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ARTICLE

GIS-based multicriteria analysis for on-bottom aquaculture of the sea scallop, *Placopecten magellanicus*, in St Pierre and Miquelon, a sub-Arctic French archipelago (NW Atlantic)

Análisis multicriterio basado en SIG para la acuicultura de fondo de vieira *Placopecten magellanicus* en Saint Pierre et Miquelon, un archipiélago francés subártico (Atlántico noroccidental)

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Abstract: The seafood industry of Saint Pierre and Miquelon (SPM) was severely impacted by the collapse of the Eastern Canadian cod fishery, which led to the 1992 moratorium. This underscored the need for diversification strategies to sustain the local economy. Scallop aquaculture (*Placopecten magellanicus*) has since been developed on a limited scale, but spatial expansion is required to ensure long-term economic viability. In 2008, a comprehensive research and development programme was launched to address this need. This study focuses on the critical stage of site selection, applying a GIS-based multi-criteria approach to identify suitable areas for on-bottom scallop aquaculture. Acoustic and video surveys, combined with ground-truthing, produced the first large-scale seabed habitat maps of eastern SPM. These maps also provide a geospatial database to support coastal zone management and decision-making in the archipelago. The results identified 8335 ha suitable for aquaculture, subdivided into areas for public stock enhancement and leasing grounds for private operations. Suitable areas are not a limiting factor for expansion, and a 2724-ha zone was identified as the most appropriate for leasing, supporting a potential annual production of ~100 t, based on existing equipment and a current five-year rearing cycle at 4 ind. m^{-2}. Habitat characterization also enables optimal matching of dredge types (New Bedford vs toothed crossbar) to seabed conditions, minimizing future benthic impacts. Management recommendations and research priorities are discussed, with particular emphasis on addressing the availability of juveniles for seeding. Large-scale development is constrained by juvenile supply, necessitating optimization of spat collection and/or hatchery production. These findings lay the foundation for a strategic aquaculture growth plan, positioning scallop farming as a key contributor to the long-term economic resilience of the SPM archipelago alongside traditional fisheries.

Keywords: sea scallop, *Placopecten magellanicus*, GIS habitat mapping, site selection, bottom aquaculture, Saint Pierre and Miquelon.

Resumen: La industria pesquera de Saint Pierre et Miquelon (SPM) se vio profundamente afectada por el colapso de la pesquería de bacalao en el este de Canadá, que desembocó en la instauración de la moratoria de 1992. Este acontecimiento evidenció la necesidad de estrategias de diversificación orientadas a garantizar la sostenibilidad de la economía local. Desde entonces, la acuicultura de vieira (*Placopecten magellanicus*) se ha desarrollado de manera incipiente, aunque resulta imprescindible una expansión espacial para asegurar su viabilidad económica a largo plazo. En 2008 se puso en marcha un programa integral de investigación y desarrollo destinado a abordar este desafío. El presente estudio aborda la fase crítica de la selección de emplazamientos, aplicando un enfoque multicriterio basado en sistemas de información geográfica (SIG) con el fin de identificar áreas idóneas para la acuicultura bentónica de vieira. Las prospecciones acústicas y de video, complementadas con verificaciones in situ, permitieron elaborar los primeros mapas de hábitats del lecho marino a gran escala en la zona oriental de SPM. Dichos mapas constituyen, además, una base de datos geoespacial de referencia para la gestión integrada de la zona costera y la toma de decisiones en el archipiélago. Los resultados señalan la existencia de 8.335 ha con aptitud para la acuicultura, subdivididas en áreas destinadas al repoblamiento de carácter público y en zonas de concesión para explotaciones privadas. La disponibilidad de áreas aptas no constituye un factor limitante para la expansión, habiéndose identificado una superficie de 2.724 ha como la más adecuada para concesión, con un potencial de producción anual estimado en ~100 t, considerando el equipamiento actualmente disponible y un ciclo de engorde de 5 años a una densidad de 4 ind. m^{-2}. La caracterización de hábitats permite asimismo ajustar de manera óptima la selección de los tipos de dragas (New Bedford frente a barra transversal dentada) en función de las condiciones del sustrato, con el fin de mitigar impactos bentónicos futuros. Finalmente, se presentan recomendaciones de gestión y prioridades de investigación, haciendo especial hincapié en la problemática de la disponibilidad de juveniles para el repoblamiento. El desarrollo a gran escala se encuentra limitado por el suministro de semilla, lo que hace necesario optimizar la captación de larvas y/o la producción en criadero. Estos resultados sientan las bases para la formulación de un plan estratégico de expansión acuícola, que sitúe el cultivo de vieira como un eje fundamental en la resiliencia económica a largo plazo del archipiélago de SPM, en complemento con las pesquerías tradicionales.

Palabras clave: vieira; *Placopecten magellanicus*; cartografía de hábitats con SIG; selección de emplazamientos; acuicultura bentónica; Archipiélago de Saint Pierre et Miquelon (Fr.).

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Supplementary information ↓

1. INTRODUCTION

The Atlantic sea scallop, *Placopecten magellanicus*, occurs in the northwestern Atlantic Ocean, ranging from Cape Hatteras to Newfoundland, and supports a major commercial fishery (Stokesbury *et al.* 2016). In response to overfishing and recruitment decline, improved fishing regulations (e.g. stock management) and attempts to diversify through aquaculture have been the management responses over the last 40 years. Aquaculture production of scallops has been developing slowly during this period, but accounts for less than 0.1% of the total landings in the North American Atlantic region (Robinson *et al.* 2016). Although still an incipient industry in the NW Atlantic, sea scallop aquaculture is considered a significant opportunity, considering that demand for scallops far outstrips supply in North America (Coleman *et al.* 2022, VIMS 2024, Noren 2024).

Intensive and extensive aquaculture potential of the sea scallop has been widely reported (Coleman *et al.* 2022) due to its favourable characteristics: a reliable spat supply, rapid growth, a large meat yield, a high level of reproduction, filter-feeding behaviour that relies on natural food sources, high market value and consumer acceptance. In addition, demand in the United States and Canada far outstrips the supply of imports from China, Japan, Argentina and Peru (National Marine Fisheries Service 2024). However, its economic feasibility was less favourable, mainly due to its long rearing cycle and the high equipment and labour demands it entails. Initially developed on the basis of Japanese expertise—first through spat collection, followed by intermediate pre-growing and final grow-out in off-bottom systems (suspended ropes under longlines)—the sector has increasingly shifted toward on-bottom grow-out (extensive culture/enhancement), which is now the dominant technique despite subsequent innovations such as polyculture (Fitzgerald 2021). In Canada, large-scale research programmes were developed to sustain the shellfish industry by studying many aspects of sea scallop culture (e.g. the Ocean Productivity and Enhancement Network (OPEN) and REcherche sur le Pétoncle à des fins d'Élevage et de Repeuplement (REPERE) (Robinson *et al.* 2016). Moreover, a recent meta-analysis of growth and mortality rates of net-cultured sea scallop was performed by Coleman *et al.* (2022) to specify optimal environmental conditions. Identifying sites that provide both optimal environmental conditions and adequate space for low-density net culture is considered an important step towards expanding sea scallop culture.

From a historical perspective, scallop aquaculture in the Saint Pierre and Miquelon (SPM) French sub-Arctic archipelago (NW Atlantic) was initiated as early as 1978 to test its feasibility by deploying 3000 spat (15 g) provided by DFO Newfoundland, Canada, in the Grand Etang lagoon in Miquelon. Using Japanese lanterns as growout facilities, scallops reached a 100 g commercial size (around 20% meat yield and 80% survival rate) over a 20-month rearing time. Based on those favourable preliminary data, additional experiments were carried out in the open sea to test spat collecting operations and various options for pre-growing and growing techniques (e.g. off-bottom longlines, on-bottom seeding) during the 1980s (Dao 2000).

Concomitantly, the SPM seafood industry was drastically affected by the cod fishery collapse in eastern Canada and its resulting 1992 moratorium. Moreover, the judgement by the International Tribunal for the Law of the Sea in New York further reduced the access of SPM to the historically shared fishery with Canada, granting access to only the narrow maritime corridor known as the "baguette". This overall situation therefore strengthened the need for a diversification approach to sustain the local economy (Le Floc'h *et al.* 2017). At present, the main fisheries operated by the SPM fishing fleet (mostly small-scale/artisanal fisheries) target sea cucumber, snow crabs, sea scallop, lobster and halibut, landing 2630 t including 307 t of sea scallop in 2022 (IEDOM 2023).

In view of the preliminary trials and this economic/historical context, since the 1970s the sea scallop aquaculture has been considered the leading candidate for further development. As early as 1996, new field trials based on Canadian spat imports were tested by the local aquaculture development technical centre ARDA (Dao 2000). Placopecten rearings monitored in the 2000s showed a growth performance of 80 g in less than 5 years from 30–40 mm pre-grown scallops at an average density of 5 individuals m^{-2} (Goulletquer *et al.* 2013). The recapture rates were gradually improved over this period, going from 7% to more than 20% thanks to a reduction in the initial mortality rates at seeding (optimization of the seeding period and the seeding techniques). Initial size at seeding, recommended to be no less than 25 mm, was reported to be critical for reducing mortality rates, as described by Coleman *et al.* (2022). However, the inconclusive and variable yearly productions obtained by a private company between 2001 and 2006 demonstrated the need for a comprehensive research and development project to optimize and sustain the industry's development, address technical questions and develop an updated management plan for reaching economic sustainability. Until now, sea scallop aquaculture in SPM remains an incipient industry.

This comprehensive and holistic research and development project was initiated as early as 2008 to support the local shellfish industry (Goulletquer *et al.* 2008, Poitevin 2016). The overall strategy is based on a local supply of settled spat, which is achieved by identifying suitable collection areas and using Japanese spat collection techniques (i.e., suspension equipment such as tiered lantern and pearl nets) (Robinson *et al.* 2016). Spat collecting practices are optimized by considering environmental conditions and assessing larval dispersal using a modelling approach and a hydrodynamical model. Pre-growing is tested using off-bottom culture. Both spat settlement and pre-growing were eventually localized in the Bay of Miquelon close to the company's facilities. The overall rearing cycle approach is also inspired by the successful scallop fishery in Brittany, where fishing and shellfish farming have coexisted and interacted for several decades (Alban and Boncoeur 2008). It is also similar to both the successful stock enhancement of the Japanese scallop *Mizuhopecten yessoensis* in Hokkaido and the *Pecten maximus* scallop restocking/sea-ranching programme operated in Brittany, France (Uki 2006, Alban and Boncoeur 2008). Additional aspects of this project include genetic characterization of the spat collection and consideration of the potential effect of spat imports on the local population, modelling of the hydrodynamic structure and thermocline patterns, multi-site monitoring of natural spawning and spat collection, habitat mapping for site selection, evaluation of various husbandry methods (e.g. optimal size for seeding, scallop densities and predation rates), studying dredge efficiency and bottom impacts, and developing an annual in situ video monitoring system for stock assessment and quantification of fishing effort efficiency. Meanwhile, environmental conditions and carrying capacity are assessed through in situ continuous monitoring using multi-parameter probes and phytoplankton samples (quantitative and qualitative surveys including toxic species). Economic analysis will be carried out once all technical aspects have been optimized. Overall, this programme aims to estimate the feasibility/constraints and to assess the overall potential of scallop aquaculture in SPM.

The present study aims to support coastal zone management decision making by identifying the most suitable sites for sustainable *Placopecten magellanicus* aquaculture using GIS-based models and related technologies. The project also contributes to the development of the local industry, already using the rearing cycle described above, which considers that spatial expansion and increased activity are critical to achieving economic balance. Meanwhile, this study provides a geomatic database suitable for zoning additional marine uses in the SPM archipelago as required for the ongoing EU Maritime Spatial Planning.

We focus on the first and critical stage to on-bottom/"enhancement" aquaculture, which is the site selection process using a multicriteria approach. Site selection criteria are an integral component to the success of any aquaculture venture (Robinson *et al.* 2016). Various methods have been used for shellfish aquaculture site selection (Longdill *et al.* 2008, Radiarta and Saito 2009, Stelzenmüller *et al.* 2017, Bandira *et al.* 2021). GIS is useful for manipulating spatial aspects for aquaculture planning due to the ability to bring together many layers of information for decision making. Most of the applications use a multicriteria approach and may further include remote sensing data and dynamic models. By way of example, Bacher *et al.* (2003) coupled a GIS tool and food depletion model to support decision making and determine suitable densities for aquaculture development. Radiarta *et al.* (2008) used GIS-based multicriteria evaluation models to identify suitable sites for Japanese scallop *Mizuhopecten yessoensis* aquaculture in Funka Bay, Japan. Palmer *et al.* (2021) used a 3D marine ecosystem model providing hydrodynamic-biogeochemical conditions over a large area to drive a dynamic energy budget growth model for the Pacific oyster (*Crassostrea gigas*); this enabled them to specify offshore areas broadly suitable for growth and useful for industry planning and policy purposes. Barillé *et al.* (2020) used also a GIS approach with remote sensing data, a growth model and socio-economic data for aquaculture site selection.

A GIS-based multicriteria site selection approach for an on-bottom aquaculture is currently used to assess the aquaculture development of the sea scallop, *Placopecten magellanicus*, in SPM.

2. MATERIALS AND METHODS

A systematic bottom-type screening was used for this study. Overall, the area is known for having a natural wild population of *Placopecten magellanicus* with a regular but low yearly natural spat recruitment. Therefore, it was considered that a combination of habitat-bottom type and aquaculture management practices were the critical criteria for determining site suitability. In contrast, although environmental hydrological conditions are the focus of a concomitant and continuous monitoring survey, they were not considered as a driven constraint for on-bottom shellfish culture in this specific case study. Located close to the mid-southern part of Newfoundland, the SPM archipelago shows favourable temperature conditions (10°C–15°C) for scallop aquaculture on around 400 days over a four-year period according to the meta-analysis of Coleman *et al.* (2022). The seawater temperature ranges between 15°C and 10°C at 10 m and 40 m deep, respectively, at its peak in August, with no temperature spike at this depth (Lazure *et al.* 2018). Coleman *et al.* (2022) also reported a significant temperature drop in September below 30 m depth due to an isolated wind-induced thermocline. Moreover, the area is undeveloped for aquaculture, with no additional growout facilities that would compete for food availability and carrying capacity.

2.1. Methodology and survey strategy

2.1.1 Study area

The study was carried out on the eastern coast of SPM, located about 20 km south of Newfoundland (Fig. 1). It lies between 47°10'N (Cap de l'Aigle) and 46°45'N (Pointe du Diamant). The area of interest was selected using an official bathymetric chart to identify the 15–80 m depth range, representing a 307.7 km² surface area to sample.

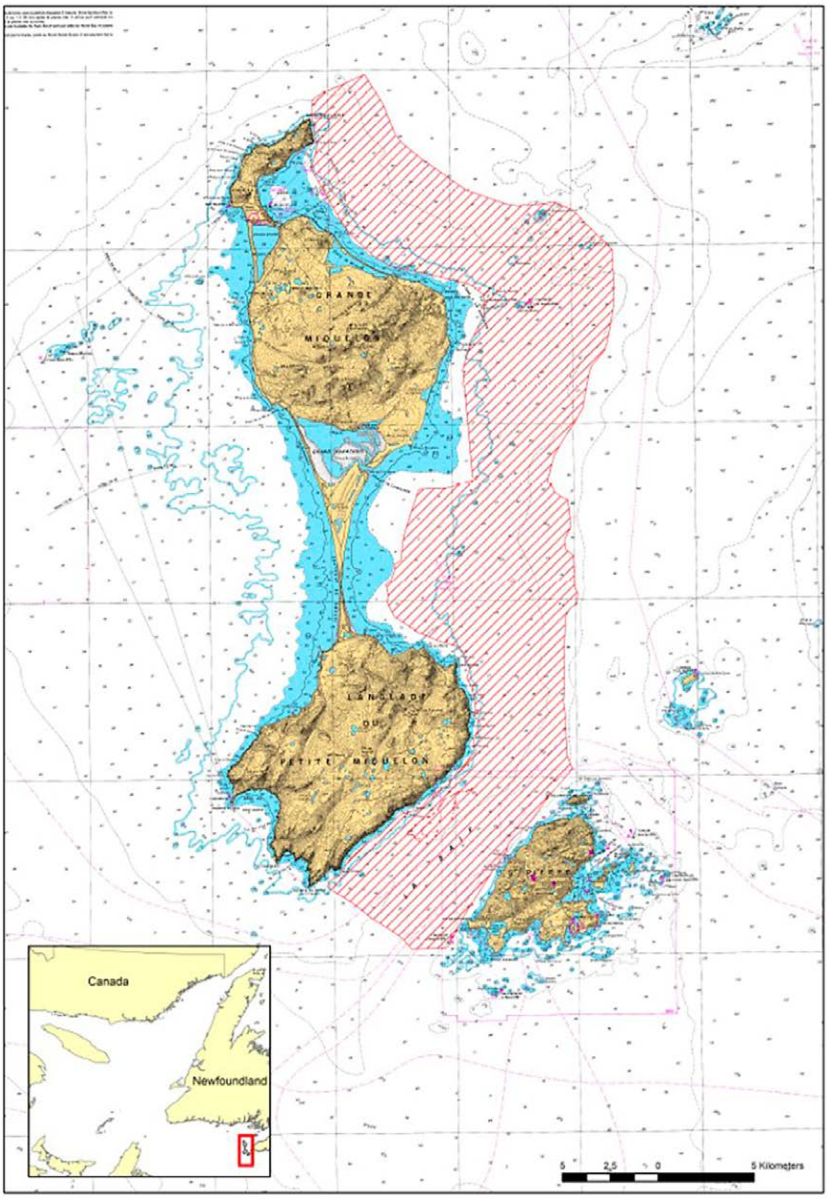

Figure 1.– Saint Pierre and Miquelon geographical location and experimental area.

Depth should also be taken into account with regard to the species' biological requirements and aquaculture technical constraints and feasibility. The following criteria were used to identify suitable depths for final analysis (Table 1). Seabeds located between 15 and 60 m depth were identified as highly favourable to Placopecten aquaculture; although sea scallops occur at depths ranging from 12 to 110 m, adults are generally found shallower in northern populations (NOAA 2004). The public scallop fishery operates down to 50–55 m depth in SPM. Seabeds less than 15 m deep were also excluded because they are potentially sensitive to dynamic disturbances generated by waves and swells, which can reach 3 to 4 m on this part of the coast. The sliding and displacement of the seeded shells resulting from this hydrodynamics limit the possibilities of management and monitoring of the future seeding areas. Although sufficiently deep, seabeds ranging from 35 to 60 m depth require specific equipment to operate. This depth range was previously selected to establish leasing grounds off the Bay of Miquelon, where a shellfish company operates (Baudrier et Orsiny 2010). Likewise, bottoms with a depth greater than 70 m were excluded because they are more difficult to exploit and less favourable to the development of sea scallops because of slow growth. Among the areas identified as favourable, it seemed unfeasible to manage technically homogeneous areas with an area of less than 100 ha. Unless there was a major development at their periphery, they were therefore excluded from potentially exploitable areas.

Table 1. – Site selection criteria and management options

Site selection criterion		Positive	Negative
Bottom Type			
sandy - cobbly gravel		++	
hard substrate - boulder			--
Ecological habitats			
Ophiura		++	
Kelps			--
Depth Range			
<15 m			--
15–35–60 m		++	
60–70 m		+	
70–80 m			--
Proposed management options			
Management type	Spat seeding density		Rearing cycle (y)
Depth range	extensive	intensive	Rearing cycle (y)
15–35 m	0.5/m²	4/m²	5
35–60 m	0.5/m²	4/m²	5
60–70 m	0.5/m²	4/m²	7
Dredge Type			
Sandy - cobbly gravel		Toothed dredge	
Sandy - pebbled		Chained dredge	

2.1.2 Field implementation: general approach

An acoustic survey track spacing of 500 m was systematically used over the whole area to give a broad coverage suitable for habitat mapping at an appropriate scale. Survey lines were planned in a GIS system and transferred to the vessel's electronic chart plotter, which allowed the vessel position to be displayed along the survey lines. The acoustic system used to survey the area was a

RoxAnn acoustic ground discrimination system (AGDS). The system was operated at a vessel speed of around 10–15 km.hr^{-1}, which enabled areas to be covered relatively rapidly. Once this dataset had been processed, a drop-down video and grab/dredge were used for ground truthing for each type of habitat. Sample stations were selected using the variation in the AGDS data, seabed features and topographic features identified from the bathymetry data.

2.2. Technical specifications

2.2.1 RoxAnn acoustic ground discrimination system

A RoxAnn™ GroundMaster AGDS operating at 50 kHz was used. AGDS are based on single-beam echo sounders and, apart from determining depth, are designed to detect different substrata by their acoustic reflectance properties: hard surfaces produce strong echoes while soft surfaces produce weak ones. Additionally, rough surfaces produce an echo that decays slowly while flat surfaces produce one that decays rapidly. These properties were used to discriminate broad categories of seafloor habitats (Foster-Smith *et al.* 2001, Foster-Smith and Sotheran 2003). The acoustic data, together with GPS data, were entered in a laptop. The data were analysed using image processing and GIS after detailed data quality assurance procedures had been implemented (Sotheran *et al.* 1997). Further processing correlated AGDS values to swathe/side scan features to assist with their interpretation.

2.2.2 Drop-down video systems

The drop-down video system was deployed to collect information on the ecology and main seafloor characteristics. A small high-resolution CCTV camera system was mounted onto an aluminium drop-frame onto which a high intensity lamp was fixed. The camera housing was mounted onto a small frame which was lowered to the seabed via an umbilical, which allowed the underwater image to be viewed in real time on the surface and recorded on MiniDV tape. GPS position was recorded using a PC and was also overlain on to the video footage as it was recorded. Video sample sites were selected according to the acoustic ground types identified from acoustic datasets.

2.2.3 Grab/dredge

During the survey, six dredge samples per habitat type were performed for selected locations within the survey area. A small dredge was lowered at several locations and towed for a duration of 2 to 5 minutes at slow speed to characterize bottom types and calibrate acoustic data. In addition to the RoxAnn AGDS data, 153 video samples were eventually collected during the survey to cover all habitat type. These videos were viewed to characterize habitats and biological community. Finally, records were assigned to biological and physical habitat classes.

2.2.4 Map production

The acoustic data were processed using image processing techniques followed by interpolation, which transforms point data into a continuous surface by calculating new values for a grid of positions covering a rectangular area that encompasses the track point data. This enables raster-based image processing techniques to be applied to the data. The edited track data were interpolated in Surfer™ using the following parameters: (1) a grid spacing of 50 m; (2) an inverse distance algorithm with a weighting toward the grid centroid of 1; (3) a search and display radius of 1250 m (to ensure there were no gaps in the coverage); (4) an eight-sector search with a maximum of 32 values per sector; and (5) a smoothing coefficient of 2.

2.2.5 Supervised clasification

The raster grid images were imported into Idrisi™ for classification. Supervised classification using the maximum likelihood classifier is generally regarded as the most satisfactory means of interpreting multispectral data. The maximum likelihood classification process also allows Bayesian prior probabilities to be included based on rules. The grid images were used for classification. The video data were categorized to biological habitats. A buffer zone of 100 m was created around each video sample, and these were then used as 'training' sites to create the acoustic signatures which were applied using the maximum likelihood classifier. The process was repeated for the physical habitat classes without the need to constrain or enhance any individual class.

2.2.6 Site selection for *Placopecten* culture using a multicriteria approach

All data integrated into the spatial database using ArcGis needed some manipulation and reclassification to weigh and overlay data layers. Based on the ground data survey and the mapping obtained, several criteria were established for positively and negatively scoring areas to assess whether they were suitable for *Placopecten* aquaculture (Table 1). Overall, the aquaculture development should not affect the local biodiversity, for example, as a result of dredging on a habitat of ecological interest such as a rocky bottom with macroalgae coverage. In contrast, gear efficiency for scallop dredging is highly dependent on bottom type. The preferred physical habitats for scallop populations are sandy gravel, sand, mixed sediment types, coarse sand and cobbly gravel, but not muddy bottoms (NOAA 2004). Extensive areas of bedrock, boulders and other hard substrates are also unfavourable. Selection of a poor bottom type would result in increased predation and scallop dispersal (Wong *et al.* 2006).

Two successive steps were performed: first, identification of favourable areas based on *Placopecten* biological requirements; second, incorporation of management practices and associated technical constraints (e.g. fishing gear). All criteria are presented in Table 1. These steps allowed us to determine a suitable zoning to develop (1) a ground-leasing system for the most suitable areas and (2) an enhancement programme (i.e. reseeding) for the remaining areas to sustain the public fishery. Arbitrarily, the 35–60 m depth zone requires specific technical constraints (boat type and dredge) to justify an aquaculture exploitation through a lease/licensing system. In addition, the 15–35 m depth zone is considered a seeding ground for a public fishery. The 60–70 m depth zone could be used for seeding operations but would show reduced scallop growth rate due to the low seawater temperature (see Lazure *et al.* 2018). Previous growout testing resulted in a longer rearing cycle (7 years vs 5 years) at this depth, which is unsuitable for economically feasible aquaculture. However, this might be an option for stock enhancement and reseeding at 0.5 individuals/m^2, which is representative of the wild population density (Shumway and Parsons 2016).

A fishing technique feasibility attribute was defined and filled in based on use of either the toothed cross bar dredge or the chained dredge for harvesting. Actually, the sandy bottoms have been identified as suitable to operate with a toothed cross bar dredge, similar to that used successfully in the scallop fishery in the Saint-Brieuc Bay, France (Fifas *et al.* 2004). Sand-to-pebble beds are more suitable for chain dredges such as the New Bedford ones. Both dredge types and bottom types were also considered in order to limit the fishing gear impact on the environment and facilitate further reseeding operations on less impacted bottoms. Although an issue, predation rate and occurrence of predators such as the sea star *Asterias vulgaris* were not taken into account at this stage, because further management practices such as the use of sea star mops might limit the predator population (Barkhouse *et al.* 2007).

3. RESULTS

3.1 Biological and physical habitats

Different patterns in biological and physical habitats were observed. The east of Miquelon Bay shows shallow areas with stable substrate occupied by kelp habitats. Denser kelp populations were associated with more stable substrates. Kelp habitats no longer predominate below 35–40 m depth, leaving encrusting red algae colonizing stable substrates. Fine sand was observed down to 60 m, with a dominant *Ophiura* biological community. The deeper area, below 60 m, is characterized by a cobble habitat. Coarse substrates such as pebbles, gravel and cobbles were observed in the eastern part of Grande Miquelon. A kelp habitat was observed in shallow waters, followed by an *Ophiothrix*-dominated biological community, whereas cobble and stable rock areas with encrusting fauna such as red algae characterized the deeper areas. The main body of sand is located between Miquelon and Langlade at the eastern isthmus of

Langlade. This area was mainly populated by three species: the common sand dollar, *Echinarachinus parma*, the ocean quahog, *Arctica islandica*, and the brittle star *Ophiura ophiura*. The northern end of Langlade down to La Baie has a mainly rocky sea floor. Macroalgae populations develop down to about 40 m depth, with encrusting Corallinaceae occurring down to 45–50 m. The soft coral *Gersemia rubiformi* and the stalked tunicate *Boltenia ovifera*, of biological interest and likely susceptible to trawling, were observed at the northeastern end of La Baie in deeper water cobble and mixed habitats.

3.2 Favourable areas

An initial selection was based upon the bottom type and biological habitats (Tables 2 and 3) (Figs. 2 and 3). The percentage agreement for the physical habitat classification was 79.3%, with a Kappa agreement (probability of agreement above chance) of 0.65. The percentage agreement for the biological habitat classification was 83.3%, with a 0.72 Kappa agreement. Both levels of agreement are fully acceptable for remote surveys in which perfect agreement is never expected due to a combination of positional error and variability in the acoustic reflectance data. Figures 2 and 3 show the distribution of the physical and biological habitats mapped within the survey area adjacent to Miquelon-Langlade.

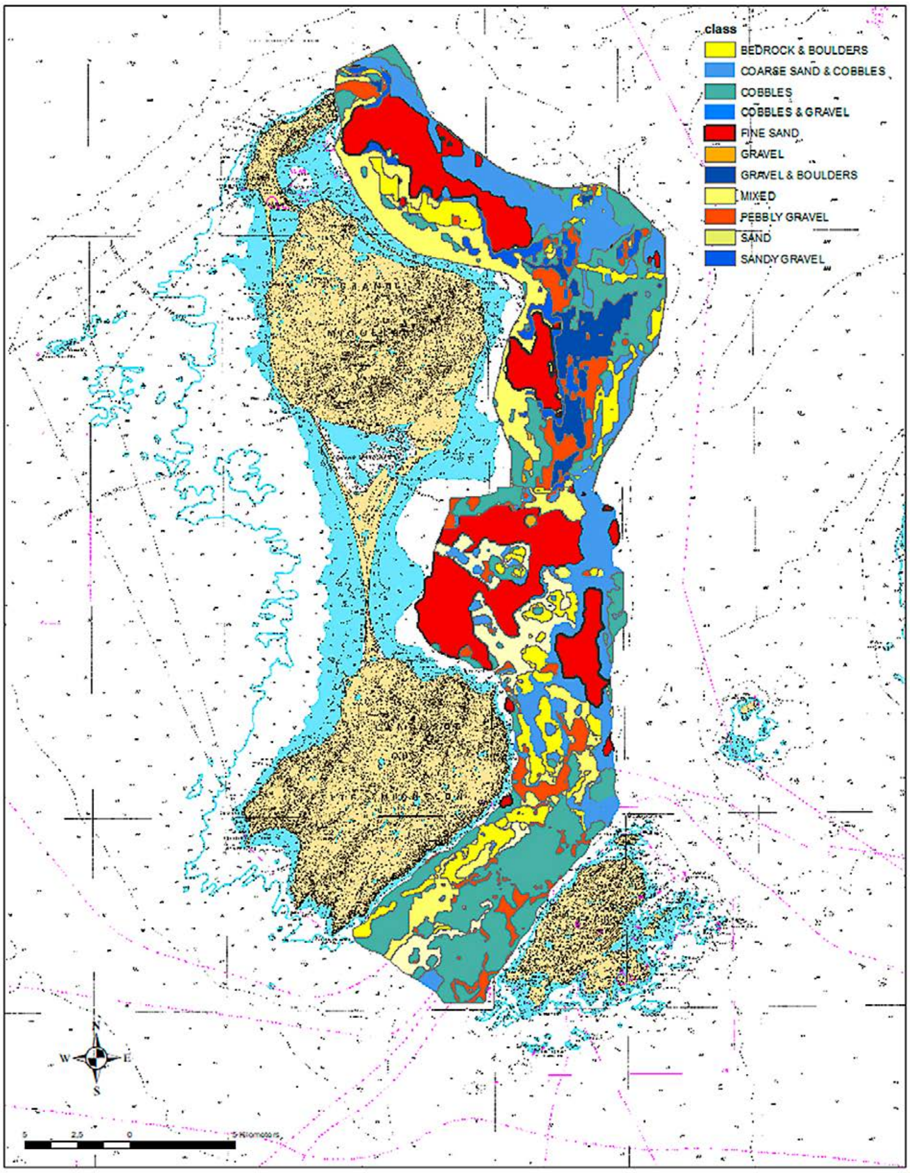

Figure 2. – Distribution of physical/sediment habitat classes. Bottom type classes were determined and characterized/calibrated by several complementary measurements with an acoustic survey covering the whole area and ground-truthed by video and dredge samples at representative stations.

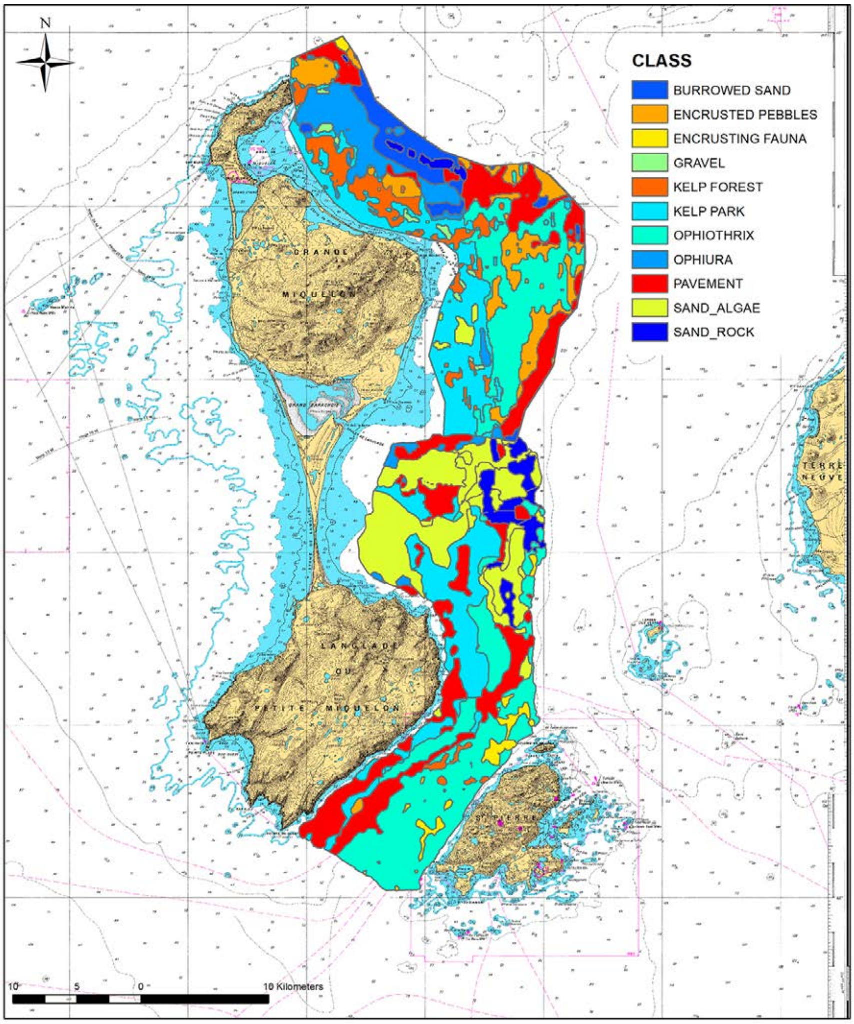

Figure 3. – Distribution of biotopes (physical and biological classes). Habitat classes were determined and characterized/calibrated by several complementary measurements with acoustic survey covering the whole area and ground-truthed by video and dredge samples at representative stations.

Table 2. – Physical habitats and descriptions identified during the survey. Name of the physical habitats identified and referred to in the maps and figures

Habitat	Description
Fine sand	Fine compact sand with some silt which is easily disturbed
Sandy gravel	Gravel with a small proportion of sand
Pebbly gravel	Gravel with a proportion of pebble material
Sand	Medium sand
Mixed	A mixture of pebbles, sand and gravel with some cobbles
Coarse sand and cobbles	Coarse sand with cobbles in patches
Gravel	Gravel with some coarse sand
Cobbles and gravel	Cobbles with gravel between
Cobbles	Clean cobbles
Gravel and boulders	Boulders with gravel material between
Bedrock and boulders	Rugged rock or boulder, very stable

Table 3. – Biological habitats and descriptions identified during the survey

Biology	Description
Burrowed sand	Fine sand with obvious mounds and burrows, occasional brittlestar (*Ophiura spp*.) and sea urchin.
Gravel	Gravel substrate with urchins and algae and occasional *Asterias*.
Ophiura	Fine sand with dense covering of *Ophiura* albida, occasional burrow and mound.
Encrusted pebbles	Pebbles or cobbles with encrusting red algae, maerl frequent in places, along with urchins and occasional *Ophiothirx spp*.
Sand and algae	Tide swept fine sand with filamentous brown algae.
Ophiothrix	*Ophiothrix fragilis* bed on cobbles, pebbles and occasional larger rocks, urchins present with the substrate encrusted with red algae.
Consolidated pavement	Cobbles with coarse sand between and encrusting fauna on cobbles. Substrate is consolidated and stable.
Kelp park	*Agarum cribosum* on a mixed substrate with other algae between or as an understory, occasional *Laminaria saccharina*.
Kelp forest	Dense *Agarum cribosum* on stable substrate, often rock or boulders.
Encrusting fauna	Encrusting polychaetes on current-swept cobbles.
Sand and rock	Larger rocks and boulders with encrusting fauna, with coarse sand between and often covering the harder substrate.

Sandy and pebble gravelly sand bottoms were considered favourable for the *Placopecten* species. Adult scallops are generally found in seabed areas with a substrate of firm sand, gravel, shells and cobble. They are typically abundant in areas with low levels of inorganic suspended particulates (NOAA 2004). The *Ophiura* habitat from the benthic survey was also considered positively. This kind of habitat was the prime target for the shellfish company to perform the first seeding operations in the northeastern part of Miquelon Island, which eventually showed appropriate individual growth rates (Lajournade and Orsiny 2010). In contrast, the kelp algae habitats were not retained. Indeed, the presence of those algae makes it impossible for conventional fishing (dredging by trawler) to operate. Moreover, these are habitats of ecological interest for conservation.

3.3 Site selection for Placopecten aquaculture

All layers of information were overlaid to determine both the area suitable for culture and the type of harvesting gear applicable to each favourable area (Figs. 4 and 5). An intersection was made between the favourable zones and those to be excluded according to the criteria of biological and physical habitats in order to obtain the first level of potential areas with different types of seabed. As stated above, potential areas smaller than 100 ha were considered too small to be exploited and were therefore removed. Figure 4 shows the areas finally chosen for scallop aquaculture using either chained or toothed cross bar dredge, amounting to a total of 8335 ha (approximately 30% of the acreage of the 15–70 m depth range). These areas can be subdivided into three parts: the northern area with 3445 ha (1466 chained dredge/1979 toothed cross bar dredge), the central area with 4662 ha (1603 chained dredge/3059 toothed cross bar dredge) and the small southern area with 228 ha (only chained dredge). This is divided into 2724 ha potentially devoted to a ground-leasing system and 5611 ha dedicated to a public fishery, including 964 ha at 60–70 m depth.

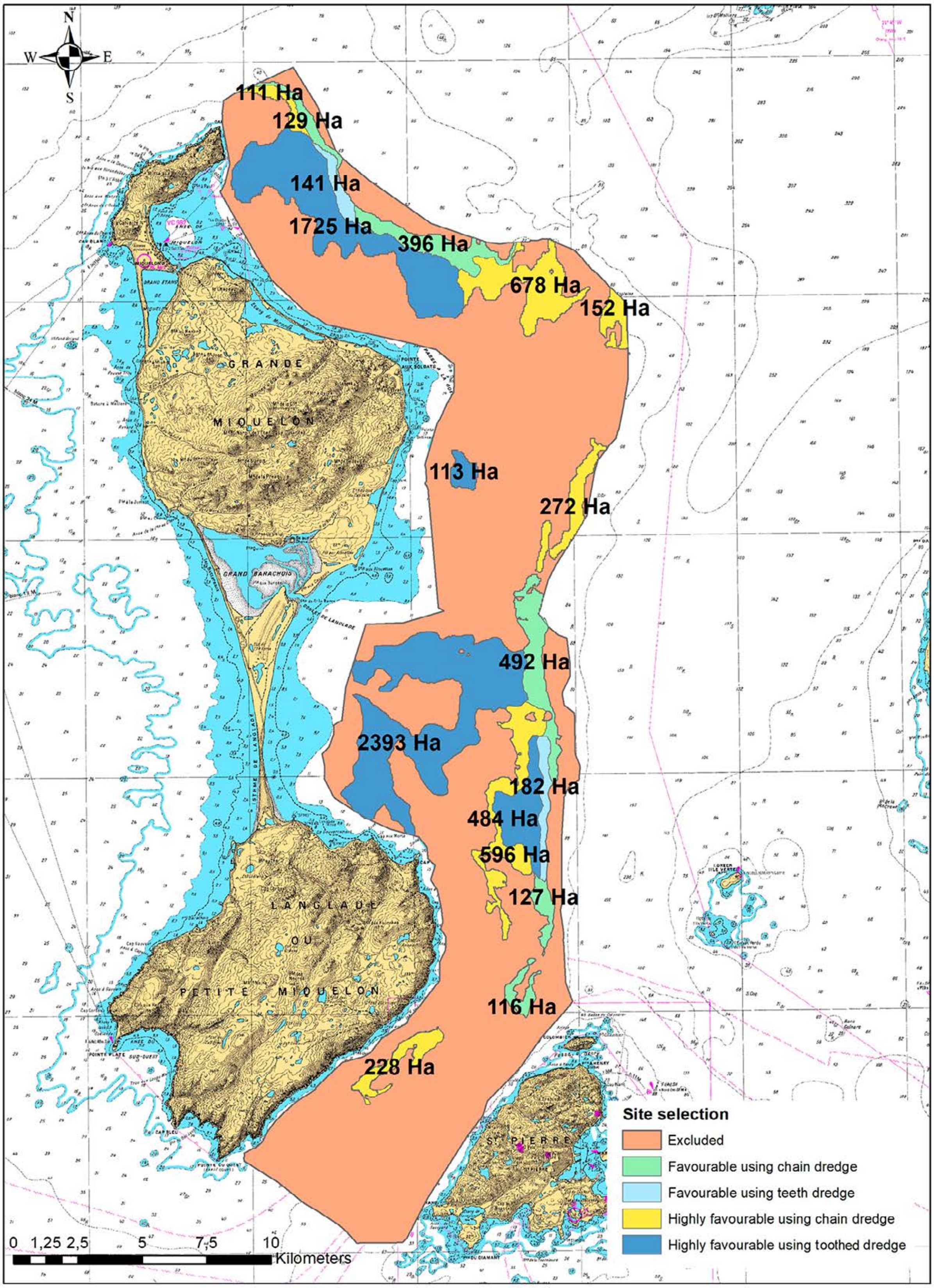

Figure 4. – Distribution of potentially suitable habitats for scallop culture using a multicriteria approach (bottom type/ biological habitat/depth) and compatibility between bottom-type and dredge type to minimize environmental side-effects (erosion) and optimize dredge efficiency.

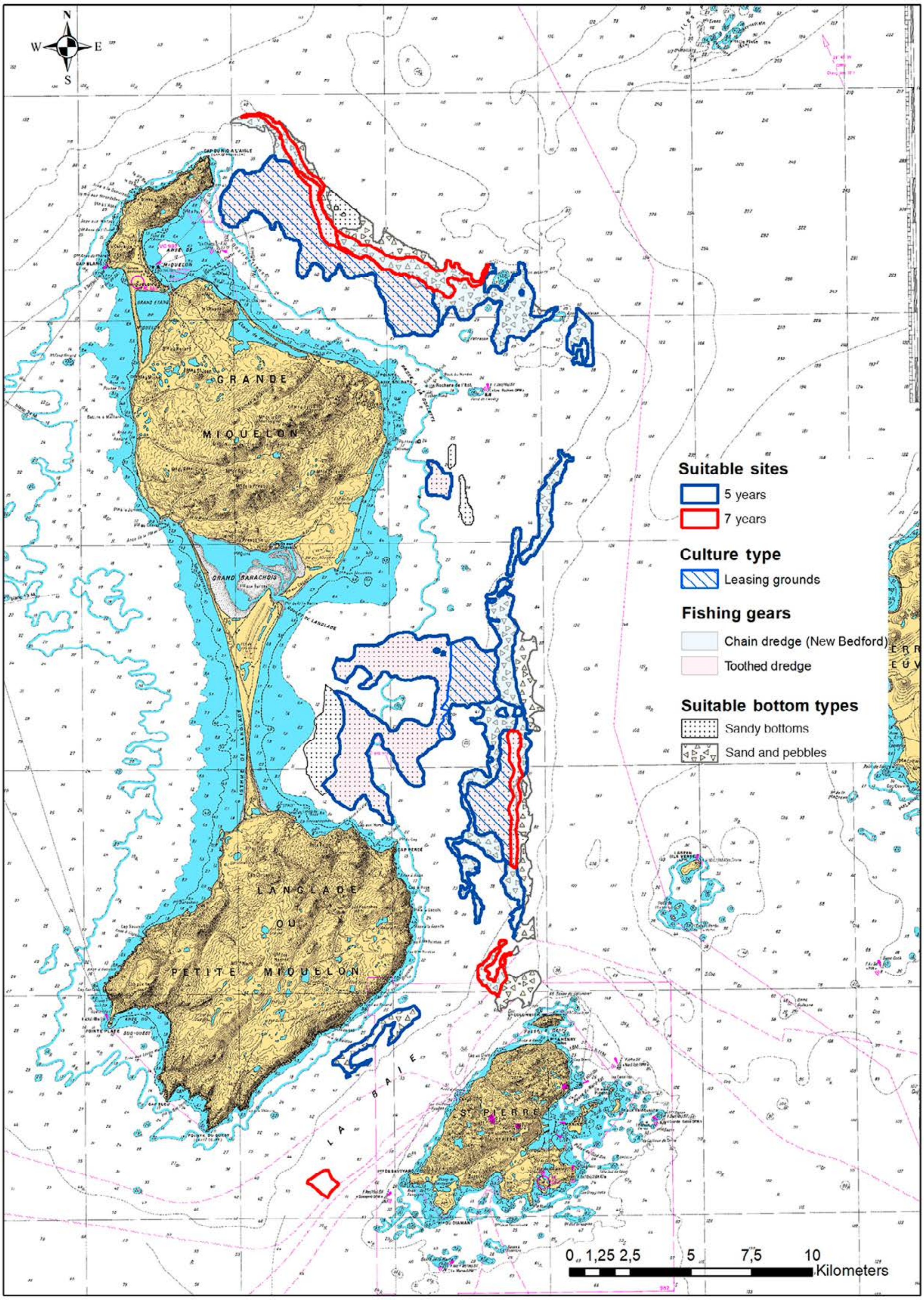

Figure 5. – Final site selection for scallop culture considering suitable areas and management practices. Areas identified for sea scallop culture in blue with a five-year breeding cycle. In red, areas potentially used for a reseeding programme/sanctuary.

4. DISCUSSION

The approach implemented combining acoustic monitoring with videos and seabed samples corresponds to the first large-scale seabed mapping of the eastern part of Miquelon-Langlade. This is a significant contribution, which makes it possible to complete the only cartographic elements available to date concerning algae.

The results obtained are quite significant with regard to the classification of habitats and the nature of the bottoms, with high percentages of agreement (>80% – Kappa index >0.7) between the acoustic data and the calibrations by sampling in the field (dredge and videos) and final habitat classification and mapping. This mapping can be considered a success, especially since it has made it possible to specify habitat patterns that are clearly identified spatially. These results also constitute a knowledge base for future projects other than aquaculture development (e.g. biodiversity, submarine cables and off-shore wind power).

4.1 Aquaculture sustainability and biodiversity

The development of this type of aquaculture must be sustainable and respectful of the environment. The mapping and the site selection process using a multicriteria approach made it possible to exclude from future exploitation ecosystems sensitive to dredging activities and those of heritage interest requiring protection (e.g. kelp forests and soft corals).

The development of extensive aquaculture by seeding and restocking goes through a phase of recapture by dredge fishing. For aquaculture sustainability in these selected areas, it appears necessary to limit the impact of fishing gear on the seabed. The precision obtained regarding the nature of the bottom makes it possible to propose the best possible match between dredge types and habitats, since the chain dredge (New Bedford style) is heavier and more impactful than the toothed cross bar dredge (Robert *et al.* 2009).

4.2 Potential development of scallop farming

During the 1980s, three favourable areas for sea scallop aquaculture in SPM were identified, including coastal lagoons and a large offshore area (6900 ha) identified east of the Miquelon–Langlade isthmus (Dao 2000). However, the identification of these areas was not based on precise data on the nature and characteristics of the seabed. Nevertheless, this area was considered easy to work, being relatively well sheltered from the prevailing westerly winds and located a short distance from the ports of SPM. These areas are similar to one of the areas identified in the present study, which is, however, smaller due to a more precise assessment of the bottom characteristics.

The present study offers a more realistic revision of the aquaculture potential of SPM to support the local shellfish industry seeking spatial expansion and increased activity to achieve an economic balance. The study demonstrates that the spatial expansion of aquaculture by seeding is possible, and suitable areas do not constitute a limiting factor. Final estimates of suitable areas amounted to 8335 hectares, with specific locations to develop aquaculture using either a chained or toothed cross bar dredge for recapture. An area of 2724 ha can be potentially used to develop a ground-leasing system using existing traditional shellfish equipment through on-bottom aquaculture with a breeding cycle lasting five years at an initial density of 4 ind./m^2.

Several technical approaches can be adopted for scallop aquaculture. The ongoing strategy of capturing spat using spat collectors, then off-bottom pre-growing followed by extensive juvenile seeding managed in the form of aquaculture leasing grounds has been considered the most likely to reach economic sustainability (Goulletquer *et al.* 2014, Legrel *et al.* 2016). Based upon a rotation of harvesting areas, this represents a much simpler mechanism toward improved and increased scallop production. It is also the closest to the traditional activities of the local fisheries industry, echoing the restocking processes carried out by the scallop fisher's unions of the Bay of Brest and the Bay of Saint-Brieuc in France, although it requires significant technical adaptations (Fifas *et al.* 2003). This type of aquaculture also requires tight monitoring of infrastructure (e.g. biofouling management) and scallop stocks to limit predation, which is unlikely to be compatible with mixed activities and traditional fishing as currently performed.

This scenario corresponds to a significant spatial extension of the current production scheme (Robert *et al.* 2009). The proposed system of leasing grounds over an area of 2724 ha theoretically makes it possible to produce more than 100 t a year for a breeding cycle lasting five years from an initial density of 4 individuals/m², using stock enhancement with rotating dredging areas to limit benthic erosion. This density, already used by the shellfish company, is considered more intensive for aquaculture than the 0.5 individuals/m² of the wild population density (Robinson *et al.* 2016). It could be used for stock enhancement outside the leasing ground area. This is of interest considering the current annual fishery landings of around 300 tonnes. It shows real potential for development and represents a complement to fisheries that can also be managed by the local shellfish plant (Goulletquer *et al.* 2014).

However, the main factor limiting this potential development remains the necessary juvenile supply to carry out extensive seeding on the large area of 2724 ha: although not yet optimized, the juvenile production by spat collecting operations using spat collectors (nets and lanterns) was of the order of 6 to 10 million individuals per year in the 2000s (Lajournade and Orsiny 2010, Goulletquer *et al.* 2014). On their own, the estimates of areas managed according to a ground-leasing system with a rotating harvesting would require more than 26 million juveniles pre-grown using off-bottom culture with a 75% survival rate.

To gradually achieve such a goal, two technical options can be considered: (1) optimization (and multiplication) of current practices by using *Placopecten* spat collectors in the environment, and (2) massive spat production by controlling sea scallop reproduction using a shellfish hatchery. However, the latter would also require a significant financial investment and highly technical skills, which are not in place and too early an option at this stage of development. Therefore, the first option remains the most likely for further development. Far from this target of juvenile figures, a concomitant high-frequency seawater monitoring system and a modelling approach would likely be useful to provide information to optimize spat collecting operations (e.g. where and when to predict larval dispersal and an optimal deployment period of collectors) and assess environmental changes (Cyr *et al.* 2007, SAFEGE 2008, Goulletquer *et al.* 2014).

These estimates for on-bottom sea scallop aquaculture are subject to several uncertainties that can impact the final results. Economic criteria are not taken into account here and require a comprehensive study as a following step to determine the economic equilibrium (Le Grel *et al.* 2016). Current recapture rates do not accurately reflect *Placopecten* survival rates due to the size-selectivity of the dredge, dredge-related mortality and discarded scallops. Similarly, the dredging techniques are not yet optimized according to aquaculture criteria but are operated according to a fishing approach (Robert *et al.* 2019, Le Grel *et al.* 2016). In addition, several factors can negatively affect survival rates: for example, shell dispersal rates and predation rates by crabs and starfish are not considered here, although they are essential for the final results of on-bottom aquaculture. Accompanying management practices such as sea star mopping and trapping to control predators could thus become necessary and affect the overall economic efficiency (Barkhouse *et al.* 2007). Obviously, a non-linear and progressive development of this aquaculture is very likely. Moreover, if such a development were to be envisaged, the implementation of a spatial planning of maritime activities would become necessary for this geographical sector. A system of licences, allocation of leasing grounds and operating specifications (a State *Schéma des Structures*) specifying the terms of allocation, all the terms of operation (e.g. stocking densities, terms of recapture and authorized fishing gear) should accompany the shellfish industry. Overall, a strategic growth plan for aquaculture development that sufficiently recognizes marine aquaculture as an essential contributor to long-term economic growth for the SPM archipelago alongside traditional fisheries would be required.

Supplementary information ↑

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Data availability

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Authorship contribution statement

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Competing interests

The authors of this article declare that they have no financial, professional or personal conflicts of interest that could inappropriately influence this study.

Statement on the use of Artificial Intelligence

Not applicable.

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