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Marine aquaculture in the pacific coast of Costa Rica: Identifying the optimum areas for a sustainable development

Felipe Calleja [a,*], Jonathan Chacón Guzmán [b,c], Henry Alfaro Chavarría [a]

[a] Unidad de Ingeniería Marítima, de Ríos y de Estuarios (iMARES-UCR), And Biosystems Engineering School, University of Costa Rica. Rodrigo Facio Campus, San Pedro de Montes de Oca, San José, Costa Rica

[b] Programa Parque Marino del Pacífico, Escuela de Ciencias Biológicas, Universidad Nacional (UNA), Heredia, Costa Rica

[c] Programa de Acuicultura y Biotecnología Marina, Parque Marino del Pacífico (PMP), Puntarenas, Costa Rica

A R T I C L E I N F O

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A B S T R A C T

Sustainable marine aquaculture requires the definition of adequate areas for its development, where the productive activity has a lower impact on the environment and avoid conflicts with other coastal activities. The aim of this research is to identify the potential areas for marine aquaculture operations in the central and northern Pacific coast of Costa Rica, considering five fish species of commercial interest and three operation scale scenarios (large, medium and small scale). The mapping procedure considers the biological suitability for the species to have an optimum development, the structural suitability for the fish cages to endure the environmental conditions (mainly waves and currents), and the operational suitability for operation and maintenance activities associated to the fish production (e.g. feeding, harvesting, maintenance). Sea surface temperature, salinity, water clarity, wind speed and currents in open coasts regions were obtained from global models and satellite data. Currents and wave data in the Gulf of Nicoya, one of the main estuaries of the country, were modeled numerically. Available docking sites, marine protected areas and tourism sites were used and obtained from the corresponding national official entities. Results show a high potential for marine aquaculture projects, specifically for large and medium scale operations. Three out of five study species present high suitability in most of the study site, and the other two species present promising results in the Gulf of Nicoya. Small scale operations have several areas with high suitability for marine aquaculture projects, with extensions ranging from 101 km^2 to 2 118 km^2 depending on the species. At a regional scale, the Pacific coast of Costa Rica presents high potential for fish aquaculture, being a promising development medium for coastal communities as long as it is environmentally sustainable and compatible with other coastal activities such as tourism.

1. Introduction

Globally, 46% of the 179 million tons of fish production in 2018 was obtained using aquaculture; this accounted also for 52% of the 156 million tons used for human consumption in the same year (FAO, 2020). Including the production of algae and ornamental seashells and pearls, world aquaculture achieved an all-time production record of 114.5 million tons in 2018, with a total farmgate sale of approximately USD 263.6 billion (FAO, 2020).

Aquaculture production in Latin America and the Caribbean region (LAC) was approximately 3 million tons in 2017, with 90% contributed by South America (Souto Cavalli et al., 2021). Chile, Brazil, Ecuador and Mexico are the main producers in the LAC region, with a combined aquaculture volume of over 80% of the total production (FAO, 2021). Specifically in Central America (CA), by 2014 the aquaculture production was approximately 363 000 tons (Wurmann, 2017), but by 2017 the total production increased to approximately 500 000 tons, with Honduras and Guatemala leading in this region (Souto Cavalli et al., 2021).

In the case of Costa Rica, the country is not one of the top Central

Abbreviations: CA, Central America; CFSv2, Climate Forecast System Version 2; CMEMS, Copernicus Marine Service Information; COW–P, Pacific's Coastal Wave; EU, European Union; LAC, Latin America and the Caribbean region; MMA, Marine Management Areas; MPA, Marine Protected Areas; NCEP, National Centers for Environmental Prediction; NOAA, National Oceanic and Atmospheric Administration; O&M, Operation and Maintenance; OSTIA, The Operational Sea Surface Temperature and Sea Ice Analysis; SMOC, Surface and Merged Ocean Currents; SST, Sea Surface Temperature; USD, United States Dollar; WW3, WaveWatch III.

* Corresponding author. Instituto de Investigaciones en Ingeniería, Ciudad de la Investigación UCR, San Pedro de Montes de Oca, 11801. San José, Costa Rica.
E-mail address: felipe.callejaapestegui@ucr.ac.cr (F. Calleja).

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American aquaculture producers (Wurmann, 2017), despite having an Exclusive Economic Zone of 581 726 km2, the largest of the CA region. Data from 2013 to 2015 indicates that the national fish and seafood consumption rounds 83 000 tons annually (fresh weight), which surpasses the national fishing and aquaculture production (Otárola and Corrales, 2019). Consequently, the country fills its local consumption with imports, with only 11 000 tons produced nationally, from which 1 400 tons are supplied by aquaculture (Otárola and Corrales, 2019). These numbers reflect a high potential for aquaculture projects that could increase the national fish and seafood supply.

Marine aquaculture projects could represent an important driver for coastal development in Costa Rica, as small, medium or large scale operations have been recognized to impact directly on the social well-being of coastal communities (Souto Cavalli et al., 2021). The country is already developing aquaculture projects in sea and estuaries, with farms of snappers (*Lutjanus* sp.) or molluscs (*Crassostrea gigas*), research on reproduction of weakfish (*Cynoscion* sp.), and production of other species at a very small scale (Otárola and Corrales, 2019; Wurmann, 2017), mostly through public projects, but with one private company farming fish in open sea. In addition, the government recently approved new legislation for environmental impact evaluation in marine aquaculture projects (MINAE, 2020), and created a governance mechanism to coordinate the entities related to the integrated management of marine and coastal areas (Poder Ejecutivo, 2019).

The high potential and recent momentum that marine aquaculture has gained in Costa Rica call for more research in several fields. One area of particular importance is site selection, a key factor in marine aquaculture projects to guarantee the activity's success while considering the economic, social and environmental implications (Dapueto et al., 2015).

Several studies address the potential of marine aquaculture at global scale (Gentry et al., 2017; McDaid Kapetsky et al., 2013; Weiss et al., 2018a). In those studies, the Central American region, and specifically Costa Rica, is included but is not clearly appreciated, due to its small size in comparison to the rest of the world. In addition, to the best of our knowledge, there is no analysis to identify potential sites for marine aquaculture in Costa Rica (or Central America), leaving an important void that limits the establishment of new projects.

Marine Spatial Planning (MSP) is a tool to organize the use of the ocean space and the interactions among human uses, allowing a sustainable ocean management and governance (Frazão Santos et al., 2019). Costa Rica lacks an official spatial ordering of its coastal and ocean activities, and requires an MSP methodology to achieve it (Comisión Interinstitucional de la Zona Económica Exclusiva de Costa Rica. (CIZEE-CR), 2008). The only official MSP development in Costa Rica is in planning phase, but it is only for the Gulf of Nicoya, the main estuary of the country (Frazão Santos et al., 2019). Other efforts have been done in different regions of the country through academic or technical reports (e.g. MarViva, 2013). Mapping the potential for marine aquaculture in Costa Rica is an important step in the country's MSP efforts, being that this tool requires objective and systematic studies that generate knowledge and support the decision making process (Comisión Interinstitucional de la Zona Económica Exclusiva de Costa Rica. (CIZEE-CR), 2008).

The aim of this study is to identify the potential areas of the Pacific coast of Costa Rica for establishing marine aquaculture projects, using several fish species of commercial interest, and considering various scenarios of production scale. The maps derived from this study can be an important and direct input in future MSP methodologies in the country. The study is focused on fish production, and it did not considered other types of marine aquaculture (algae, mollusk). In addition, the analysis is focused on mean conditions, and does not include the analysis of extreme meteo-oceanic events. From now on, every mention to marine aquaculture is referring to fish production specifically.

The identification process follows the procedure proposed by Weiss et al. (2018a, 2018b), due to its feasibility for application in the study site. Also, this procedure considers both the biological potential of the selected species, and the structural and operational potential based on the fish cages. This allows the analysis to consider not only the biological aspects, but also the infrastructure and operability aspects in the farm. In addition, some considerations are added to the original procedure to account for specific characteristics of Costa Rica, such as the Marine Protected Areas (MPA) and zones of interest for tourism.

2. Materials and methods

The identification of the optimum areas for a marine aquaculture farm considered the adequacy of environmental conditions for fish growth (i.e. biological suitability), the adequacy of met-ocean conditions to assure the integrity and durability of the cages where the fish is grown (i.e. structural suitability), and the feasibility of carrying out operation and maintenance (O&M) activities in those cages (i.e. operational suitability) (Weiss et al., 2018b).

The analysis assessed 3 scenarios associated to the potential operation scale:

1. Large scale operations that could use robust cages that can be installed in sites with high exposure to the environmental conditions (wave height <5 m and water currents <1.5 m/s);
2. Medium scale operations using cages that can endure substantial exposure (wave height <3 m and water currents <1 m/s);
3. Small scale operations that would use cages in sites with moderate exposure or less (wave height <1 m and water currents <0.5 m/s).

2.1. Study site

The identification of potential aquaculture farming sites was developed in the central and northern Pacific coast of Costa Rica (Fig. 1). This area includes some of the most important fishing towns of the country, and shows unemployment levels higher than the national average (Cortés, 2016), justifying the analysis for new development mechanisms such as marine aquaculture projects.

The region presents semi-diurnal tides with an average tidal range of 207 cm (extreme values of 256 cm) in the Central Pacific area (7 in Fig. 1). Sea water temperature is around 28 °C, except at the Santa Elena area (1 in Fig. 1), which presents very strong winds and seasonal upwelling, reducing the water's temperature, oxygen and pH during the upwelling periods (temperatures as low as 15.5 °C have been recorded in the site) (Cortés, 2016) . Most of the coastal areas (1–5 in Fig. 1) present a marked dry season between December and April–May, and the central areas (6 and 7 in Fig. 1) are a transitional zone towards more humid climate in the south (Cortés, 2016).

One important area included in the study site is the Gulf of Nicoya (5 and 6 in Fig. 1). This is a tectonic estuary, with depth that varies from less than 1 m (at low tide) near the Tempisque river mouth, to more than 500 m at the external part of the estuary (Vargas, 2016). It has three main fluvial inputs: the Tempisque river at its northern region, and the Barranca and the Tárcoles rivers at its east side. The fluvial contributions generate a seasonal variation on nutrients, turbidity, and salinity (Kress et al., 2002; Palter et al., 2007; Vargas, 2016). During the rainy season (May to November) nutrients and turbidity tend to increase, while the salinity forms a distinct vertical gradient with lower salinity near surface (at the inner part of the Gulf). This condition changes during dry season, when the reduced fluvial inflows and high winds allow for a better mixing of the estuarine waters (Vargas, 2016).

There are some marine aquaculture projects currently functioning in the study site. Most of them are small scale projects in the Gulf of Nicoya, developed in collaboration between the benefited community, the Parque Marino del Pacífico (https://parquemarino.org/), and the National University. There is also a commercial operation in the central Pacific (near 7 in Fig. 1) by the MARTEC company (https://martec.co.cr/).

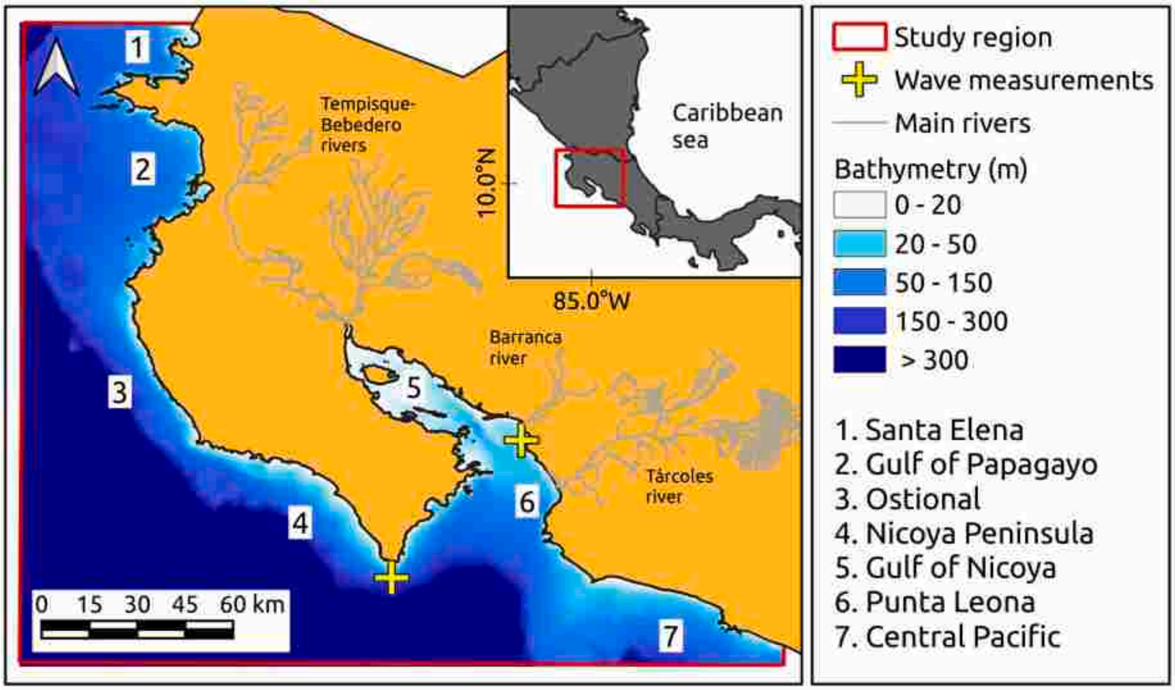

Fig. 1. Study site. Annotations for important areas. Bathymetry shaded with darker values indicating higher depth. Areas 5 and 6 are part of the Gulf of Nicoya, but are separated in this study for specific analysis of each area. Southern yellow cross indicates the wave gauge at Cabo Blanco for calibrating the wave model. Eastern yellow cross indicates the wave gauge at the port of Caldera for validating the wave model. Main rivers are indicated in gray lines.

2.2. Study species

Five fish species were selected based on three main considerations: i) they are native species with theoretical feasibility for aquaculture production in the Pacific coast of Costa Rica; ii) some of the species are currently exploited successfully in both small and large scale fish farms; and iii) they are species commonly consumed inside and outside Costa Rica (high market potential) (Table 1).

The thresholds of the physical and chemical variables were initially defined based on previous research with the study species, or at least similar species that could offer a comparable view on the biological requirements. As far as possible, the thresholds were obtained from studies that worked with individuals during the fattening period in marine aquaculture projects. Nevertheless, only a minority of references fulfilled this criterion, forcing to use a wider scope of published data that included field and laboratory studies not necessarily related to marine aquaculture. The definite thresholds (Table 1) were defined after consulting with aquaculture experts from different parts of the world, which analyzed the initial values and helped to create the final set of thresholds for rearing individuals in marine aquaculture projects (by modifying or confirming the initially established values).

2.3. Biological suitability

The environmental variables used to calculate the biological suitability were the sea surface temperature, salinity and water transparency following Weiss et al. (2018a).

The SST data was obtained from the OSTIA global foundation Sea Surface Temperature product (Good et al., 2020), at a spatial resolution of 0.05° (5.55 km approx.) (reference system WGS84, EPSG: 4326) and daily records between January 1st, 2007 and March 10th, 2020. The data was downloaded from the E.U. Copernicus Marine Service Information (CMEMS), through the OSTIA Near Real Time Level 4 SST products over the global ocean (Martin et al., 2019).

The salinity data was obtained from the Operational Mercator global ocean analysis and forecast system, at a spatial resolution of 1/12° (9.25 km approx.) (reference system WGS84, EPSG: 4326) and daily records between January 1st, 2016 and March 20th, 2020.The data was downloaded from CMEMS through the GLOBAL Ocean Sea Physical Analysis and Forecasting Products (Law Chune et al., 2019).

Water transparency was analyzed using the Secchi disk depth calculated with Doron et al. (2007). It was downloaded from the GlobColour dataset (ACRI-ST GlobColour Team, 2020; Fanton D'Andon et al., 2009) with a spatial resolution of 1/24° (4.62 km approx.) (Plate

Table 1
Study species, physical and chemical threshold for optimum development at the fattening period, and sources.

Common name	Scientific name	Sea Surface Temperature (°C)	Salinity	Transparency (m)	Sources
Spotted rose snapper	*Lutjanus guttatus*	26–30	25–35	1 ≤	(Alcalá-Carrillo et al., 2016; Castillo-Vargasmachuca et al., 2007; Vargas-Machuca et al., 2008)
Longfin yellowtail	*Seriola rivoliana*	24–30	26–35	1 ≤	(Brodie, 2016.[a]; Pirozzi and Booth, 2009.[a]; Roo et al., 2014; Streich et al., 2017)
Whitefin weakfish	*Cynoscion albus*	26–30	6.5–34	0.25 ≤	(Andrade-Vera et al., 2017; Bartels et al., 1984)
Black snook	*Centropomus nigrescens*	26–30	0–31	0.25 ≤	(Dutka-Gianelli, 2010; Escárcega-Rodríguez, 2018; Günther, 1995; Velázquez-Velázquez et al., 2008)
Atlantic goliath grouper	Epinephelus itajara	26–30	10–31	0.25 ≤	(Chapman et al., 2014; García et al., 2013; Shideler et al., 2015)

[a] Studies with *Seriola lalandi*.

Carrée projection) and daily records between December 12th, 2010 and April 8th, 2012.

All three environmental variables were evaluated according to the percentage of time they remained between the biological thresholds for each species (0–1 scale). Time series analysis was performed using the information in its original extension and spatial resolution. The resulting maps were adjusted to a projected reference system (CRTM05, EPSG: 5367), and a spatial resolution of 1 km. In specific cases (salinity and transparency), empty pixels in the percentage maps were filled with the weighted average of the surrounding cells (equivalent to a inverse distance weighted interpolation). The final maps were combined using the critical value criterion to create the biological suitability map for each species. The critical value criterion means that the lowest value for each base variable was selected as the final suitability. For example, if the temperature had a percentage of time between its corresponding threshold of 0.86 in a specific cell, salinity had a value of 0.7 and water transparency of 0.9, the final biological suitability in that cell was recorded as 0.7. All calculations were made using Python 3.6 and QGIS 3.14.1.

2.4. Structural suitability

The adequacy of the study site to ensure the integrity and durability of the cages was assessed with the current speed, wave height, depth, and bottom slope at the potential farming areas. These variables were selected following the procedure presented by Weiss et al. (2018a), who considered a generic cage and resistance parameters based on Norwegian standards. Wave height is directly related to the structural integrity of the cage. Current speed is related to the stress in cage and mooring system. Depth and bottom slope are related to the stress and stability of the mooring system (e.g. stability of anchors, weight of required mooring lines).

The analysis considered three possible scenarios (Table 2). Each scenario was associated to an operation scale (large, medium, small) and a specific level of exposure that their respective cages can endure. The relation between operation scale and level of exposure is conceptually established as follows: a large scale operation might be economically more capable to acquire stronger cages that can be located in more exposed sites. On the contrary, small scale operations might be able only to purchase smaller cages that can endure moderate exposure in sheltered areas.

Thresholds for wave height, maximum current speed and bottom slope were obtained from Weiss et al. (2018a). The minimum threshold for current speed was obtained from Falconer et al. (2013). The depth threshold was adapted from Weiss et al. (2018a) using a lower value to consider the possible critical depth in small scale operations.

2.4.1. Currents

The study site was divided into two sub-areas according to the currents speed analysis. Inside the Gulf of Nicoya the currents were modeled using the Delft3d-FLOW module (Deltares, 2014). This allowed a better understanding of the currents' dynamic around the Gulf's islands, which was not adequately represented by globally modeled currents due to their spatial resolution. The model used a curvilinear grid with an approximate spatial resolution up to 1 km. The model was forced with a tidal wave with an amplitude equal to the 95 percentile of the tide amplitude from the last 5 years, and a period of 12 h as it is in Costa Rica's pacific coast. All details of the hydrodynamic model, including its validation can be found on Appendix A (Fig. A1 and Table A1).

Outside the Gulf of Nicoya, total currents (addition of circulation, tides and waves currents) were analyzed directly from a global currents model to reduce computational time on a large coastal hydrodynamic model. The data was obtained from the Surface and Merged Ocean Currents (SMOC), with spatial resolution of 1/12° (reference system WGS84, EPSG: 4326) and hourly records between April 1st, 2016 and December 27th, 2019. The data was downloaded from CMEMS through the GLOBAL Ocean Sea Physical Analysis and Forecasting Products (Law Chune et al., 2019).

Both data sources were analyzed using the percentage of time the currents remained between the cages' thresholds (0–1 scale). The percentage maps were adapted to a projected reference system (CRTM05, EPSG:5367) and a resolution of 1 km. Both sources were joined into a single map by replacing the values in the inner part of the Gulf of Nicoya in the SMOC derived map, with the values generated by the Delft3d-FLOW model in that same area. This defined a hard boundary approximately at the entrance of the inner region of the Gulf (at the imaginary line that connects the Caldera port and the Nicoya Peninsula). Visual inspection of the data at the boundary showed that there were no abrupt changes between both sources.

Empty pixels on the final map were filled using the weighted average of the surrounding cells. All calculations were made using MATLAB 2019b (license 1095402), Python 3.6 and QGIS 3.14.1.

2.4.2. Waves

Wave data was obtained from a hybrid downscaling procedure made in the Pacific coasts of Costa Rica, named the Pacific's Coastal Wave (COW–P) (Alfaro, 2017; Zumbado, 2021). It is derived from the wave reanalysis developed by National Oceanic and Atmospheric Administration (NOAA) using the generation and propagation operational model Wavewatch III (WW3) in its 4.15 version (Tolman, 2002). The WW3 data was calibrated using wave measurements at the Cabo Blanco site (southern yellow cross in Fig. 1) during a four year period (2014–2017) (Alfaro, 2017) using the direction dependent parametric wave calibration methodology by Mínguez et al. (2011). A visual representation of the calibrated data can be found at Fig. B1 in Appendix B.

Wave series on deep waters were translated to coast with hybrid downscaling techniques (Camus et al., 2011, 2013), using the SWAN model (Booij et al., 1999) and bathymetric data from GEBCO (GEBCO Compilation Group, 2020). The COW–P product consisted of 10015 numeric nodes, distributed along the Pacific coast of Costa Rica, with 3-h resolution time series for significant wave height, peak period and mean direction, from 2005 to 2019. Validation of the final product (Fig. B2, Appendix B) was assessed with a wave time series measured in Caldera's port (Fig. 1) between 2015 and 2018 (iMARES, 2020).

Wave's time series in each node were analyzed using the percentage of time the significant height remained under the cages' threshold (0–1 scale). The percentage maps were adapted to a projected reference system (CRTM05, EPSG:5367) and a resolution of 1 km. The maps' extension was set to the biological suitability maps' extension. All calculations were made using MATLAB 2019b (license 1095402), Python 3.6 and QGIS 3.14.1.

Table 2
Description of analyzed development scenarios. Structural and operational thresholds obtained from Weiss et al. (2018a), Falconer et al. (2013) and NOAA National Weather Service (2015). Hs: Significant wave height.

			Structural suitability				Operational suitability		
Scenario	Operation scale	Max. Site Exposure	Hs (m)	Current speed (m/s)	Depth (m)	Bottom slope (%)	Hs (m)	Wind speed (m/s)	Distance to ports (km)
1	Large	High	≤5	$0.025 \leq x \leq 1.5$	<150	<25	≤3	≤15	<20
2	Medium	Substantial	≤3	$0.025 \leq x \leq 1.0$	<150	<25	≤2	≤10	<20
3	Small	Moderate	≤1	$0.025 \leq x \leq 0.5$	<150	<25	≤1	≤7.5	<20

2.4.3. Structural suitability calculation

Structural suitability for the cages was calculated with the percentage of time that the currents and waves remained between the thresholds defined for each scenario(Table 2). The critical value of each analysis (currents and waves separately) was defined as the structural suitability, only in areas where the depth was less than 150 m and the bottom slope was less than 25%.

Each map was adjusted to the projected reference system (CRTM05, EPSG:5367), a spatial resolution of 1 km, and an extension of the other maps created prior. All operations were made using QGIS 3.14.1.

2.5. Operational suitability

The operational suitability was calculated based on Equation (1), as presented in Weiss et al. (2018b).

$$O.S. = \frac{(3^{*}wave + 2^{*}wind + ports)}{6} \quad 1$$

Where O.S. is the operational suitability (0–1 scale), wave and wind are the relation between the available 8 h windows with conditions under the operational thresholds (Table 2) and the maximum number of possible windows in their corresponding time series, and ports is the distance to ports normalized by the maximum distance allowed (20 km).

The wave thresholds (Table 2) were obtained from Weiss et al. (2018b). Wind speed thresholds were adapted from the minimum values used by NOAA to rise warnings for small crafts at sea in Florida (National Weather Service, 2015), considering the potential conditions that could endanger the O&M operations at the farms in the different scenarios. The distance to ports threshold was adapted from Weiss et al. (2018b) to a value more suited to the Costa Rican navigation capabilities of low-income fishermen.

The wave time series was the same as the one used for the structural suitability calculation. Winds at 10 m above ground data were obtained from the NCEP Climate Forecast System Version 2 (CFSv2) (Saha et al., 2014), with hourly records between January 1st, 2016 and November 1st, 2020, in a grid with 0.205° spatial resolution (22.75 km approx) (reference system WGS84, EPSG: 4326). For the distance to ports, population centers with piers were defined along the coast based on aerial imagery and main roads information. A map of the distance to the closest port (pier) was derived with a threshold of 20 km using Equation (2).

$$ports = \frac{1 - min.distance}{20} \quad 2$$

Where ports is the normalized distance used in Equation (1) and min. distance is the distance to the closest ports in kilometers.

The final operation suitability map was adjusted to the projected reference system (CRTM05, EPSG:5367), a spatial resolution of 1 km and the extension of the prior maps.

2.6. Marine aquaculture suitability

The biological, structural and operational suitability maps were combined using the critical value criterion to derive the final marine aquaculture suitability map.

The final suitability maps were adjusted to consider MPA and Marine Management Areas (MMA). The first, is a legal category that does not allow any marine aquaculture activities. The second category allows marine aquaculture operations at small scale as long as there is a valid management plan for the area, but no medium or large scale marine aquaculture operations are allowed. This consideration was included in the final suitability maps by fixing the value of all cells inside a MPA to zero. The same was made inside the MMA in the medium and large scale scenarios.

The maps also indicate tourism development centers, as defined by the Costa Rican Tourism Institute (Instituto Costarricense de Turismo, 2021), to show areas with potential interactions (synergies or conflicts) between the aquaculture and tourism activities. In this case, it is highly specific for each site if the tourism of the area could be positive or negative to the marine aquaculture operation. This made impossible to define a standard criterion to apply to the suitability maps. Nevertheless, the touristic sites where marked in the final maps, to help future users to be aware and evaluate the potential factor of touristic activities near the site where the fish farm would be installed.

3. Results

This research generated maps for the biological, structural, operational and general suitability for marine aquaculture projects in the northern and central Pacific coast of Costa Rica. The individual maps can be accessed for a detailed analysis using any Geographic Information System (GIS) (Calleja, 2021).

3.1. Biological suitability

The potential to develop aquaculture farms for each of the 5 study species based only on the biological suitability is shown in Fig. 2.

For the species *L. guttatus*, *S. rivoliana*, and *C. albus* (Fig. 2a, 2b, and 2c) the biological suitability shows high values along most of the study site. The Gulf of Nicoya presents lower values for *L. guttatus* and *S. rivoliana* (Fig. 2a, 2b), especially at the most inner part of the estuary. This is due to the lower, more variable salinity and the lower water clarity, both affected by the fluvial inputs of the Tempisque river. For *C. albus* (Fig. 2c), the biological suitability shows high values inside the Gulf of Nicoya due to its euryhaline nature, and lower values in the northern part of the country (Santa Elena) due to the lower temperature affected by upwelling phenomenons. *L. guttatus* also shows a slight reduction of its biological suitability near Santa Elena, also related to the lower water temperature.

In the case of *C. nigrescens* and *E. itajara* (Fig. 2d and 2 e), the biological suitability is lower than the values for the other 3 species along all the study site. Both species show their higher potential inside the Gulf of Nicoya, due to their preference for sites with lower salinity and water clarity.

3.2. Structural suitability

Fig. 3 shows the potential for aquaculture farms based only on the structural suitability of the cages.

For scenarios 1 and 2, i.e. large and medium scale operations in sites with high and moderate exposure, structural suitability is high in almost all the study site (Fig. 3a and 3 b). Exceptions are due to deep or steep areas (or both) that surpass the 150 m depth and 25% slope thresholds. In addition, in the inner part of the Gulf of Nicoya and some cells very near to coast, low suitability is due to low current velocity that remains below the 0.025 m/s threshold most of the time.

In the case of scenario 3, i.e. small scale operations in sites with moderate exposure, structural suitability is more restricted to sheltered areas (Fig. 3c). Higher values can be seen in the Santa Elena area, the south part of the Gulf of Papagayo, inside the Gulf of Nicoya and near Punta Leona.

3.3. Operational suitability

The potential for aquaculture farms based only on the operational suitability of the cages is shown in Fig. 4.

Similar to the results of the structural suitability, scenarios 1 and 2 (large and medium scale operations respectively) show very similar maps (Fig. 4a and 4 b), with high suitability in most of the study site. The highest values are near the ports, showing the main limitation is the ability to travel between shore and the potential farm site.

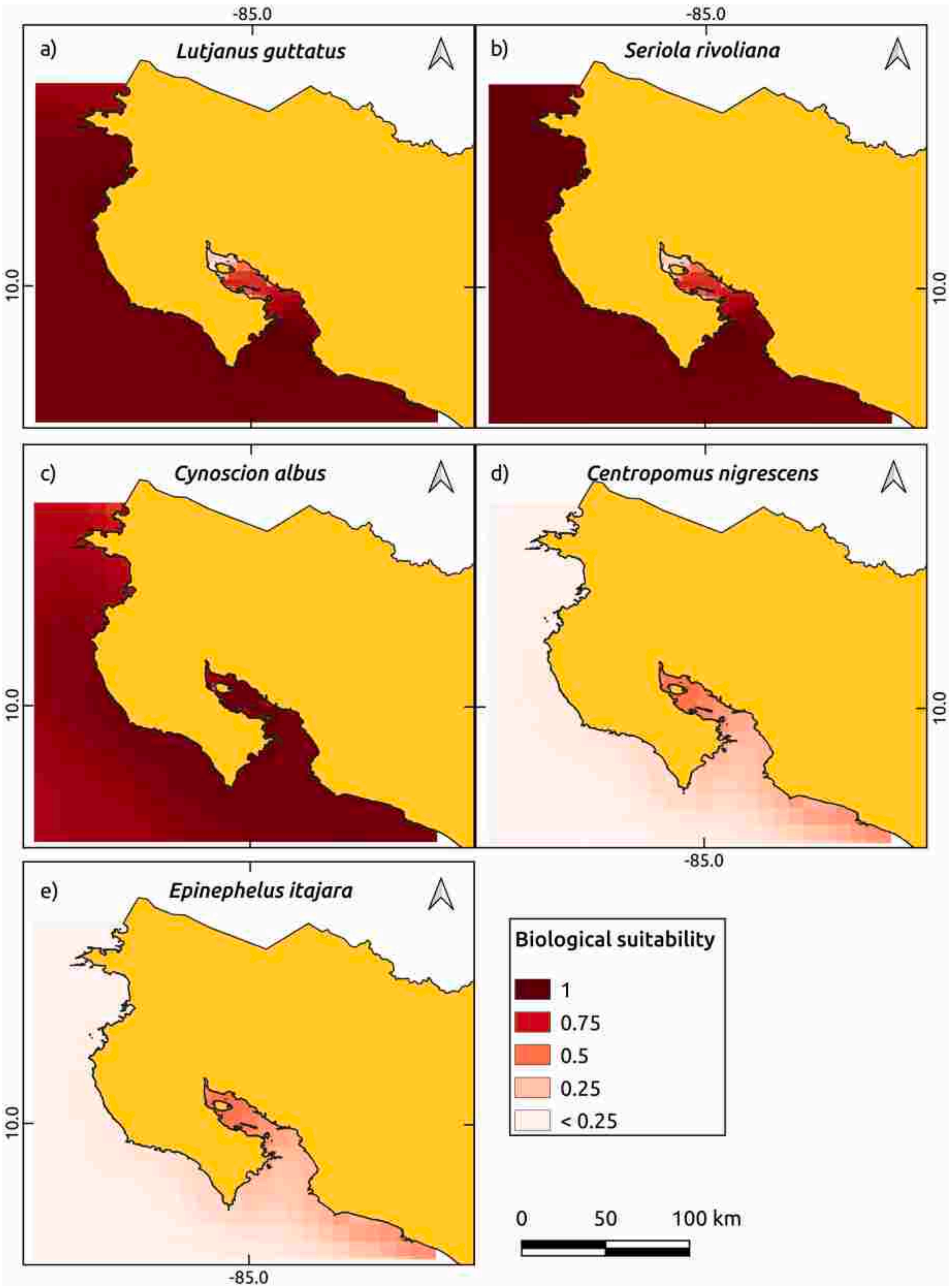

Fig. 2. Biological suitability for the study species. Scale from <0.25 (lighter tone) to 1 (darker tone).

In the case of scenario 3 (small scale operations) (Fig. 4c), the suitability is reduced in almost all the study site. Once again, sheltered areas show higher values and thus, higher potential for an aquaculture farm. The Santa Elena area, south part of the Gulf of Papagayo, inside the Gulf of Nicoya, and sites near Punta Leona seem as the most suitable areas from an operational perspective. These lower suitability values are related to the lower capacity for O&M operations in higher wave and wind conditions, supporting the need for sheltered areas in small scale operations.

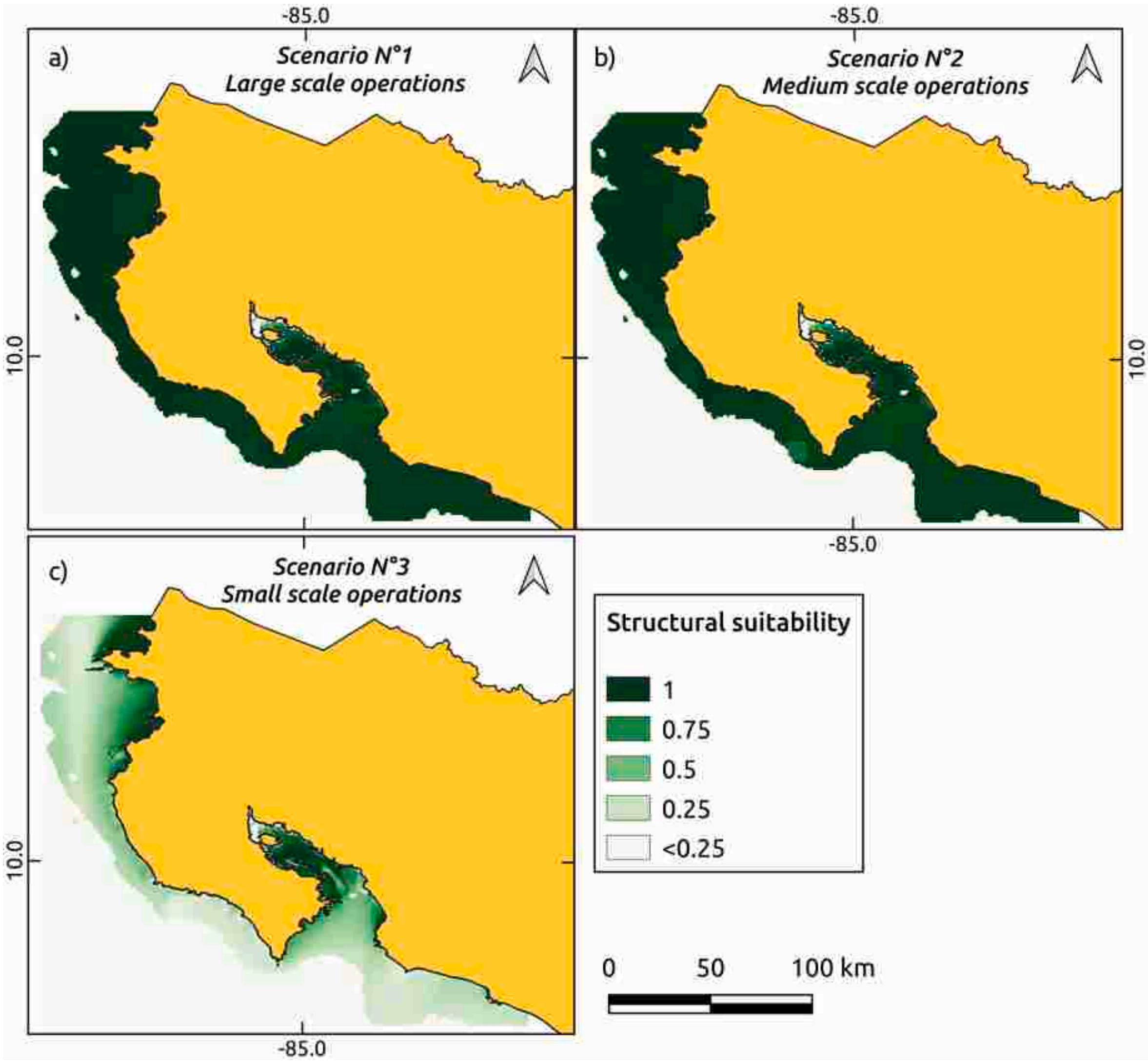

Fig. 3. Structural suitability for three scenarios according to the size of the operation scale.

3.4. Marine aquaculture suitability

The final marine aquaculture suitability maps for all 5 species and 3 operation scenarios are shown in Fig. 5 (scenario 3, small scale operations), and Fig. C1 and Fig. C2 in Appendix C (scenarios 1 and 2, large and medium scale operations).

For large and medium scale operations, the structural and operational suitability showed that almost all the study site has high values. Thus, the marine aquaculture suitability map is only restricted by the biological suitability and the marine protected areas (Appendix C), leaving very similar results to the biological suitability maps.

The suitability for small scale marine aquaculture projects (Fig. 5) varies according to the species to use. *L. guttatus* and *S. rivoliana* show high suitability for the northern parts of the study site (Santa Elena, Gulf of Papagayo), and slightly less values in the Gulf of Nicoya, although still promising (>0.75). At the sites of Ostional, Nicoya Peninsula and Central Pacific, the suitability values decrease to near 0.5. This shows the need for specific studies in more sheltered sites, where the protected conditions would increase the marine aquaculture suitability of this species in small scale operations.

With *C. albus,* the marine aquaculture suitability is high at the Gulf of Papagayo, the Gulf of Nicoya and near Punta Leona. It shows lower values than *L. guttatus* and *S. rivoliana* around Santa Elena, and in Ostional, Nicoya Peninsula and Central Pacific, the suitability drops to near 0.5.

For *C. nigrescens* and *E. itajara* the higher suitability is at the Gulf of Nicoya, coherent with the ecology of the species, adapted to estuarine waters with lower salinity and water transparency. The inner part of the gulf shows a low suitability area (lighter colors). This is an inaccuracy related to the very low current velocity modeled in that area due to the limitations of the hydrodynamic model discussed in the next section. The Punta Leona and Central Pacific areas show a reduced suitability (near 0.25). The rest of the study site shows low suitability values (<0.25) that suggest that there are not many suitable areas for rearing *C. nigrescens* or *E. itajara* outside the Gulf of Nicoya. Nevertheless, there could be specific sites near river outlets in sheltered areas where cultivation of these species is feasible at small scale. More specific site analysis would be required to confirm this possibility.

The study site presents an optimistic potential for marine aquaculture projects at different operation scales (Table 3). For instance, by defining a 50% suitability threshold, the potential area with a high scale operation can be up to 7 317 km^2 for *C. albus*. In the case of *C. nigrescens* and *E. itajara* the potential areas are fewer than for the other species, as expected being the two species that have higher values only inside the Gulf of Nicoya. Nevertheless, both species show a potential area as high as 105 km^2, leaving a wide range of possible sites in which to establish marine aquaculture projects.

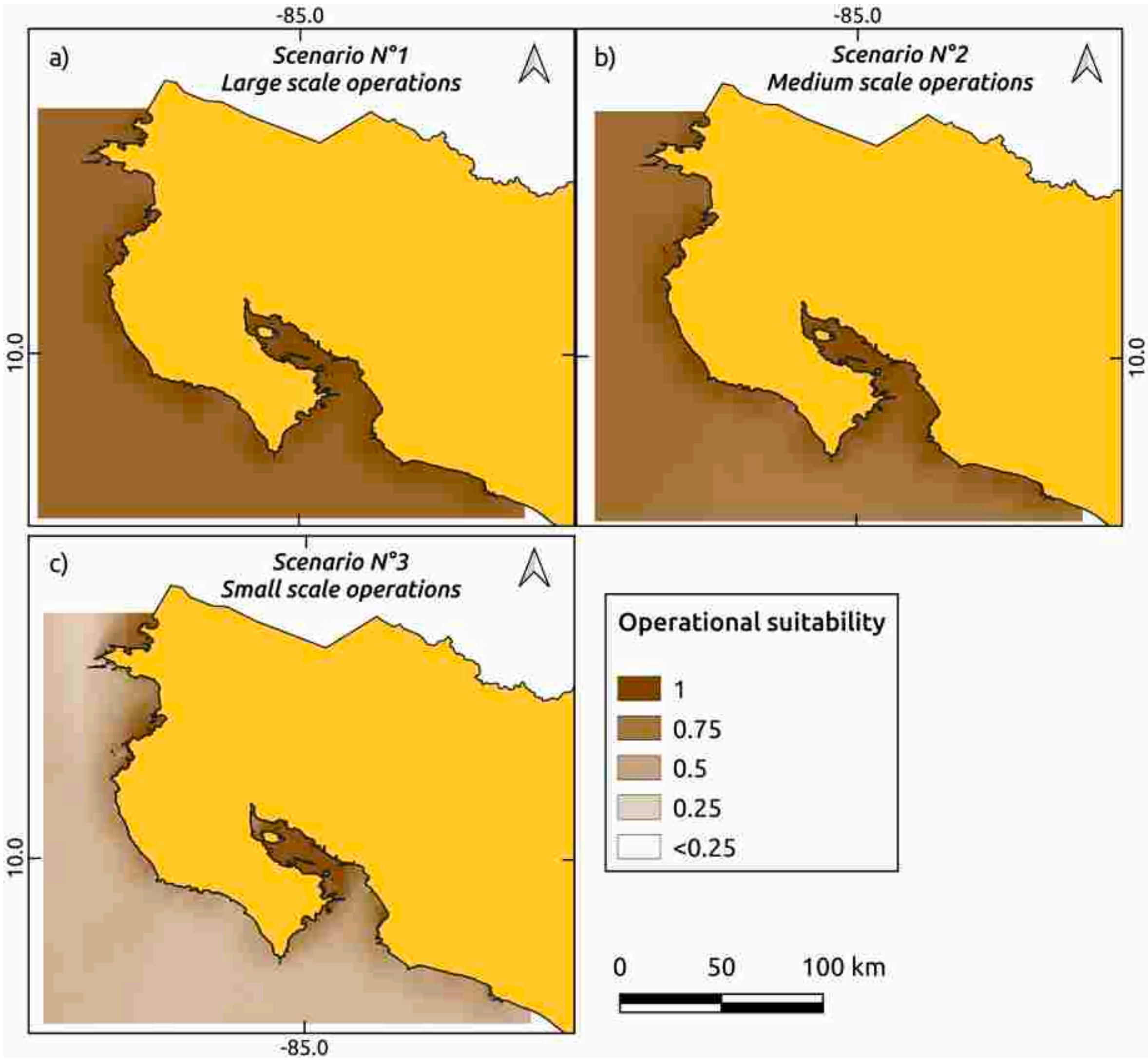

Fig. 4. Operational suitability for three scenarios according to the size of the operation scale.

4. Discussion

This study identified potential areas for cultivating 5 fish species in marine aquaculture projects along the central and northern Pacific coast of Costa Rica. The areas were selected based on the biological suitability for developing each species, the structural suitability for assuring the resistance of the cages to the environmental conditions (waves and currents), and the operational suitability to guarantee O&M operations (e.g. feeding, cleaning, harvesting). Marine protected areas and tourism zones were considered for the final maps of potential marine aquaculture areas.

These results complement other global scale studies that have identified marine aquaculture potential in Costa Rica but did not calculate the specific area due to their working scale. Those global analyses identified the study site as suitable for producing species like Cobia *Rachycentron canadum* (Weiss et al., 2018a). They also gave an approximate maximum national production potential of 500 000 tons of marine finfish in low-density productions (Gentry et al., 2017), and even considered the country among the top 10 non-mariculture nations based on the Exclusive Economic Zone and water current speed (McDaid Kapetsky et al., 2013).

The final suitability maps show the tourism development centers, as defined by the Costa Rican Tourism Institute. This centers will interact with the marine aquaculture operations, so they have to be taken into account when considering a specific site for establishing fish farms. This is specially important in areas near the Gulf of Papagayo and the Nicoya Peninsula, where most of these centers are located, and potential synergies (or conflicts) could arise from having both activities in the same area. For example, the presence of hotels and touristic activities near a fish farm could represent a local market to sell its production and potential visitors to the fish farm (synergies), but could also generate conflicts if beach users are not comfortable seeing the cages in the sea near them, or if the cages are installed near areas of touristic activities such as scuba diving (conflicts).

The Gulf of Papagayo and the Gulf of Nicoya are two promising areas for marine aquaculture development. The first has high suitability for three of the five study species, and the high amount of tourism centers could generate valuable synergies given the adequate management (e.g. fish supply for hotels and restaurants, tours to the fish farms). In the case of the Gulf of Nicoya, all five species show promising results, and the lower amount of MPA and touristic centers could facilitate the establishment of fish farms.

The mapping procedure allowed to obtain results in a region that, in general, lacks measurements and modeled data of the physical variables used as predictors. All of this was, in part, possible to international programs that offer information on variables such as SST, salinity, water clarity, wave height and current speeds on a global basis. This highlights the importance of earth observation and environmental modeling

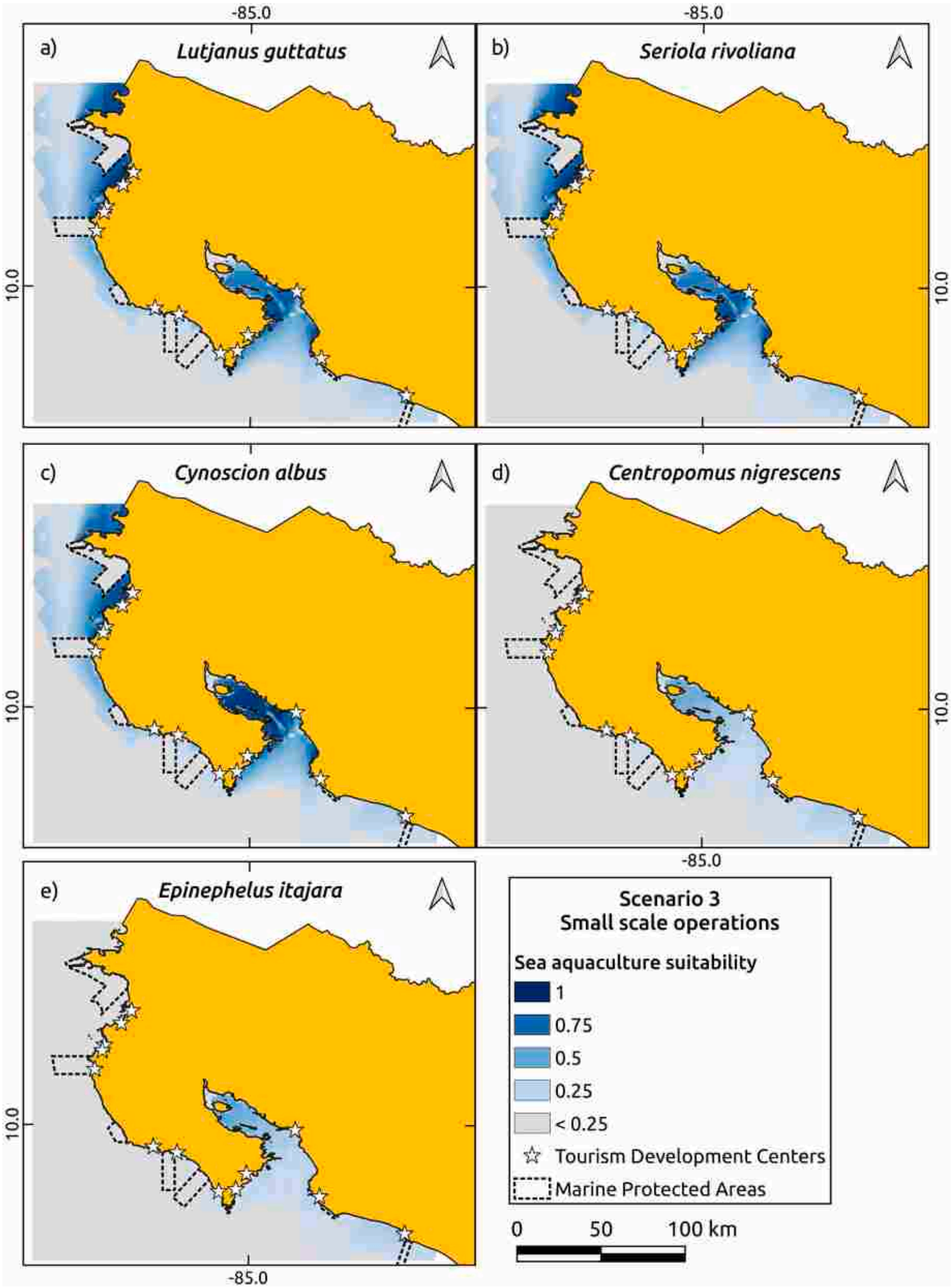

Fig. 5. Marine aquaculture suitability for a Scenario N°3 operation (Small scale operation).

programs for developing countries like Costa Rica, where marine aquaculture can be an important driver for economic and social growth, but its proper study and management needs high amounts of base data that is not always available empirically.

The results show potential areas that agree with the expectations based on knowledge of the study region and species. Nevertheless there are some inaccuracies that need to be addressed. First, the operational suitability values for the Santa Elena area are higher than expected, mainly for the small scale operations. Although this could be right, site knowledge and previous experience with navigation in the area indicate that winds are usually too strong to develop a small scale aquaculture farm that could be accessed most of the time. This same limitation could

Table 3
Potential areas (km^2) with marine aquaculture suitability >50% for the study species according to the operation scale scenarios.

Study species	High scale operation	Medium scale operation	Small scale operation
Lutjanus guttatus	7 230	7 230	2 031
Seriola rivoliana	7 230	7 230	2 031
Cynoscion albus	7 317	7 317	2 118
Centropomus nigrescens	105	105	105
Epinephelus itajara	105	105	105

Note that the final marine aquaculture suitability maps (Fig. 5, C1 and C2) consider the MPA by setting the suitability to zero. Also, the maps for the large and medium scale operations include the MMA, also with suitability set to zero. Finally, the maps show the tourism development centers using a star symbol.

be present at the general northern Pacific coast of Costa Rica. The described inaccuracy is derived from the working scale used in this study, and supports the need for more local analyses to determined the specific potential sites for marine aquaculture.

Another inaccuracy occurs at the most inner part of the Gulf of Nicoya, where structural suitability values are very low (near 0), due to very slow currents that fall under the minimum threshold defined. This affects the final marine aquaculture suitability map, and it is specially notorious with the species *C. nigrescens* and *E. itajara*, which have their natural habitat in this area and should present their higher suitability values there. In this case, the hydrodynamic model used in the Gulf of Nicoya is not properly modeling the most inner part of the estuary due to inaccuracies in the bathymetry, and also due to the lack of a hydrogram of the Tempisque and Bebedero rivers at the entrance of the estuary. Both variables should be measured or developed for future analysis in this inner estuary area.

The mentioned limitations are related to the study's working scale and missing base information, which reinforce the need for local studies and field measurements of environmental variables. The results presented here show a general view on the marine aquaculture potential, and they could serve as a guide in the future selection of specific sites where local studies could be made. These local studies should consider more environmental and social variables to determine the optimum areas for fish farms (e.g. sea bed type, occurrence of extreme weather events, social capacities for establishing the associated production infrastructure). In addition, local measurements are required to identify singularities that could affect the fish production, such as asymmetries in the currents' vertical profile like the ones in the Gulf of Nicoya (Lizano and Alfaro, 2004).

One variable that requires field data and further analysis is wind speed. The CFSv2 data used in this study offered an extensive temporal and spatial record, that allowed to calculate the possible wind effect on the O&M operations on future fish farms. Nevertheless, it seems to be underestimating the wind speed at the Santa Elena area, specially near the shore, where the suitability values are higher than expected. For this, it would be highly beneficial to have a specific wind model for the Costa Rican coasts, with higher resolution and calibrated for the specific conditions of each region. In addition, it is highly recommended that, in case of analyzing a specific site to establish a marine aquaculture farm, the project managers invest in measuring wind data prior to the design process, so they can have an accurate depiction of the conditions that will affect the operational aspects of the project.

Finally, both the structural and operational suitability analyses are based on the exposure and endurance to the environmental conditions, and not directly on the operation scale associated to each scenario. This means that in case of considering a small scale operation that would be able to use strong cages in exposed sites, the structural and operational maps that should be consulted are the ones for the large or medium scale operations (depending on the characteristics of the cages used).

This study represents an initial effort to localize the optimal areas for marine aquaculture projects in the Pacific coast of Costa Rica, and could be an important asset in the national marine spatial planning process. In a country recognized for its conservation efforts, but with increasing needs for social and economical development options, marine aquaculture can be an important driver for sustainable growth. Fish farms could be implemented along other living organisms with commercial interest (e.g. algae, mollusks) creating integrated multi-trophic aquaculture projects (McDaid Kapetsky et al., 2013). At the same time, they could be integrated with tourism and energy production, offering a wide variety of activities that would impact directly on the coastal communities.

5. Conclusions

This research represents an initial, systematic and objective calculation of the potential areas for developing fish marine aquaculture projects in the central and northern regions of the northern and central Pacific coast of Costa Rica. Three out of five fish study species show high suitability values in almost all the study site, and the remaining two show promising results inside the Gulf of Nicoya. In the case of large and medium scale operations (using cages for high and substantial exposure), almost all the study site presents high structural and operational suitabilities. For small scale operations, the potential areas are reduced, but still present high values in several sheltered areas.

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.

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Appendix A. Hydrodynamic model in the Gulf of Nicoya

The hydrodynamic model used for calculating the water currents was established using the Delft3d-FLOW model, using a curvilinear grid with a resolution of approximately 1 km at its smaller cells. Recommendations from the developers on grid orthogonality (<0.04), smoothness (<1.2) and aspect ratio (<2) were respected to improve the calculation stability. Bathymetric data was obtained from GEBCO, with specific areas with field measurements from previous projects. The original bathymetry resolution was approximately 400 m, and was translated to the grid points using the Delft3d-RGFGRID module.

The model was forced using the astronomic tide during the modeling period, included in the southwest border of the grid as a time series with records every 30 min from January 27th' 2020 until February 28th' 2020. The northwest and southeast borders of the grid were set with a fully absorbent Neumann condition. Atmospheric pressure and wind speed were also included as model forcings, with a space varying wind and pressure input in grid format (11 × 13 cells with 0.5° spatial resolution). Wind and pressure input covered the same temporal range as the tide wave, and were obtained from the "NCEP Climate Forecast System Version 2 (CFSv2) 6-hourly Products" (Saha et al., 2014).

The model was calibrated using four parameters: bottom roughness, horizontal eddy viscosity and diffusivity, and the wind drag coefficient. Bottom roughness was set using a space varying Manning coefficient map, with values defined in the calibration process using as reference Manning coefficients for sand. The horizontal eddy viscosity and eddy diffusivity were set as a space varying map using a turbulent Schmidt number of 1, a reference velocity of 1 m/s and an Elder constant of 0.05. Wind drag coefficient was set to 0.00063 at 0 m/s and 0.00723 at 1 m/s or more (with a lineal interpolation in between values).

The model's calibration-validation was made using three control points. The reference data to compare the model's results was obtained from the Surface and Merged Ocean Currents (SMOC) of the GLOBAL Ocean Sea Physical Analysis and Forecasting Products. The reference and model data were compared visually (Figure A1), using only the data between February 9th and February 27th, to remove the instability of the first weeks of simulation. Quality parameters of R^2 and RMSE (Table A1.) were also considered to select the best values for each parameter. In control points 2 and 3, the modeled series presented an adequate form but a 3 h lag in relation to the reference series. This was accepted as the modeled series shows acceptable high and low values, and a similar frequency to the reference series, despite not being able to model properly the exact time of each value.

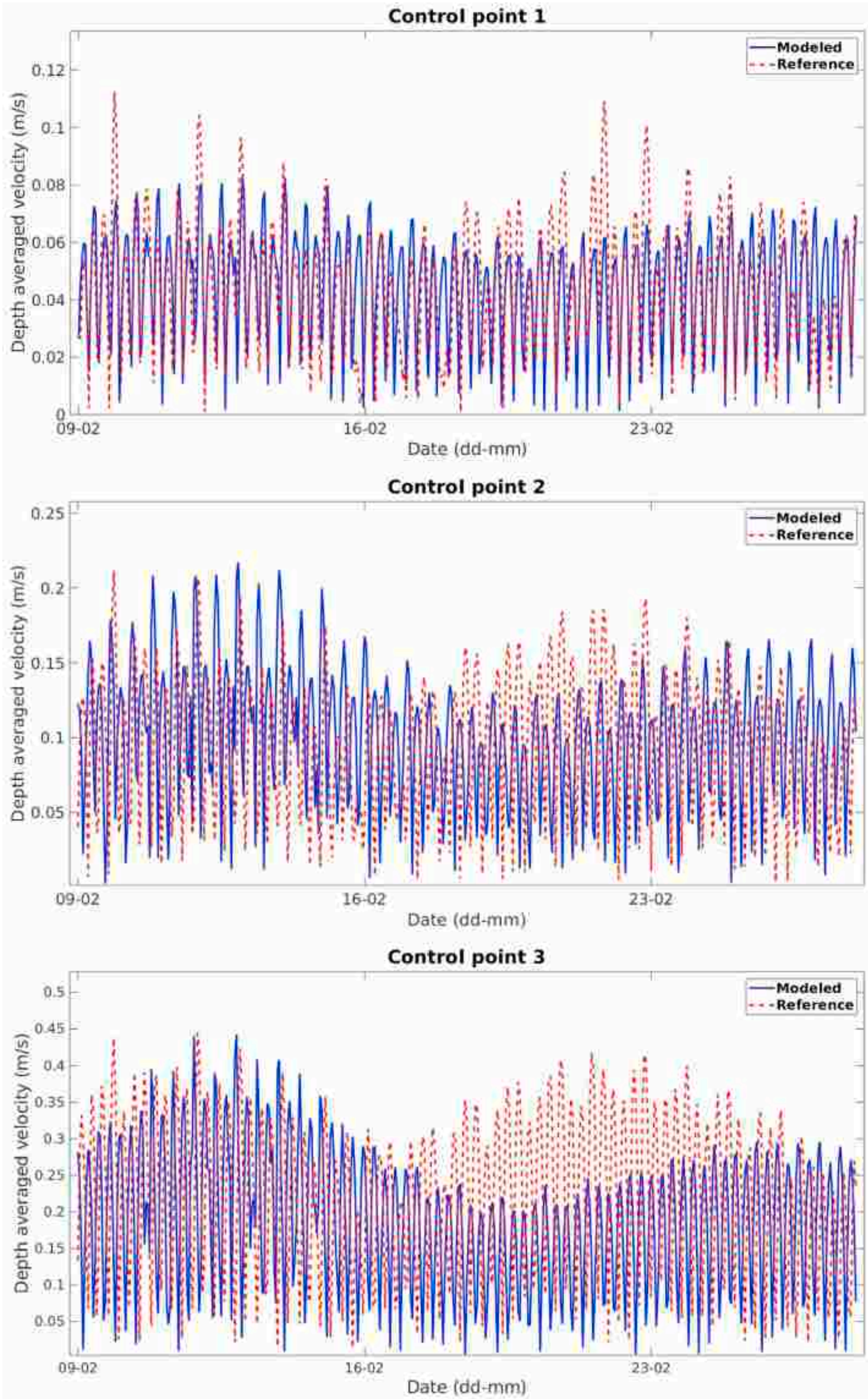

Fig. A1. Current velocity time series. Reference data (discontinuous, red), modeled data (continuous, blue)

Table A1
Numeric quality parameters in hydrodynamic model. Values in control points 2 and 3 are calculated with a lag of 3 h between the reference and modeled series.

Control point	R^2	RMSE (m/s)
1	0.61	0.017
2	0.56	0.039
3	0.56	0.090

The final model was set using the calibrated variables and a critical scenario with regular tidal wave with 3.3 m of amplitude, that corresponded to the 95th percentile of the last 5 years (2016–2020), with a period of 12 h, modeled for 2 days. The wind speed forcing was set to the critical case of 9.3 m/s with a 45° direction, corresponding to the 95th percentile of the critical month (February) in the study site (Gulf of Nicoya). The numerical parameters were maintained to the default values established by the software, and the time step was set to 0.3 min to satisfy the Courant-Freidrichs-Lewy condition.

Appendix B. Wave model validation figures

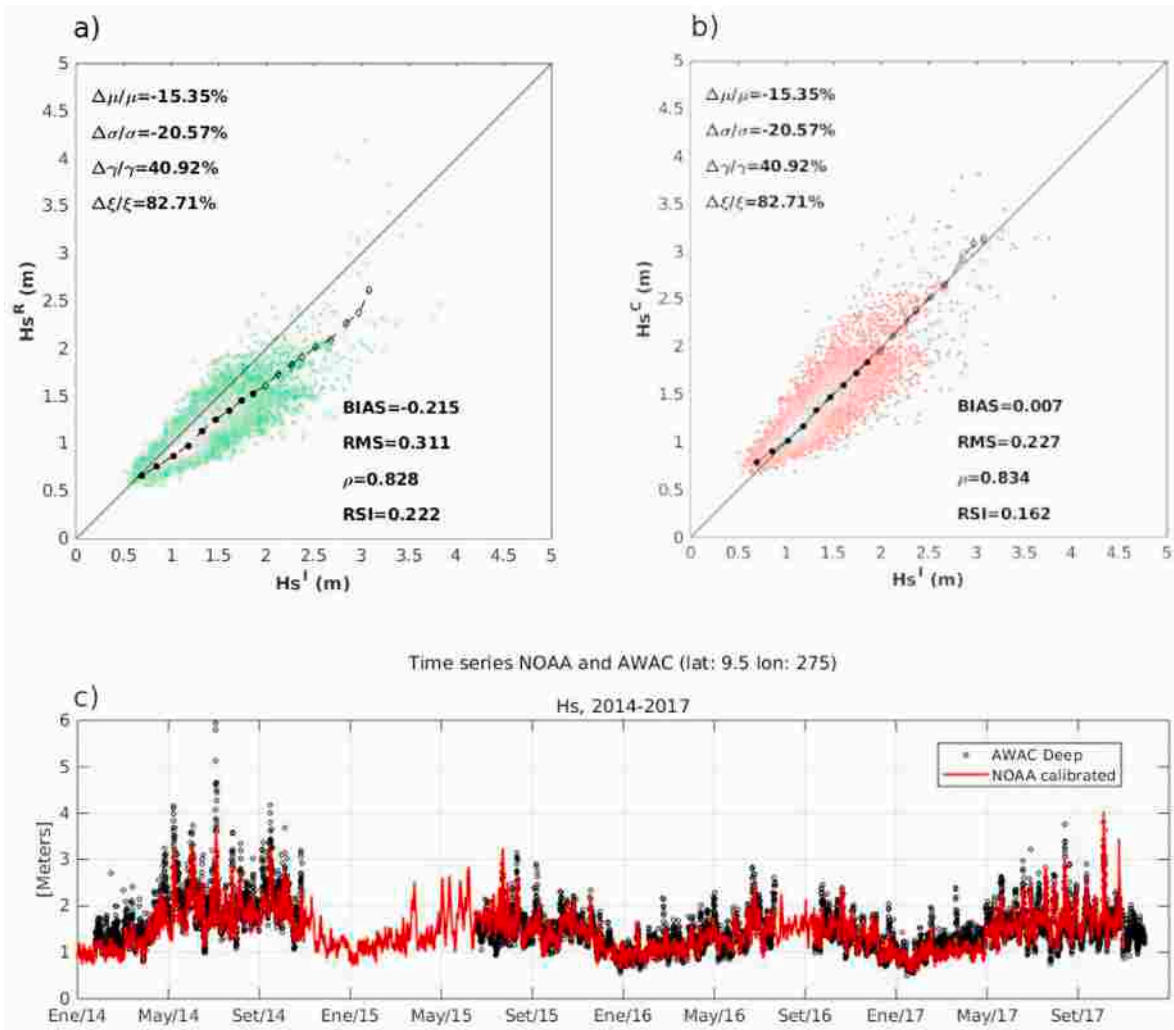

Fig. B1. Quantile-quantile dispersion graphics. a) Reanalysis Hs (Hs^R) vs measured Hs (Hs^I). b) Calibrated Hs (Hs^c) vs measured Hs (Hs^I). c) Hs time series from the WW3 reanalysis (NOAA) and the measured data (AWAC) translated to undefined depth.

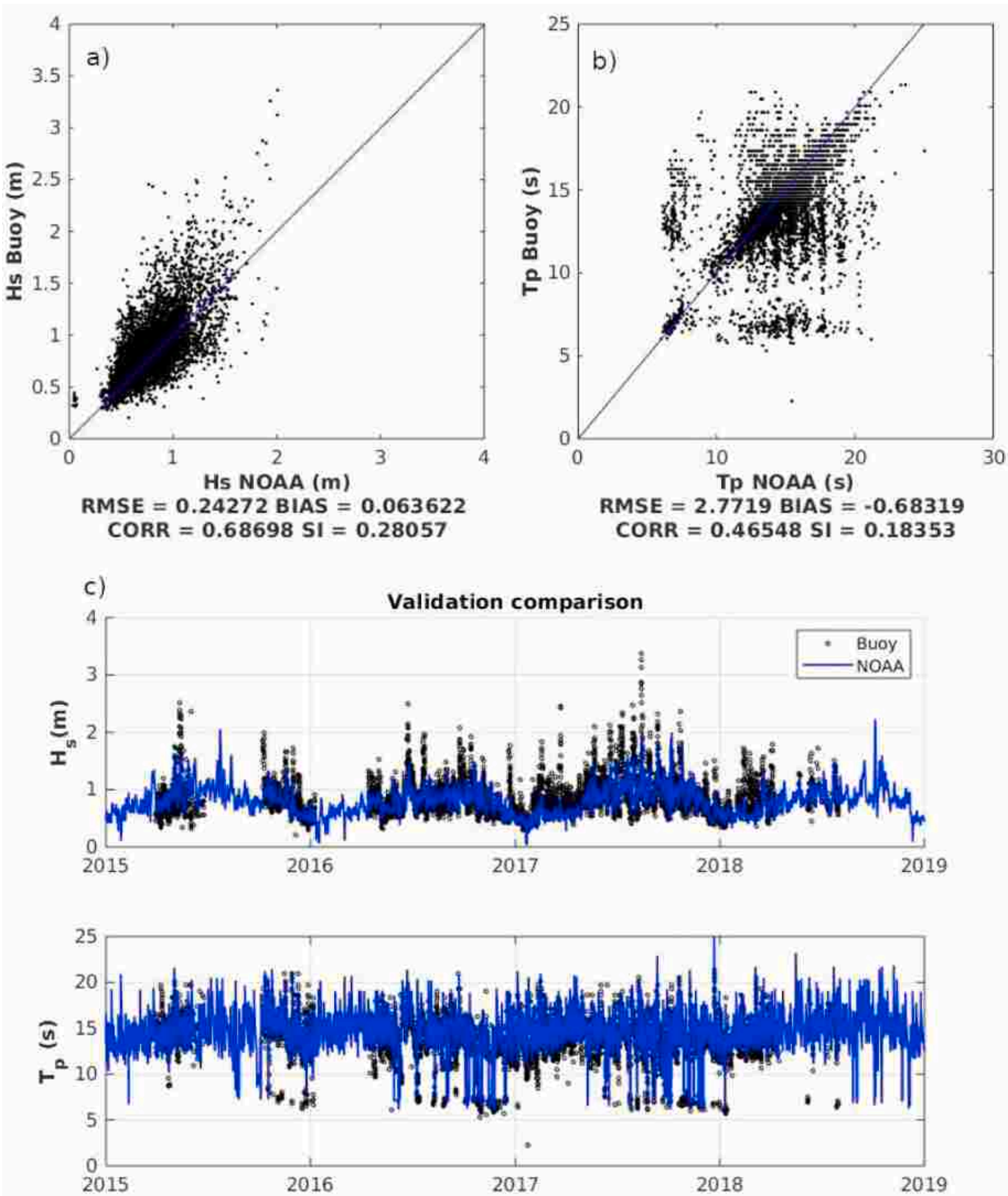

Fig. B2. Validation graphics for waves in Caldera between 2015 and 2019. a) Hs dispersion graphic. b) Tp dispersion graphic. c) Modeled and measured Hs and Tp time series.

Appendix C. marine aquaculture suitability for large and medium scale operations in the study site

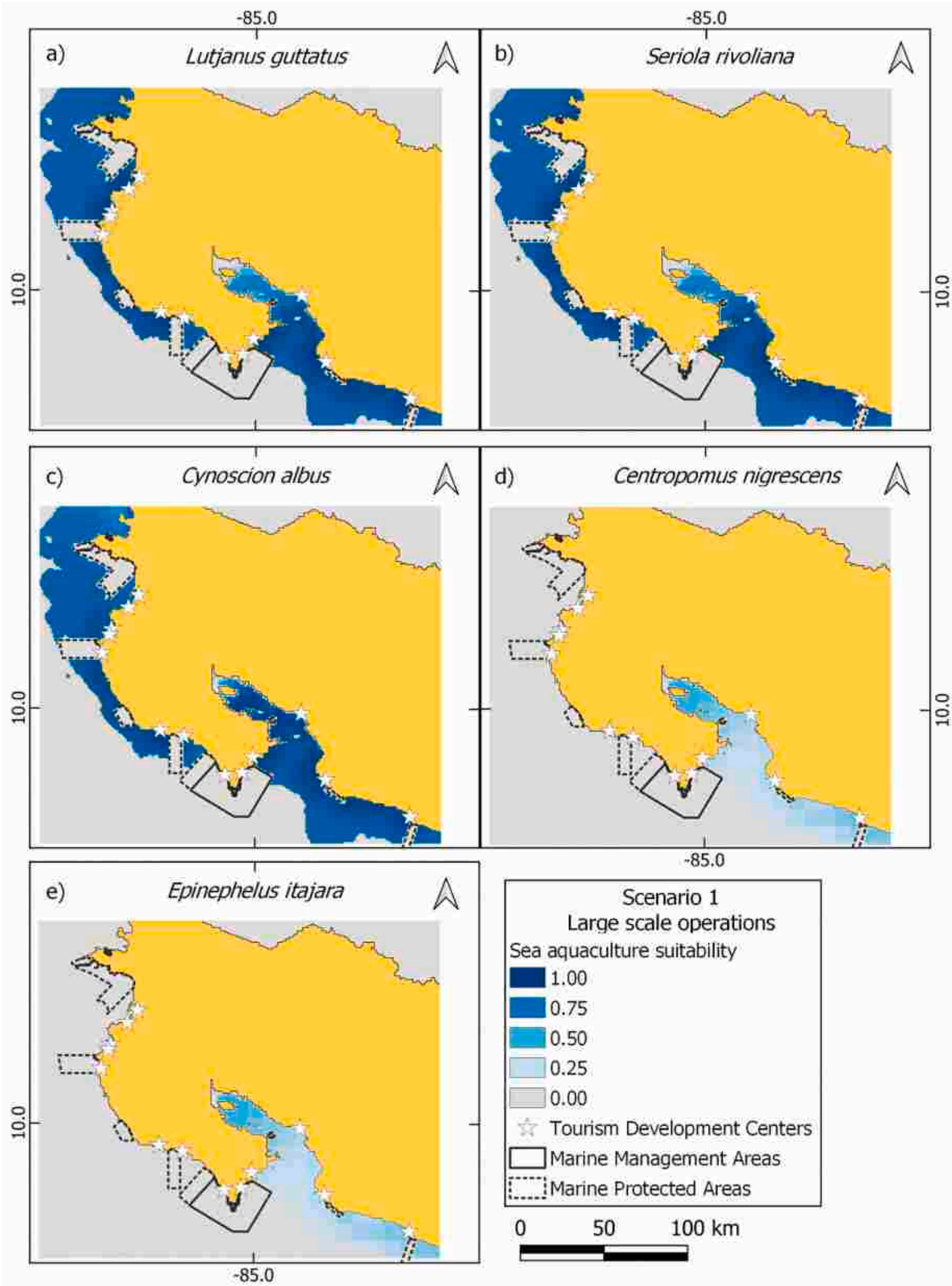

Fig. C1. Marine aquaculture suitability for large scale operations with the five study species. Indicated the Marine Protected Areas and the Marine Management Areas in which it is not allowed to establish large scale operations. Also indicated the tourism development centers.

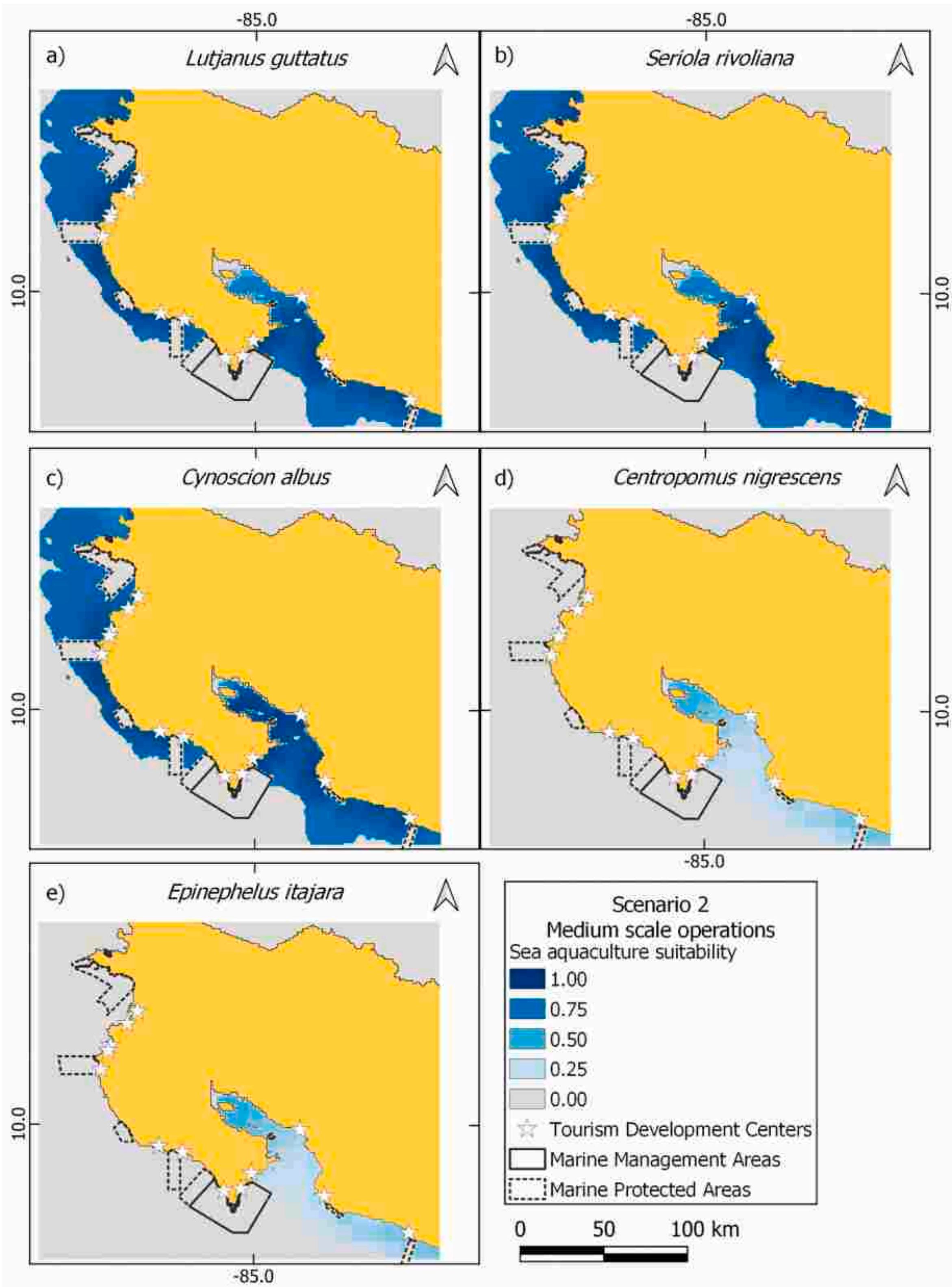

Fig. C2. Marine aquaculture suitability for medium scale operations with the five study species. Indicated the Marine Protected Areas and the Marine Management Areas in which it is not allowed to establish medium scale operations.

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