Drawing lessons from a pluridisciplinary approach associating stakeholders for a better management of a bivalve population (French Atlantic coast)?

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Abstract

Initially introduced for aquaculture purposes in the 70's on French territory, Manila clam (*Ruditapes philippinarum*) is now a neonatural resource within Arcachon Bay (SW of France). Its exploitation by professional fishermen represents around 300-450 tons per year and involves around 60-70 licenses depending on the year. The management of this species relies on both European and regional scale decision. In 2000, a partnership between professionals and scientists was established in order to implement a sustainable management of this resource. Since then, a co-organized biannual survey has been performed to assess clam stock. Workings groups and research programs were concomitantly developed.

Initially stakeholders requested this survey only to assess clam stock in the bay. Nowadays, an integrative approach of the population functioning is privileged. Such approach is particularly relevant for population with high spatial and temporal distribution variations.

The main considered drivers are diseases including constant infection by Perkinsus but also the discovery of a recently described pathology - BMD (Brown Muscle Disease), other environmental factors (i.e. trophic resources, hydrodynamic conditions, temperature…) and professional fisheries. Alternatively to classical stratified random sampling, the survey method is currently improved to optimize the sustainable management of this resource. New spatially balanced sampling design showed promising results increasing the efficiency of this survey. Knowledge is mobilized not only to meet the needs for expertise expressed locally but also at the national level.

This paper aims to introduce how the different disciplines are combined to understand the dynamics of Manila clam population within its environment and how stakeholders are involved to ensure her sustainability and to improve management between users. Successes and failures are identified, as well as the points of improvement for future actions.

Keywords: co-management; collaborative process; Manila clam fisheries; *Ruditapes philippinarum*; Arcachon Bay; integrative approach

1. Introduction

Present in all latitudes and at all ocean depths worldwide, bivalves are an important component of the benthic marine ecosystem (Berke et al., 2013). The exploited bivalves, mainly mussels, oysters, scallops and clams, are mainly located in the intertidal and shallow subtidal zones; some may still reach depths of about 200 m (Gosling, 2003). Most of their habitats are therefore located close to the coastline. They are characterized by frequent, diverse and spatially heterogeneous disturbances compared to offshore deep marine systems.

This causes natural fluctuations in populations at different stages of the life cycle and contributes to significant variations in biomass and demographic structure (Daget & Le Guen, 1975). This sensitivity to environmental condition variations is reflected spatially and can even be expressed on the scale of a few meters (Caddy & Defeo, 2003), but also temporally e.g. by extremely variable recruitment levels from one year to another (Miyawaki & Sekiguchi, 1999; Munroe & McKinley, 2007; Toba et al., 2020).

World production of bivalves is estimated at 17 million tonnes in 2017. Fisheries provide 8 % of these inputs, the remaining comes from aquaculture (source: http://www.fao.org/fishery/statistics/fr). Clams / cockles / arches and oysters dominate those productions with respectively 36 % and 34 % of contributions. For the group including clams, fishing accounts for between 9 and 25 % of the total production over the period 2000 and 2017, with a continuous sharp decrease in the share of fisheries. Within this multi-specific group, Manila clam (*Ruditapes philippinarum*) occupies an important place with about two thirds of the total amount (fishing and aquaculture combined) since 2010. In Europe and for this species, the most contributing countries in the fisheries sector are Portugal, France and Russian Federation. For aquaculture sector, the main producing European country regarding Manila clam is by far Italy, next come Spain and France. However, European production from fisheries provided by FAO is underestimated for some countries. In the case of France, 80 % of the Manila clam production from commercial fishing are carried out from two areas, Arcachon Bay (~ 500 t in 2018; CRPMEM Nouvelle-Aquitaine, personal communication) and Morbihan Gulf (~ 230 t in 2018) (D'Hardivillé and Bouché, 2018). Manila clam is a species initially introduced for aquaculture purposes in those two sites in the 70's. However, this activity was quickly interrupted for economic reasons and the species found favourable conditions to its development "in the wild" (for Arcachon - Auby, 1993). Since there was no previous monitoring of the European clam and no fishing statistics available before 1992 for Arcachon Bay, it is therefore difficult to argue that Manila clam development has come at the expense of the European clam. With nearly 98% of the intra-basin clam population, this resource is considered neonatural and is managed as a classic resource, namely to ensure the sustainability of the stock.

In France, legislation applied to Manila clam exploitation involves various level of authorities as European, National and local. European legislation sets a minimum harvest size corresponding to the anteroposterior length of the shell. For the waters of the North Atlantic, English Channel and North Sea, the size was 40 mm from 1998 to 2008 and has been set at 35 mm since 2008 (EC Regulation n° 40/2008 providing a derogation from EC Regulation n° 850/1998). For Mediterranean waters, the size is 25 mm (EC Regulation n° 40/2008). French legislation requires the detention of a national fishing license since 2010 (Decree n° 2010-1653 December 28, 2010). Last, local legislation may concern complementary measures such as license restrictions, closed areas and seasons, fishing time limits, catch quotas. They are established by the departmental and regional professional organizations in conjunction with the administration. Since they are adapted to each shellfish bed, their implementations by the various local fisheries committees are independent one from the others. They are based on biological and/or economic considerations essentially. Most of the time, biological considerations come from data collected during shellfish bed prospecting or stock assessments. In many case studies, collaborative research programs are also undertaken. Combination of stock assessment and research program is a relevant tool to reinforce a management strategy (de Montaudouin et al., 2016a).

The sustainable management of these species, for conservation and / or exploitation by humans, requires knowledge of major environmental effects on the population dynamics. This applies in particular to less mobile or sedentary species that may further exhibit density-dependent mechanisms at different stages of their life cycle (Caddy & Defeo, 2003). In the case of exploited species, the interaction of natural and anthropogenic effects complicates the understanding of observed phenomena. Anthropic effects themselves are often difficult to apprehend. It implies reliable data over time, in particular for all harvesting activities, namely professional and recreational fishing. Anthropic effects can also not be limited to fishing (effect of pollution for example) (Caill-Milly, 2012). Thus, while the abundance estimates for most of the species exploited in these coastal ecosystems are facilitated by their low mobility and near location, Defeo (2011) notes that the fisheries dependent on these resources are among the least well understood systems in terms of structure and stock dynamics.

In Arcachon Bay, along the Atlantic coast of France, professional structures, administration and scientists are involved in the management process applied to Manila clam. In 2000, professionals experienced difficulties of resource values and requested the scientists to carry out a study of the clam deposit. Since then, stakeholders work together to a better management of this resource. Interactions among those structures correspond to a co-management approach according to Jentoft et al. (1998), Gutiérrez et al. (2011) and Uchida & Wilen (2004). Jentoft et al. (1998) defined the co-management as “a collaborative and participatory process of regulatory decision-making among representatives of user-groups, government agencies and research institutions”.

This paper aims to analyse how stakeholders are involved to ensure the sustainability of Manila clam resources and to improve the co-management implemented since 2003. The paper also addresses how the different stakeholders are mobilized and how the disciplines are combined to understand the dynamics of Manila clam population within its environment. Successes and failures are identified, as well as the point of improvement for future actions.

2. Study area and fisheries

Arcachon Bay is a 156 km² semi-sheltered lagoon located on the southwest Atlantic coast of France (Fig. 1). The bay is both influenced by oceanic and continental inputs. The water exchange between the ocean and the bay is performed by a wide two-channel inlet, mainly forced by semi-diurnal tides (Cognat et al., 2018). The major part of annual freshwater inputs (4/5) come from the Leyre river located in the southeastern part of the bay (Plus et al., 2009). These characteristics coupled with the slow renewal of water by tides (Plus et al., 2006) influence salinity and temperature within the bay. Thus, seawater temperature ranges from 1.8 to 27.4°C (mean value 15.4°C) and salinity ranges from 15.4 to 35.4 (mean value 30.2) (Caill-Milly, 2012). Muddy intertidal flats colonized by *Zostera noltei* seagrass bed dominate the inner part of the lagoon. *Z. marina* occupies the shallow subtidal sector around the channel edges (Cognat et al., 2018).

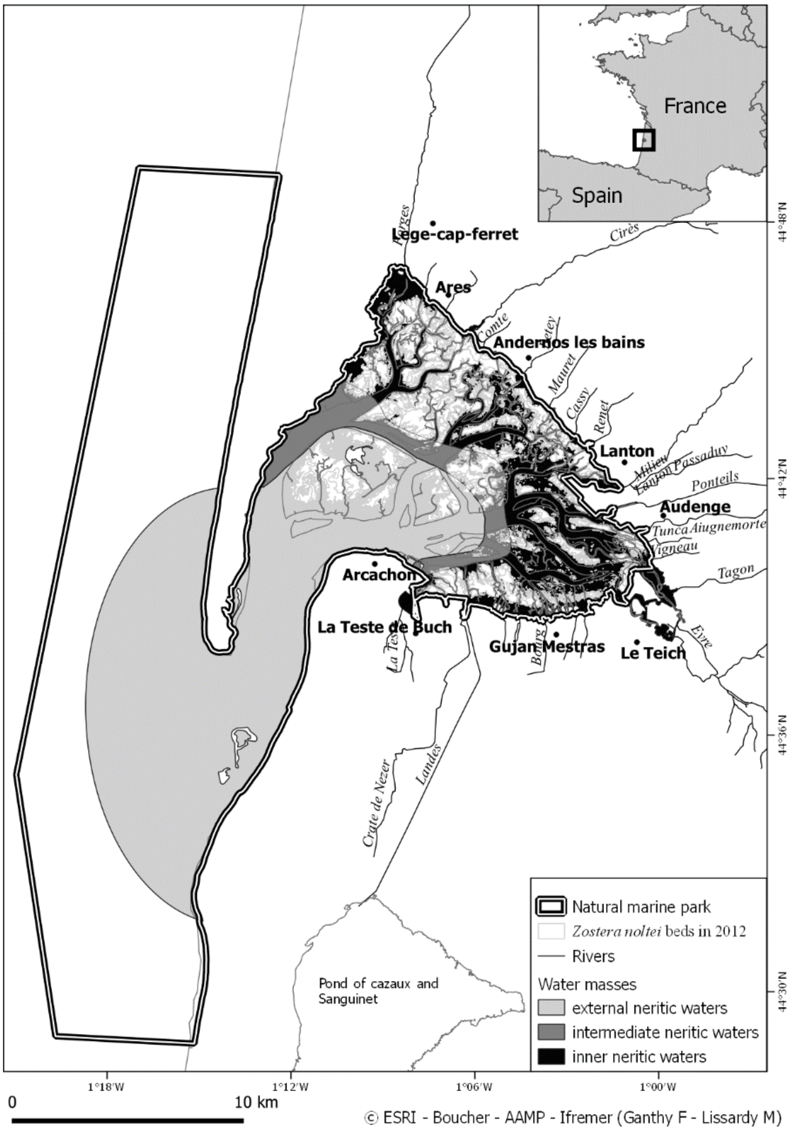

Fig. 1. Location of the studied area (Arcachon Bay), extent of *Zostera noltei* beds, distribution of the water masses and boundaries of natural marine park of Arcachon Bay.

Such dynamic system, characterized by water exchanges and a variety of habitats, plays a key role as spawning grounds for fish and shellfish and then enhances local fishery production. (Deborde et al., 2008; Bertrand, 2013). Clam harvesting is an important activity on the intertidal area of Arcachon Bay. It is essentially carried out by professional fishermen. Manila clams are also caught by recreational fishermen but their impact is considered negligible compared to professional activity (in particular because of the conditions of access to sites which are very muddy and by boat) (FMPAA, 2017). Clam harvesting is carried out by hand at low tide one or twice per day. Fishermen go to the fishing areas by boat and use wooden boards to help them move around the mudflat. The professional fishermen essentially harvest the Manila clam when the tide coefficient (which tells us the magnitude of the tide at the planet scale, independently from local characteristics; with value ranging between 20 and 120) is higher than 50.

Regarding fisheries, after a peak in 2007 with 1000 tons landed, the production decreased to achieve in recent years values comprised between 300 and 400 tons per year (Fig. 2) (Sanchez et al., 2018). Looking at the number of fishing licenses, it evolves over the years depending on applied management measures by professional fishermen. The license system changed in 2016 with the establishment of two types of licenses separating the "owner" license (i.e. ship owner) and the "employee" license (Deliberation No. 2016-15 CRPMEM NA). The granted number of licenses for “cockles and Manila clams” for each category is limited to 47 and 94 respectively. In addition, to establish a new "owner" license, two “owner” licenses must leave the quota (rule "-2 + 1"). Since then, the granted number of “owner” licenses is around 44 and the number of “employee” licenses has increased with 48 requests in 2019. It is therefore not possible to compare the number of licenses before and after the system modification.

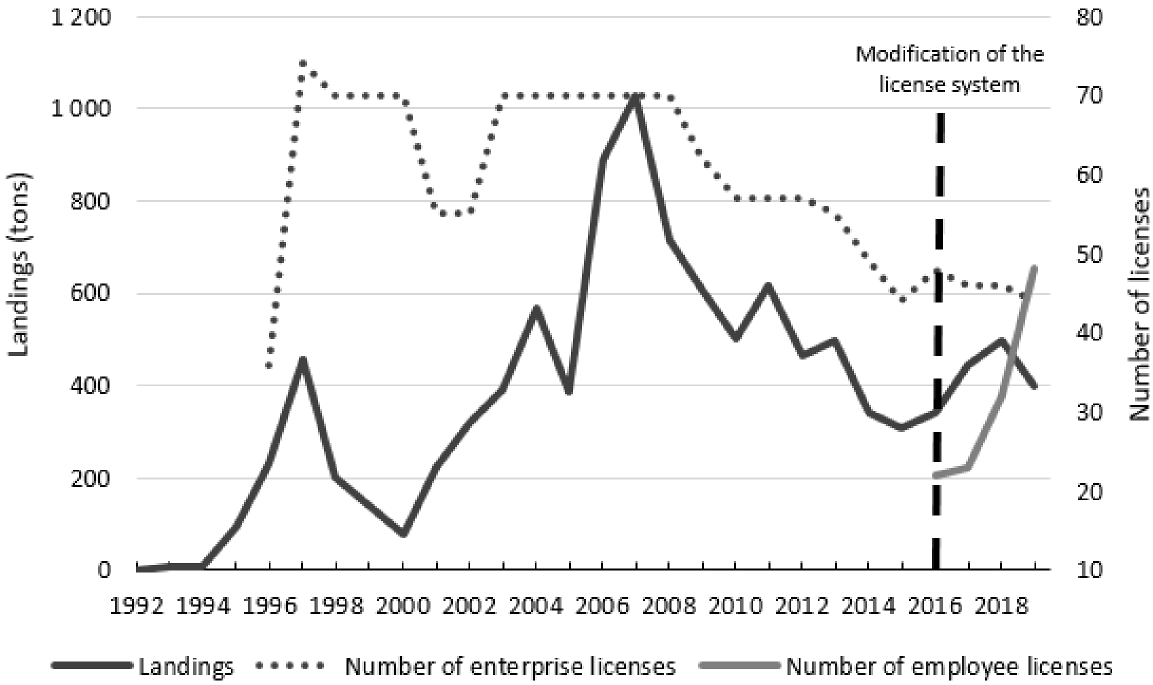

Fig. 2. Clam fishing production by professional fishermen and number of delivered licenses discriminating the enterprise and employee categories since 2016 (sources: CRTS La Rochelle, SIH Ifremer, CRPMEM Nouvelle-Aquitaine).

In Arcachon Bay, the management of clam fisheries is conducted by professional organizations through regional regulations implemented by prefectoral orders. Different measures were applied since 1999 such as license restrictions, no-fishing areas (for details see Sanchez et al., 2018) or restriction of fishing time period (fishing prohibition on Sundays for example). Those management measures can be applied separately or can be pooled, depending on fishermen decisions. It was the case between 2009 and 2013 when several measures have been proposed (proposal of two no-fishing areas, licenses restriction and no fishing on Sunday) due to a Manila clam stock renewal not maintained.

The clam fishing, professional as well as recreational, is prohibited in two areas since 1st November 2016 (Fig. 3). Among the criteria applied for the choice of closure zones, the fraction of Manula clam spawners and the spatial complementarity of the zones are considered.

Fig. 3. Current local spatial regulation regarding clam fishing in Arcachon Bay: closure of two areas “Ile aux Oiseaux” (3.1 km²) and “La Humeyre” (1.8 km²) since 1st November 2016 by prefectoral order October 28, 2016.

3. Stakeholders

Various stakeholders are involved in the Manila clam management in Arcachon Bay.

Professional organizations

French professional fishermen are organized at national, regional and local level: the National Committee of Marine Fisheries and Aquaculture (CNPMEM) as well as their regional committee and their local office. In Arcachon Bay, the regional committee is CRPMEM Nouvelle-Aquitaine and the local committee is CDPMEM Gironde. Membership is mandatory for professionals. Their committee members include fishermen, ship-owners, others representing as producer organizations and cooperative associations. These committees are under the authority of the French State. Their role is to bring professional interests and to take decisions about inshore fisheries management.

Administration

For regional resources management, French administration is involved at two levels: “Directions interrégionales de la Mer” (DIRM) and “Délégations de la mer et du littoral” (DML).

The DIRMs are the purview of the Ministry of the Environment, Transport and the Sea and are under the authority of the Regional Prefect. They are in charge of conducting State policies on sustainable development of the sea, resource management and regulation of maritime activities. They also include maritime signalling and management missions for the inter-departmental POLMAR (marine pollution) storage centers. They have a coordinating role regarding all the policies of the sea and the littoral. For Arcachon Bay, the South Atlantic DIRM (DIRM-SA) has this competence.

The DMLs exist within departmental directions of the territory and the sea (DDTM). The latter being interdepartmental directorates, under the authority of the Prefect, created in 2010. They implement at the departmental level the policy of the sea and the littoral, including marine fisheries and cultures. They manage ships and seafarers.

Scientists

In general, researchers contributes to a mission of national interest that includes the practice of scientific expertise (L411-1 of the Research Code). Scientists working on the clam questionings of Arcachon Bay belong to research institutes or universities. These structures are mainly French and located in the neo-Aquitaine territory: Ifremer; University of

Bordeaux; University of Pau and Pays de l'Adour. Foreigners' structures are also involved as Azti-Tecnalia (Spain) and the University of Canterbury (New Zealand). In the case of Ifremer, institutional expertise is specified by the amended decree No. 84-428 ("The institute is responsible for providing the State and other legal persons with public right to assist in the exercise of their responsibilities "). In the case of other structures, the clam resource fits into the research themes of the different laboratories. Collaborations often begin by common scientific interests and can also be formalized by a partnership agreement.

Other actors

In France, a new management structure adapted to the marine environment was created: the Marine Protected Areas (MPAs). The French Environment Code recognizes 15 categories of MPA: marine natural parks, national parks, nature reserves, Natura 2000 sites, sites of the Conservatoire du littoral (Coastal Protection Agency). In France, there are seven marine natural parks including Arcachon Bay. This latter was created by an inter-ministerial decree in June 5th 2014. Arcachon Bay natural marine park is thus a recent actor in Manila clam management device. The park extends to 435 km² and runs along 127 km of coastline. It depends on a public institution, the French Biodiversity Agency. The governing body of this marine park is composed of representatives of territorial authorities, officials, professional fishermen and recreational users, scientists, environmental NGOs… It defines and implements the park policy, within the framework of its management guidelines and its management plan. This natural marine park have tree main objectives: knowledge of the marine environment, its protection and the sustainable development of marine activities (MPAs Agency, 2015).

4. Requirements and relevant issues for clams management

The exploitation of this resource began in the 1990s. Following a decrease in yields in the late 90s raising fears of an overexploitation of the stock, professional fishermen asked scientists to carry out a first study of the deposit in order to assess the Manila clam stock (Bertignac et al., 2001). A first study was undertaken on part of the deposit (~ 24 km²) in order to test the sampling method. It demonstrated its applicability but partially answered the questioning. The whole area (~ 47 km²) was prospected from 2003. This date constitutes the period of acceptance of the method by most fishermen.

As the assessment is a snapshot view of the stock at a given time, specific additional research studies were implemented to better understand the population dynamics and to attempt to answer to fishermen issues:

- Characterisation of population dynamics: they mainly concern growth, size, morphology, mortality, diseases, production, reseeding and environmental drivers;
- Projection of effect of management strategies through several scenarios: a decision-support tool (analytical model) was developed to guide management regarding this species;
- Stock evaluation: furthermore, optimization of the survey sampling protocol was considered to reduce the survey costs.

The main questions raised according to these 3 axes were as follows: How can spatial dependent mortality be explained? Can clams suffer from a genetic impoverishment? Why does clam's shape differ from other sites (globular aspect)? How can sustainability of the activity be ensured? Can the survey be optimized?

5. Stakeholders collaboration

Many experiments associating fishermen and scientists in a collaborative fisheries research highlight the benefits of a mutual partnership (Johnson & van Densen, 2007; Yochum et al., 2011; Massé et al., 2016). By involving fishermen in each phase of the research project (sampling, logistics, collecting data…), they become "actors of science" and they have more confidence in the data and the results (Yochum et al., 2011; Massé et al., 2016). In the case of Manila clam of Arcachon Bay, exchanges between fishermen and scientists take the form of working groups (before and after the campaigns – see 5.1.), systematic partnership to carry out monitoring surveys from 2003 and support in carrying out certain field experiments. Whereas the initial objective of these monitoring surveys was to assess the Manila clam stock, they generated data to conduct research programs with specific questions and hypotheses. The discussions during the working groups also made it possible to identify gaps in knowledge essential for management. They were then the subject of specific work.

5.1. Clam monitoring survey

To reinforce management strategy, stock assessments were undertaken. When possible, these surveys were carried out every other year since 2006 during late Spring, the first one being however undertaken in 2003 considering the total distribution area of Manila clam (~ 47 km²). Based on a co-management approach, the organization, implementation and data processing have been shared between professional fishermen and scientists. Professional organizations were in charge of carrying out the survey (funding request, logistics and sampling) and the scientists defined the sampling protocol, were involved in the sampling and data processing. A working group involving scientists, professionals and the administration has also been established since 2003 to discuss about the areas to be surveyed, the identification of knowledge gaps and specific issues.

A stratified random sampling was applied dividing the study area into 16 reference strata, based on expert knowledge (Fig. 4). These strata are homogeneous in terms of hydrology, sediment particle size characteristics and current patterns (Kermorvant et al., 2017). Over time new strata in adjacent areas have been added. This mainly concerns the addition of fishing restricted areas or other areas of interest for fishermen. For sampling protocol, see details in Sanchez et al., 2018; Kermorvant et al., 2017; Kermorvant et al., 2019a).

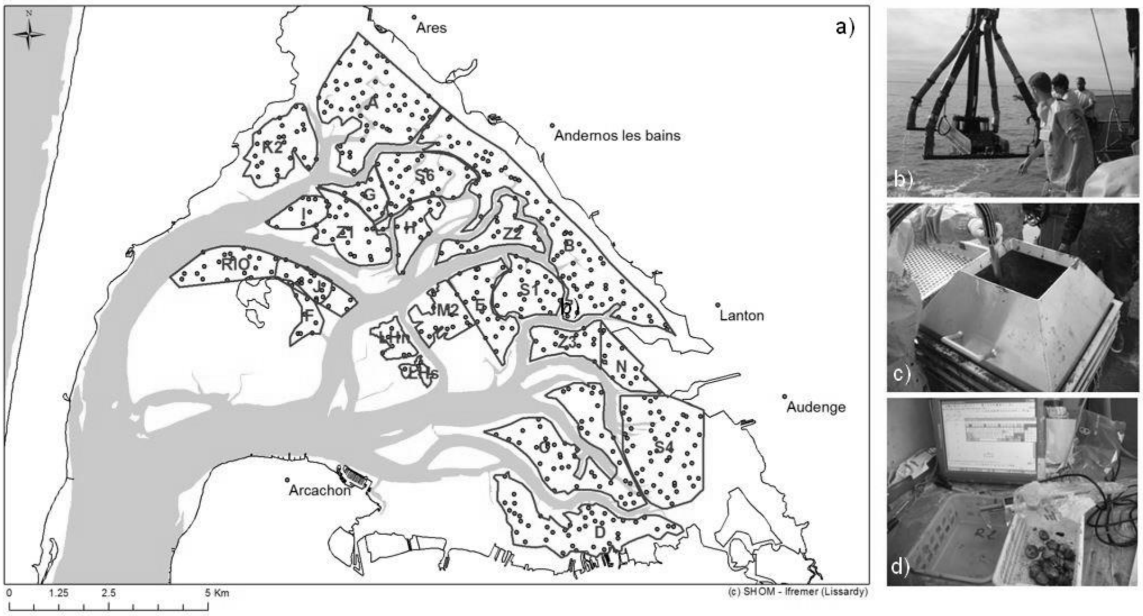

Fig. 4. Protocol applied to Manila clam monitoring survey in Arcachon Bay: (a) sampling design applied in 2018; (b) use of the Hamon grab; (c) sediment sieving onboard with running water over a set of three sieves; (d) measurement of clams using an electronic calliper.

These surveys provide a dataset of indicators such as abundance indices (number.m^{-2} and g.m^{-2}), length-frequency histograms, total abundance and biomass (number and weight), fraction of juveniles (individuals measuring less than 17 mm), spawners (individuals measuring more than 25 mm) and exploitable stock (individuals measuring more than 35 mm) (%), as well as their abundance (number and weight) and maps of clam densities (Fig. 5). The dataset includes 7 years of monitoring (2003, 2006, 2008, 2010, 2012, 2014 and 2018). The 2016 survey could not take place for financial reasons. After each campaign, the results of the survey are presented to the working group and to all the fishermen. The evolution of those indicators constitutes essential knowledge to make recommendations or advices from scientists to professional organizations in charge of Manila clam management.

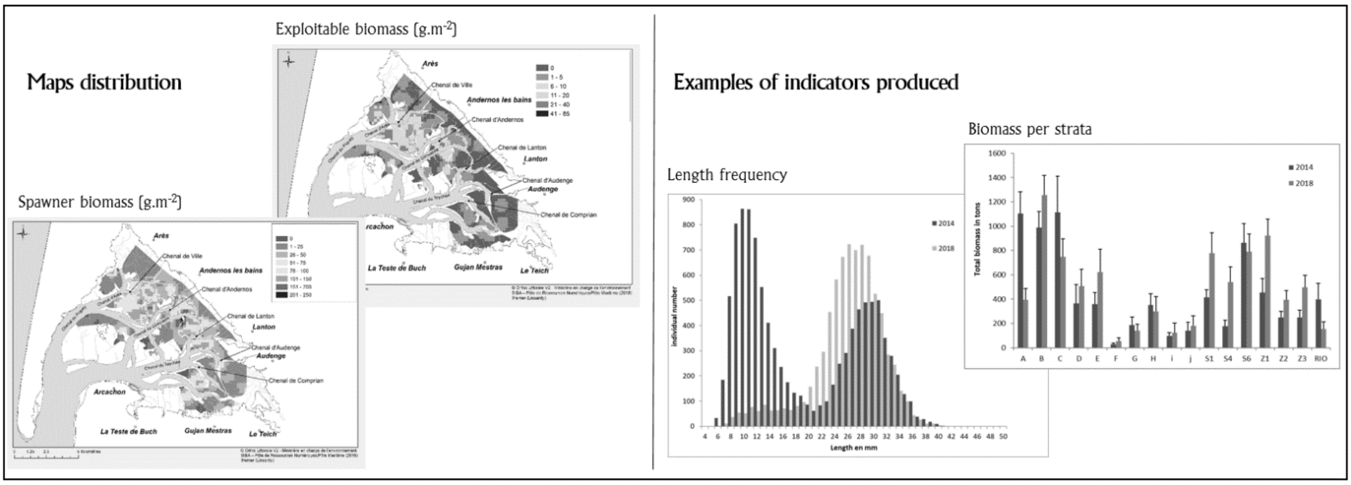

Fig. 5. Examples of maps distribution and indicators produced from the Manila clam monitoring.

5.2. Progression in the knowledge of population dynamics

5.2.1. Growth/diseases

Size-structure histograms of Manila clams, including those obtained in the framework of stock-assessment surveys (see § 5.1), revealed a lack of large individuals, i.e. > 40 mm shell length. Monitoring of growth and searching the main involved drivers (natural and anthropic) became rapidly a priority.. Using a capture-tagging-recapture method, shell growth rates were determined in four different areas, and at four different tidal levels. Surprisingly for a suspension feeder, tidal level poorly explained growth performance (Dang et al., 2010b). The main scheme was a "normal" growth until a size of approx. 30 mm, and a strong reduction after leading to a relatively small asymptotic size. In the same time, condition index (CI) (flesh weight/shell weight) displayed low values compared to other sites throughout the world. Professional fishermen proposed a genetic impoverishment as an explanation, due to the semi-enclosed status of Arcachon Bay. This hypothesis was discarded, since these Manila clams, when transplanted in a site where growth is reputed to be high for oyster (Banc d'Arguin), displayed rapidly high growth rate and elevated asymptotic shell length (Dang, 2009). The hypothesis that fishing may have an effect on the selection of slower-growing individuals in Arcachon Bay cannot be totally ruled out. However, Manila clam cross-transplant experiments between contrasted areas highlight the strong relationship between growth and environment features (phenotypic plasticity). Moreover, in situ capture-tagging-recapture experiments enabled the assessment of the Von Bertalanffy growth function parameters. For Arcachon Bay, mean growth parameter K is 0.72 $year^{-1}$ (Dang et al., 2010) which is relatively high in comparison with other geographical areas such as Canada, England and Turkey [values between 0.14 and 0.54 $year^{-1}$, Bourne (1982); Çolakoğlu and Palaz (2014); Clarke et al. (2019)]. Regarding environmental conditions, linear growth is mainly influenced by seawater temperature (Toba, 1987 in Nakamura et al., 2002; Fan et al., 2007). For Jiaozhou Bay (China), the temperature range of 18-23 °C was determined to be the most suitable for shell growth (Fan et al., 2007). Growth was also described for the Manila clam in Thau lagoon (Maitre-Allain, 1982): no growth occurs below 6 ° C and optimal growth is expected between 12 and 20 ° C. Considering the temperature conditions prevailing in the Arcachon Bay, this factor may not explain the observed growth deficit. In addition, scanning different pathogens and diseases in Manila clams highlighted their detrimental effects on CI with possible knock-on effect on shell growth parameters. Trematode parasites, at the stage of metacercariae (i.e. larvae with generally small interaction with host tissues), were present at low intensity and are certainly innocuous at that infection level (Dang et al., 2009a). Perkinsosis, a disease related with different protozoan parasite species belonging to *Perkinsus* genus and responsible of most infectious pathologies in bivalves worldwide (Soudant et al., 2013), were present in Arcachon Bay. Its prevalence (% of infected individuals) was 93% and mean infection abundance was 96 x 10^3 cells g^{-1} wet weight gill tissues (Dang et al., 2010a, Dang et al., 2013). At this level of infection, the population of Manila clams must be impacted. Besides, Manila clams suffered from another disease, the Brown Muscle Disease (BMD) (Dang et al., 2008), only reported in Arcachon Bay, lethal for individuals and causing moderate population mortality as long as the prevalence remains low (Dang & de

Montaudouin, 2009; Binias et al., 2014). The infectious agent of BMD is supposed to be a virus (Dang et al., 2009b; Binias, 2013; Pierron et al., 2019) but supplementary studies should be envisaged to confirm the aetiology and understand this emergent disease. Finally, Brown Ring Disease (BRD), a worldwide scattered disease related to a prokaryote, remains anecdotic in Arcachon Bay (Dang, 2009). The last investigated hypothesis to explain growth impairment was a possible default of trophic source quality and quantity. A clear relationship between Manila clam fitness and the possible trophic sources was not identified by stable isotopic analysis (Dang et al., 2009c). In contrast, a large bibliographic analysis showed that the main driver of Manila clam CI (a proxy of fitness) was the concentration of chlorophyll *a* in the water, and that this concentration in Arcachon Bay is, in average and compared to other ecosystems where Manila clam CI is higher, particularly low (de Montaudouin et al., 2016b).

5.2.2. Morphometrics variability and links with geographical or environmental considerations

The main addressed questions concerning morphometrics regarding Manila clam and Arcachon Bay were: do Manila clam populations exhibit morphometrics variability? If yes, can they be linked to environmental or geographical considerations?

So, morphometric studies were conducted to consider intra-site (at the Arcachon Bay scale) and inter-site phenotypic variabilities of Manila clam (on four deposits distributed along the French Atlantic coasts). They concerned conventional shape analysis based on metric (length, ventral length, height, width, lateral and ventral areas) and weight (shell mass) measurements. The first study (Caill-Milly et al., 2012) was conducted on 2070 sub-sampled shells from the Arcachon Bay monitoring survey of 2010. It established allometric relationships between pairs of descriptors that were specific to the lagoon. A significant change in morphology was highlighted from a length close to 16-20 mm which corresponds to the second year of life [with reference to the work of Dang (2009)]. From this size, the growth rates of the height and weight of the valve are therefore greater than that of the length. Intra-site phenotypic variability study led to the identification of three morphological patterns among adult clams within the Arcachon basin, which differed in particular by their distance to the ocean connection (Fig. 6). Relative heavy and globular clams were associated with low density and the specific local pathology (BMD). The results converge to indicate that certain intra-basin areas seem unfavorable for the development of individuals (strata A, S1 and C, Fig. 6). Conversely, they identify the north central part of the Basin as favorable for their good development (Strata I, G, H and Z1, Fig. 6). In addition, clams in the Arcachon Bay appear to be much less elongated (elongation index) and more globular (compacity index) than in other sites including Europe confirming poor conditions for some individuals (Caill-Milly et al., 2012).

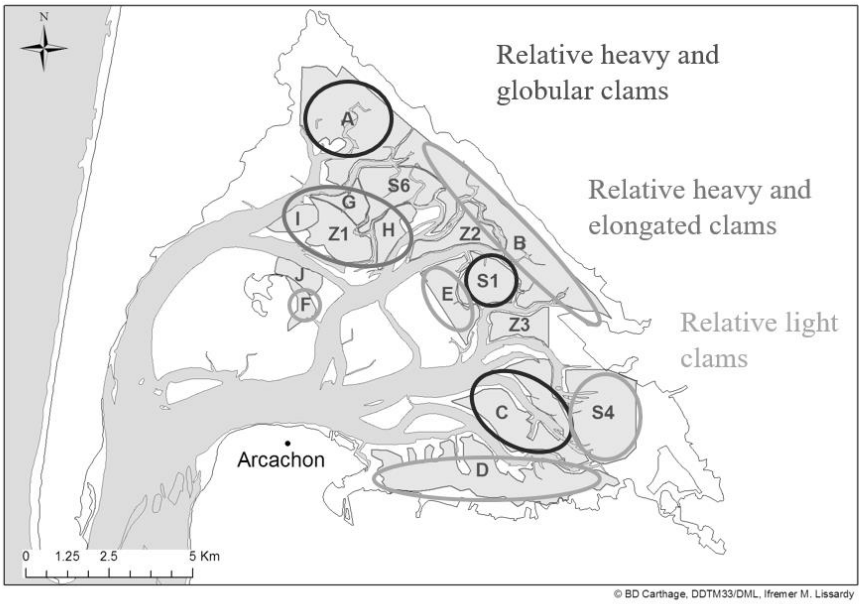

Fig. 6. Location of the three morphological patterns among adult clams within Arcachon Bay (Caill-Milly et al., 2012).

The second study (Caill-Milly et al., 2014) tested the hypothesis of a specific shape on the Arcachon Bay by a comparative morphometric study on four Japanese clam (*R. philippinarum*) deposits distributed along the French Atlantic coasts (Banc du Guer, Gulf of

Morbihan, Bellevue and Arcachon basin). Moreover, correlations between discriminant morphometric characteristics and environmental factors (temperature, salinity and trophic conditions) were studied. A total of 238 shells were analysed for those purposes. The study identified three discriminatory morphometric ratios (describing elongation, valve density and weight related to length) and revealed morphometric-latitudinal trends between northern and southern populations of *R. philippinarum* (Caill-Milly et al., 2014). Significant relationships with chlorophyll *a* concentrations and to a lesser extend with seawater temperature ranging from 12 to 20°C were revealed. The results' interpretation illustrates the complexity of the factors intervening on the individual morphology both at the intra and inter-site scale and opens on the potential effect of other factors (such as the substrate nature and the hypsometric level).

5.2.3. Knowledge regarding clam habitat

Since the beginning of the clam survey, some intertidal habitats have drastically changed. Indeed, an important seagrass decline has been reported in years 2003-2007 (Plus et al., 2010). Concurrently, some modifications of the sediment dynamics within the Bay have been observed by both local scientists and stakeholders: increase in suspended sediment concentrations (ARCHYD hydrological network, Ifremer 2017), infilling of secondary channels or grain-size changes (Blanchet et al., 2005), important mud deposits on north-eastern sandy beaches, mudflat erosion in the center of the Arcachon Bay where seagrass disappeared. Recent studies based on field experiments, decadal analysis of morphological changes and numerical hydrodynamics modelling demonstrated that such modifications of sediments dynamics within the Arcachon Bay can be mainly explained by the direct consequences of the seagrass regression on tidal propagation and associated current velocities, leading to a self-amplification of the seagrass regression (Cognat, 2019 ; Ganthy et al., 2018; Mütterlein et al., 2016). Current research is attempting to forecast possible future evolutions of intertidal habitats regarding present environmental conditions and potential local consequences of the global changes.

5.3. A management tool to support the decision-making process

In order to help management decision, a tool adapted to the Manila clam population of the Bay was developed by gradually integrating knowledge specific to Arcachon Bay (Bald et al., 2009; Dang, 2009; Caill-Milly, 2012). It is a deterministic type simulation model based on a dynamic systems approach. It was structured into four shell length size classes (0-20 mm, 21-34 mm, 35-39 mm and greater than 40 mm). On the one hand the "Stock/Maturation/Mortality" block is fueled by the "Recruitment" block itself influenced by "Environmental parameters". On the other hand, the "Stock/Maturation/Mortality" block is also influenced by the "Fishery" block that defined the fishing mortality according to the different size classes (Fig. 7). This tool was implemented under Vensim ©. It allowed to envisage various combinations of management measures or environmental conditions and to compare differences in biomass trends in response to these various *scenarii*.

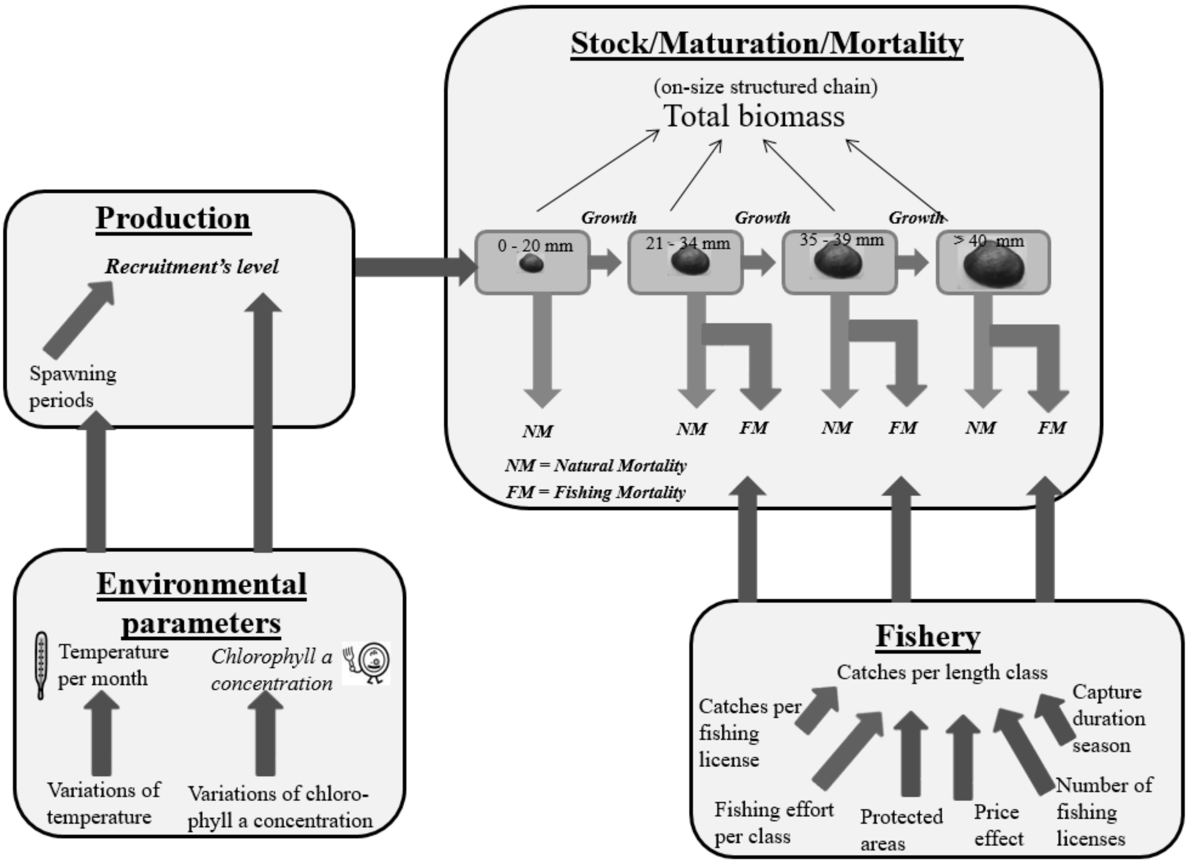

Fig. 7. Structuring in four blocks of the management tool developed for the Manila clam population of Arcachon Bay.

A weakening of the stock was observed in 2008 and stakeholders had to take radical management measures. Management scenarios (cases) were defined during working groups associating fishermen and scientists. For each case, simulations were run to assess forecast of total biomass. As a result, a combination of three measures was retained by the stakeholders and applied from 2009 to 2013: reduction of number of fishing licenses; choice of two complementary protected areas and fishing prohibition on Sundays.

5.4. Optimization of the monitoring survey

Recent development in statistics and geostatistics allows survey designs theory and implementation to be more and more efficient. Spatially balanced sampling (SBS) designs are a newly developed family of survey designs (Kermorvant et al., 2019b). For a survey design, efficiency means a lower sampling size and/or a higher precision reached on final estimates. Spatially balanced sampling (SBS) designs are one of these newly developed survey designs. SBS provides a good sampling coverage of the study area thought balancing samples geographically. They have precise design-based estimators and they can potentially reduce the survey cost (Kermorvant et al., 2019a). Based on the Arcachon Bay Manila clam monitoring optimization issue, a thesis was conducted. The main aim was to develop a generic method allowing comparing survey designs between them to select the more efficient for a given population.

For the Manila clam monitoring in Arcachon Bay, it was proven that using SBS instead of usual simple random sampling design could greatly improve the final abundance and biomass estimates (Kermorvant et al., 2017 and 2019a). As local variation of Manila clam abundance and biomass is very strong and not modeled yet, optimization of sample size is not finished.

5.5. Co-management process between fishermen/scientists/administration

The co-management Manila clam process has been really in place since 2003, including biomass monitoring, research and exchanges in working groups in response to fishermen issues. Different steps were performed in response to a decrease of the Manila clam stock occurring in 2008 (Fig. 8). The questioning mainly concerned the capability of the Manila clam stock renewal, the establishment of closed areas and the reseeding. Several sources of knowledge and capacities were considered and shared between the actors to make proposal actions to address this decline such as the approach described by Léopold et al. (2019) in small-scale fisheries of Vanuatu and New Caledonia (South Pacific). Scientists used different tools as a specific compartmental single-species model developed to assess different management strategies (Bald et al., 2009), a numerical hydrodynamics modelling (Plus et al., 2009) to study larval dispersion to choose the best closed areas and transplant experiments (Dang, 2009). All stakeholders then meet together during working groups to discuss about the results and to take decisions. The use of mapping tools is particularly implemented during exchanges.

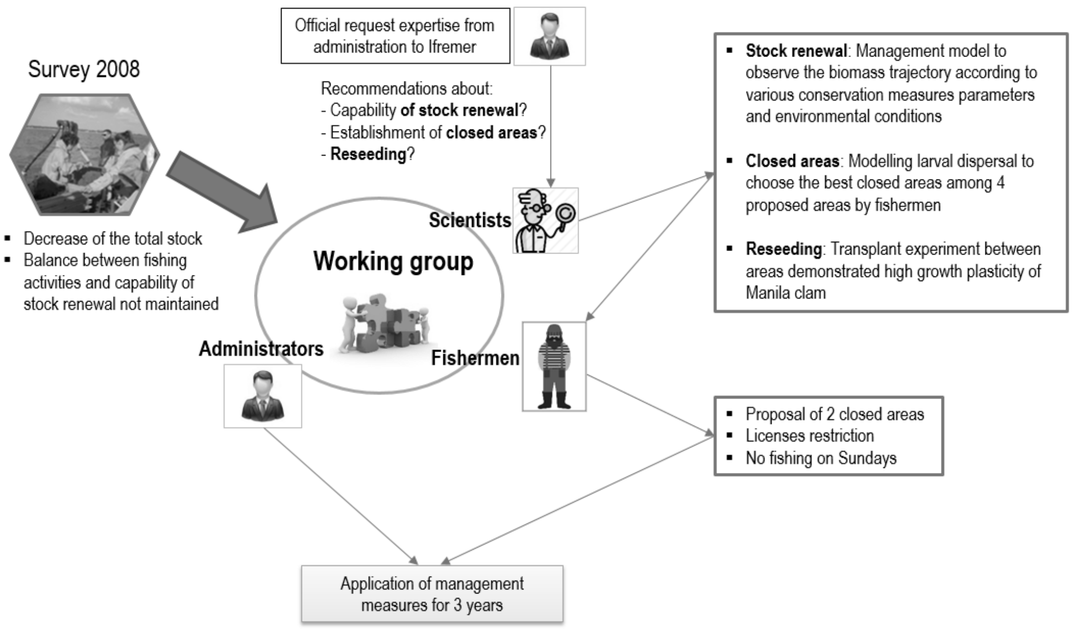

Fig. 8. Co-management process example in response to a Manila clam stock decrease in Arcachon Bay.

Since the first study in 2000, the co-management process for the Manila clam fisheries was established and improved gradually. The strong willingness to maintain sustainable Manila clam fisheries has led to all stakeholders to interact with each other. This collaborative process to manage this resource takes the form of various collective actions such as co-organized monitoring surveys, research programs that have been intensified since 2006 and working groups to have discussion and make decisions. Figure 9 shows the chronology of developed actions since 2000 with the realized monitoring surveys, the research undertaken and the different management levels and their applications. As highlighted by Léopold et al. (2019), the implementation of cooperative co-management in small-scale fisheries is a slow process lasting several years. It is an illustration of the adaptive ability of management mode at a local scale.

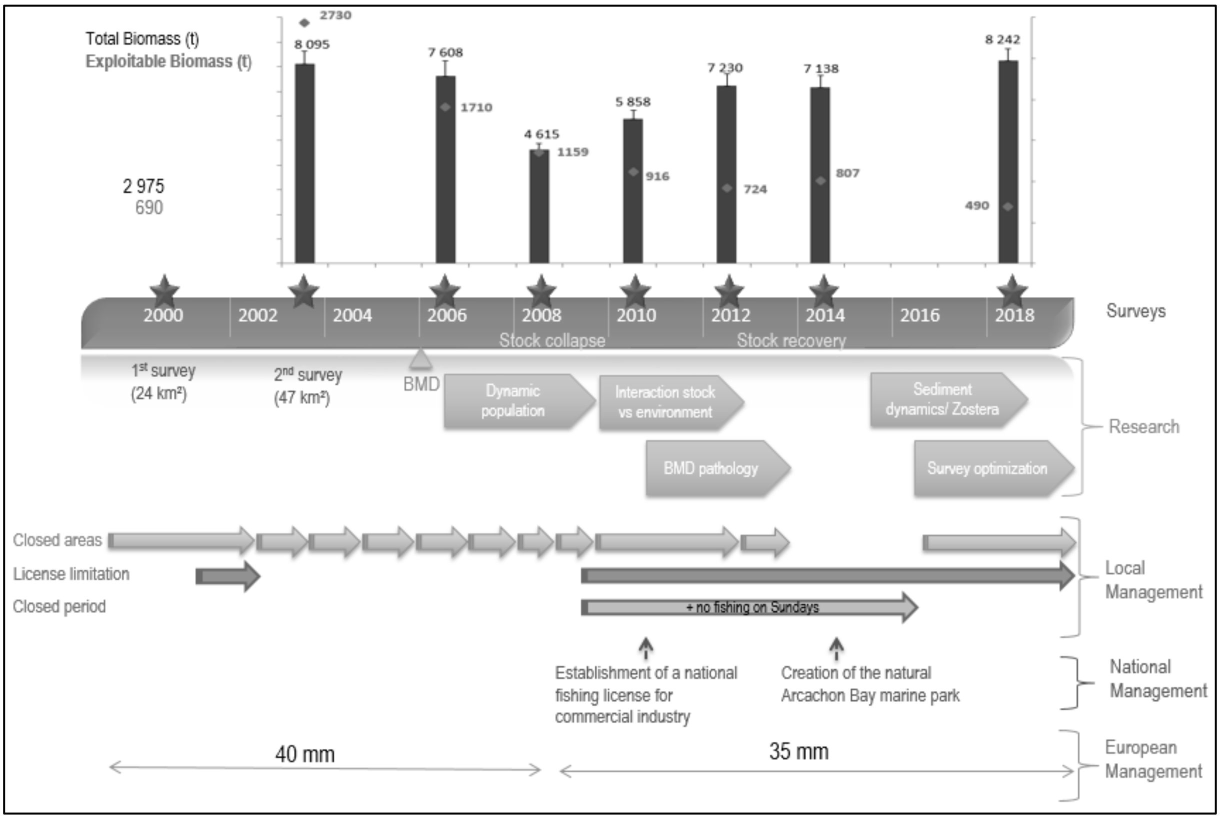

Fig. 9. Sequence and articulation of the surveys, the research activity and the management implementation regarding Manila clam stock in Arcachon Bay.

The role of the actors in this process is different, some roles are shared equally, others are not (Table 1). Regarding the “animation/exchanges organization”, there is no real stakeholder leader. The interactions take place mainly during the working groups or during research projects. They can be intense on these occasions but apart from that, they remain infrequent. Some tasks are formalized (by conventions), but most of them are not. Mackinson et al. (2011) wrote about it that prescribed or mandated participation is rarely effective for fisheries and marine research.

Table 1. Roles of the stakeholders in the collaboration with regard to the nature of the participation to the Manila clam studies (H: high contribution; M: medium contribution; L: low contribution).

	Stakeholders			
	Scientists	Fishermen	Administration	Natural park
Prior knowledge contribution	H	H		
Knowledge acquisition (from collection to data analyses)	H	H		L
Animation/exchanges organization	M	M		
Regulatory considerations		H	H	H
Financial contribution (including self-financing)	M	M		L

6. Discussion

6.1. Success and failure

The Manila clam case study in Arcachon Bay demonstrates that a collaborative process between stakeholders in the present case is a real success to monitor species abundance in small case areas (Table 2). The investment of the fishermen in the monitoring survey indicates a successful collaboration. It increased and encouraged mutual understanding raising new research questions considering fishermen local knowledge and taking advantage of their experience because they are well placed to perceive fine-scale changes in the environment (Daw et al., 2011; Yochum et al., 2011; Massé et al., 2016). Orensanz et al. (2014) perceived a collaborative engagement as an intellectual partnership between fishermen, scientists and managers. In our case, the approach can be considered as collaborative due to fishermen involvement in the monitoring survey, the holding of working groups involving several actors (administration, scientists, fishers, managers) to discuss and exchange about specific issues or scientific objectives. The different questions raised have taken the form of research programs (Dang et al., 2009; Caill-Milly et al., 2012; Montaudouin et al., 2016b; Kermorvant et al., 2019a) that assembled scientists from several disciplines. According to Dutra et al. (2015), the success of natural resources management depends on both improving the knowledge about resource dynamics, governance and the stakeholder engagement in the management decision. However, some difficulties are to be highlighted such as the available funds to schedule regular surveys (with a financial contribution supported by the professionals which is the structure carrying out the campaign from funders) and available funds for research programs applied to local issues (Table 2). It also revealed the discrepancy between the outcomes of research for a global management vision and the individual expectations of professionals, the difficulty in maintaining sufficient contact due to other individual activities and the turnover of State and fishermen representatives *etc*. This last difficulty is consistent with the roles of the fishermen organization representatives described by Marín and Berkes (2010): they are the ‘‘gatekeepers’’ of the co-management process and the links between fishermen and the organizational environment. The term “gatekeepers” (or “sentinel”) also has a meaning in terms of environmental monitoring. Indeed, it is the daily presence of professional fishermen that has made it possible to detect abnormal localized mortalities which have proven to be linked to a hitherto unknown disease.

Table 2. Positive and negative outcomes identified in the collaborative process in this case study.

☺	☹
Good partnership to co-organize the clam survey	Mobilization of available funds/significant financial implication for a local professional structure and mobilization of available funds for research programs applied to local issues
Correct ownership of the results by professionals	Difficulties to maintain continuous contact with stakeholders (changes and availability in professional partners)
Pluridisciplinary scientific approach to respond to policy concerns	Discrepancy between outcomes of survey/research for global management vision and individuals expectations of professionals (short term enterprise vision)
Scientific findings (applied research) used to a better management process	Difficulties to assert local characteristics of the
Recognition of the approach and the developed competencies (requests from other sites)	

Sentinel role of the fishermen regarding environmental quality	resources (growth) to adapt European legislation

This type of collaboration between scientific and professional structures exists for numerous other local French deposits or resources such as bivalves (Manila clam, scallop, mussel …), crustaceans (spiny lobster) or algae, mainly in Brittany and/or in Normandy (Picault et al., 2014; D’Hardivillé and Bouché, 2018; ICES, 2018). Spatial extents of those stocks are generally restricted and well delimited (little or no mobile resources). In addition, the number of stakeholders involved in the management is also relatively limited (questioning at local or regional level). Those two aspects must have favoured the implementation of this type of collaboration for longer than for other resources such as fish which are essentially shared resources between States. These collaborations regarding inshore fisheries are often the subject of technical reports and not scientific papers; thus, they are poorly disseminated and not always well identified by the scientific community and by managers, apart from those directly involved.

6.2. Lessons and perspectives

The co-management process looks like a perpetual search for balance (*i.e.* stay connected between stakeholders, acts, ensure medium and long-term financing, be available to explain the ins and outs when changing representatives…) but it is worthwhile. In the case of small-scale artisanal fisheries in Chile, Schumann (2007) identified four social benefits of co-management initiatives involving fishermen organizations: improving relationships between fishermen and the State; increasing fishermen sensitivity regarding ecology and management; cooperation between fishermen and scientists; and approach promoting a feeling of unity between fishermen in particular regarding management interest. This current work is in agreement with this analysis for the 2^{nd} and 3^{rd} points. For the first one, information is missing on the relations between fishermen and the State apart from those with the presence of scientists. For the last one, the question is inherent in fishermen. From the moment when it was the fishermen who mobilized the scientists at the start of year 2000 to have factual elements to manage the local resource, it can be considered that the local committee CDPMEM Gironde already created the conditions of unity among fishermen. One could ask the question of the unity between professional fishermen and recreational fishermen. Nonetheless, as explained previously, recreational fishing is considered to have a negligible impact on the stockcompared to that of professional fishing..

Inputs of knowledge for co-management process is important for action research. It makes it possible to mobilize scientists (sometimes with limited human resources) on significant issues at the territorial level. It promotes the match between the knowledge produced and the user needs. Macher et al. (2018) also demonstrated that, in certain cases, it better aligns scientific development timelines with political agenda and impact assessment, especially in the Bay of Biscay. This is all the more interesting when it comes to resources which dynamics are strongly influenced by the local environment. The knowledge thus gathered, but also the tools developed, can be mobilized to meet the expected expertise but also potentially other needs. As an illustration, a recent consultation was made on application for the minimum catch size for Manila clams in Arcachon Bay. The request came from the "Direction des Pêches Maritimes et de l'Aquaculture" (DPMA) of the French Ministry responsible for fisheries (administration at national level). Within tight deadlines, the accumulated knowledge, tools already used and the network involving both scientists and professionals to have relevant data could be mobilized to meet this expertise request. This recent experience also highlighted that certain tools still need to be enhanced to make them more operational. It is the case of the management model which is very difficult to reclaim after a while and which currently lacks an interface to be also easily used by managers.

All the actions implemented in Arcachon to ensure the sustainability of the Manila clam stock illustrate that this species is not perceived as invasive. This is not always the case. In some other European countries such as Italy or Portugal, Manila clam is always considered as an invasive species or as a competitor for other species, contributing to their decline (Pranovi et al., 2006; Moura et al., 2017). To explain this difference, two assumptions are proposed. The lack of historical reference points on the native Groove carpet shell clam (*R. decussatus*) stock and fisheries partly explains why it is impossible to say whether the intra-basin development of the Manila clam has come at the expense of that of the endemic species. In addition, unlike other bivalves such as mussels, its life cycle does not cause inconvenience at certain times for a category of users, as can be the fixation of mussel spat for oyster farmers.

Defined roles for each of the stakeholders in the decision support process should be explicit. This is a key issue identified for the success of this process (Röckmann et al., 2017 in Macher et al., 2018). In this study, roles of the stakeholders are already well defined (with high involvement of some) and shared, but for some roles, there are no leader. For example, regarding “animation/exchange organization”, nothing formal exists outside working groups and it would be more efficient if a structure supports it. In any case, it is crucial to keep a clear separation between decision-support and decision making process. Otherwise, confusion may occur between stakeholders’ involvement in decision support and consultation for decision making (Macher et al., 2018). Such deviance may lead to instrumentalization of science in the decision process and is often cited. But a certain instrumentalization of producers may also be a source of fear. Finally, the communication between stakeholders is also a point to improve. Exchanges take place during working groups and dissemination of results is done through technical reports. All monitoring survey campaign reports are also available online (https://w3.ifremer.fr/archimer/) as well as reports and scientific papers. But are they really consulted by non-scientists (even if some of them are in French)? Would a specific Internet site as the one developed for the Canadian Northern Gulf sentinel programs on groundfish fisheries (Gillis, 2002) be better to inform? A reflection on other forms of communication should be carried out. For example, would a dashboard on the main results of the survey (using selected indicators) be of interest to better share observations on the state of the stock with professional fishermen? To reinforce the links between the stakeholders outside the highlights of campaigns and some specific research, would it be appropriate to set up a dedicated half day of exchanges between scientists, fishermen on this resource with a large place for discussion? Such possible initiatives will be discussed soon among the stakeholders.

More generally, consolidation of support processes for management of the natural resource should make easier for stakeholders to find their place alongside new actors (for example NGO), especially in a context of development of ecosystem based management of the marine environment. The opening of science to society is a significant subject at national level since a dedicated charter is currently revised by eight French institutes (public establishments for research, expertise and / or risk assessment in the fields of health and the environment) with a signature planned for the end of 2020. In this context, it will be very interesting for the local group to participate in sharing of experiences.

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