38.50	50	1	1	0.62	0.72	0.83	1.02	0.95	1	691	1900*
17	189.74	50	1	1.33	0.62	0.72	0.83	0.8	0.95	1	3553	8000*
18	29.48	50	1	0.66	0.62	0.72	0.42	0.8	0.95	1	13,862	1250
19	19.31	50	1	0.66	0.62	0.72	0.42	0.37	0.95	1	42	2200*
20	63.38	50	1	0.86	0.82	0.72	0.42	0.37	0.95	1	238	2500*
21	7.11	50	1	0.86	1.05	0.72	042	0.37	0.95	1	34	450*
22	144.00	50	1	1,33	1.05	0.72	1.08	0.8	0.95	1	5942	5000
23	50.40	50	1	0.86	1.05	0.72	0.83	0.8	0.95	1	1034	5000*
24	26.31	50	1	1	1.05	0.72	0.83	0.37	0.95	1	290	1250*
25	55.00	50	1	1	1.05	0.72	1.08	0.8	0.95	1	1706	3000*
26	82.00	50	1	1	1.27	0.72	0.83	0.8	1.05	1	2614	5000*
27	100.00	50	1	1	1.05	0.72	0.42	0.8	1.05	1	1334	2360*
28	118.80	50	1	0.86	1.05	0.72	0.83	0.8	1.05	1	2693	5000*
29	3.54	50	1	1	1.47	0.72	0.42	0.37	1	1	29	145*
										TOTAL	80,227	79,440

T1 (*Food conversion rate*), T2 (*Space arrangement of the concession*), T3 (*Distance between facilities*), A1 (*Distance to priority habitats*), A2 (*Depth*), A3 (*Current velocity*), S1 (*Employment provided*) and E1 (*Investment in R&D*).
* This installation has a high degree of constraint.

round. During this round our objective was to present the results of the validation and to propose possible alternatives in terms of factor changes, ranges and weighting values. At its conclusion re-adjustments led to a final model after reaching a consensus analysis of the alternatives presented.

3. Results and discussion

During the first round, recognising the importance of appropriate selection of baseline production and carrying capacity estimators, the experts identified a total of 36 sustainability indicators classified according to their appropriate carrying capacity categories (technical–productive, environmental, social and economic) and their degree of importance (Appendix I). After the first round of the 36 indicators, 14 were excluded from the study, since they usually appear in environmental monitoring programmes; and 21 indicators were grouped into 7 factors each containing three very similar indicators. In addition, the experts also identified 3 new indicators of sustainability (Appendix II), culminating in a total of 11 factors as possible estimators of carrying capacity (Table 1). After a consensus analysis by the Delphi expert panel, the second round ended with a model proposal based on a baseline production and 8 factors estimating carrying capacity, together with their respective ranges and weighting values (Table 2).

3.1. Preliminary carrying capacity model

First, the Delphi expert panel proposed a model built on basal production and applied different factors—representing different types of carrying capacities—to the model. In the second round, in the absence of a homogeneous, licensed production scheme in terms of concessions authorising cultivation, the experts determined a basal production value of 50 t per hectare of concession. They established this value based on a previously proposed model (Karakassis et al., 2013) and the production data from the annual report on the evolution of the aquaculture sector in Spain and Europe (APROMAR, 2018)—as a precautionary measure, allowing for a maximum of 20% variation. The Delphi expert panel ensured that this value generally represented that of standard, commercially productive companies implementing environmental monitoring plans (APROMAR, 2018).

Second, the application of factors used in estimating carrying capacity shows how basal production is modulated. The expert panel considered that, under same environmental conditions, the carrying capacity is mostly driven by operational management of aquaculture facilities. Therefore, they selected three technical–productive and three environmental factors to include in the model. Additionally, and to achieve a holistic approach, one each of economic and social factors were selected.

3.1.1. Selection of factors

For the consensus selection of the model factors, for each of the carrying capacity categories the Delphi expert panel identified tipping points. For the technical–productive factors, the Delphi expert panel considered mainly those factors that had a more direct effect on the seabed, based on suggestions, opinions and technical documentation presented in the workshops (Aguado-Giménez et al., 2012). Experts identified this category as that most affected by aquaculture activity, and therefore one of the most important when determining the carrying capacity of the system. They therefore selected the *food conversion rate*, which expresses the efficiency of the animal in relation to the amount of feed required to achieve the final biomass of the culture (Abdel-Tawwab et al., 2015), and thus indirectly assesses the uneaten feed that is lost (Islam, 2005). Other selected factors were related to the hydrology of the

Table 4
Proposed readjustment of the ranges for some model's factors.

Factor of the model	Initial range	Initial multiplier value	Final range	Final multiplier value
Technical and production				
Space arrangement of the concession (T2)	>4*	1.33	>3.5*	1.33
	4–3*	1.14	2.5–3.5*	1.14
	3–2*	1.00	1.5–2.5*	1.00
	2–1*	0.86	0.5–1.5*	0.86
	<1*	0.66	<0.5*	0.66
Environmental				
Distance to priority habitats (A1)	>4 nm	1.48	>3 nm	1.48
	2–4 nm	1.20	2–3 nm	1.32
	1–2 nm	0.97	1.2–2 nm	1.10
	0.5–1 nm	0.72	0.5–1.2 nm	0.97
	<0.5 nm	0.37	<0.5 nm	0.72
Depth (A2)	>60 m	1.57	>50 m	1.57
	50–60 m	1.32	40–50 m	1.32
	40–50 m	1.08	30–40 m	1.08
	30–40 m	0.83	25–30 m	0.83
	<30 m	0.42	<25 m	0.42

* This factor is a dimensionless index and lacks unit of measurement.

facility as it impacted the prevention of pathologies—in particular, the *distance between facilities* and the *space arrangement of the concession*; the experts defined both as factors that influence the concentration of the remains of the activity (faeces and food) on the seabed (Dosdat et al., 1996).

In relation to environmental factors and considering the benthos as a relevant ecological compartment and source of organic enrichment (Dosdat et al., 1996), the Delphi expert panel included in the model the *depth* below the floating cages and the *current velocity* in the production area, as both are closely related to the capacity to spread the nutrients and solids generated by the activity (Borja, 2002). The greater the depth and the higher the current velocity, the greater the volume of particulate debris that can be dispersed, thereby reducing both the impacts of the farming activity on both the seabed and the spread of diseases (Dosdat et al., 1996; Bostock et al., 2010; Holmer, 2010; Price et al., 2015; APROMAR, 2018). In addition, the panel also included *distance to priority habitats* which, although there is no clear legislation in this regard, was identified by experts as an important indicator that could potentially alter adjacent priority habitats such as seagrass meadows (Herrera-Paz et al., 2015), maerl beds (EC (European Community), 1992; Ruiz et al., 2001; Sanz-Lázaro et al., 2011) and gorgonian beds, all included in Annex I of the Habitats Directive 92/43/EEC of the Council of 21 March 1992 (EC (European Community), 1992).

Regarding social factors, the experts included the *employment provided*, citing the increase in social acceptability accompanying demonstrable socio-economic benefits, the assessment of impacts on the environment and open communication with communities that are kept informed about the management requirements to be met by the companies (Carvalho, 1998; Wilson, 2001; Whitmarsh and Palmieri, 2009). Thus, the experts established the *employment provided* as an indicator of social carrying capacity, reflecting the acceptance by society of the activity thanks to the generation of new jobs in the area. As regards economic factors, to the panel included *investment in R&D* as an indicator of economic carrying capacity despite its lower score in the rounds, as legal security of the concession was initially established as a determining factor due to the industry perception that it is necessary to a certain degree. This factor thus reflects the willingness of companies and administrations to contribute to the improvement of current farming systems by increasing their efficiency through participation in R&D projects.

3.1.2. Selection of ranges and weighting values

While the selection of the model factors was guided by the considerations described above, the experts also called on their personal suggestions, opinions and experiences to agree on the ranges and weighting values. In considering what increases in production from the 50 t/ha threshold could be allowed to produce similar effects when a facility's assimilation rate was high, its spatial organisation adequate and its location in deeper sites, away from both priority habitats and facilities, with high current velocity and with feasible social and economic impacts, the experts established optimal, partial and adverse scenarios for basal production (Table 2).

3.2. Readjustment of the model

The project's technical team then analysed the model, detecting inconsistencies and difficulties in data collection and observing a high restrictive power in 72.4% of the facilities analysed (Table 3). After informing of this limitations, the experts considered the option of modifying some of the model's factors; changing their multiplier values and numerical range; or even substituting factors where applicability was complex. Round 3 thus ended with a final readjustment to three of

Table 5
Proposed change of factors.

Factor of the model	Initial range	Initial multiplier value	New model factors: Factor	Description	Calculation	Final range	Final multiplier value
Technical and production							
** Food Conversion Rate (T1)	<1.60*	1.38	** Tonnes feed per hectare (T1)	Reflects nutrient input to the environment	Tonnes of feed per hectare of concession per annum	35–45 t/ha	1.38
	1.6–2*	1.18				45–55 t/ha	1.18
	2–2.5*	1.00				55–65 t/ha	1.00
	2.5–3*	0.87				65–75 t/ha	0.87
	>3*	0.50				>75 t/ha	0.50
Economic							
Investment in R&D (E1)	>10 M€	1.09	Unit Cost of Production (E1)	Reflects economic stability	Amount of € it costs to produce one kg of fish in each facility	3.25–3.5	1.09
	10–5 M€	1.04				3.5–3.75	1.04
	5–1 M€	1.00				3.75–4	1.00
	1–0.5 M€	0.98				4–4.25	0.98
	>0.5 M€	0.93				4.25–4.5	0.93

* This factor is a dimensionless index and lacks unit of measurement.
** The values of this factor are valid for sea bream/bass farming, and the ranges and values must be adjusted for different species.

Table 6
Final carrying capacity model.

Factor of the model	Description	Calculation	Range	Weighting value (V)
Carrying capacity = BP * V_{T1} * V_{T2} * V_{T3} * V_{A1} * V_{A2} * V_{A3} * V_{S1} * V_{E1}				
Basal production allowed (BP) = 50 t/ha				
Technical and production				
Tons feed per hectare (T1)	Reflects nutrient input to the environment	Tonnes of feed per hectare of concession per annum	35–45 t/ha	1.38
			45–55 t/ha	1.18
			55–65 t/ha	1.00
			65–75 t/ha	0.87
			>75 t/ha	0.50
Space arrangement of the concession (T2)	Reflects the spatial organisation of the productive area in the concession	Average clear area between two system of floating cages / average area of system of floating cages	>3.5*	1.33
			2.5–3.5*	1.14
			1.5–2.5*	1.00
			0.5–1.5*	0.86
			<0.5*	0.66
Distance between facilities (T3)	It is considered by experts as a factor affecting health safety, together with the environmental impact due to cumulative effects	Distance (nm) between one installation and the next nearest installation	>20 nm	1.47
			10–20 nm	1.27
			2–10 nm	1.05
			1–2 nm	0.82
			<1 nm	0.62
Environmental				
Distance to priority habitats (A1)	Expresses the potential for disturbance of adjacent priority habitats	Distance (nm) from the installation to marine phanerogams, maërl and gorgonian beds	>3 nm	1.48
			2–3 nm	1.32
			1.2–2 nm	1.10
			0.5–1.2 nm	0.97
			<0.5 nm	0.72
Depth (A2)	Reflects the influence on the amount of solid materials deposited on the seabed	Average depth (m) of the installation	>50 m	1.57
			40–50 m	1.32
			30–40 m	1.08
			25–30 m	0.83
			<25 m	0.42
Current velocity (A3)	Reflects the influence on the amount of solid materials deposited on the seabed	Annual average current velocity (cm/s) in the installation at a depth of 15 m	>10 cm/s	1.35
			10–6 cm/s	1.18
			6–4 cm/s	1.02
			4–2 cm/s	0.80
			<2 cm/s	0.37
Social				
Employment provided (S1)	Reflects the amount of employment generated by the activity.	Annual Work Units / number of inhabitants of the coastal province (mil.)	>800	1.10
			600–800	1.05
			400–600	1.00
			200–400	0.95
			0–200	0.90
Economic				
Unit Cost of Production (E1)	It reflects the economic stability of compresses, as well as their competitiveness.	Amount of money (€) it costs to produce one kilo of fish in each facility.	3.25–3.5	1.09
			3.5–3.75	1.04
			3.75–4	1.00
			4–4.25	0.98
			4.25–4.5	0.93

* This factor is a dimensionless index and lacks unit of measurement.

its factors—*space arrangement of the concession*, *distance to priority habitats* and *depth* (Table 4)—and the replacement of two of them—*food conversion rate* and *investment in R&D* (Table 5).

3.2.1. Readjustment of the factors

Some of the factors of the model were difficult to implement in real situations of the activity, and the technical team of the project had some reservations regarding real reference values of the facilities; the Delphi expert panel therefore proposed a readjustment in the ranges of the factors *space arrangement of the concession* and the *depth* below the floating cages. First, they split the lowest multiplier value for *space arrangement of the concession* (<1) into two ranges, <0.5 and 0.5–1, as they considered these values to be the only ones with the power to decrease the carrying capacity of the system, and second, they established an a priori appropriate d*epth* of 30–40 m. Furthermore, based on the premise that all aquaculture facilities should be located in an area which has been considered a suitable site for aquaculture, the Delphi expert panel proposed a change in the ranges and weighting values for *distance to priority habitats*, thereby decreasing the model's restriction on the effects that the activity may have on adjacent habitats. The experts considered a distance of 1 nm to a priority habitat for conservation to be a considerable distance at which the effects of the activity on the seabed would no longer be detected (Pérez et al., 2008). In this case, they set 1.2 nm as the distance at which the activity would not affect the seabed

Table 7
Results of the final model, where BP is the basal production in t/ha and V is the weighting value for each of the factors.

Farm	Hectares	BP	V_{T1}	V_{T2}	V_{T3}	V_{A1}	V_{A2}	V_{A3}	V_{S1}	V_{E1}	Capacity estimated (t)	Production granted (t)
1	48.75	50	0.5	1.33	1.47	0.72	1.08	0.8	1.1	1	1631	2500*
2	1.60	50	1	0.86	1.47	0.72	0.42	1.02	1.1	1	34	300*
3	178.25	50	1.33	1.33	1.05	1.1	1.32	1.18	1.1	1	31,199	4500
4	51.97	50	0.5	1.33	1.05	0.72	1.08	1.18	0.95	1	1582	1000
5	95.01	50	1.18	1	1.47	0.72	1.32	1.35	0.95	1	10,044	4000
6	28.44	50	1.18	1	1.47	0.72	1.08	1.18	0.95	1.04	2236	2000
7	30.39	50	1.18	1.33	0.62	0.72	1.08	0.8	0.95	1.4	1223	1000
8	71.68	50	0.5	1.33	0.62	0.97	1.08	0.8	0.95	1	1176	1500*
9	29.50	50	0.5	1	0.82	0.72	1.08	0.37	0.95	1	165	1085*
10	64.00	50	1	1	0.82	0.97	1.32	0.37	0.95	1	1181	1500*
11	140.77	50	1.18	1.33	0.82	0.97	1.32	0.37	0.95	1	1853	1500
12	64.00	50	1.38	1	0.82	1.1	1.32	0.8	0.95	1	3996	1500
13	90.00	50	1	1.14	0.82	1.32	1.32	0.8	0.95	1.04	5488	3000
14	45.00	50	1	1	0.82	1.1	1.08	0.37	0.95	1	770	3000*
15	221.87	50	1	1.33	1.05	1.1	1.32	0.8	0.95	1	17,096	8000
16	38.50	50	1	1.14	0.62	0.72	1.08	1.02	0.95	1	1025	1900*
17	189.74	50	0.5	1.33	0.62	0.97	1.08	0.8	0.95	1	3114	8000*
18	29.48	50	1	0.66	0.62	0.97	0.83	0.8	0.95	1.04	384	1250*
19	19.31	50	1	0.66	0.62	0.97	0.42	0.37	0.95	1.04	59	2200*
20	63.38	50	1	1	0.82	0.72	0.42	0.37	095	1	276	2500*
21	7.11	50	1	1	1.05	0.72	0.83	0.37	0.95	1.04	82	450*
22	144.00	50	1	1.33	1.05	1.1	1.32	0.8	0.95	1	11,096	5000
23	50.40	50	1	1	1.05	0.72	1.08	0.8	0.95	1.04	1626	5000*
24	26.31	50	0.5	1	1.05	0.72	1.08	0.37	0.95	1	189	1250*
25	55.00	50	1	1.14	1.05	0.97	1.32	0.8	0.95	1.04	3331	3000
26	82.00	50	1	1.14	1.27	0.97	1.08	0.8	1.05	1	5224	5000
27	100.00	50	1	1	1.05	1.1	0.42	0.8	1.05	1.04	2119	2360
28	118.80	50	1.38	1	1.05	1.1	1.08	0.8	1.05	1.04	8933	5000
29	3.54	50	1	1	1.47	0.72	0.42	0.37	1	1.04	30	145*
										TOTAL	117,162	79,440

T1 (*Tons feed per hectare*), T2 (*Space arrangement of the concession*), T3 (*Distance between facilities*), A1 (*Distance to priority habitats*), A2 (*Depth*), A3 (*Current velocity*), S1 (*Employment provided)* and E1 (*Investment in R&D)*.

* This installation has a high degree of constraint.

of priority habitats for conservation.

3.2.2. *Substitution of factors*

In view of the difficulty in applying certain factors of the model and, consequently, its possible rejection by the administrations as a viable system for regulating aquaculture, the Delphi expert panel proposed a series of alternatives for the change in the *food conversion rate* and *investment in R&D* factors (Table 5). First, they proposed three alternatives as the most representative in terms of the most realistic way to determine the amount of organic matter discharged into the environment, and two to encompass the economic aspects of the activity. For the first factor (*food conversion rate*), the alternatives they proposed were based on the amount of feed provided, either by tonnes of feed produced, by cost-value of sale or by year-area of concession; and for the second one (*investment in R&D*), alternatives were based on unit cost of production and the price of first sale. Among all the alternatives, the Delphi panel of experts selected the tonnes of feed supplied per year per hectare of concession (*tonnes feed per hectare*) and the amount of money it costs to produce one kilogram of fish in each facility (*unit cost of production),* for their generalist behaviour in representing the reality of the nutrient input to the environment and for their easy applicability and more direct implication in the economic aspects.

3.3. *Final model*

After the substitution of unsuitable factors, and modification of some ranges and weighting values of the model (Table 6), and applying it to real operational conditions, we found that the results showed an acceptable restriction (Table 7). Taking the production granted by the administration as the potential annual production value of each concession, we found 24.1% of the concessions to be below the estimate of the carrying capacity (same as with the preliminary model), 24.1% to be around the maximun carrying capacity (13.8% with the preliminary model) and 51.7% to exceed the carrying capacity calculated by the model (62.1% with the preliminary model). All in all, and subject to the execution of an in-situ validation of the model, the Spanish Mediterranean aquaculture production may be sustainably increased by 47.5% (from 79,440 to 117,162 t/year). However, marine fish production in Spain is far from reaching even the granted production (79,440 t), being in 2021 close to 40,000 t (APROMAR, 2022). The latter suggests that carrying capacity should be addressed in terms of holding capacity (i.e. maximum biomass that can be held in a facility at a given time) rather than the annual production, although both values should be closely connected, their values might be significantly different.

4. Conclusions

Despite the great effort of the scientific community to implement the concept of 'carrying capacity' in aquaculture planning and management (Weitzman and Filgueira, 2020; Weitzman et al., 2021), its application remains complex. Several recent studies have established carrying capacity as a potentially important tool in the assessment of the ecological, productive and social sustainability of aquaculture (McKindsey et al., 2006; Weitzman et al., 2021), yet the lack of interdisciplinary and integrated frameworks to assess carrying capacity in a holistic way remains (Guyondet et al., 2010; Weitzman et al., 2021) based not only on bivalve culture—which is well studied (Inglis et al., 2000; Filgueira et al., 2020)—but also on finfish culture (Karakassis et al., 2013). Ours is thus the first study to generate consensus on the need to address carrying capacity in a holistic and innovative way (McKindsey et al., 2006; Weitzman et al., 2021) by developing simple and effective models. Our model does not explicitly consider conflict with other users, the latter being globally identified as a constrain in the spatial expansion of marine aquaculture (Galparsoro et al., 2020). Therefore, it seems clear that it must be coupled with a maritime spatial planning strategy that identifies suitable areas for aquaculture in which the model will address maximum holding capacity.

Modelling by consensus methodologies, involving all stakeholders of the activity, is one of the fundamental pillars in the sustainable development of an activity, of necessity considering a wide variety of perceptions as a relevant part of marine aquaculture management and planning (Robertson et al., 2002; Foley et al., 2005; Mazur and Curtis, 2008; Chu et al., 2010; Ross et al., 2013). Insufficient involvement of stakeholders could lead to resource mismanagement and the emergence of social conflicts (Kaiser and Stead, 2002; Shindler et al., 2002; Buanes et al., 2004). Thus, the development of aquaculture management models should be based on the estimation of carrying capacity through effective stakeholder participation, where both present and future conditions of the activity are assessed through simple sustainability indicators encompassing all aspects of the activity (McKindsey et al., 2006). Simple models have been shown to be as accurate as complex models requiring much more information (Sakamoto, 1966) and they will be adopted as a final regulatory system only if they are feasible. In applying the Delphi technique in our study, we have achieved consensus on the development of a simple model for the estimation of carrying capacity for open sea fish farming in floating fisheries off the Spanish Mediterranean coast based on physical, environmental, social and economic factors. The incorporation of social and economic aspects in the model renders it holistic and innovative, as no previous study to date has included all the components of the activity in the same model. Most studies have focused only on the productive and ecological aspects of the activity, ignoring the socio-economic aspects due to their possible subjectivity and dependence on the environment in which the activity takes place (Guyondet et al., 2010). This model is therefore an example of how the carrying capacity could be incorporated in the planning and management of marine aquaculture. The need to develop an in-situ validation of the model after observing an acceptable level of constraint in its theoretical application will inform future projects.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix I. Relevance of the sustainability indicators identified in Round 1

Sustainability indicator	Mean level of importance Round 1
Technical and production	
Food Conversion Rate	7.5
Volume of water occupied per kg of product (Kg/m^3)	6.5
Implementing an Environmental Monitoring Plan (EMP)	7.65
Compliance with code of good practice	6.83
Existence of a well-defined aquaculture environmental policy, programme and/or strategy	6.33
Distance to the coast	6.50
Carbon footprint index	5.67
Environmental	
Depth	8.5
Microbiological indicators	5.67
Oxygen saturation	5.83
Existence of common criteria for site selection	7.33
Current velocity	8.67
Social	
Sustainability or staff turnover rate	6.67
Quantity and quality of employment	7.17
Communication effort	7.17
Employee-management relations	7.33

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Sustainability indicator	Mean level of importance Round 1
Number of professional associations	6.83
National training in aquaculture	7.00
Existence of a national aquaculture strategy	7.00
Annual marine fish aquaculture production at national level	7.50
Quantity of fish produced for domestic markets and apparent consumption	3.33
Price of fish compared to the minimum wage	4.33
Percentage of farmers with specialised and certified training in aquaculture	7.67
Number of hours per month currently worked by aquaculture workers	6.00
Economic	
Market-oriented aquaculture (in-company market strategy)	7
Diversification of goods and services	6.66
Sales price development	5.83
Evolution of total aquaculture production value	6.0
Existence of quality certification systems	6.33
Cost of feed /kg fish produced (and % of total)	6.17
Cost of fry /kg (and % of total cost/kg)	5.83
Investment in aquaculture R&D	6.33
Legal security of the concession	7.33
Duration of an authorisation/concession	6.83
Number of domestic hatcheries (and % imported)	4.17
Existence of a national support mechanism for aquaculture	5

Appendix II. Relevance of the sustainability indicators identified in Round 2

Sustainability indicator	Mean level of importance Round 1	Mean level of importance Round 2
Technical and Production		
Food conversion rate	7.5	8.5
Percentage of space used (%)	new	10
Volume of water occupied per kg of product (Kg/m^3)	6.5	
Distance between facilities	new	8.5
Implementing an Environmental Monitoring Plan (EMP)	7.65	excluded
Compliance with code of good practice	6.83	excluded
Existence of a well-defined aquaculture environmental policy, programme and/or strategy.	6.33	excluded
Distance to the coast	6.50	excluded
Carbon footprint index	5.67	excluded
Environmental		
Distance to priority habitats	new	10
Depth	8.5	9
Microbiological indicators	5.67	8
Oxygen saturation	5.83	
Existence of common criteria for site selection	7.33	7
Current velocity	8.67	
Social		
Sustainability or staff turnover rate	6.67	10
Quantity and quality of employment	7.17	
Communication effort	7.17	7.11
Employee-management relations	7.33	
Number of professional associations	6.83	
National training in aquaculture	7.00	excluded
Existence of a national aquaculture strategy	7.00	excluded
Annual marine fish aquaculture production at national level	7.50	excluded
Quantity of fish produced for domestic markets and apparent consumption	3.33	excluded
Price of fish compared to the minimum wage	4.33	excluded
Percentage of farmers with specialised and certified training in aquaculture	7.67	excluded
Number of hours per month currently worked by aquaculture workers	6.00	excluded
Economic		
Market-oriented aquaculture (in-company market strategy)	7	8
Diversification of goods and services	6.66	
Sales price development	5.83	
Evolution of total aquaculture production value	6.0	
Existence of quality certification systems	6.33	
Cost of feed /kg fish produced (and % of total)	6.17	
Cost of fry /kg (and % of total cost/kg)	5.83	
Investment in aquaculture R&D	6.33	
Legal security of the concession	7.33	9
Duration of an authorisation/concession	6.83	

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(*continued*)

Sustainability indicator	Mean level of importance Round 1	Mean level of importance Round 2
Number of domestic hatcheries (and % imported)	4.17	excluded
Existence of a national support mechanism for aquaculture	5	excluded

References

Abdel-Tawwab, M., Hagras, A.E., Elbaghdady, H.A.M., Monier, M.N., 2015. Effects of dissolved oxygen and fish size on Nile tilapia, Oreochromis niloticus (L.): growth performance, whole-body composition, and innate immunity. Aquac. Int. 23, 1261–1274. https://doi.org/10.1007/s10499-015-9882-y.

Aguado-Giménez, F., Carballeira Ocaña, A., Collado Sánchez, C., González Henríquez, N., Sanchez-Jerez, P., 2012. Propuesta Metodológica para la realización de los planes de vigilancia ambiental de los cultivos marinos en jaulas flotantes. Junta Nacional Asesora de Cultivos Marinos (JACUMAR). Ministerio de Agricultura, Alimentación y Medio Ambiente, p. 164.

APROMAR, 2018. La Acuicultura en España. (Aquaculture Business Association of Spain), 2018, p. 94.

APROMAR, 2022. La Acuicultura en España. (Aquaculture Business Association of Spain), 2022, p. 106.

Borg, J.A., Crosetti, D., Massa, F., 2011. Site Selection and Carrying Capacity in Mediterranean Marine Aquaculture: Key Issues (WGSC-SHoCMed), p. 180.

Borja, Á., 2002. Los impactos ambientales de la acuicultura y la sostenibilidad de esta actividad. Bol. Inst. Esp. Oceanogr. 18, 41–49.

Bostock, J., McAndrew, B., Richards, R., Jauncey, K., Telfer, T., Lorenzen, K., Little, D., Ross, L., Handisyde, N., Gatward, I., Corner, R., 2010. Aquaculture: global status and trends. Philos. Trans. R. Soc. Lond. Ser. B Biol. Sci. 365, 2897–2912. https://doi.org/10.1098/rstb.2010.0170.

Buanes, A., Jentoft, S., Runar Karlsen, G., Maurstad, A., Søreng, S., 2004. In whose interest? An exploratory analysis of stakeholders in Norwegian coastal zone planning. Ocean Coast. Manag. 47, 207–223. https://doi.org/10.1016/j.ocecoaman.2004.04.006.

Carvalho, P., 1998. Results of a South Australian Coastal Aquaculture Survey. Waves Reg, Ripples (November).

Chu, J., Anderson, J.L., Asche, F., Tudur, L., 2010. Stakeholders' perceptions of aquaculture and implications for its future: a comparison of the USA and Norway. Mar. Resour. Econ. 25, 61–76.

Clark, M.J., Richards, K.J., 2002. Supporting complex decisions for sustainable river management in England and Wales. Aquatic Conserv: Mar. Freshw. Ecosyst. 12, 471–483. https://doi.org/10.1002/aqc.530.

Cranford, P.J., Kamermans, P., Krause, G., Mazurié, J., Buck, B.H., Dolmer, P., Fraser, D., Van Nieuwenhove, K., O'Beirn, F.X., Sanchez-Mata, A., Thorarinsdóttir, G.G., Strand, Ø., 2012. An ecosystem-based approach and management framework for the integrated evaluation of bivalve aquaculture impacts. Aquacult. Environ. Interact. 2, 193–213. https://doi.org/10.3354/aei00040.

Dalkey, N., Helmer, O., 1963. An experimental application of the Delphi method to the use of experts. Manag. Sci. 9, 458–467.

Díaz, I., Laura Mello, A., Salhi, M., Spinetti, M., Bessonart, M., Achkar, M., 2015. Integración SIG-EMC-Análisis de agrupamiento como herramienta para la regionalización acuícola en Uruguay. Rev. Geogr. Valpso 52, 14–27.

Dosdat, A., Héral, M., Katavic, I., Kempf, M., Prou, J., Smith, C., 1996. Approaches for zoning of coastal areas with refenrence to Mediterranean aquaculture. In: Priority Actions Programme Regional Activity Centre (PAP/RAC). PAP-10/EAM/GL.1. Split, Croacia. iv + 37 pp.

EC (European Community), 1992. Council directive 92/43/ECC. Off. J. Eur. 94, 40–52.

FAO, 2020. The state of world fisheries and aquaculture 2020. In: Sustainability in Action. Food and Agriculture Organization, Rome. https://doi.org/10.4060/ca9229en.

Fernández-Ávila, D.G., Rojas, M.X., Rosselli, D., 2020. The Delphi method in rheumatology research: are we doing it right? Rev. Colomb. Reumatol. 27, 177–189. https://doi.org/10.1016/j.rcreue.2019.04.007.

Filgueira, R., Comeau, L.A., Guyondet, T., Mckindsey, C.W., Byron, C.J., 2020. Modelling carrying capacity of bivalve aquaculture: a review of definitions and methods. In: Encyclopedia of Sustainability Science and Technology, 1–33. https://doi.org/10.1007/978-1-4939-2493-6.

FOESA (Fundación Observatorio Español de Acuicultura), 2013. Estrategia para el desarrollo sostenible de la Acuicultura Española. Madrid, España (88 paginas).

Foley, J.A., DeFries, R., Asner, G.P., Barford, C., Bonan, G., Carpenter, S.R., Chapin, F.S., Coe, M.T., Daily, G.C., Gibbs, H.K., Helkowski, J.H., Holloway, T., Howard, E.A., Kucharik, C.J., Monfreda, C., Patz, J.A., Prentice, I.C., Ramankutty, N., Snyder, P.K., 2005. Global consequences of land use. Science 309, 570–574. https://doi.org/10.1126/science.1111772.

Galparsoro, I., Murillas, A., Pinarbasi, K., Sequeira, A.M., Stelzenmüller, V., Borja, Á., O'Hagan, A.M., Boyd, A., Bricker, S., Garmendia, J.M., Gimpel, A., Gangnery, A., Billing, S.-L., Bergh, Ø., Strand, Ø., Hiu, L., Fragoso, B., Icely, J., Ren, J., Papageorgiou, N., Grant, J., Brigolin, D., Pastres, R., Tett, P., 2020. Global stakeholder vision for ecosystem-based marine aquaculture expansion from coastal to offshore areas. Rev. Aquac. 12, 2061–2079. https://doi.org/10.1111/raq.12422.

Green, H., Hunter, C., Moore, B., 1990. Assessing the environmental impact of tourism development. Tour. Manag. 11, 111–120.

Guyondet, T., Roy, S., Koutitonsky, V.G., Grant, J., Tita, G., 2010. Integrating multiple spatial scales in the carrying capacity assessment of a coastal ecosystem for bivalve aquaculture. J. Sea Res. 64, 341–359. https://doi.org/10.1016/j.seares.2010.05.003.

Hasson, F., Keeney, S., 2011. Enhancing rigour in the Delphi technique research. Technol. Forecast Soc. 78, 1695–1704. https://doi.org/10.1016/j.techfore.2011.04.005.

Herrera-Paz, D.L., de la Nuez, D., Valero-Rodríguez, J.M., 2015. Comunidades de algas como bioindicadores de calidad ambiental en la costa rocosa del Mediterráneo (SE Península Ibérica). Rev. Cienc. 19, 25–40.

Holmer, M., 2010. Environmental issues of fish farming in offshore waters: perspectives, concerns and research needs. Aquacult. Environ. Interact. 1, 57–70. https://doi.org/10.3354/aei00007.

Inglis, G., Hayden, B.J., Ross, A.H., 2000. An Overview of Factors Affecting the Carrying Capacity of Coastal Embayments for Mussel Culture. National Institute of Water and Atmospheric Research.

Islam, M.S., 2005. Nitrogen and phosphorus budget in coastal and marine cage aquaculture and impacts of effluent loading on ecosystem: review and analysis towards model development. Mar. Pollut. Bull. 50, 48–61. https://doi.org/10.1016/j.marpolbul.2004.08.008.

Kaiser, M., Stead, S.M., 2002. Uncertainties and values in European aquaculture: communication, management and policy issues in times of 'changing public perceptions'. Aquac. Int. 10, 469–490. https://doi.org/10.1023/A:1023963326201.

Karakassis, I., Papageorgiou, N., Kalantzi, I., Sevastou, K., Koutsikopoulos, C., 2013. Adaptation of fish farming production to the environmental characteristics of the receiving marine ecosystems: a proxy to carrying capacity. Aquaculture 408–409, 184–190. https://doi.org/10.1016/j.aquaculture.2013.06.002.

Macias, J.C., Avila Zaragozá, P., Karakassis, I., Sanchez-Jerez, P., Massa, F., Fezzardi, D., Yücel Gier, G., Franičević, V., Borg, J.A., Chapela Pérez, R.M., Tomassetti, P., Angel, D.L., Marino, G., Nhhala, H., Hamza, H., Carmignac, C., Fourdain, L., 2019. Allocated zones for aquaculture: a guide for the establishment of coastal zones dedicated to aquaculture in the Mediterranean and the Black Sea. In: General Fisheries Commission for the Mediterranean. Studies and Reviews, 97. FAO, Rome, 90 pp.

Mazur, N.A., Curtis, A.L., 2008. Understanding community perceptions of aquaculture: lessons from Australia. Aquac. Int. 16, 601–621. https://doi.org/10.1007/s10499-008-9171-0.

McKindsey, C.W., Thetmeyer, H., Landry, T., Silvert, W., 2006. Review of recent carrying capacity models for bivalve culture and recommendations for research and management. Aquaculture 261, 451–462. https://doi.org/10.1016/j.aquaculture.2006.06.044.

Mohorjy, A.M., Aburizaiza, O.S., 1997. Impact assessment of an improper effluent control system: a Delphi approach. Environ. Impact Assess. Rev. 17, 205–217. https://doi.org/10.1016/S0195-9255(97)00012-7.

Neofitou, N., Papadimitriou, K., Domenikiotis, C., Tziantziou, L., Panagiotaki, P., 2019. GIS in environmental monitoring and assessment of fish farming impacts on nutrients of Pagasitikos gulf, eastern Mediterranean. Aquaculture 501, 62–75. https://doi.org/10.1016/j.aquaculture.2018.11.005.

OESA (Observatorio español de acuicultura), 2019. Plan Estratégico Plurianual de la Acuicultura Española 2014–2020. Ministerio de Agricultura, Alimentación y Medio Ambiente, p. 396.

Pérez, M., García, T., Invers, O., Ruiz, J.M., 2008. Physiological responses of the seagrass Posidonia oceanica as indicators of fish farm impact. Mar. Pollut. Bull. 56, 869–879. https://doi.org/10.1016/j.marpolbul.2008.02.001.

Price, C., Black, K.D., Hargrave, B.T., Morris, J.A., 2015. Marine cage culture and the environment: effects on water quality and primary production. Aquacult. Environ. Interact. 6, 151–174. https://doi.org/10.3354/aei00122.

Robertson, R.A., Carlsen, E.L., Bright, A., 2002. Effect of information on attitudes towards offshore marine finfish aquaculture development in northern New England. Econ. Manag. 6, 117–126. https://doi.org/10.1080/13657300209380307.

Ross, L.G., Telfer, T.C., Falconer, L., Soto, D., Aguilar-Manjarrez, J., 2013. Site selection and carrying capacities for inland and coastal aquaculture. In: FAO/Institute of Aquaculture, University of Stirling, Expert Workshop, 6–8 Dec 2010. Stirling, FAO Fish Aquacult Proc 21. FAO, Rome.

Ruiz, J.M., Pérez, M., Romero, J., 2001. Effects of fish farm loadings on seagrass (Posidonia oceanica) distribution, growth and photosynthesis. Mar. Pollut. Bull. 42, 749–760.

Ruiz-Zarzuela, I., Halaihel, N., Balcázar, J.L., Ortega, C., Vendrell, D., Pérez, T., Alonso, J.L., De Blas, I., 2009. Effect of fish farming on the water quality of rivers in Northeast Spain. Water Sci. Technol. 60, 663–671. https://doi.org/10.2166/wst.2009.435.

Sakamoto, M., 1966. Primary production by the phytoplankton community in some Japanese lakes and its dependence on lake depth. Arch. Hydrobiol. 62, 1–28.

Sanchez-Jerez, P., Karakassis, I., Massa, F., Fezzardi, D., Aguilar-Manjarrez, J., Soto, D., Chapela, R., Avila, P., Macias, J.C., Tomassetti, P., Marino, G., Borg, J.A., Franičević, V., Yucel-Gier, G., Fleming, I.A., Biao, X., Nhhala, H., Hamza, H., Forcada, A., Dempster, T., 2016. Aquaculture's struggle for space: the need for coastal spatial planning and the potential benefits of allocated zones for aquaculture (AZAs) to avoid conflict and promote sustainability. Aquac. Environ. Interact. 8, 41–54. https://doi.org/10.3354/aei00161.

Sanz-Lázaro, C., Belando, M.D., Marín-Guirao, L., Navarrete-Mier, F., Marín, A., 2011. Relationship between sedimentation rates and benthic impact on Maërl beds derived from fish farming in the Mediterranean. Mar. Environ. Res. 71, 22–30. https://doi.org/10.1016/j.marenvres.2010.09.005.

Shindler, B.A., Wilton, J., Wright, A., 2002. A Social Assessment of Ecosystem Health: Public Perspectives on Pacific Northwest Forests. Oregon State University, Department of Forest Resources.

Taylor, J.G., Ryder, S.D., 2003. Use of the delphi method in resolving complex water resources issues[1]. J. Am. Water. Resour. As 39, 183–189.

UICN (Unión Internacional para la Conservación de la Naturaleza y de los Recursos Naturales), 2009. Guía para el Desarrollo Sostenible de la Acuicultura Mediterránea 2. Acuicultura. Selección y gestión de emplazamientos. Gland, suiza y Málaga, España: UICN. viii + 332 páginas.

Weitzman, J., Filgueira, R., 2020. The evolution and application of carrying capacity in aquaculture: towards a research agenda. Rev. Aquac. 12, 1297–1322. https://doi.org/10.1111/raq.12383.

Weitzman, J., Filgueira, R., Grant, J., 2021. Development of best practices for more holistic assessments of carrying capacity of aquaculture. J. Environ. Manag. 287, 112278 https://doi.org/10.1016/j.jenvman.2021.112278.

Whitmarsh, D., Palmieri, M.G., 2009. Social acceptability of marine aquaculture: the use of survey-based methods for eliciting public and stakeholder preferences. Mar. Policy 33, 452–457. https://doi.org/10.1016/j.marpol.2008.10.003.

Wilson, D., 2001. Community Consultation Survey of Aquaculture Developments in the Bowen Region. Queensland Department of State Development, Brisbane.

Yigit, M., Ergun, S., Buyukates, Y., Ates, A.S., Ozdilek, H.G., 2021. Physical carrying capacity of a potential aquaculture site in the Mediterranean: the case of Sigacik Bay, Turkey. Environ. Sci. Pollut. Res. Int. 28, 9753–9759. https://doi.org/10.1007/s11356-020-11455-y.

Zuboy, J.R., 1981. A new tool for fishery managers: the Delphi technique. N. Am. J. Fish Manag. 1, 55–59.