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IDENTIFYING SUITABLE ZONES TO *KAPPAPHYCUS ALVAREZII* (DOTY) L.M.LIAO FARMING IN DENSELY PORTION OF BRAZIL SOUTHERN COAST

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ABSTRACT

Sampaio, F. M. & Landuci, F. S. (2023). Identifying suitable zones to *Kappaphycus alvarezii* (Doty) L.M.Liao farming in densely portion of Brazil southern coast. Braz. J. Aquat. Sci. Technol. 27(1). eISSN 1983-9057. DOI: 10.14210/bjast.v27n1.19333. Macroalgae aquaculture is growing even though still holds a remarkable potential for innovation, particularly on the development of valuable products. Algae aquaculture rapidly expanded into what currently represents approximately half of global marine aquaculture production landings (51%). In Brazil, seaweed aquaculture is more concentrated on the exotic species *K. alvarezii*, and the rearing areas are restricted to the southern coast of Rio de Janeiro State, northern São Paulo State, and central Santa Catarina State. The southern coast of Rio de Janeiro State, which comprises two socio-economical and geographically important bays: Ilha Grande and Sepetiba, is densely populated with multiple economic activities using coastal environments, where recently algae farming is considered strategic to its socioeconomic development, an alternative to oil-based economy. This study serves as a tool to identify suitable areas for *Kappaphycus* farming in this densely urbanized portion of southern Atlantic. We formulated suitability maps, as a marine spatial planning tool to facilitates decision making, for civil society, managers and investors while providing resources for algae farming sustainable development. Thirty-one maps were generated related to the criteria and constraints that influence their productivity. Individual weights were obtained through the judgment of technicians, researchers, and other stakeholders using the pairwise comparison method. The criteria and weights were combined using the multicriteria decision rules and the suitability map was created derived from reclassifications. Of the total area calculated, 12,88% are areas restricted for cultivation and 87,12% were considered suitable areas. The analyses indicated aquaculture potential for the entire region. Sepetiba Bay has more most suitable areas than Ilha Grande bay. However, the presence of heavy metals in Sepetiba Bay should be taken account when the biomass is for human consump even if it can be used for other purposes. In Ilha Grande bay due to intense use of the coastline and conflicts between existing heavy industries and conservation units, conflicts already overlap areas considered as very appropriate. The results contribute to the construction of a marine spatial planning, which assists producers, decision makers, and social actors in the sustainable development of seaweed farming.

Key Words: Marine Spatial Planning. *Kappaphycus*. GIS.

INTRODUCTION

Macroalgal production is the fastest growing sector in global marine aquaculture generating a total of 35.1 million tone and an value of US$ 1.1 billion in 2020 even though still holds a remarkable potential for innovation, particularly on the development of valuable products and is expected to gain further traction given the increasing perception of algae as healthy and sustainable foodstuffs, particularly in developing markets of western cultures (FAO 2022). Algae aquaculture rapidly expanded into what currently represents approximately half of global marine aquaculture production landings (51%). There is a growing interest in seaweeds, with a particular focus on their potential as a source of nutritious food to feed the growing human population and for the ecosystem services they provide, particularly in reducing greenhouse gas emissions (Vijn et al. 2020). Aquaculture offers numerous social, environmental and economic benefits, and the potential contribution of seaweeds to multiple Sustainable Development Goals – SDGs (e.g. SDG 1, SDG 2, SDG 3, SDG 8, SGD 10, SDG 12, SDG 13 and SDG 14) has been widely recognized, as for example, in the Seaweed Manifesto (Cai et al. 2021).

In Brazil, seaweed aquaculture still remains on a small scale today (Valenti et al. 2021) - is a small economic activity that has an inclusive character and causes a huge social impact (Menezes 2020; Landuci et al. 2021b), more concentrated on the exotic species *K. alvarezii*, which has several uses in the food, feed, pharmaceutical and nutraceutical industries (Campbell & Hotchkiss 2017; Quirino et al. 2020) good nutritional value (Kumar et al. 2014; Khotijah et al. 2020), antioxidant properties (Araújo et al. 2020), anti-inflammatory (Hayashi & Reis 2012), antimicrobial (Deepa et al. 2018; Bhuyar et al. 2019) , immunostimulant and antitumor (Yuan et al. 2011; Rahman & Sathasivam 2015), in addition to its use as a biofertilizer (Gelli et al. 2020) (Gelli et al. 2020), bioremediator (Tresnati et al. 2021) and carbon sequestration (Ulises et al. 2017). Rearing areas are restricted to the southern coast of Rio de Janeiro State, northern São Paulo State, and central Santa Catarina State (IBAMA 2008, 2020).

In the southeastern region of Brazil, Rio de Janeiro state, concentrates the third largest Brazilian population, 6.7 million inhabitants, (IBGE 2021) that comprises more than 600 km of coastline, equivalent to more than 7% of the country's coastline, where, recently algae farming are considered strategic to its socioeconomic development - an alternative to oil based economy (Rio de Janeiro, 2021). An adequate spatial planning for installation before the operation phase is a critical factor for marine aquaculture success (Landuci et al. 2020). RJ southern coast – where *Kappaphycus* farming is legally allowed - is characterized by containing two large, sheltered areas: the Ilha Grande Bay (IGB) and the Sepetiba Bay (BSP), where several activities form the basis of the regional economy, such as tourism, fishing, oil and gas industries, docks, shipyards, and nuclear power plant (Landuci et al. 2021a), and ecosystems have been significantly modified by human activity (Kjerfve et al. 2020).

Thus, to contribute to the development of algae farming in an especially important stretch of the South Atlantic, we formulated suitability maps, as a marine spatial planning tool to facilitates decision making, for civil society, managers and investors while providing resources for algae farming sustainable development.

MATERIAL AND METHODS

Data source

Temperature, salinity, and dissolved oxygen data were obtained from *Instituto Estadual do Ambiente (*INEA), the State Environmental Institute, through a monitoring program at 36 points in the region, for 2 years, and presented as average. The same method was used for the sewage pollution layer. Data obtained through monthly monitoring by INEA, expressed in categories ranging from improper to adequate conditions. The total suspended solids layer was formulated by processing digitization by the heatmap Kernell function of the digitized points of the river mouths existing in the study area. Data from Meteorological Stations of Marambaia (-23.05 S, -43.60 W), Angra dos Reis (-22.98 S, -44.30 W) e Paraty (-23.22 S, -44.73 W) were provided by the National Institute of Meteorology (INMET) and presented as one year average. This included solar radiation transformed to irradiance (μmol photons $m^{-2}.s^{-1}$) by the conversion of hourly solar radiation data ($KJ.m^{-2}$).

The construction of the bottom sediment layer was done with data from the National Geographic Data Bank BNDO/DHN based on kriging. The substrate data were reclassified according to (Falconer et al. 2013). The bathymetry layer was created by interpolation using points digitized through Admiralty charts 1607, 1620, 1633 and 1634 with scales from 1:40,075 to 1:120,000, produced by the national hydrographic authority of Brazil, Directorate of Hydrography and Navigation (DHN) of the Navy.

The generation of the layers related to wind and waves were based on the methodology described by Falconer et al. (2013) and the average wind speeds were recorded over a 3-month period at the Marambaia Station of the National Institute of Meteorology (INMET). The images of the layers were overlaid, and the arithmetic mean was calculated resulting in a final image with the value of the maximum potential, which served as a control point in the fuzzy reclassification process. The marine current velocity layer was created using the modeling system developed by the Marine and Environmental Technology Research Center (MARETEC). The validation procedure was performed using data from three tide gauges located at different points in the study area and computing statistical parameters according to (Willmott 1981).

The distance criteria layers (supporting infrastructure, young forms, technical support, labor, processing industry) were performed using Euclidean distance by means of points digitized on high resolution images in QGIS. To be considered an onshore facility, the site must be able to receive and unload fully loaded supply trucks so locations with adequate docks and access roads were considered. A road layer was created using the network road map (scale 1:500,000) provided by the National Department of Infrastructure and Transportation (DNIT), the national infrastructure and transportation agency. The map of the Human Development Index layer was created based on the describe in (Landuci et al. 2020).

We included all restrictions found in the current legislation for coastal zoning (INEA 2015a). The prohibited marine algaculture activities include the distance of 50 m from rocky coasts, 200 meters from the beach (IBAMA 2008), 1.5 m of minimum depth (INEA 2015a), and within environmental protection areas, as well as in navigation channels, mooring areas, and areas for military purposes. The Boolean method was used to obtain a single map of the restrictions layer.

Modelling suitable areas Data source

For the selection of suitable sites for *Kappaphycus alvarezii* culture along the southern RJ coast (Figure 1), we chose thirty-one criteria, considering their importance to the activity and their use in other GIS-Multi-Criteria Decision Analysis (MCDA) applications undertaken to identify suitable sites for aquaculture. In summary, the choice of criteria was made based on similar studies throughout the literature, personal consultations held with experienced experts including stakeholders, scientists and decision makers

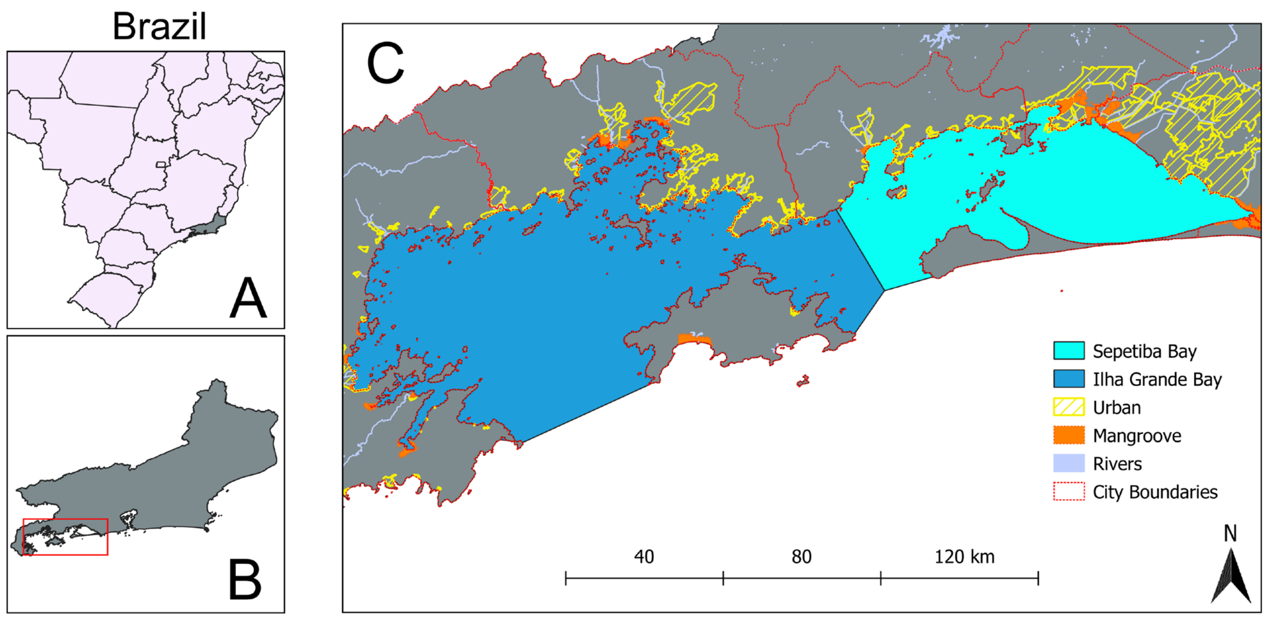

Figure 1 – A) Limits of the Brazilian states and in highlight the State of Rio de Janeiro. B) State of Rio de Janeiro and in cutout the area of Sepetiba Bay and Ilha Grande Bay. C) Highlight the limits between Sepetiba Bay and Ilha Grande Bay.

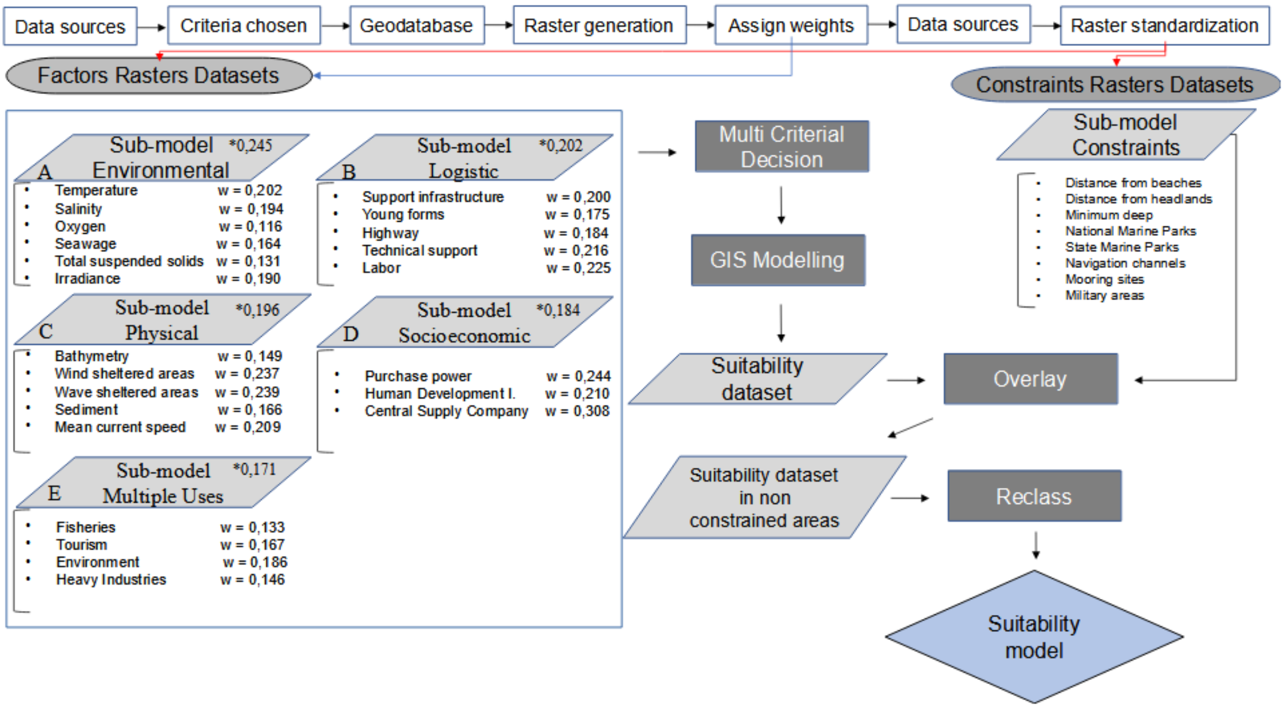

Figure 2 – Conceptual GIS model framework for providing decision support for *K. alvarezii* farming w = weights; * Consistency Index.

coordinated by the authors as well as current coastal aquaculture regulations. The model was built based on Multi-Criteria Evaluation (MCE) (Figure 2), a flexible and transparent methodology as explained by Landuci et al. (2021a) using both available geographic data and the preferences of decision makers, to identify a potential location for algae farming.

For each criterion (Table 1), a layer was created to represent its distribution based on the methodologies brought to light by the scientific community (Willmott 1981; Miranda et al. 2002; Falconer et al. 2013) in addition to the data obtained directly from the competent agencies, holders of more reliable national and international public information in addition to those - Brazilian Institute of Geography and Statistics (IBGE), National Department of Infrastructure and Transportation (DNIT), National Institute of Meteorology (INMET), State Institute of Environment (INEA), Directorate of Hydrography and Navigation (DHN), National Oceanographic Data Bank (BNDO/DHN).

Table 1 – Criteria descriptor, data range, raster source, Fuzzy reclass, control points and control points sources of criteria.

Description of criteria	Data range	Data source	Raster Operation	Fuzzy reclass	Control Point	CP source	Weight
Submodel Environmental (0.245)							
Temperature (°C)	22 - 28	1	Krg	Sig Incr	22;32	a;b;c	0.202
Salinity (mg/L)	15 - 35	1	Krg	Sig Incr	20;35	c; d	0.194
Dissolved oxygen (mg/L)	6.5 - 8.5	1	Krg	Sig Incr	5;8	e	0.116
Sewage pollution (class)	1 - 4	2	Krg	Sig Incr	1;4	f	0.164
Total Suspended Solids (mg.L)	2.7 - 261	1	Krg	Sig Incr	0,máx	j	0.130
Irradiance (micromolar)	0 - 1300	1	Krg	Sig Incr	0,máx	-	0.190
Submodel Logistic (0.202)							
Support Infrastructure (km)	0 - 32.5	3	Dist	Lin Decr	0;máx	-	0.200
Plantlets (km)	0 - 69.2	3	Dist	Lin Decr	0;máx	-	0.175
Distance from highways (km)	0 - 32	3	Dist	Lin Decr	0;máx	-	0.184
Technical support (km)	0 - 70	3	Dist	Lin Decr	0;máx	-	0.216
Skilled labor (km)	0 - 22	3	Dist	Lin Decr	0;máx	-	0.225
Submodel Physical (0.196)							
Depth (m)	1.5 - 50	5	N-itrpl	Sig Sym	0;máx	g;h	0.149
Areas sheltered from winds (km)	0 - 27.5	6	USGS	Lin Decr	0;máx	i	0.237
Areas sheltered from waves (m)	0 - 2.3	6	USGS	Lin Decr	0;máx	i	0.239
Substrate type (class)	1 - 4	7	N-itrpl/Recls	Sig Sym	1;2;3;4	i	0,.66
Speed of marine currents (cm/s)	0 - 98	8	MHID	Sig Sym	0;10;20;100	b	0.209
Submodel Socioeconomic (0.184)							
Purchasing power (pts10³)	0 - 256.3	9	M-Op/Dist/Recls	Lin Decr	0;1	f	0.244
HDI (pts10³)	0 - 905.5	10	M-Op/Dist/Recls	Lin Decr	0;1	f	0.210
Processing industry (km)	34.4 - 160.7	3	Dist	Lin Decr	0;máx	-	0.308
Submodel Multiple Uses (0.171)							
Fishing activities (km)	0 - 55	3;11	Dist	Lin Decr	0;máx	-	0.133
Tourism activities (km)	0 - 39.2	3;11	Dist	Lin Decr	0;máx	-	0.167
Environmental preservation units (km)	0 - 72.1	3;12	Dist	Lin Decr	0;máx	-	0.186
High impact industry (km)	0 - 61.6	3	Dist	Lin Decr	0;máx	-	0.146
Submodel Constraints							
Distance from beaches (m)	0 - 200	14	Bool	-	-	-	-
Distance from rocky shore (m)	0 - 50	14	Bool	-	-	-	-
Navigation channels	-	5	Bool	-	-	-	-
Military areas	-	5	Bool	-	-	-	-
Docking areas	-	5	Bool	-	-	-	-
Federal Marine Parks	-	12	Bool	-	-	-	-
State Marine Parks	-	13	Bool	-	-	-	-
Minimum Depth	1.5	14	Bool	-	-	-	-

Note 1: (a) (Bulboa & de Paula 2005); (b) (Nursidi et al. 2017); (c) (Simatupang et al. 2021); (d) (Reis et al. 2011); (e) (Benetti et al. 2010); (f) (CONAMA 2005); (g) (da Silva Filho 2015); (h) (Granbom et al. 2002); (I) (Brazil Federal Government 2004); (j) (Stigebrandt 2011; Falconer et al. 2013); (k) (Stigebrandt 2011); 1—bi-monthly surveillance of environmental monitoring program of Rio de Janeiro Environmental Institute (INEA); 2—monthly coliform monitoring program of INEA; 3—Point digitalization over high-resolution image (3.2m); 4—National Department of Transit Infrastructure (DNIT) official roadmaps; 5—nautical charts (1607, 1620, 1633 and 1634), provided by the Hydrography Center of Brazilian Navy; 6— Marambaia Metereological Station (Latitude: −23.050334° Longitude: −43.595685) of the National Meteorology Institute (INMET); 7— National Bank of Oceanographic Data (BNDO/CHN); 8—Three-dimensional water modelling system MOHID; 9—Gross domestic product from RJ state provided by Rio de Janeiro State Center of Statics (CEPERJ 2015); 10—Brazilian Human Development Atlas 2013 from United Nations Development Program (PNUD, IPEA & FJP 2012); 11—Diagnosis of the Coastal Sector of the Bay of Ilha Grande (INEA 2015b); 12—Tamoios Ecological Station area provided by Chico Mendes Institute for Biodiversity and Conservation (ICMBio); 13—Aventureiro State Marine Park area provided by INEA; 14—Standart Operation Norm 32/205 (INEA 2015a). KRG = Krigging; Dist = Euclidean Distance; N-itrpl = Neighbourhood interpolation; USGS = USGS Wind Fetch and Wave model; MHID = MOHID hydrodynamic model; M-Op = Mathematical operation; Recls = Reclassification; Bool = Boolean operation.

These criteria were distributed in two groups (Factors and Constraints) and framed in hierarchical structures that subdivided all criteria into submodels. Within the factors are the environmental submodels with the criteria temperature, salinity, dissolved oxygen, sewage pollution, total suspended solids and irradiance; logistical submodel with the criteria support-infrastructure, plantlets, road network, technical support and manpower; physical submodel including depth, wind sheltered areas, wave sheltered areas, sediment type and speed of marine currents; socio-economic sub-model with purchasing power, Human Development Index, processing industry; the multiple use sub-model including shared use with fisheries, shared use with tourism, shared use with preservation, and high impact industry; finally, constraints sub-model, distance from beaches, distance from rocky coast, minimum depths, distance from marine national parks, navigation channels, distance from quays and military areas.

Spatial data representing each of the criteria were organized, processed, and overlaid on images. Since the criteria contain ordinal values, the layers were standardized, using a linear or sigmoidal fuzzy function, into a continuous function from 0 to 1, where 0 represents the least suitable and 1 the most suitable. Reclassification control points were defined for each criterion, according to the parameters suggested in the literature review. Figure 2 summarizes the arrangement and processing, data source and layer generation methods for these criteria, some represent primary data and others, resulted from data modeling. To obtain weights for the model, questionnaires were used to find the best judgment of decision makers. Peer judgment, a comparison method of the analytic hierarchy process is a practical and useful method to assist in decision making, which ensures consistency across all options considered, in which attributes are ranked against each other to assess their relative importance and has been used in recent decades in many applications related to multi-criteria decision making (Shih 2017).

The use of questionnaire results can synthesize the views of different people who have different roles and perform activities at various levels (e.g. policy makers; government planners; scientists; farmers, private industry representatives, and local authorities). The questionnaires also provided the opportunity to assess distinct preferences, which result in more realistic assessments of local scenarios (Landuci et al. 2020). To answer the questionnaires, experts in fields such as engineering, fisheries science, livestock, biology, environmental science, economics and decision makers in natural resource and fisheries management, research institutions, government agencies; related to aquaculture, marine services and farmers were invited to contribute their assessment for the weight to be assigned to each criterion and submodels.

For the Hierarchical Criteria Analysis, it is strictly necessary that the decision makers are consistent in the process of peer comparison and judgment. Therefore, to define the acceptable value for this inconsistency (Table 2), a consistency ratio (CR) was calculated by comparing the index consistency (IC) of the matrix in question to an index random consistency, or RI (Francisco et al. 2019). As suggested by Saaty (1994) for satisfactory consistency of the data, the result of the CR must be < 0.10% or 10%, a value which indicates the reliability of the specialists judgement; if the CR result is higher than 0.10, there will be inconsistencies, and the Analytic Hierarchy Process (AHP) method will not produce significant results a condition met by all criteria and models evaluated. All models had consistency index and ratio < 0.1 (Table 2) suggesting that the criteria's weights of pair-wise comparisons were acceptable.

Table 2 – Weights, Consistency Index (CI) and Consistency Ratio (CR) of Analytic Hierarchy Process (AHP) from sub-models.

Sub-models	Weight	C.I.	C.R.
Environmental	0.245	0.022	0.017
Logistic	0.202	0.002	0.002
Physical	0.196	0.014	0.012
Socioeconomic	0.184	0.003	0.002
Multiple Uses	0.171	0.035	0.033

For data preparation, processing and model development, the present study used IDRISI Selva GIS software (Clarks Labs) and QGIS v3.24.1 (QGIS Develop ment Team, QGIS Geographic Information System, Open-Source Geospatial Foundation Project). All component models were converted to the UTM-23 S Datum Sirgas 2000 georeferencing system at 30 m resolution prior to analysis. For site-specific features, elements of interest were marked on high-resolution imagery using Plug-in HCMGIS (version 2.7.28) map service with Google Satellite. All maps are presented at a regional scale of 1:1,850,000.

Spatial data representing each one a single criterion from different sources were organized, processed and overlaid in mask images. Figure 3 shows all criteria and Figure 4 Presents constraints. The environmental (ENV), logistical (LOG), infrastructure (INF), physical (PHY), socioeconomic (MKT), and multiple uses (MUL) submodels had their importance weights (w) also combined in MCE process, producing a final suitability map and the constraint submodel was overlaid on it (Figure 5), subsequently reclassified into five suitability classes (< 0.2; 0.2 - 0.4; 0.4 - 0.6; 0.6 - 0.8; > 0.8) used by (Landuci et al. 2020) and equally distributed considering the range from 0 to 1, from least suitable to most suitable.

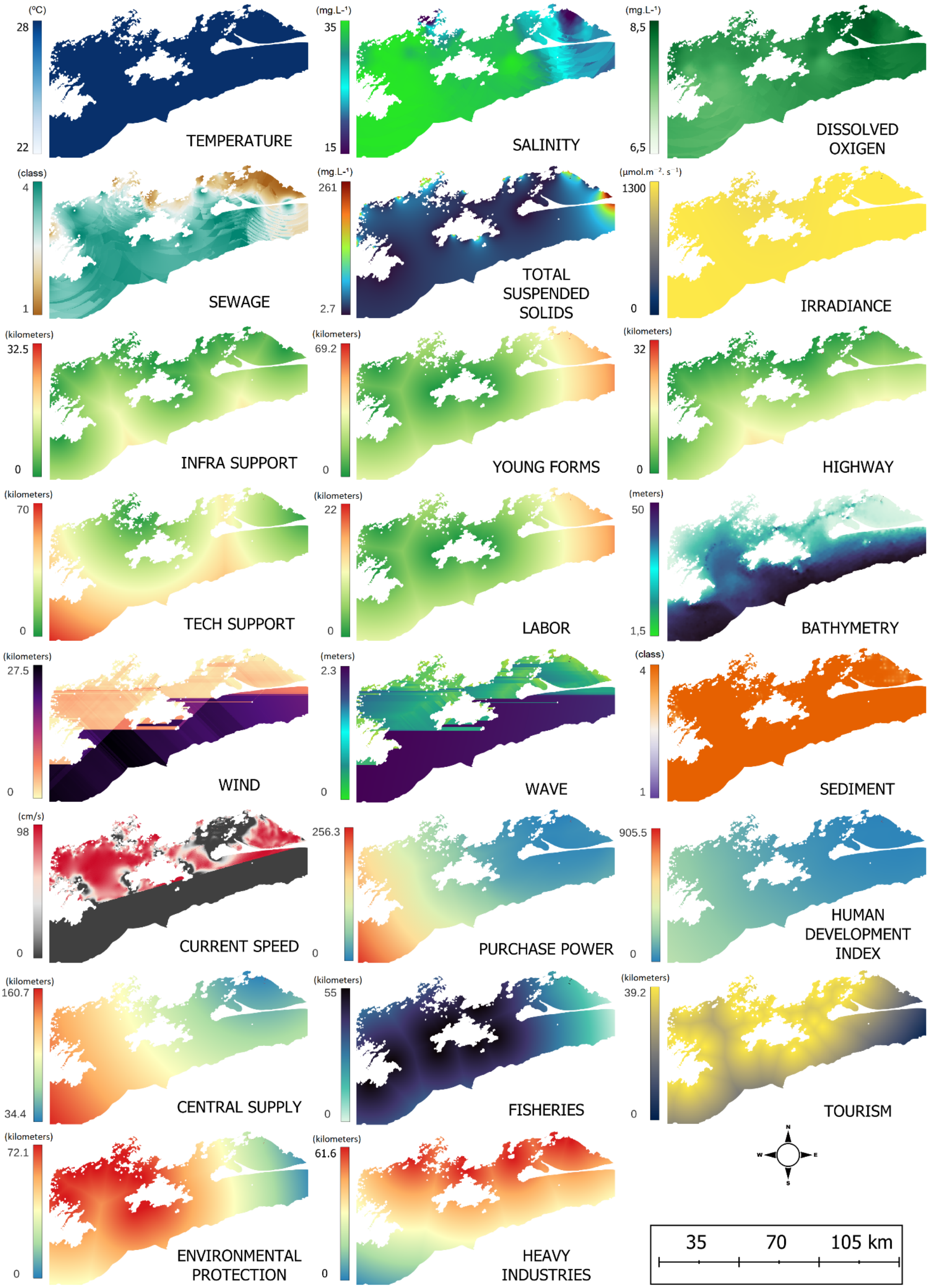

Figure 3 – Spatial distribution of criteria and its value ranges.

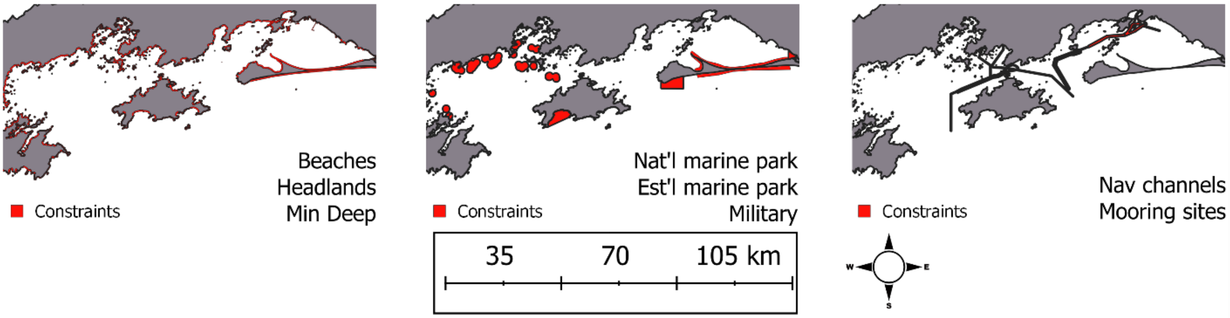

Figure 4 – Constraints model.

RESULTS

In general, the submodels value assignments were close, indicating that there was not a predominance for a single sub model in the final suitability map (Table 2). Among the submodels, the highest weight assign was for environmental, follow by logistical, physical, socioeconomic and multiple uses. Among the criteria, the processing industry (w = 0,308) and purchasing power (0.244) received the highest weights followed by wind sheltered areas, wave sheltered areas, labour, and technical support.

On the environmental submodel (0.245) the spatial distribution of suitable areas was most influenced by the salinity and sewage pollution criteria. Sewage pollution negatively influenced the whole BSP and the IGB region was worse near urban centers and at the mouth of the Bracuí River. The most suitable areas in this submodel were near the sandbank of Marambaia (BSP) and near Barra Grande, Taquari and Itarituba (IGB). The highest dissolved oxygen values are in Sepetiba Bay, between the islands of Itacuruçá and Jaguanum. Since this criterion after fuzzy reclassification, had homogeneous distribution, it did not influence the submodel. No unsuitable areas were identified in this submodel.

The logistic submodel received the second highest weight (0,202) and represents the cost and risk assessment when considering a sea farm. The spatial distribution of suitable areas was most influenced by the criteria support infrastructure, follow by technical support, and labor. The IGB region was positively influenced by these aforementioned factors. In the BSP the criteria young forms and labor influenced negatively this submodel.

The physical submodel had a similar weight (0,196) compared to the logistics. The spatial distribution of suitable areas based on the physical submodel was most influenced by the criteria wind speed, wave height and current speed. In IGB, the criterion that influenced negatively was wave height and in BSP the criterion current speed influenced positively, water needs nutrients and needs to stay in the crop structure relatively stable. To represent areas most likely to achieve commercial success, with better access to consumers, the socioeconomic submodel received the fourth lowest weight (0,184). The spatial distribution of suitable areas based on the socioeconomic submodel was most influenced by the purchasing power and processing industry criteria. In IGB, the criteria that influenced negatively were purchasing power and processing industry; and in BSP, the criteria purchasing power, HDI and processing industry influenced positively, being considered fully suitable.

The multiple uses submodel received the lowest weight (0,171). The spatial distribution of suitable areas based on the multiple use submodel was influenced by all criteria. The multiple use submodel represented the possible conflicts and synergies between marine aquaculture and other activities in the coastal zone. It is a challenge to find suitable sites in many coastal areas that do not conflict with pre-existing uses that may be considered more socio-economically significant to the region. In the IGB, the developments and preservation sites have a lot of influence, this region was considered unsuitable for development and in the BSP, the criterion that had a positive impact was the distance with environmental preservation areas.

The spatial distribution of restrictive areas was presented (Figure 4 and Table 3). Of the 424,448 hectares of total area analysed for implementation of *K. alvarezii* culture structures, 54,000 hectares (12,88 %) are restricted sites, thus resulting in 369,785 ha of areas suitable for installation. The restriction layer includes restricted areas under current state and federal legislation, navigation channels, anchorages, and installation areas that are restricted areas imposed by Brazilian Legislation Waterway Safety Regulatory Authority (Brazil Federal Government 1998). Anchoring is not allowed in these areas, making them off limits for aquaculture. The Brazilian environmental legislation defines marine protected areas that can be restrictive or prohibitive. In the study area, there were two different types of marine protected areas, areas that prohibit landing, diving, fishing, anchoring and construction and

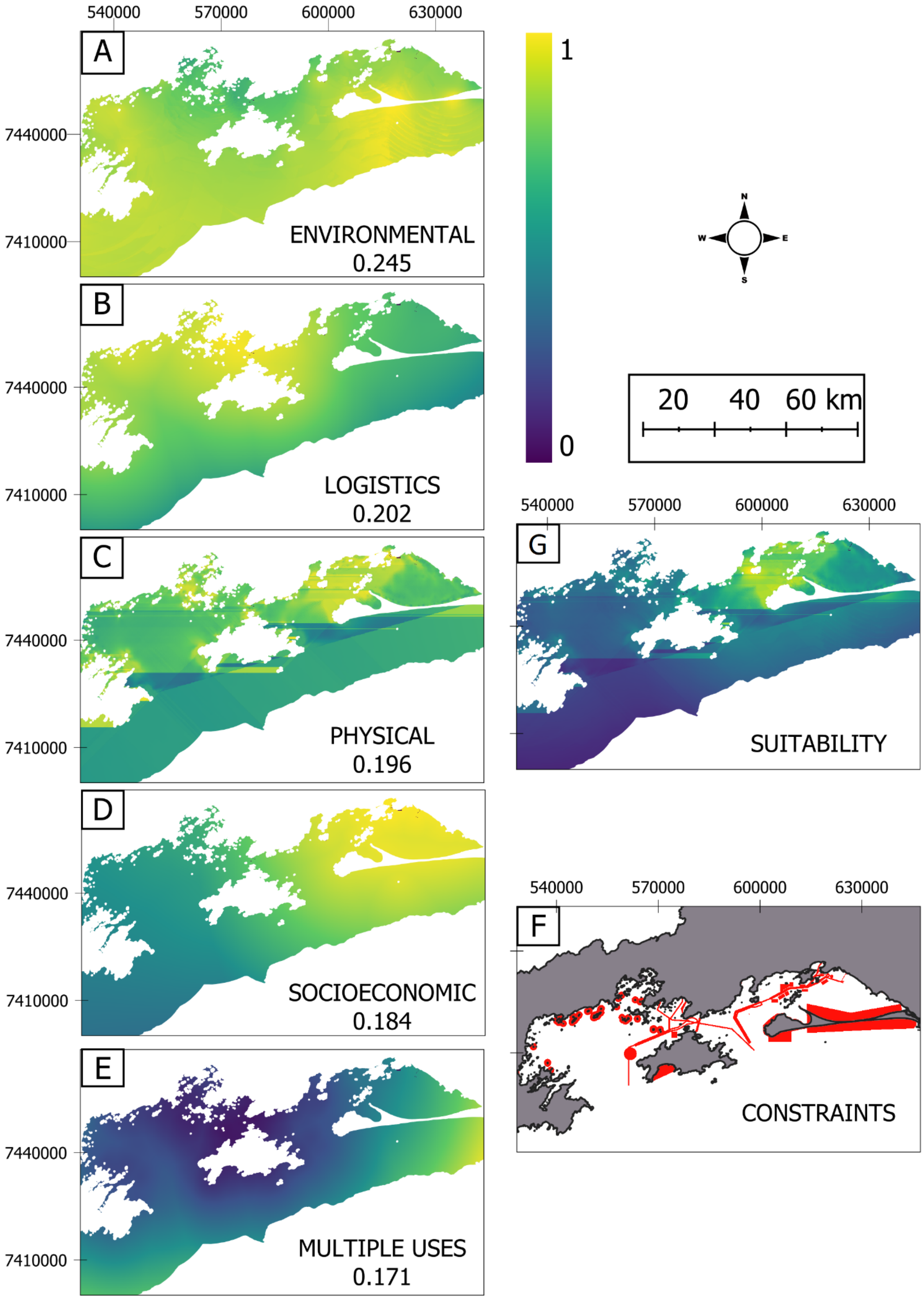

Figure 5 – Output map from submodels. (A) Environmental; (B) Logistic; (C) Physical; (D) Socioeconomic; (E) Multiple uses; (F) Constraints; (G) suitability model.

Table 3 – Total area (ha) for each bay in each class.

Suitability	BSP	Total %	IGB	Total %	Total per category	Total %
Constraints	31947	7,53	22716	5,35	54663	12.88
Unsuitable	25	0,01	384	0,09	409	0.10
Reasonably suitable	0	0,00	85232	20,08	85232	20.08
Suitable	34799	8,20	108476	25,56	143275	33.76
Very suitable	70686	16,65	52470	12,36	123156	29.02
Extremely suitable	17540	4,13	173	0,04	17713	4.17
		Total area (ha)			424448	100

prohibit the implementation of activities that can damage, pollute or degrade an ecosystem. These areas have additional rights and conditions based on environmental legislation, so areas within their perimeters were excluded.

For the composition of the final model (Figure 6), the environmental submodel had low impact on the two bays. The logistical submodel negatively influenced most of the IGB and BSP, with the region near Angra dos Reis being considered adequate. The physical submodel showed suitability only for the coast of the Mangaratiba municipality and the other areas were considered less suitable. The socio-economic sub-model had positive influence in the BSP region and negative influence in the IGB region. In the multiple uses submodel, the whole region of the IGB and BSP was considered of low potential.

Table 3 presents the values of the areas in hectares of each category of importance. With a total area (369,785ha) where 33,19% are considered as very suitable areas (class 0,6 to 0,8) or extremely suitable areas (class 0,8 to 1,0). In the BSP, 20,78% of the total areas are considered as very suitable areas (class 0,6 to 0,8) or extremely suitable areas (class 0,8 to 1,0), the main constraints were navigation channels and mooring sites. The extremely suitable areas were observed between the Castilho Beach region to Madeira Island, from Jaguanum Island to the restinga of Marambaia, where Sino Beach is located. Other suitable areas were observed east of Itacuruçá Island, Sepetiba and Pedra de Guaratiba, besides the region between restinga da Marambaia to Ilha Grande.

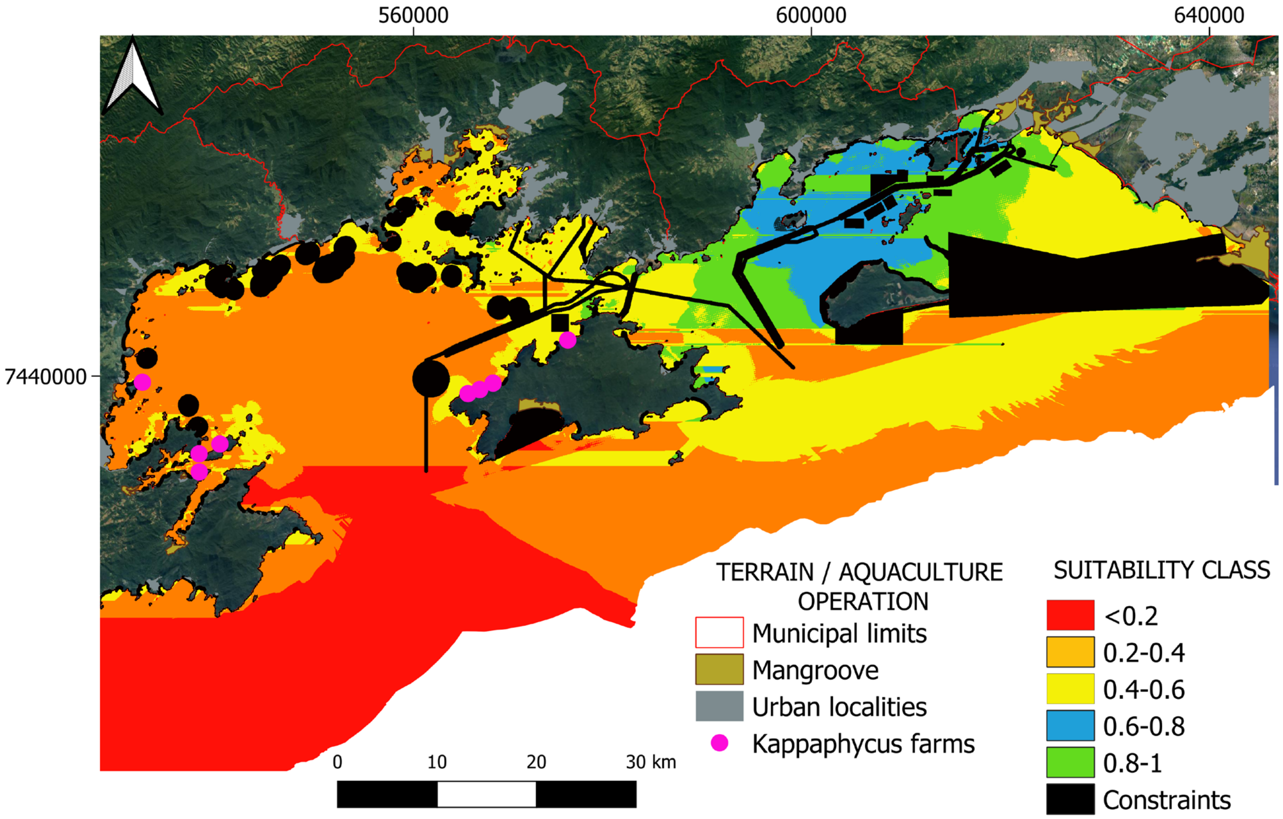

Figure 6 – Final output suitability map and total areas available. Different numbers and colours indicate different potential classes. Diagonal patterns areas are considered to be offshore aquaculture. Pink circles represents existing *K. alvarezii* farms.

The IGB presents 12,4% of the areas considered as very suitable areas (class 0,6 to 0,8) or extremely suitable areas (class 0,8 to 1,0). In IGB is where the largest environmental protected areas are concentrated and the presence of conservation units overlaps in areas considered as very suitable areas or extremely suitable areas, which eventually reduces these. Extremely suitable areas were observed east of Ilha Grande, near Ilha das Palmas. Very suitable areas extend from Praia do Sono on Ilha Grande, continuing along Praia do Abrahão towards the continent, near Jacuecanga, Angra dos Reis and Ilha Comprida do Boqueirão.

DISCUSSION

Site selection requires geographically related data and information with multiple viable alternatives. However, these alternatives are often conflicting and involve incompatible evaluation criteria. The suitability of a site can change over time, so it is important to consider short- and long-term issues that may affect a site overestimating or underestimating site availability (Landuci et al. 2020).

Analysis of time-series data can provide valuable information for both present day and future planning and management for the sector, this stresses the importance of incorporating seasonal measurements and infrequent events and extreme conditions, where possible, into site suitability studies (Falconer et al. 2013). Although in this study the data, especially from the environmental model, is presented in the form of a measure of central tendency, it originates from the average of the data obtained over a 2-year monitoring period as explained in the Material and Methods section.

Likewise, acquiring data of an adequate resolution for the study is also an important consideration and often a challenge. There usually is a fairly close correlation between data resolution and extent of geographic coverage and data requirements for Decision Suport System expand with the scale of the aquaculture operation (Aguilar-Manjarrez & Kapetsky 2007). Although some of the spatial databases used in this study, especially those not obtained by digitizing features directly from HCMGis images, are not structured in high resolution, they remain as the most reliable data available at regional and national level.

The questionnaire was created digitally to have access to the most diverse actors of society linked to the cultivation of marine macroalgae, in an easy and fast way to be answered. Even so there was difficulty in obtaining the response by experts and the general public, although renowned national researchers in the area of marine aquaculture contributed to the study.

Weighting can be subjective. The use of expert opinion to help assign weights can be an advantage but it must also be noted that experts with different backgrounds and agendas may have differing views on the weights (Nath et al. 2000). Usually, many individuals (i.e. managers, decision makers or interest groups) evaluate alternatives, characterized by their unique preferences concerning the relative importance of the evaluation criteria (Pérez et al. 2005). This can lead to conflict over model development and uncertainty in the final results. To ensure meaningful results and no inconsistencies in peer review, a necessary condition for the Analytical Hierarchy Process, we calculated and ensure the condition of Consistency Index and Consistency Ratio as explained above.

The ideal growth conditions for most Brazilian species are between 22 and 28°C and salinity between 28 and 36 ppm, although other species are more tolerant (Oliveira 1997). Temperature and irradiance registered in Sepetiba and Ilha Grande Bay were within the range considered suitable for *K. alvarezii* farming, 24-28ºC (Doty et al. 1987; Glenn & Doty 1990; Hurtado et al. 2001; Ask & Azanza 2002; Granbom et al. 2002; Paula & Pereira 2003; Munoz et al. 2004). Depending on the temperature, the crop may produce more or less, which influences the supply/demand and consequently the commercialization price (dos Santos & Hayashi 2022). There is also a positive correlation between algae growth and the availability of light for its growth (Guan et al. 2013; Lideman et al. 2013). Terada et al. (2016) demonstrated that irradiance associated with temperature, is one of the main factors stimulating or inhibiting photosynthesizing activity and growth for *K. alvarezii.*

The sewage pollution concentration map indicates that the coastline, from the municipality of Rio de Janeiro to Angra dos Reis, including almost the entire Sepetiba Bay, presents low suitability for seaweed cultivation. The population concentration in the region has been intensifying and several industries with high environmental impact are located, mainly in the western part of Sepetiba Bay, in the municipalities of Rio de Janeiro and Itaguaí, also contributing to the intensification of the circulation of oil and mining vessels. Most of these corporations basically boil down to the first sector of the Brazilian economy, farming and mining (Rocha et al. 2010, 2012; Gonçalves et al. 2020). According to the responses, total suspended solids, were not a crucial factor to seaweed cultivation. The existing cultures in the Bay of Ilha Grande are floating rafts which leaves the algae as close to the surface or centimeters below it, where theoretically there is no influence of solids on water turbidity (de Góes & Reis 2012; Nogueira & Henriques

2020), however areas with greater proximity to rivers, should be evaluated with caution since dozens of rivers flow into the area studied (Kjerfve et al. 2020).

When evaluating a site, infrastructure support and logistics are the first and foremost aspects to consider. A lack of proper infrastructure resources around aquaculture facilities could increase costs and cause an initiative to fail (Landuci et al. 2020). To ensure that the growing structures are located properly is critical to sustain the operation and provides a high level of security for the operators. The support infrastructure (proximity to piers, marinas and docks) is important for the production flow. In same manner proximity to established farms where it is possible to obtaining clones was a positive factor in the Bay of Ilha Grande because there are at least four seaweed farms. The central area of the IGB is home to several *K. alvarezii* cultivars, both experimental and commercial and the use of certified algae is a legal prerequisite for the activity in Brazil. The logistics of the production flow is linked to the existence of a quality road network, and so it is in the region. There are federal highways connecting the coastal region to the ports and airports, which also give access to urban centers where processing industries are installed. Large-scale commercial deployment of a seaweed cultivation also depends on skilled labor, equipment, drying, transportation, and water availability (Nogueira & Henriques 2020). Thus, areas closer to certain inputs or services represent a strategic, logistical, and economic advantage. IGB has an extension of the Rio-Santos highway, and at a shorter distance from its coastline. It also has a greater number of local maritime supports, compared to Sepetiba Bay. and more probability to had qualified labor which is important for the venture success since the proximity of the crops and workers with experience represent a gain in productivity (Marroig & Reis 2016) and a reduction in travel costs.

Physical characteristics of the site are crucial to success or failure of algae farming. Hydrodynamism is important for culture because it moves the water that will bring nutrients, enables dominance by certain organisms which reduced *K. alvarezii* (Hurtado et al. 2008; Vairappan et al. 2008; Marroig & Reis 2016). Water movement caused by meteorological changes (Castelar et al. 2009) often break the floating rafts, decreasing productivity (de Góes & Reis 2012; Reis et al. 2015). Most of the cultivated areas are around small islands, in deeper places, subject to climate change, such as winds and storms (Nogueira & Henriques 2020). Winds could induce structure failure too and the position of the farm in relation to the wind direction and intensity can diminish the productivity by detaching the seedlings. Among the undesirable environmental conditions for the growth of eucheumatoids the strong wave action and the wind direction are considered important factors (Glenn & Doty 1990; Hurtado et al. 2001; Munoz et al. 2004).

The higher suitability index of Socioeconomic model in the BSP region reflects the value of Human Development Index (HDI) and the proximity to the central state market of Rio de Janeiro. This pattern inverts as the distance from Rio de Janeiro increases, resulting in lower suitability in IGB especially in the west zone close to the border with São Paulo state. The HDI a summary measure of the average achievement in terms of the significant dimensions of human development, created to emphasize that a person and his/her capabilities and should be the ultimate criteria for assessing the development of a country could indicate a potential to host more successful initiatives in areas with high grades, since its residents have better living conditions (Landuci et al. 2020).

Understand synergies or conflicts with other activities or users sharing farming areas are crucial. It is fundamentally important to monitor possible establishment of introduced seedlings in the environment as a preventive action for marine conservation once *Kappaphycus* is an alien species (Castelar et al. 2009; Marroig & Reis 2011). The proximity to environmental protection areas represents a concern because of the limited understanding of our sea perimeters and rights and duties by officials and producers. In IGB, there is a respectful mentality regarding the environmentally protected marine areas, which is based on the fear of the potentially substantial penalties (Begossi et al. 2011). So far, in both bays, neither fisheries nor tourism activities conflict with mariculture. The region has intense fisheries that have shifted from traditional fishing methods to business sectors. The primary industrial fisheries use trawling and purse seines (Landuci et al. 2020). In the region, aquaculture represents a tourist attractor, and tourism is an important consumer market for the aquaculture products of IGB and BSP, offering advantages related to the reduction in transportation costs and improvement in market prices.

In general, the suitability model for both bays pointed out few unsuitable sites for seaweed farming and many areas in favorable environmental and geographical conditions. On the other hand, there are few extremely suitable sites, mainly due to intense use of the coastline and conflicts between existing heavy industries and conservation units, especially in the IGB. These results may initially seem disappointing due to the low amount of highly suitable areas we identified. However, to put these results in context, the southeast coast of Brazil is densely populated, and tourism and marine-related industries are the main sources of income for the local population (Landuci et al. 2020). However, the total amount of area considered to be of extremely important (17,540 ha) is sufficient to ensure the establishment and expansion of an important marine algiculture industry along the southeast coast of Brazil especially in Rio de Janeiro where environmental operating permits are still awaiting to be released.

With their various social, environmental and economic contribution and benefits, the potential contributions of seaweeds to multiple Sustainable Development Goals – SDGs (e.g. SDG 1, SDG 2, SDG 3, SDG 8, SGD 10, SDG 12, SDG 13 and SDG 14) have been recognized, for example, in a "Seaweed Manifesto" (FAO 2022) but anthropogenic stressors such as eutrophication, habitat degradation, overfishing and climate change are increasingly chalenging coastal ecosystems and communities reliant on their productivity. These threats have left coastal communities searching for new solutions to sustain livelihoods and support the needs of nutritionally vulnerable nations, all while keeping food production for a growing population within planetary ecological limits (Theuerkauf et al. 2022). In the same way, if there are no major concerns in planning and executive management, which can receive oversight and intervention from the state, the activities can result in various environmental and social problems, in some cases irreversible.

The state of Rio de Janeiro has great potential for the development of aquaculture on a commercial level due to a number of characteristics, including favorable climatic conditions and a large amount of areas to start an enterprise. Aquaculture can fulfil an important role in providing income alternatives for coastal communities and with proper planning of the sector, it would avoid the loss of benefits generated by the production chain (Landuci et al. 2021a). In addition, macroalgae cultivation does not require inputs such as fertilizers and pesticides and is independent of irrigation (Hargreaves 2013). As much as the final model points Sepetiba Bay with more most suitable areas due to logistics and costs, this environment is known to suffer from heavy metal contamination (Rocha et al. 2010, 2012; Souza et al. 2014), thus some algae-derived products may become unfeasible. Much like the direct influence of aquatic metal concentrations, the availability of the metals is impacted directly as well as indirectly by anthropogenic activity, such as the acidification of waters which may increase the availability of trace metals. Also, salinity is a factor that is often discussed with respect to metal accumulation in marine macroalgae.

An idea to destiny metal contaminated biomass is an assessment of the feasibility of using macroalgae for bioenergy and bio-coal production in facilities with small scale gasification (Arena 2012; Schultz-Zehde & Matczak 2012). The main final product is biogas that through combustion it is possible to generate electricity and heat, renewable natural gas and transportation fuels; and bio-coal as the decomposition component which may be used as a soil fertiliser that facilitates soil formation, improves soil functional redundancy, increases organic carbon stability, favours water circulation, and supports the soil pH buffering capacity (Hilber et al. 2017; Tammeorg et al. 2017; Verheijen et al. 2017). The ecosystem services provided by macroalgae are fully aligned with several Sustainable Development Goals, which encompass the three pillars of sustainability (environmental, social and economic) (Ferreira et al. 2021).

The cultivation of macroalgae may also have a role on the effects of climate change, especially global warming, due to its great photosynthesizing capacity and atmospheric carbon sequestration, which it uses as a source for fixation and biomass gain (Chung et al. 2011). The photosynthesizing activity of plants also plays a key role in the carbon cycle, being primarily responsible for fixing CO_2 from the atmosphere. Chung et al. (2011) points out the importance of macroalgae and their ecological role in the current scenario of global warming and rising CO_2 rates in the atmosphere.

Through further research, environmental engineers, aquaculturists, and agriculturists can determine optimal times and environments appropriate for macroalgae cultivation, depending upon application. Some of the challenges associated with pollution of open water cultivation sites may be addressed through several major engineering projects. Remote sensing technologies, long established in agriculture, may soon allow farmers to evaluate coastal environments to identify potential cultivation sites for open-water cultivation by assessing various water parameters.

These results should be seen as a complementary tool for decision-making, and not as a single and definitive solution for territorial planning. Other factors such as stakeholder engagement and an environmental and social impact analysis need to be considered to ensure that seaweed aquaculture is developed in a sustainable and responsible manner. Furthermore, a greater understanding of accumulation capacity will help remediation specialists to investigate polluted areas. The information will further assist in future designs of biological remediation systems in marine settings.

CONCLUSION

Ilha Grande and Sepetiba bay presents a lot of suitable areas for the development of the production chain of *Kappaphycus*, meeting the current demand for phycolloids, biofertilizers, and other possible bioproducts. The still small production has room for its growth in a sustainable way.

Although the Sepetiba Bay is very suitable, the issue of algae contamination must be evaluated, which limits certain products and consequently limits their benefits. In relation to the BIG, it is mandatory to define, as soon as possible, exclusive areas for *Kappaphycus* cultivation in light of the different use conflicts that already overlap areas considered as very appropriate.

The proposed methodology can help in the execution of a marine spatial planning of the south Fluminense coast being used by several actors and decision makers, but not could view as a single and definitive solution for territorial planning thinking about the support to the sustainable and responsible development of seaweed aquaculture in Brazil.

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