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Biological, socio-economic, and administrative opportunities and challenges to moving aquaculture offshore for small French oyster-farming companies

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ABSTRACT

Oyster production has historically taken place in intertidal zones, and shellfish farms already occupy large extents of the French intertidal space. The expansion of French shellfish aquaculture within intertidal areas is therefore spatially limited, and moving production to the subtidal offshore environment is considered to be a possible solution to this problem. Finding new sites along the French Atlantic coast was studied here from the perspective of small oyster companies run by young farmers, who are interested in offshore bivalve aquaculture expansion compatible with their investment capacity. In assessing the feasibility of such offshore production, we considered three main issues: (1) bivalve growth potential and (2) technical feasibility and conflicting uses, both within a spatial framework, as well as (3) the steps and barriers of the administrative licensing process. Oyster spat in an experimental offshore cage showed significantly faster growth, in terms of both weight and length, compared to those in an intertidal cage, mainly due to lower turbidity and full-time feeding capacity (i.e., constant immersion in the water). A combination of Earth Observation data and bivalve ecophysiological modelling was then used to obtain spatial distribution maps of growth potential, which confirmed that offshore sites have better potential for oyster growth than the traditionally oyster-farmed intertidal sites overall, but that this is highly spatially variable. Small-scale producers indicated two technical factors constraining where farms could be located: bathymetry must be between 5 and 20 m and the distance from a harbor no more than five nautical miles. These were included along with maps of various environmental and socio-economic constraints in a Spatial Multi-Criteria Evaluation (SMCE). Touristic traffic and bottom trawling by fisherman were found to be the two other most restrictive variables. The GIS-based SMCE developed in this study showed that there is almost 400 km^2 of highly- to very highly-suitable area within which to develop offshore aquaculture using simple, low-cost bottom-cage techniques, and can be used to assist the shellfish industry in the Marine Spatial Planning decision-making process, still in progress in this coastal area. However, the complexity of the administrative processes necessary to obtain an offshore license is perceived as a stronger barrier by farmers owning small companies than site selection, technical feasibility, and required investments, and will be crucial to address in order to realistically proceed to offshore cultivation. The process demonstrated here, and the results are relevant to other coastal and offshore locations throughout the world and can be adapted for other species.

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1. Introduction

In Europe, shellfish production has historically taken place in intertidal zones, with oyster aquaculture dating to the middle of the 19th century (McKenzie Jr. et al., 1997; Sauzeau, 2005). As a result, shellfish farms now occupy large areas of the intertidal space of the European Atlantic coast, and sometimes have for more than a century (Goulletquer and Le Moine, 2002). The expansion of shellfish aquaculture within intertidal areas is therefore spatially limited, and is also constrained by carrying capacity, seawater quality, conflicting uses, and ecological impact issues. Moreover, intertidal aquaculture is labor-intensive and the potential for automation and the use of industrial equipment is limited (Buestel et al., 2009). Similar issues have also led to interest in moving finfish aquaculture further offshore (Edwards, 2015; Gentry et al., 2017; Marra, 2005). However, before offshore production sites can be established, this new environment must be better characterized in terms of its suitability for mariculture. Along the European coastline, there is already significant mussel production on ropes that can be found a few nautical miles from the intertidal zone. Oyster cultivation on longlines remains rather rare, but this bivalve is now seen as a viable candidate for potential offshore aquaculture (Pogoda et al., 2011, 2013), notably in co-production with wind energy within wind farms (Buck et al., 2004). It is now also timely to plan aquaculture development concomitantly to the implementation of the EU Marine Spatial Planning Directive (MSP -2014/89/EU; European Community, 2014), to ensure its integration within related planning, optimizing use of space and reducing conflict between multiple activities.

Over the past decades in France, offshore aquaculture has been considered an opportunity to develop the shellfish industry at the national level, using both on- (cages) and off-bottom (longlines) cultivation techniques (Goulletquer and Héral, 1997). In a similar way to French offshore finfish aquaculture, which has not been allocated any additional space in over 30 years, the development of offshore shellfish cultivation has been rather limited. The first initiatives to develop offshore longlines were associated with the scallop pre-growing facilities deployed in Brittany as part of a comprehensive management plan to improve scallop production in the early 1980s (Buestel et al., 1982). Similarly, mussel longlines were deployed to promote mussel spat settlement, which had become irregular in the late 1980s along the southwestern Atlantic coast (Prou and Goulletquer, 2002). The deployment of spat collectors in subtidal areas was found to be an effective response to this issue, and mussel farmers also reported enhanced mussel growth on those long lines, prompting a new type of cultivation (*'moules de cordes'*) targeting the production of fully grown, marketable-sized mussels. The combined success of this offshore mussel cultivation, and the coinciding reduction in oyster growth in overstocked intertidal areas, prompted a similar response by oyster farmers, who initiated experiments to assess oyster growth in unexploited offshore areas. The first experimental leasing grounds made use of bottom-cage cultivation (Goulletquer and Le Moine, 2002). In addition to potentially adding to total cultivated tonnage, there was also the idea that production offshore would lead to a reduction in the overall stocking density within intertidal areas, thereby improving food availability so as to recover oyster growth there. However, in contrast to the intertidal areas used predominantly for oyster culture since the 19th century, which are widely accepted for this purpose, expansion to offshore sites is challenging due to conflicting potential uses and users of the space, including fishermen and recreational sailing.

The identification and selection of suitable sites is the first crucial step in moving shellfish aquaculture offshore (Benetti et al., 2010; Falconer et al., 2019). Finding suitable new offshore sites to expand aquaculture requires the consideration of a combination of different criteria and limitations, including the locations of conflicting uses (Dempster and Sanchez-Jerez, 2008). An essential prerequisite is the ability to obtain sufficient growth, survival, and a good product condition. Bivalves are suspension-feeders that exploit the organic fraction of suspended particulate matter (SPM) (Cranford et al., 2011), and phytoplankton is expected to be their main food source in the offshore environment. However, this resource is characterized by strong temporal variability (seasonality and interannual variation) and spatial patchiness. Moreover, offshore sites may still be affected by coastal turbidity in turbid plume regions, and SPM concentrations are known to negatively affect bivalve ecophysiological responses (Barillé et al., 1997; Hawkins et al., 1999). Investigating the impact of spatiotemporal variability of seawater organic and inorganic particles, as well as of water temperature through ecophysiological growth modelling allows potential growth to be considered in optimal aquaculture site selection in the offshore environment, as well as assessment of possible gains in productivity over intertidal farming.

Mapping potential areas for shellfish aquaculture must also consider the locations and distributions of environmental and socio-economic constraints (Brigolin et al., 2017; Lester et al., 2018; Longdill et al., 2008) related to industrial development (energy, sand extraction), commercial and recreational shipping, fisheries, and the protection of marine biodiversity (European Union Marine Strategy Framework Directive, European Community, 2008), as well as seawater quality (EU 2000 Water Framework Directive). Some of these are known or are expected to fully preclude aquaculture, and some to have either a positive or negative effect where cultivation remains possible. Assessments of the potential for offshore production must also consider the necessary technological and infrastructural developments (Goseberg et al., 2017). Beyond a certain scale, this may not be affordable for small companies, which represent the majority of European aquaculture companies. Of the greater than 14,000 aquaculture enterprises in the EU27, almost 90% are micro-enterprises, employing less than 10 employees (STECF, 2016). Even if environmental and socio-economic conditions are suitable for offshore culture, farms can only be established if producers are willing to set up sites in these new locations. Consequently, this work considers the perspective of small companies producing Pacific oysters (*Crassostrea gigas* (Thunberg)) with an annual production between 30 and 60 tons in the intertidal area of the French Atlantic coast. Some of these companies are run by a new generation of educated young farmers interested in offshore bivalve aquaculture that would be compatible with their investment capacity.

The main objective of this study was to highlight the potential for and limitations to offshore Pacific oyster cultivation on the French Atlantic coast, and to proceed to optimal site selection using a variety of data sources. We investigated whether there is sufficient suitable space available to grow oysters in the offshore environment using low-cost bottom cages, given the various spatial constraints and growth conditions. Data from an experimental offshore site were compared with those from an intertidal site currently exploited for the oyster cultivation, and were used to calibrate ecophysiological growth modelling, using satellite remote sensing data as input. Oyster spat growth was then mapped for an area characterized by highly variable turbidity and food (i.e., phytoplankton) availability. A spatial multi-criteria evaluation (SMCE) of the feasibility and suitability of offshore cultivation was then carried out through a GIS approach combining technical, environmental, and socio-economic factors, as well as modelled oyster growth. This work relied on interaction with and input from oyster producers running small companies in the intertidal area, and interested in offshore cultivation. The constraints they have encountered were considered in the SMCE, which was complemented by a summary of the administrative process in France, which would be required of them to obtain a license for offshore cultivation.

2. Materials & methods

2.1. Study site

Located southeast of the Loire estuary, Bourgneuf Bay is a macrotidal embayment with a tidal range varying from 2 to 6 m during neap and spring tides respectively. The bay is connected to the ocean and to the Loire estuary by a 12 km opening to the northwest, and is enclosed

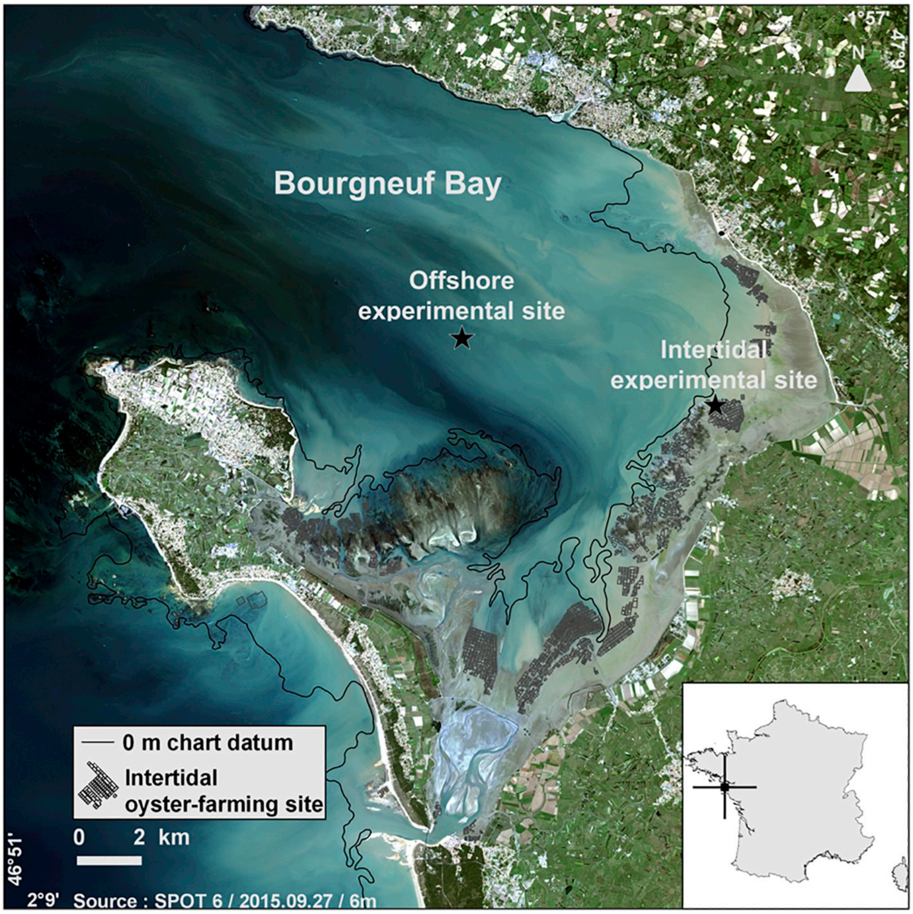

Fig. 1. SPOT satellite imagery of Bourgneuf Bay (France) at low tide. Offshore and intertidal experimental sites are indicated, as are the delimitation of the intertidal zone and existing oyster-farming sites within this zone. The decreasing turbidity toward the offshore entrance of the bay can be observed.

in the southwest by the island of Noirmoutier (Fig. 1). The surface area of the bay is 340 km^2, of which the 100 km^2 of intertidal area is comprised of mudflats and rocky areas. All intertidal areas belong to the Public Maritime Domain, which is mainly controlled by the State Directorate of Maritime Affairs. Bourgneuf Bay is a site of extensive *C. gigas* aquaculture, with 5330 metric tons produced in 2012 (Agreste, 2015). The bay belongs to the administrative region of Pays de la Loire, which was the third highest oyster-producing region in France in 2012, producing 7122 metric tons (i.e. 9% of the national production; Agreste, 2015). The standing stock biomass in Bourgneuf Bay was estimated to be approximately 46,000 tons two decades ago (Haure et al., 2003) and has not been updated since. Additional oyster biomass has also resulted from wild, feral oyster beds, due to increasing annual oyster spat settlement concomitant to seawater temperature increase (Le Bris et al., 2016). The lack of knowledge on the current standing stock is a limitation with respect to estimating the biological carrying capacity of the bay (McKindsey et al., 2006). The productivity estimated using the available data, taken as the ratio of production to standing stock, is 11%. This is likely an underestimation, but Bourgneuf Bay was nonetheless among the least productive by this measure compared with other French shellfish production areas (Fleury et al., 2018). This study evaluated the offshore area extending beyond Bourgneuf Bay into the Bay of Biscay between the latitudes 47°20′32”N and 46°41′27″S and the longitude 2°58′25″ W for a total surface of ca. 5000 km^2.

There are currently 283 farms in Bourgneuf Bay, most of which are organized as family businesses, selling their product within the local market (Guillotreau et al., 2018). The most frequent legal status is individual companies (75%), employing two to three full time workers on average, and with a production of between 30 tons (direct sales in local markets) and 60 tons (sold to a retailer) of Pacific oysters. A typology of these small companies revealed a duality between nearly-retired farmers with no investment dynamics and young farmers with their businesses in a growth phase and who appear to have a better understanding of market-related and regulatory hazards (Le Grel and Le Bihan, 2009). The latter category of farmers is interested in offshore bivalve aquaculture compatible with their investment capacity. At present, oyster farmers can access their leasing grounds at low tide, with flat-bottomed boats or tractors. Oysters are traditionally grown in plastic mesh bags set on 3 × 1 m metal trestles, at a height of 1 m off the bottom, and with a maximum of 20 kg per bag (Fig. 2 A). The average production cycle is three years for diploid oysters. In this work, we do not consider the production of triploid oysters.

The bay is highly turbid, with annual mean SPM concentration ranging from 27 to 129 mg L^{-1} from south to north, and maximum values exceeding 1000 mg L^{-1} during spring tides (Gernez et al., 2017). This high turbidity has a negative impact on oyster growth and reproduction (Dutertre et al., 2009; Barillé et al., 2011), which in turn contributes to the relatively slow growth of oysters in the bay. Satellite images have revealed a marked decreasing turbidity gradient from the intertidal areas to the center of the bay (Gernez et al., 2014).

2.2. Oyster growth experiments

Together with a regional organization that supports innovation in the shellfish industry (Syndicat Mixte pour le Développement de l'Aquaculture et de la Pêche en Pays de la Loire (SMIDAP)), a group of interested growers decided to test and compare oyster spat growth in bottom cages within and outside of the currently-exploited intertidal zone to demonstrate the potential suitability of the offshore

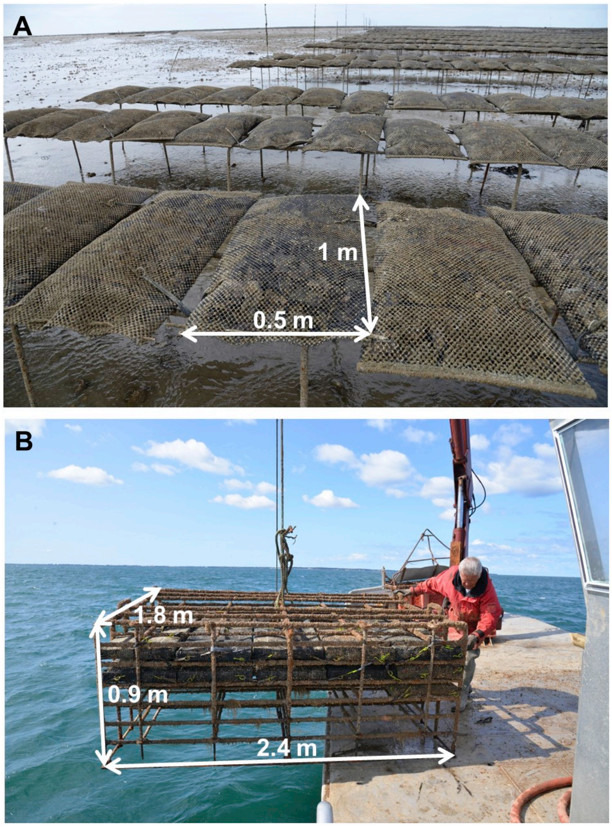

Fig. 2. (A) Traditional intertidal oyster cultivation in plastic bags on metal trestles, and (B) the bottom cage used at the offshore experimental site.

environment for oyster cultivation (Fig. 2 B). For a typical three-year cycle in intertidal conditions, this phase corresponds to the pre-growing period, during which spat are left to grow for between six months and a year depending on the interannual variability. This pre-growing period ends when oysters reach approximately a 3 cm shell length. It is followed by the final year of the cycle, the grow-out phase, during which the oyster will reach a marketable size.

In May 2008, diploid hatchery-born Pacific oyster spat with a mean length of 15.5 mm (Standard deviation = 1.9 mm; $n = 30$) were placed in plastic mesh bags (800 individuals per bags) and deployed in the cages at each experimental site. Each cage measured 2.4 × 1.8 × 0.9 m, with steel bars organized in rows to place the mesh bags horizontally. The surface in contact with the bottom substrate was $4.32\,\mathrm{m}^2$ and the cage weight was 600 kg. Sixty mesh bags with a 6 mm mesh size were set up in each cage, with the last two rows of the cage left empty to allow water circulation. Each cage was loaded with the equivalent of 10 metal trestles (one trestle = 3 m long) traditionally used in the rack cultivation of the intertidal zone (Fig. 2 A). The offshore cage was immersed in Bourgneuf Bay at a depth of between 5 and 10 m and located within five nautical miles a harbor used by oyster farmers (47° 2′ 28.8″N, 2° 8′ 55.9″W). The intertidal cage was installed at bathymetry of 2 m, corresponding to an immersion time of 88% (47°1′ 34.2″N, 2° 2′ 11.5″W); Fig. 1). A boat equipped with a crane was used to deploy the cages both offshore and intertidal. A significant advantage of using the cage over a longline setup is the possibility to move it between sites for a combined off-shore/intertidal growth cycle. This allows optimal use of space to maximize production. Once a month three plastic mesh bags were randomly sampled from the offshore and the intertidal cages, from a total of 60 mesh bags per cage. From each bag 10 oysters were sampled, removed from the bag and their shell length and total weight was measured. These were considered as pseudoreplicates and averaged. The sample size considered for the statistical analysis was $n = 3$. A *t*-test was used to test the null hypothesis of no difference in growth between the off-shore and the intertidal oysters.

2.3. Dynamic energy budget model and remote sensing data

For site selection and spatial planning, spatially explicit information is needed. Satellite remote sensing image data were therefore coupled to oyster ecophysiological modelling to map oyster growth and to identify the most suitable offshore areas. Dynamic Energy Budget (DEB) theory describes the uptake and use of energy by an organism throughout its lifecycle (Kooijman, 2010). DEB theory was applied here to *C. gigas* (Pouvreau et al., 2006; Thomas et al., 2016), by considering three forcing variables: sea surface temperature (SST), chlorophyll-*a* (Chl-*a*) concentration as a proxy for food availability, and suspended particulate matter (SPM) concentration. The overall scheme, equations, and parameters of the Pacific oyster DEB model are described in detail in Thomas et al. (2016). All parameter values except the Chl-*a* and SPM half saturation coefficients (Xk and Xk_y respectively) were based on the studies performed by Bernard et al. (2011), which refined the processes of energy allocation to gametogenesis and resorption, and by Thomas et al. (2016), which introduced SPM as a forcing variable in order to take the influence of high SPM concentrations on the ingestion function into account. Here, the values of Xk and Xk_y were calibrated using the in situ offshore oyster growth data described in Section 2.2. The agreement between field observations and DEB model simulations was quantified with the coefficient of determination of the linear regression between the two and the root mean square error (RMSE).

The forcing variables used to simulate oyster growth using the DEB model were obtained from a 16-year (1998–2013) archive of satellite remote sensing data. Daily SST data were obtained from the advanced very high-resolution radiometer (AVHRR) from 1986 to 2009 at a 4 km resolution, and from the group for high resolution sea surface temperature (GHRSST) from 2010 to 2013 at a 1 km resolution (Dash et al., 2012). Daily Chl-*a* and SPM concentrations were obtained using merged SeaWiFS, MODIS, and MERIS data at 1 km spatial resolution, as described in Saulquin et al. (2011), retrieved using a regional algorithm specifically designed for the Bay of Biscay (Gohin et al., 2005; Gohin, 2011). Images were averaged over the 16 years' time-series to produce the Spatial Multi-Criteria Evaluation figures. In this macrotidal system and at the depth of the offshore cage (5–10 m), the water column is considered homogenized by the tide and wind mixing, and we assumed that surface observations represent bottom conditions sufficiently. Simulations were run from May 1st to August 31th for each of the 16 years, for spat with an initial length of 1.55 cm, total weight of 0.28 g, and dry flesh mass of 0.05 g. This timing corresponds to the dates of the in situ experimental measurements. The final shell length (L; cm) from each year was used to allometrically calculate and map the mean final total weight (TW; g) using a regionally calibrated relationship ($TW = L^3 * 0.076$; g). The interannual coefficient of variation (standard deviation/mean) of the final total weight was also calculated and mapped as a proxy of interannual growth variability.

2.4. Suitability criteria and spatial multi-criteria evaluation

Spatial Multi-Criteria Evaluation (SMCE) is a hierarchical process commonly used in spatial planning and management, notably for aquaculture site selection (Brigolin et al., 2015, 2017; Falconer et al., 2016; Longdill et al., 2008; Radiarta et al., 2008). SMCE aims to first identify areas within which aquaculture would not be feasible at all, excluding those areas within which precluding conflicts exist, and to subsequently identify optimal areas where aquaculture would be feasible using a suitability index. In this study, 23 spatialized suitability criteria were inventoried in the offshore region of Bourgneuf Bay, within 20 nautical miles of the coast. In accordance with Brigolin et al. (2017), the SMCE was carried out in three steps: (1) all data were scaled to a common spatial grid and values were normalized for each criterion; (2) each criterion was weighted through the application of coefficients; and (3) all

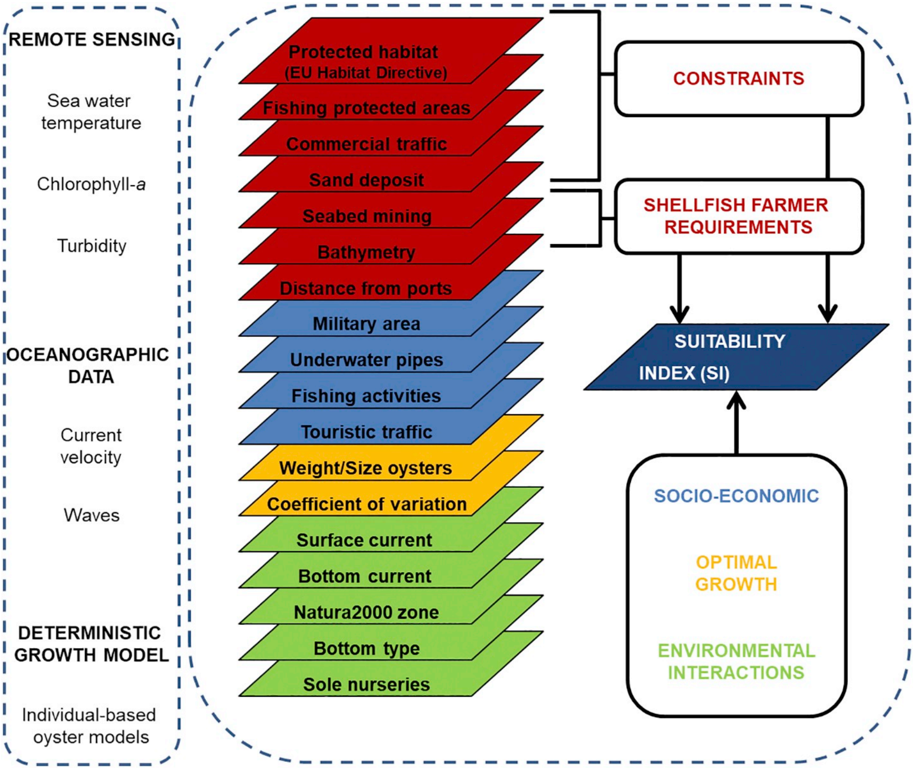

Fig. 3. List of variables identified included in the SMCE site selection. Constraints and shellfish farmer requirements are represented as red layers, and correspond to boolean data. The Intermediate Level Criteria (ILC) include the socio-economic data in blue, optimal growth output in yellow, and environmental criteria in green. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

weighted criteria were aggregated to obtain the final suitability index. As in Radiarta et al. (2008), Longdill et al. (2008), and Brigolin et al. (2017), the criteria database was organized into macro-categories, referred to as Intermediate Level Criteria (ILC; Fig. 3), which correspond to the feasibility (constraints and shellfish farmers requirements), socio-economic criteria, optimal oyster growth, and environmental criteria layers. For each ILC, a score was computed and mapped.

The feasibility map was obtained by aggregating the specific requirements noted by the shellfish farmers, as well as constraint criteria that would preclude aquaculture at a given location, namely the presence of protected habitat (via the EU Habitat Directive), protected fishing areas, commercial traffic channels, sand deposit sites, and seabed mining sites. The potential area for aquaculture was in this study strongly constrained by technical specifications highlighted by the shellfish farmers: 1) a 5 to 10 m bathymetric range for aquaculture cages and 10 to 20 m for longline aquaculture, 2) the locations of harbors which are equipped to manage specific equipment (cultivation structures and boats) and the regulatory distance of 5 nautical miles (from those ports or coasts), beyond which expensive changes to their professional boat license and certification would be required. The data were obtained from national and regional datasets from public institutes (IFREMER, DREAL, SHOM) or professional organizations (Shellfish producers (SPRC), fisherman (RFMA) see Glossary in S2 for acronyms). They were standardized in Boolean format, with 1 indicating a location where it would be possible to develop offshore aquaculture (i.e., all aforementioned requirements were met and no constraints were encountered) and 0 where aquaculture would not be possible (i.e., at least one of the requirements was not met or at least one constraint was encountered).

Within the areas where aquaculture was found to be feasible, a suitability index was calculated based on socio-economic variables (SE), optimal growth (OG), and environmental criteria (E). SE variables are the presence of a military zone, for which licensing of leasing grounds is partially restricted, the existence of underwater pipes or cables, which are favorable to potential aquaculture, since no fishing activity takes place at these locations, the occurrence of fishing activity (i.e., bottom trawling, pelagic trawling, or net fishing), and touristic use. OG data refers to the mean annual oyster growth obtained through DEB modelling, and its interannual variation, as described above. Faster mean growth is obviously favorable, whereas lower interannual variability is sought, so as to reduce economic uncertainty for farmers. As temperature, Chl-a, and SPM concentrations have been integrated as input into the growth model, they are therefore not considered separately as has been done elsewhere (e.g., Brigolin et al., 2017). The environment criteria were bottom and surface currents, protected Natura2000 areas, bottom type (i.e., rocks, mud, sand, or pebbles), and the presence of sole nurseries.

All vector and raster data were spatially standardized to a uniform ~1 km × 1 km grid, corresponding to the highest spatial resolution of the satellite data used as input into DEB oyster growth modelling. The quantitative criteria (e.g., mean oyster weight, currents) were then normalized linearly between 0 and 1 by subtracting the minimum value encountered in the whole study area, and dividing this by the full range of the values encountered (Eastman, 1999). For the qualitative criteria (e.g., bottom type, presence of fishing activity), a score from 0 to 1 was assigned on a categorical scale (0 = highly unsuitable, 0.25 = unsuitable, 0.5 = intermediate, 0.75 = suitable, and 1 = very suitable) informed by the literature and expert opinions (Supplementary Fig. S1).

The data aggregation into ILC categories was carried out by weighting all criteria according to their relative importance (Table 1). Parameters which appeared to be more restrictive for aquaculture activity (e.g., fishing and tourism pressure in the SE layer) were weighted more heavily than the less restrictive layers (e.g., Military and underwater pipes areas in the SE layer). The final step in the suitability index calculation considered four different scenarios, which are summarized in Table 2: (1) no priority attributed to the different ILC categories (i.e., all three were considered to be of equal importance; a weighting of 33% assigned for all); (2) priority given to maximizing the speed of oyster growth (75% weighting for OG and 12.5% for both SE and E); (3) priority given to environmental constraints (75% weighting for E and 12.5% for both OG and SE); and (4) priority given to social and economic requirements (75% weighting for SE and 12.5% for both OG and E). The resulting suitability index was scaled from 0 to 1 for the four scenarios, and divided into five classes: 0–0.25 (very low suitability), 0.25–0.35 (low suitability), 0.35–0.5 (intermediate suitability), 0.5–0.75 (high suitability) and > 0.75 (very high suitability).

Table 1
Assigned weighting coefficient within their respective Intermediate Level Criteria (ILC).

ILC	Criteria	Scale	Weighting coefficient
Socio-Economic (SE)	Military areas	–	0.1
	Underwater pipes	–	0.1
	Bottom trawling	–	0.3
	Pelagic trawling	–	0.1
	Net fishing	–	0.1
	Touristic traffic	–	0.3
Optimal Growth (OG)	Total oyster weight	1 km	0.75
	Coefficient of variation	1 km	0.25
Environment (E)	Bottom current	500 m	0.1
	Surface current	500 m	0.1
	Natura 2000 zone	–	0.4
	Bottom type	–	0.3
	Sole nurseries (number of individuals)	–	0.1

2.5. Governing systems and administrative process summary

Oyster producers are organized at the regional level through a Shellfish Production Regional Committee, which contributes to the implementation of national laws and regulations, including the regional management plan (See Glossary, Supplementary Fig. S2). There are seven regional committees in France, which fall under the umbrella of a National Shellfish Council (Conseil National de la Conchyliculture (CNC)), representing the shellfish industry on national or European committees. The prevailing constitutional law governing aquaculture concerns access to intertidal farming sites and to offshore areas. Leases are granted to oyster farmers by the state to parts of the public maritime domain and cannot be traded, as the public domain is unalienable. Farming sites are usually leased for a period of 30 years and should be in compliance with several technical specifications (e.g., type culture, rearing density). In this work, we synthetized the steps of the administrative process to request a lease for an offshore leasing ground, with the help of the Maritime Affairs from the State Directory of Land and Sea (see glossary). Using real examples of growers from the Bourgneuf Bay and Marennes-Oléron Bay, the largest oyster production site in Europe (Goulletquer and Le Moine, 2002), the main barriers within this process were highlighted.

3. Results

3.1. Oyster growth

3.1.1. Measured intertidal and offshore oyster growth

At the end of the in situ experimental period, the oyster spat in the offshore cage showed significantly higher growth, in terms of both weight and length, compared to those in the intertidal cages (*t*-test $p < .05$; Fig. 4). In three months, the mean total weight was almost three times higher offshore than in the intertidal zone (13.6 g vs. 5.4 g), while the shell length reached 5.3 cm offshore and only 3.6 cm in the intertidal zone. The 3 cm threshold, corresponding to the end of the pre-growing phase (year two of the cycle), was reached a full month earlier for oysters in the offshore cage. Mortality was 10.3% offshore and 68% in the intertidal zone.

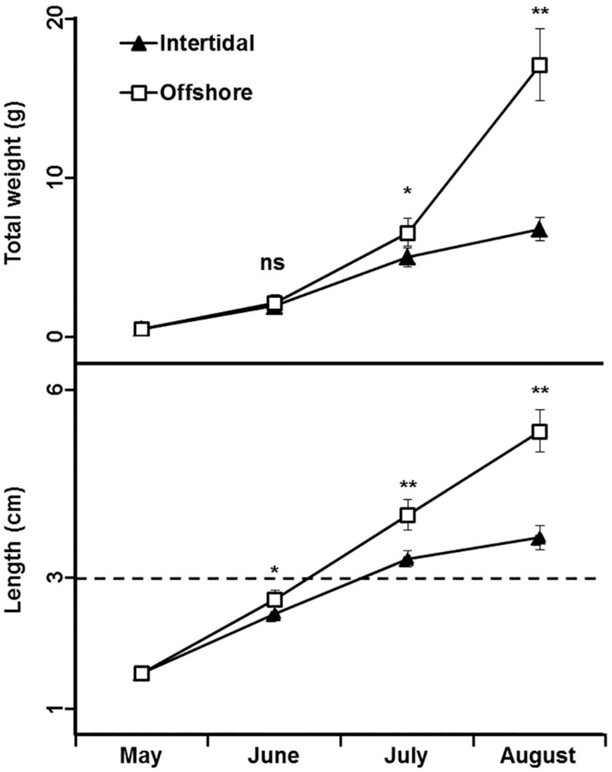

Fig. 4. Comparison of intertidal and offshore growth measurements of *C. gigas* spat; (A) total weight (g) and (B) shell length (cm).

3.1.2. DEB-modelled and mapped offshore oyster growth

The in situ offshore growth data described above were used to calibrate the half-saturation coefficients of the DEB model using satellite input data, with values of $X_K = 2.3$ and $X_{KY} = 5$ resulting. There was a good fit between modelled and observed growth, with a correlation coefficient of 0.95 for total weight ($P < .01$; RMSE = 1.47 g), and 0.89 for shell length ($P < .01$; RMSE = 0.73 cm). The DEB model was then run using the 16-year satellite data time-series as input to obtain daily spatial distribution maps of oyster spat shell length and weight from May 1 through August 31 for each year from 1998 to 2013, from which the 16-year mean final growth and coefficient of variation were calculated and mapped (Fig. 5). This period covering spring/summer corresponds to the primary growing season.

A marked spatial structure was revealed in both parameters, characterized by low growth areas inside Bourgneuf Bay in the vicinity of the intertidal area, and higher growth areas in front of the Loire estuary and along the northern coast (Fig. 5A). Higher growth areas were also associated with lower growth variability, as estimated by the coefficient of variation (Fig. 5B). Beyond the 20 m isobath, growth was lower and

Table 2
Relatively suitable areas for offshore oyster aquaculture for each scenario. The suitability index is divided into 5 classes: very low suitability (0–0.25), low suitability (0.25–0.35), moderate suitability (0.35–0.5), high suitability (0.5–0.75), and very high suitability (0.75–1).

Priority	Weigth			Available area		Relative suitability Surface (%)			
	Growth	Environment	Socio-economic	(Feasibility)	Very low	Low	Intermediate	High	Very high
No priority	0.33	0.33	0.33		0.3	1.4	16.7	**81.1**	0
Environment	0.125	0.75	0.125	800 km^2	0	0	32.9	**64.6**	2
Socio-economic	0.125	0.125	0.75		0.5	4.6	**45.1**	32.7	16.7
Optimal growth	0.75	0.125	0.125		1.6	6.6	25.2	**35.1**	31.1

The class with the largest area is indicated in bold.

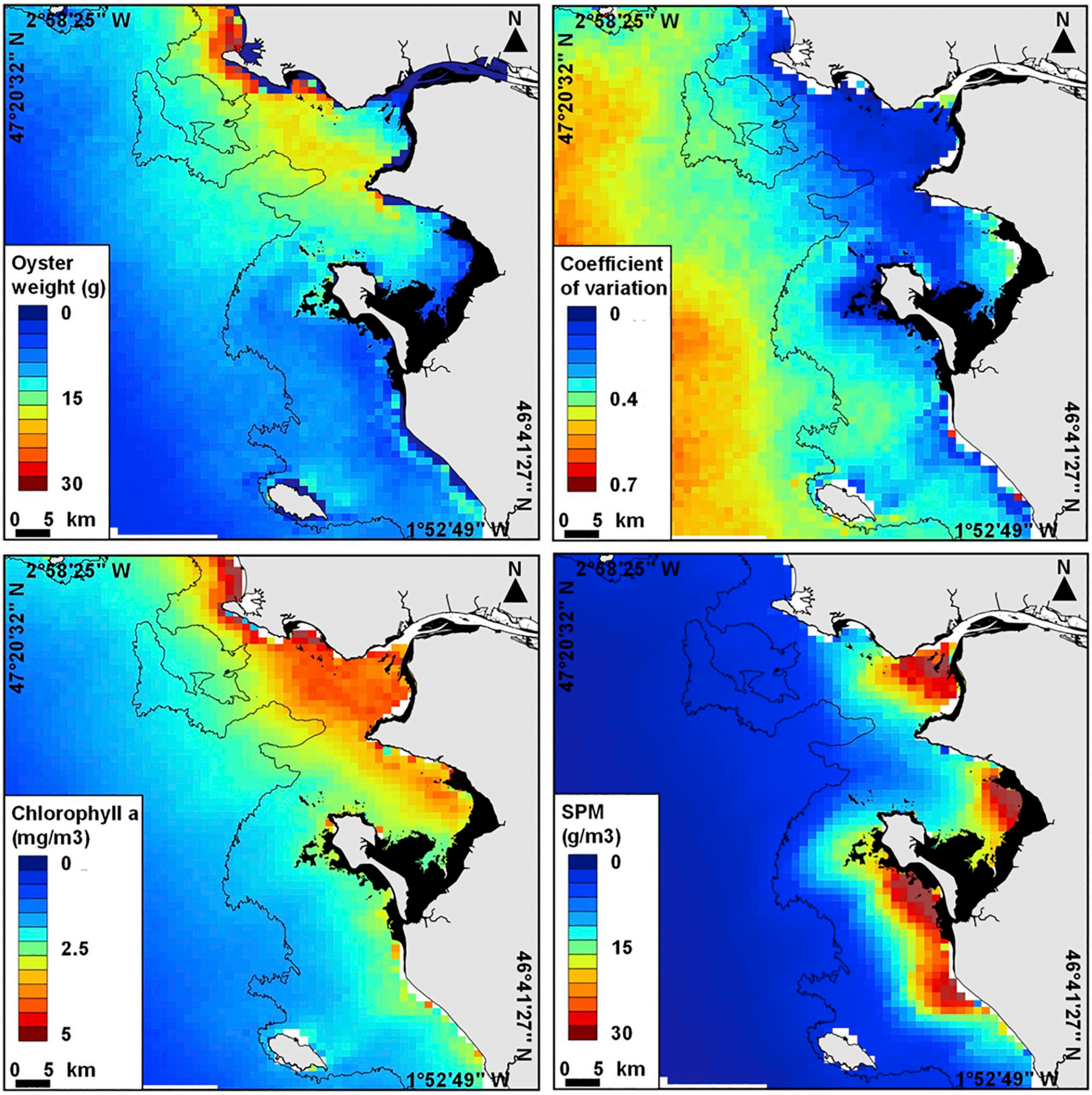

Fig. 5. Dynamic Energy Budget simulation maps of mean oyster growth (final weight) from May to August (A) and interannual coefficient of variation (B) of total mass calculated using 16 years of simulations; Chl-a and (C) SPM (D) concentration maps represent the respective means of all days of all 16 years. The black line represents the 20 m isobath.

more variable. Higher growth areas corresponded expectedly to both high Chl-*a* (Fig. 5C) and low SPM concentrations (Fig. 5D). There was a seaward gradient in Chl-*a*, decreasing from the coast offshore, with a northwest/southeast spatial structure inside the bay. The higher Chl-*a* in the northern part of the bay could not be exploited by the oysters because of the measured concurrent high SPM concentration adjacent to intertidal mudflats (Fig. 5D). The turbid plume detected at the mouth of the Loire estuary was also found to be a low growth area.

3.2. Suitability and spatial site selection

All of the data used in the SMCE analysis revealed that many constraining activities or uses already take place or are located in the nearshore region of Bourgneuf Bay. In terms of other activities, dredging occupies the largest area, but this is further offshore where there are other constraints related to the Loire estuary, occupying smaller surfaces: navigation channel, shipping waiting area, sediment deposits from the river (6A). Regarding the requirements identified by shellfish farmers, more of the area is within the depth range for longlines compared to cages (Fig. 6B). There are many harbors so access is not one of the main restricting factor, as well as the regulatory distance of 5 nautical miles (from those ports or coasts) (Fig. 6C). Part of the socio-economic data concerned fishing activity, which takes place throughout the entire study area within 10 nautical miles from the coast. However, within these fishing areas, certain zones are closed to fishing during the fish reproduction periods or restricted to specific boat categories (Fig. 7A). Moreover, net fishing and pelagic trawling were considered to be less of a hindrance to aquaculture than bottom trawling, which is a conflicting activity for bottom cage aquaculture particularly. The military zone along the coast can be used for aquaculture, but is occasionally restricted during the French navy firing exercises (Fig. 7B). The relative importance of tourism activities, such as sailing, was included by considering the available port capacity within a six nautical miles limit for 80 to 90% of leisure boats, and can be in strong conflict with shellfish farms. Areas with the presence of underwater pipes are restricted for fishing activities, but can be used for offshore aquaculture since bottom trawling is prohibited in these areas, thereby avoiding conflict with fishing.

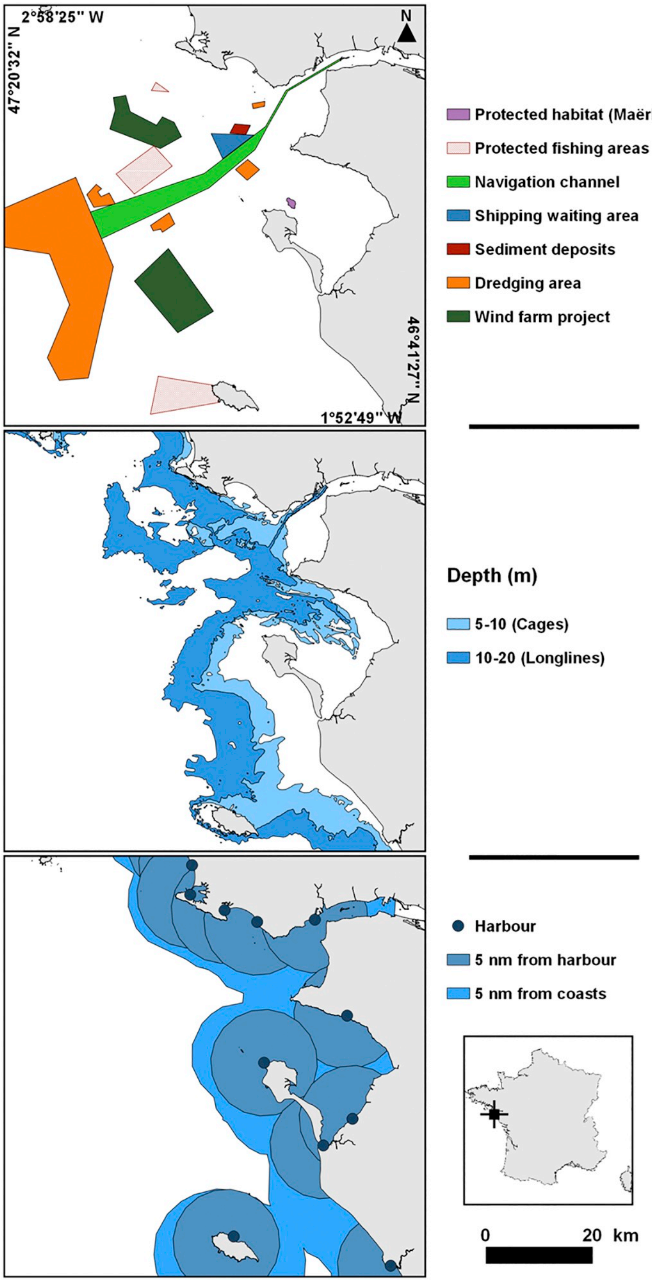

Fig. 6. Maps (A) of various types of spatial uses identified which are constraints to oyster production, (B) of bathymetric restrictions for offshore cage (must be located in 5–10 m depth) and longline (must be located in 10–20 m depth) oyster production, and (C) indicating areas within five nautical miles of the coast (light blue) and of existing harbors (dark blue) which are prerequisites of the oyster producers, areas beyond 5 nautical miles are constraints. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

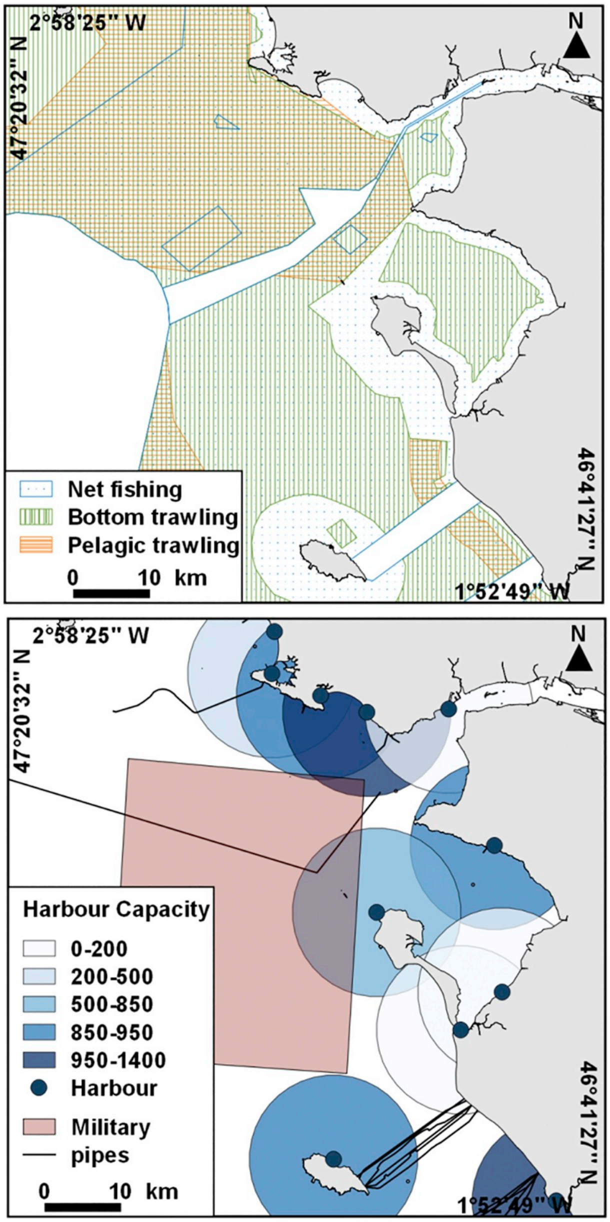

Fig. 7. Maps of the main socio-economic information identified for fishing activities (A) and for military areas, underwater pipes, and tourism activities (B).

Over the 5000 km^2 study area, 800km^2 were feasible for offshore aquaculture activities after aggregating the constraint data (Fig. 8A). Shellfish farmer requirements were the most restrictive layers. The environmental ILC ranked between "intermediate" and "very suitable", with lower index values close to the coast due to the presence of Natura2000 and rocky areas (Fig. 8B). Socio-economic data revealed that most of the potential conflicts were located close to the coast, especially where fishing activities are combined with high tourism density (Fig. 8C). For the optimal growth ILC, the best values (i.e., green areas; Fig. 8D) were found in association with high Chl-*a* concentration (due to the nutrient-rich inflow of the Loire estuary) and relatively low SPM concentration. The lowest index values were found in Bourgneuf Bay nearest the coast, where Chl-a concentration was very high, but SPM concentration was too high, negatively affecting oyster ecophysiology. Low growth values were also found in offshore regions characterized by low Chl-*a* and SPM concentrations, due to the seaward dilution of suspended particles in the water column, and resulting in food resource availability too low to sustain oyster growth (Fig. 8D).

Final suitability index maps were produced for the four different scenarios (i.e., without priority, priority to the environment, socio-economic priority, and priority to optimal growth; Fig. 9), with relatively suitable areas summarized in Table 2. Strong spatial differences were observed between the four scenarios, with generally high suitability (81.1% of the area scored between 0.5 and 0.75) when the same priority was given to all layers (Fig. 9A). For the environmental priority, the overall suitability index decreased slightly and the suitable areas were more fragmented, with only 64.6% of the area scoring high suitability (0.5–0.75) and 32.9% scoring intermediate suitability (0.35–0.5; Fig. 9B). The lowest suitability index values were found

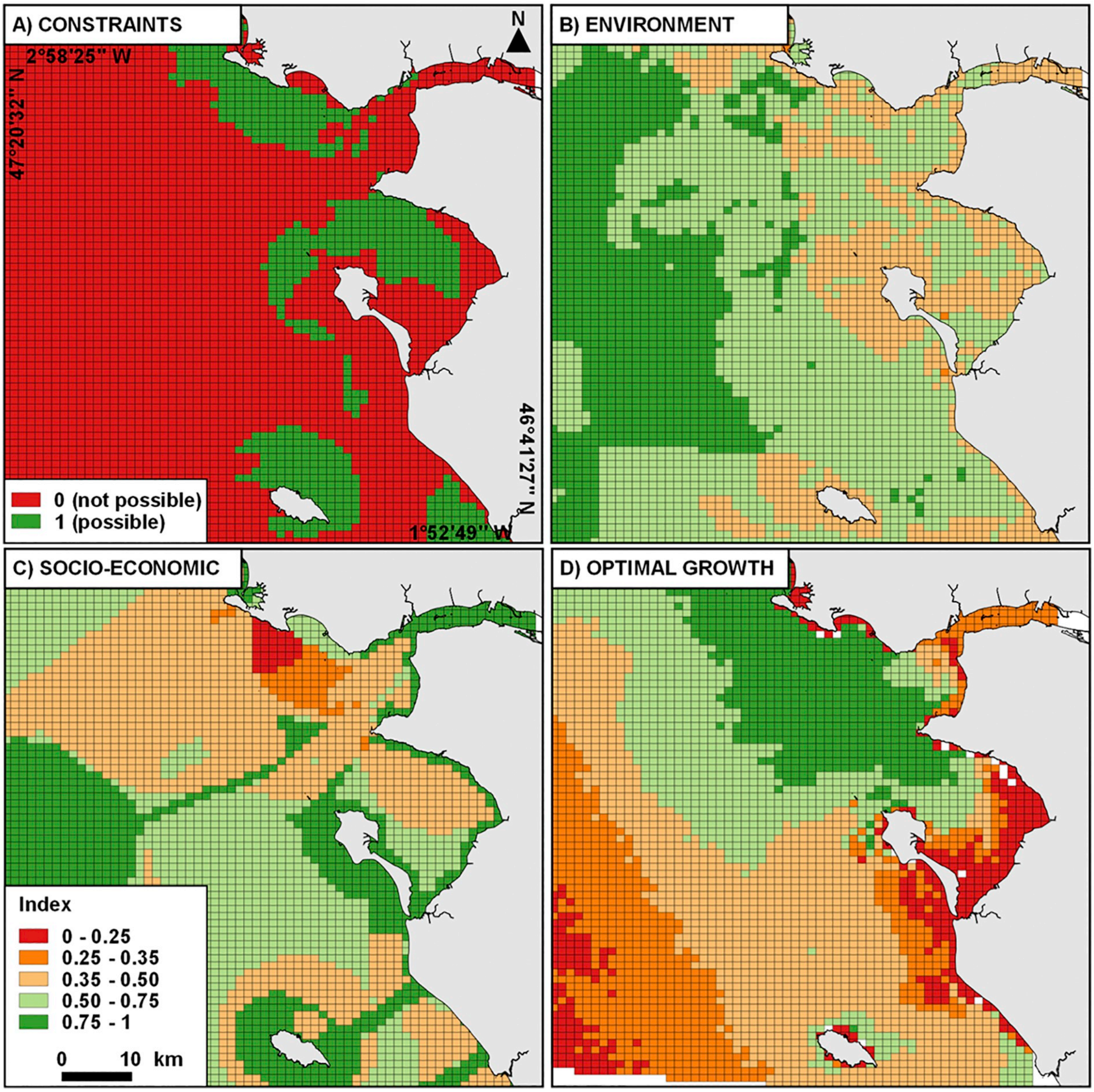

Fig. 8. (A) SMCE results for the feasibility map, combining constraints and shellfish farmer requirements in a boolean format (zero for unavailable aquaculture areas and one for available aquaculture areas). (B), (C), and (D) represent SMCE result maps for the three ILC, Environment, Socio-Economic criteria, and Optimal Growth respectively. Suitability range: 0–0.25 very low suitability, 0.25–0.35 low suitability, 0.35–0.5 intermediate suitability, 0.5–0.75 high suitability, 0.75–1 very high suitability. Earth-observations images were averaged over a 16 year time-series to produce the SMCE figures.

when priority was given to socio-economic activities, with most of the area (45.1%) ranked in the intermediate suitability class, and only 32.7% falling in the high suitability class (Fig. 9C). Finally, when optimal oyster growth prioritized, 31.1% of the total available area was classified with a very high suitability, 35.1% high suitability, and 25.2% intermediate suitability (Fig. 9D).

3.3. Administrative process for lease application

The steps of the administrative process to request a lease for an offshore ground are summarized in Fig. 10. A glossary is included as supplementary material, detailing all acronyms used and describing the different actors (Supplementary Fig. S2). The process falls into three overarching steps: first, experimentation is required to show the biological and technical interest, and the environmental suitability of an offshore project. This first step begins at the local level of the Shellfish Production Regional Committee (SPRC), which must collectively submit the request. The application is then processed by Maritime Affairs to check for regulatory navigational and environmental issues, followed by a public consultation, and then further processed by a regional Marine Cultures Committee (MCC) before being granted the exploitation authorization by the State representative. The MCC assesses the application in light of the regulatory context and scientific recommendations, but also from a social point of view, and in compliance with the overall professional organization.

The second step corresponds to defining the area that is requested for offshore farming, which must be consistent with strategic documents established by the Interregional Administration of the Sea (IAS). At this step, the geographic location and the technical characteristics of potential shellfish farming leases must be integrated into what is known as the structural plan document (SPD). This is also submitted to the Environmental Authority (EA), which will conduct an environmental evaluation of the SPD update. In specific cases, such as large aquaculture projects, an Environmental Impact Assessment (EIA) should be

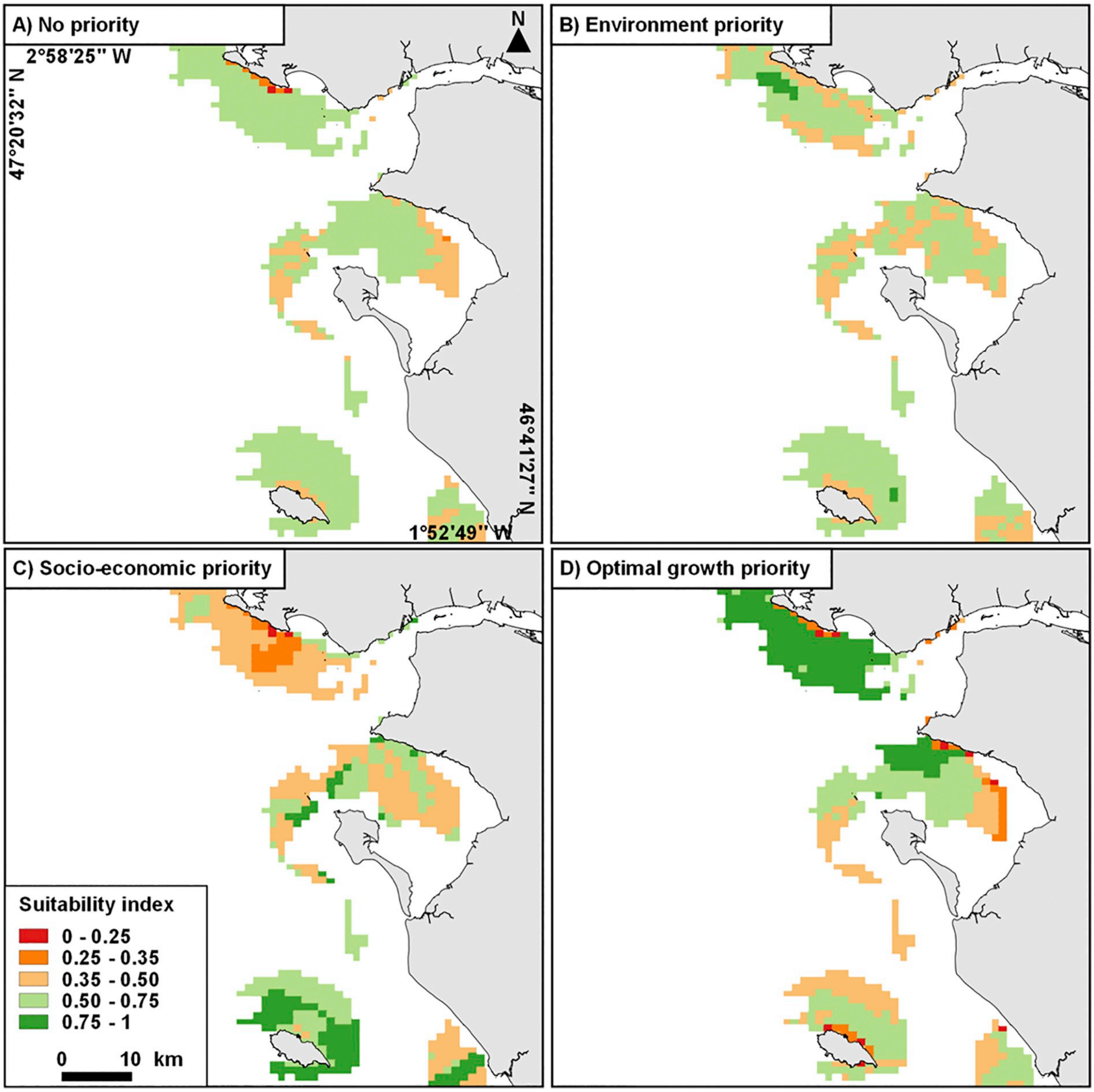

Fig. 9. Suitability index maps for the four scenarios: (A) without specific priority (33% weighting for all ILCs), (B) priority to Environment, (C) priority to Socio-Economic activity and (D) priority to Optimal Growth, whereby prioritized ILCs receive a 75% weighting, and those not prioritized in a given scenario receive a 12.5% weighting.

provided by the applicant in compliance with legal requirements arising from the French Water Law to assess potential effect on seawater quality. Step 2 ends with a public consultation.

Step 3 comprises the submission of a request by an oyster farmer for an offshore lease within the area defined during step 2. There is another administrative verification by Maritime Affairs, another public consultation, validation by the prefect (State representative), and a final examination of the request by the regional MCC. In Fig. 10, the main barriers to farmers encountered within this process have been identified in red.

4. Discussion

4.1. Offshore versus intertidal oyster growth

To ensure the results would be relevant for the French oyster industry and could support planning and management decisions, producers were consulted in each stage of this study. Consequently, as suggested by the producers, we paid particular attention to the pre-growing phase (first year) of the typical three-year growing cycle for diploid oysters grown in the intertidal area. The three times higher growth of *C. gigas* spat observed for subtidal vs. intertidal conditions was consistent with results from another offshore experiments performed in Marennes-Oléron Bay to the south (Mille et al., 2008). This faster pre-growing phase could reduce the time needed to complete the overall production cycle, but a range of growing strategies combining off-shore and intertidal farming could also be envisaged, and the growth of other life-stages offshore warrants further investigation, including comparison with that of the intertidal zone. At the intertidal site, the average bivalve immersion time of 88% accounts for only part of the observed differences. In fact, there are strong turbidity gradients in the bay with too high SPM concentrations negatively affecting bivalve physiology (Barillé et al., 1997; Gernez et al., 2014). In spite of phenotypic adaptations of their palleal organs (Dutertre et al., 2016), oysters cannot cope with high SPM, which impacts their growth (Barillé et al., 2011). To simulate oyster growth using DEB modelling in this environment, we used the formulation of Thomas et al. (2016), which

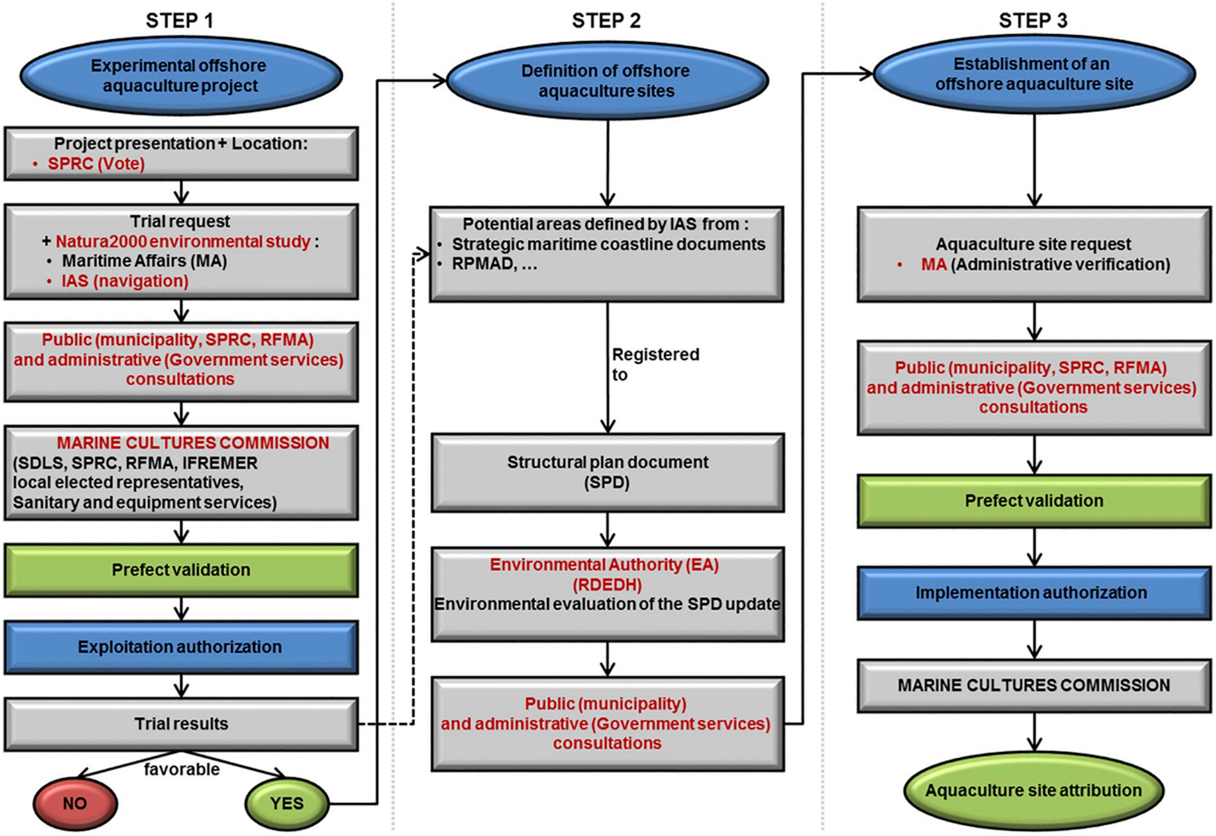

Fig. 10. Step-by-step administrative process to install an experimental offshore farm (step 1), to delimit the potential offshore concession (step 2), and to obtain a concession for an offshore farm (step 3). Potentially blocking steps are in red. Acronym definitions are given in the glossary of Supplementary Fig. S2. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

includes turbidity as a forcing variable. The higher growth at the subtidal site therefore resulted from the combination of lower turbidity and constant immersion. There was also sufficient food concentration inside the bay, even in the subtidal zone, to sustain oyster growth. Growth simulations suggested that this may not be the case for the offshore waters located beyond a depth of approximately 20 m, for which turbidity was not an issue, but food estimated by Chl-a concentration was too low to grow oysters. The experimental offshore site tested in this study was less than 5 nautical miles from any harbor in a semi-protected bay corresponding more to coastal offshore or nearshore conditions than what might be considered to be "offshore" for large industrial operations (Corbin et al., 2017). However, even here, cultivation during the winter period should be avoided due to higher hydrodynamism and related higher turbidity during this period, and also because there is almost no growth due to low temperature and food availability (Dutertre et al., 2009). Natural resource availability is an obvious, but critical prerequisite for shellfish cultivation (Pogoda et al., 2011). Offshore sites that are within a ~20 m bathymetric limit therefore have greater potential for oyster growth than the traditionally farmed intertidal oyster-farming sites. However, if the stocking biomass were to be significantly increased, affecting the overall carrying capacity, further study would first be required.

4.2. An economic opportunity for small companies

Oyster cultivation in the intertidal area is challenged by many sources of land-based and marine pollution or epizootics jeopardizing the future of the shellfish farming industry and its resilience to anthropogenic and environmental shocks (Guillotreau et al., 2017; Soletchnik et al., 2007). Monoculture bivalve systems in shallow coastal waters are more vulnerable than others to global warming and ocean acidification, which can be considered 'slow variables' affecting the environment (Walker and Salt, 2006). In Bourgneuf Bay, as in many oyster farming ecosystems worldwide, the oyster farming industry has been hit since 2008 by mass mortalities of juveniles caused by a type 1 *Ostreid herpesvirus* (OsHV-1; Pernet et al., 2016), decreasing the output of commercial-sized oysters by 25% within just a few years (Guillotreau et al., 2018). Fortunately, the market response in terms of price increase (of 50 to 75%) has generally allowed farmers to temporarily cope with the epizootic. However, several farm closures by bankruptcy have taken place as a result. Zoosanitary problems are considered major risks by shellfish farmers who develop risk hedging strategies in an attempt to reduce both the likelihood and consequences of such outbreak events, since no private insurance scheme can cover the loss of disease-related shellfish mortality (Le Bihan et al., 2013). In this study, lower mortality was observed at the subtidal than at the intertidal site. A similar observation was made for oysters grown in offshore lantern nets on floating longlines in Marennes-Oléron Bay (Mille et al., 2008). Although Pernet et al. (2018) have shown that OsHV-1 can persist for at least 24 h in seawater and travel over long distances (> 5 nautical miles), the lower risk of clinical infection by OsHV-1 offshore could be explained by (i) better food quality due to lower terrestrial organic matter inputs and lower turbidity, resulting in oysters with higher energy reserves, (ii) the lower density of susceptible hosts, and (iii) the seaward dilution of viral particles. In their large-scale study, Pernet et al. (2018) showed the epidemiological advantage of offshore aquaculture compared to traditional intertidal cultivation, provided that the oyster stock brought offshore is pathogen-free and farmed at a moderate density. In this context, offshore cultivation emerges as a relevant economic opportunity for small businesses, as long as it can be developed not too far from the coast and with cheap and practical equipment (Cheney et al., 2010). A bottom-cage can be filled with 60 plastic bags, each containing between 2000 and 2500 small-size Pacific oyster spat (T6-T8 size according to the measurement used by French hatcheries corresponding to spat, graded on a 6 or 8 mm square mesh size). Three bottom cages would therefore be filled with 450,000 small-size spat, which corresponds to the number of spat to start a new growing cycle for a small company producing 30 tons of marketable oysters (Le Grel and Le Bihan, 2009). With a price of 10 euros for a thousand small-size spat (T6), 400 euros for a cage and 4 euros for a plastic bag, the investment would be 2140 euros per cage. A more rigorous cost-benefit analysis should be undertaken to integrate an offshore component in small business financial scenarios (Ferreira et al., 2014). Nevertheless, this simple calculation intends to demonstrate that with a few low-cost bottom cages, small companies could afford moving to offshore waters to grow oyster spat. The logistics and operating costs will certainly increase (fuel costs and handling equipment on board for cages), but beneficial growth and risk management aspects should also be considered for a fair analysis and balance of opportunities and costs. The regional structure supporting innovations for the shellfish industry (SMIDAP) has also successfully tested the growth of European oyster, *Ostrea edulis*, and black scallop, *Chlamys varia* (Glize P., pers. comm.), using the same experimental design as described here for *C. gigas*. Similar offshore growth potential was identified for these two species, indicating the diversification potential for oyster producers. The construction of two offshore wind farms in the area (“wind farm projects”; Fig. 6A) could also be seen as an opportunity for a co-use with shellfish farming (Buck et al., 2017). However, the future wind farms have not been considered as such in this work, mainly because of their distance to the coast (> 20 nautical miles) and the related constraint determined by the small-scale producers. Moving production to wind farms areas would require more investment, but also, more importantly, significant incentives and a regulatory framework for the energy industry to accept an aquaculture co-use (Griffin et al., 2015).

4.3. Spatiotemporal resolution of mapped oyster growth

Along the European Atlantic coast, conditions in the nearshore environment can be highly variable in space and time, due to the combined effects of coastal geomorphology, tides, and river run-off. Since spatiotemporal variability in the environmental variables considered was expected, time series satellite remote sensing data was used to capture the main patterns of food, turbidity and temperature. Earth Observation products are increasingly used at various spatial resolutions to support the development of shellfish aquaculture (Dean and Salim, 2013; Gernez et al., 2017; Saitoh et al., 2011; Snyder et al., 2017). For the 5000 km^2 study area, a 1 km^2 spatial resolution was appropriate to describe the broad offshore spatial patterns and to set up the SMCE. However, this resolution is too coarse to provide information at the farm level, and the next step will be to use higher resolution products for areas found to be of interest through the current work, and to explore the different strategies combining intertidal/offshore production for an oyster producer. To improve the methodology via model input data selection, it would be interesting to consider the European Space Agency's medium resolution sensors (MERIS in full spatial resolution or Sentinel3/OLCI), due to their balance of enhanced spatial (300 m) and reasonable temporal (2–3 day overpass frequency) resolutions, and potential to develop inversion algorithms that may perform better across optical water types. The coastal zone is optically complex and it is challenging to separate the contribution of the different colored constituents, Chl-a, SPM, and colored dissolved organic matter. In the present study, Chl-a and SPM were retrieved using the OC5 algorithm (Gohin et al., 2005), which was specifically developed and validated for the European Atlantic coastal waters (Gohin, 2011; Tilstone et al., 2017). The MERIS archive would also approximately cover the period considered in this study (1998–2013), spanning from 2002 to 2012, thereby permitting complementarity. In this work, we used a daily dataset from merged ocean colour products (Saulquin et al., 2011), but weekly data may have been sufficient to describe the seasonal variations. In the European temperate zone, seasonal maps would also be useful products. The growth model was run every year of the 16 year input time-series and the interannual variability was integrated for each individual oyster growth simulation as the calculated mean and CV. The use of the interannual mean of final oyster weight allowed the identification of persistently productive regions, independent of short-term, sub-annual variability (Longdill et al., 2008).

4.4. Site selection

The availability of suitable locations for cultivation is a key constraint to the further expansion of shellfish aquaculture. To support future development, producers and licensing authorities must identify locations by looking across many criteria and dimensions (Benetti et al., 2010; Brigolin et al., 2017; Cheney et al., 2010; Lester et al., 2018; Longdill et al., 2008; Silva et al., 2011; Falconer et al., 2019). Based on the constraint criteria, where aquaculture is not feasible, 83% of the initial area was excluded. Unlike similar studies, the strongest restrictions were set by the small-scale producers themselves, with a maximum depth of 20 m, together with the 5 nautical miles distance to the harbor. Interestingly, this offshore limit corresponding to a 20 m bathymetry, is also an area beyond which low food concentration appears to biologically restrict oyster growth. The optimal growth map suggests that further offshore waters are unlikely to be of interest to grow Pacific oysters, even for larger enterprises that may have the capacity to exploit deeper areas, up to 100 m (Kapetsky et al., 2013) to 200 m (Gentry et al., 2017). Remote sensing data can only be expected to provide information suitable for well-mixed areas. Our case-study is a macrotidal system with a tidal range of ca. 6 m during spring tides, but in other locations the potential for vertical stratification should be considered even at the shallower depths. After excluding areas with constraints, an area of 800 km^2 where aquaculture is feasible was identified.

Within this area, suitability maps varied according to the different scenarios considered. When no priority is given to any one of the ILCs, 81.1% of the area was classified as highly suitable (suitability index between 0.5 and 0.75). Similar to the Adriatic case study of Brigolin et al. (2017), the socio-economic constraint was found here to be the most restrictive ILC. Touristic traffic and bottom trawling were the main limiting criteria in the socio-economic ILC (Table 1). Prioritizing environmental criteria still resulted in 64.6% of the total area being highly suitable, but this was fragmented. Fragmentation may not be a problem for growing spat in a limited number of bottom cages, but could become an issue if a larger area is needed to grow adults on longlines. Furthermore, it may present a challenge for establishing aquaculture zones as part of marine spatial plans. European Natura2000 protection was considered to be the most limiting environmental criterion, because detailed environmental impact assessment studies would be mandatory before proceeding with site leasing, taking into account the site's conservation objectives and integrity. Inside Bourgneuf Bay, the other environmental criteria did not impact the suitability. Most of the bay is made up of muddy to sandy-muddy substrates, and the very few rocky areas known for their higher benthic diversity did not influence the suitability index (Silva et al., 2011). In this macrotidal system, bottom currents are often > 0.25 m/s, preventing the accumulation of biodeposits and were considered to be suitable (Silva et al., 2011).

The optimal growth scenario identified a large area at the mouth of the Loire estuary with very high suitability. However, this area is highly used for recreational sailing, and, when socio-economic criteria are prioritized, most suitability index values decreased to within the medium and low range. Nevertheless, even under this most constraining scenario, there is almost 400 km^2 of highly to very highly suitable area for small producers to develop offshore aquaculture. Within this area, Yeu Island, located 11 nautical miles off the coast, was one of the most interesting zones no matter which scenario was considered, whereas other sites (e.g., northern and central Bourgneuf Bay and to the north of the Loire estuary) were highly suitable under some scenarios, but unsuitable under others. Use of different scenarios is advantageous in the decision making process as it allows producers and regulators to assess trade-offs and provide alternative options.

4.5. Marine spatial planning context

The European seas Marine Spatial Planning Directive (MSPD; 2014/89/EU) has now been adopted and provides an overall framework for its implementation (Douvere and Ehler, 2009), offering broad directions rather than precise technical recommendations. In France, its application first gave rise to a national maritime strategy (MTES, 2017), which will be followed in 2021 by three Strategic Coastline Documents (SCD; Supplementary Fig. S2). One of these is centered on the Northern Bay of Biscay and the Western Channel, where Bourgneuf Bay is located. Essentially, the national strategy represents the conceptual side of the planning process, while the SCD represents its operational side and application. Within the study site, the strategy has to deal with a large range of uses, including the development of wind energy, the support to the small-scale fisheries sector, which operates throughout the area, nautical activities, such as boating practiced throughout, sand extraction (the most important zone in terms of production in France is located just off the bay), the fourth largest commercial port in France, and several marine protected areas all along the coast, as well as the aquaculture sector.

Results from this study should be communicated to the Interregional Administration of the Sea (IAS, see S2 glossary), which is in charge of implementing developing the SCD. This document outlines two main objectives: (1) to achieve the good status of the marine environment by 2020 (see MSPD), for the whole French territorial sea, including Bourgneuf Bay at the regional level, and (2) to prioritize sustainable fisheries and aquaculture, while making space for the possible coexistence of marine renewable energy, boating, and tourism. The SMCE developed and demonstrated here considers the stakeholders identified by the administration and should be regarded as compatible with implementing the SCD. This GIS-based analytical tool developed for offshore aquaculture site selection can assist in the decision-making process (Stelzenmüller et al., 2017), which is still in progress in this coastal area. It may be used to resolve conflicts in future multi-user discussions, in particular with fisherman, whose activities are widely distributed spatially and who perpetuate a tradition of strong sectoral claim.

5. Conclusion

In this work, we showed that the growth of Pacific oyster spat deployed in low-cost bottom cages was significantly higher for subtidal conditions offshore compared to traditional intertidal farming sites. This leads to the possibility for an oyster producer to shorten the production cycle and increase their profit without investing in expensive high-tech equipment. Satellite remote sensing data coupled to a deterministic *C. gigas* growth model, and included with other technical, socio-economic, and environmental criteria in a SMCE, showed that large areas are suitable for offshore Pacific oyster spat aquaculture in bottom cages, despite existing other uses of the offshore coastal area. The growth-modelling approach described here does not estimate carrying capacity, however, which would be useful within site selection and an interesting future research direction (Ross et al., 2013). Increasing standing stock biomass would likely affect overall oyster yield, therefore requiring further studies and updated DEB model parameters. In another next step, the SMCE should be further refined, using higher resolution Earth Observation products, which would be more applicable to the farm scale.

The complexity of the administrative process to obtain an offshore lease, including multiple public consultations, appeared to be a strong constraint for shellfish representatives and producers. Most of the EU27 member states acknowledge that administrative procedures are long and cumbersome and they need to be made less complex to support sustainable aquaculture (Anon, 2016a, 2016b). Spatial planning is also expected to constitute an important tool to be used by administrations to inform the decision-making process for licenses. This is reflected in the France *Multiannual National Plan for the Development of Sustainable Aquaculture* (Anon, 2016a, 2016b) which outlines plans to simplify administrative procedures, and encourages use of spatial planning to support aquaculture development in favorable environments. This plan also aims to develop attractiveness of jobs in the aquaculture industry through diversification of activities and support installation of young entrepreneurs. These areas should be prioritized to facilitate progress.

For the small producers, this is likely the main obstacle to their goal of offshore cultivation, ahead of technical, investment, or biological considerations, and would need to be addressed for this avenue to realistically be pursued. In Bourgneuf Bay, the Shellfish Production Regional Committee could leverage their national organization, the National Shellfish Council, to negotiate for more effective and efficient regulations to facilitate the development of offshore aquaculture in France, and to emphasize the contribution of shellfish farming in the implementation of the Marine Spatial Planning Directive. We propose that this GIS-based tool be transferred to stakeholders, and particularly to the oyster growers and representatives, to help them to participate and self-advocate in the ongoing MSPD debate and implementation. The suitability maps also provide materials that could be used as part of the administrative and management process to acquire leases, combining maritime public domain occupation authorizations and sectorial management documents, such as the regional plans for marine aquaculture development and the structural plan document (S2 Glossary).

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Declaration of Competing Interest

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

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