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Nathalie Caill-Milly, Florence Sanchez, Muriel Lissardy, Xavier de Montaudouin, Noëlle Bru, et al.. Drawing lessons from a pluridisciplinary approach associating stakeholders for a better management of a bivalve population (French Atlantic coast)?. *Estuarine, Coastal and Shelf Science*, 2021, 251, pp.107194. 10.1016/j.ecss.2021.107194 . hal-03593885

HAL Id: hal-03593885

<https://hal.science/hal-03593885>

Submitted on 13 Feb 2023

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

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11

12 **Abstract**

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

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

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

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

36

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

39

40 **1. Introduction**

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

47 This causes natural fluctuations in populations at different stages of the life cycle and
48 contributes to significant variations in biomass and demographic structure (Daget & Le Guen,
49 1975). This sensitivity to environmental condition variations is reflected spatially and can
50 even be expressed on the scale of a few meters (Caddy & Defeo, 2003), but also temporally
51 e.g. by extremely variable recruitment levels from one year to another (Miyawaki &
52 Sekiguchi, 1999; Munroe & McKinley, 2007; Toba et al., 2020).

53 World production of bivalves is estimated at 17 million tonnes in 2017. Fisheries provide 8 %
54 of these inputs, the remaining comes from aquaculture (source:
55 <http://www.fao.org/fishery/statistics/fr>). Clams/cockles/arches and oysters dominate those
56 productions with respectively 36 % and 34 % of contributions. For the group including clams,
57 fishing accounts for between 9 and 25 % of the total production over the period 2000 and
58 2017, with a continuous sharp decrease in the share of fisheries. Within this multi-specific
59 group, Manila clam (*Ruditapes philippinarum*) occupies an important place with about two
60 thirds of the total amount (fishing and aquaculture combined) since 2010. In Europe and for
61 this species, the most contributing countries in the fisheries sector are Portugal, France and
62 Russian Federation. For aquaculture sector, the main producing European country regarding
63 Manila clam is by far Italy, next come Spain and France. However, European production from
64 fisheries provided by FAO is underestimated for some countries. In the case of France, 80 %
65 of the Manila clam production from commercial fishing are carried out from two areas,
66 Arcachon Bay (~ 500 t in 2018; CRPMEM Nouvelle-Aquitaine, personal communication)
67 and Morbihan Gulf (~ 230 t in 2018) (D'Hardivillé and Bouché, 2018). Manila clam is a
68 species initially introduced for aquaculture purposes in those two sites in the 70's. However,
69 this activity was quickly interrupted for economic reasons and the species found favourable
70 conditions to its development "in the wild" (for Arcachon - Auby, 1993). Since there was no
71 previous monitoring of the European clam and no fishing statistics available before 1992 for
72 Arcachon Bay, it is therefore difficult to argue that Manila clam development has come at the

73 expense of the European clam. With nearly 98% of the intra-basin clam population, this
74 resource is considered nonatural and is managed as a classic resource, namely to ensure the
75 sustainability of the stock.

76 In France, legislation applied to Manila clam exploitation involves various level of authorities
77 as European, National and local. European legislation sets a minimum harvest size
78 corresponding to the anteroposterior length of the shell. For the waters of the North Atlantic,
79 English Channel and North Sea, the size was 40 mm from 1998 to 2008 and has been set at 35
80 mm since 2008 (EC Regulation n° 40/2008 providing a derogation from EC Regulation n°
81 850/1998). For Mediterranean waters, the size is 25 mm (EC Regulation n° 40/2008). French
82 legislation requires the detention of a national fishing license since 2010 (Decree n° 2010-
83 1653 December 28, 2010). Last, local legislation may concern complementary measures such
84 as license restrictions, closed areas and seasons, fishing time limits, catch quotas. They are
85 established by the departmental and regional professional organizations in conjunction with
86 the administration. Since they are adapted to each shellfish bed, their implementations by the
87 various local fisheries committees are independent one from the others. They are based on
88 biological and/or economic considerations essentially. Most of the time, biological
89 considerations come from data collected during shellfish bed prospecting or stock
90 assessments. In many case studies, collaborative research programs are also undertaken.
91 Combination of stock assessment and research program is a relevant tool to reinforce a
92 management strategy (de Montaudouin et al., 2016a).

93 The sustainable management of these species, for conservation and/or exploitation by
94 humans, requires knowledge of major environmental effects on the population dynamics. This
95 applies in particular to less mobile or sedentary species that may further exhibit density-
96 dependent mechanisms at different stages of their life cycle (Caddy & Defeo, 2003). In the
97 case of exploited species, the interaction of natural and anthropogenic effects complicates the
98 understanding of observed phenomena. Anthropogenic effects themselves are often difficult to

99 apprehend. It implies reliable data over time, in particular for all harvesting activities, namely
100 professional and recreational fishing. Anthropogenic effects can also not be limited to fishing
101 (effect of pollution for example) (Caill-Milly, 2012). Thus, while the abundance estimates for
102 most of the species exploited in these coastal ecosystems are facilitated by their low mobility
103 and near location, Defeo (2011) notes that the fisheries dependent on these resources are
104 among the least well understood systems in terms of structure and stock dynamics.

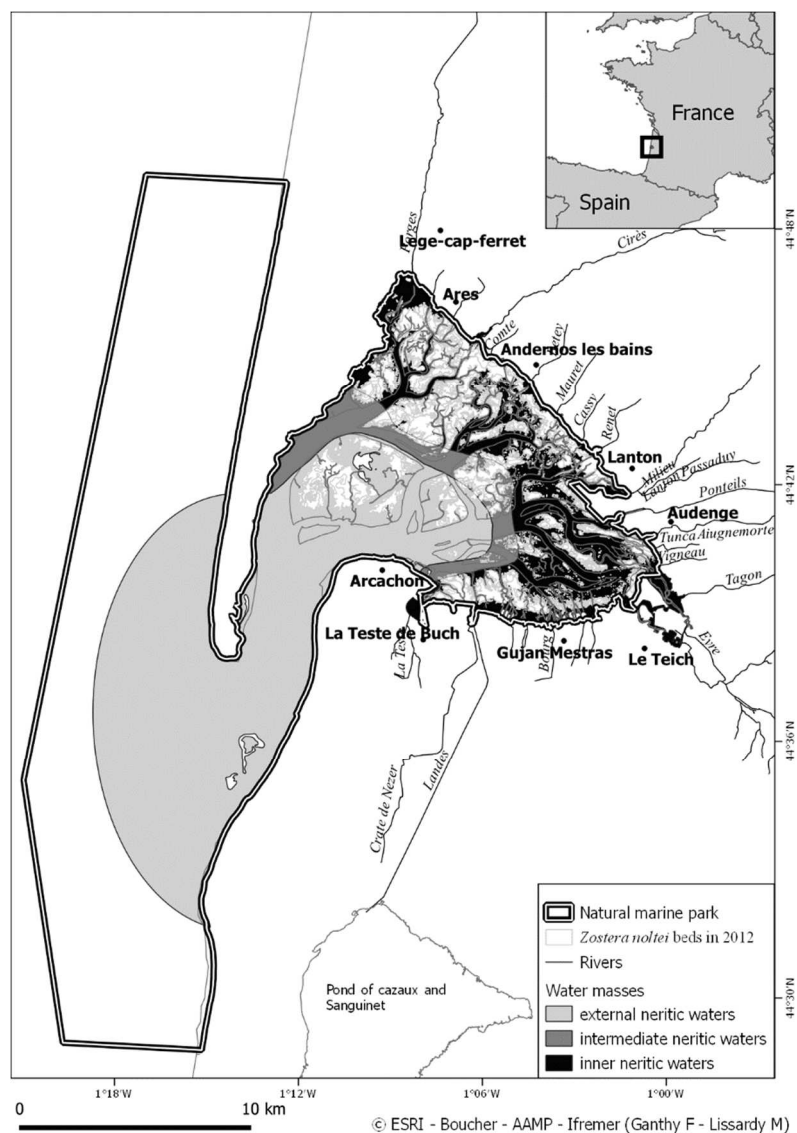
105 In Arcachon Bay, along the Atlantic coast of France, professional structures, administration
106 and scientists are involved in the management process applied to Manila clam. In 2000,
107 professionals experienced difficulties of resource values and requested the scientists to carry
108 out a study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

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

119 **2. Study area and fisheries**

120 Arcachon Bay is a 156 km² semi-sheltered lagoon located on the southwest Atlantic coast of
121 France (Fig. 1). The bay is both influenced by oceanic and continental inputs. The water
122 exchange between the ocean and the bay is performed by a wide two-channel inlet, mainly

123 forced by semi-diurnal tides (Cognat et al., 2018). The major part of annual freshwater inputs
 124 (4/5) come from the l'Eyre river located in the southeastern part of the bay (Plus et al., 2009).
 125 These characteristics coupled with the slow renewal of water by tides (Plus et al., 2006)
 126 influence salinity and temperature within the bay. Thus, seawater temperature ranges from 1.8
 127 to 27.4°C (mean value 15.4°C) and salinity ranges from 15.4 to 35.4 (mean value 30.2) (Caill-
 128 Milly, 2012). Muddy intertidal flats colonized by *Zostera noltei* seagrass bed dominate the
 129 inner part of the lagoon. *Z. marina* occupies the shallow subtidal sector around the channel
 130 edges (Cognat et al., 2018).

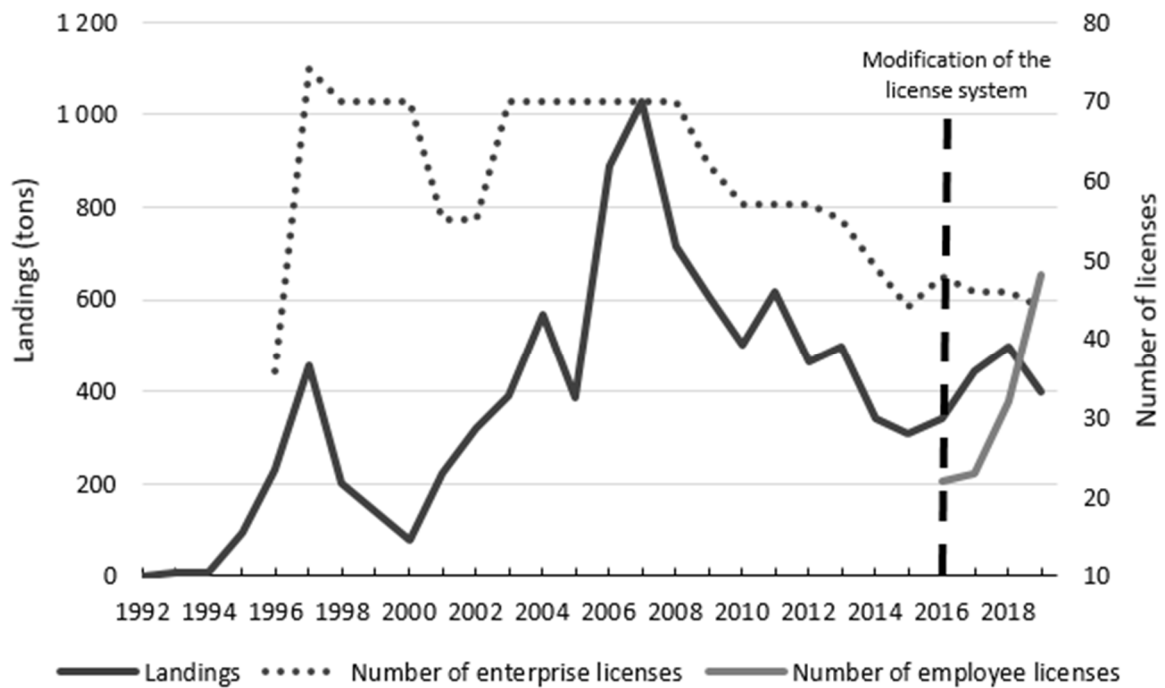


131
 132 Fig. 1. Location of the studied area (Arcachon Bay), extent of *Zostera noltei* beds, distribution
 133 of the water masses and boundaries of natural marine park of Arcachon Bay.

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

146 Regarding fisheries, after a peak in 2007 with 1000 tons landed, the production decreased to
147 achieve in recent years values comprised between 300 and 400 tons per year (Fig. 2) (Sanchez
148 et al., 2018). Looking at the number of fishing licenses, it evolves over the years depending
149 on applied management measures by professional fishermen. The license system changed in
150 2016 with the establishment of two types of licenses separating the “owner” license (i.e. ship
151 owner) and the “employee” license (Deliberation No. 2016-15 CRPMEM NA). The granted
152 number of licenses for “cockles and Manila clams” for each category is limited to 47 and 94
153 respectively. In addition, to establish a new “owner” license, two “owner” licenses must leave
154 the quota (rule “-2 + 1”). Since then, the granted number of “owner” licenses is around 44 and
155 the number of “employee” licenses has increased with 48 requests in 2019. It is therefore not
156 possible to compare the number of licenses before and after the system modification.

157

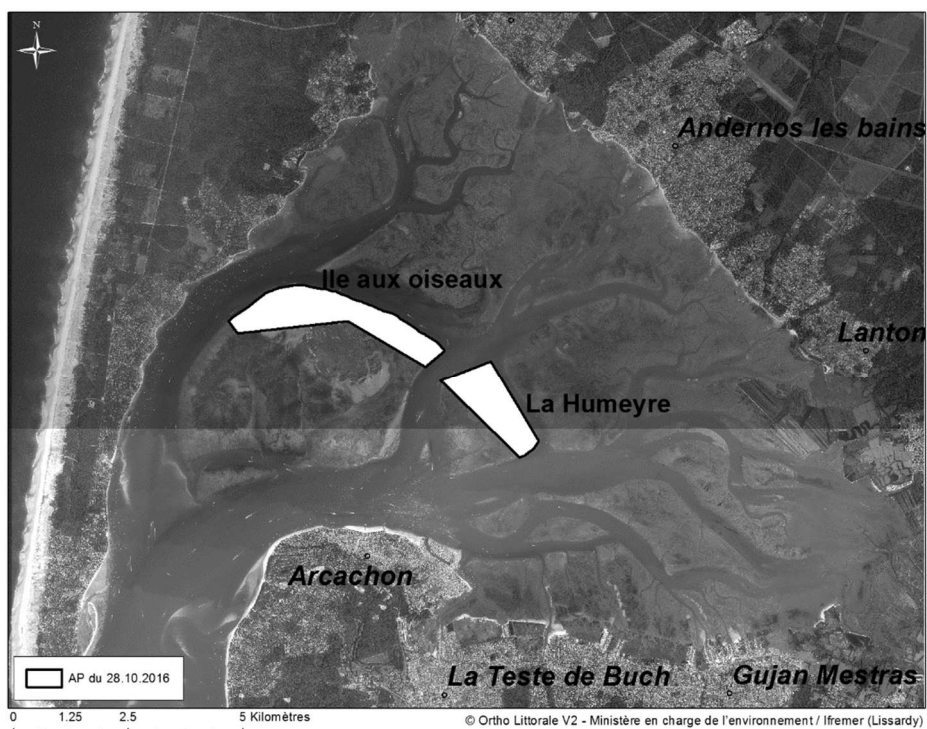


158

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

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

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



174

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

178

179 **3. Stakeholders**

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

181 *Professional organizations*

182 French professional fishermen are organized at national, regional and local level: the National
 183 Committee of Marine Fisheries and Aquaculture (CNPMM) as well as their regional
 184 committee and their local office. In Arcachon Bay, the regional committee is CRPMEM
 185 Nouvelle-Aquitaine and the local committee is CDPMEM Gironde. Membership is
 186 mandatory for professionals. Their committee members include fishermen, ship-owners,

187 others representing as producer organizations and cooperative associations. These committees
188 are under the authority of the French State. Their role is to bring professional interests and to
189 take decisions about inshore fisheries management.

190 *Administration*

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

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

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

205 *Scientists*

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

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

217 *Other actors*

218 In France, a new management structure adapted to the marine environment was created: the
219 Marine Protected Areas (MPAs). The French Environment Code recognizes 15 categories of
220 MPA: marine natural parks, national parks, nature reserves, Natura 2000 sites, sites of the
221 Conservatoire du littoral (Coastal Protection Agency). In France, there are seven marine
222 natural parks including Arcachon Bay. This latter was created by an inter-ministerial decree in
223 June 5th 2014. Arcachon Bay natural marine park is thus a recent actor in Manila clam
224 management device. The park extends to 435 km² and runs along 127 km of coastline (Fig. 1).
225 It depends on a public institution, the French Biodiversity Agency. The governing body of
226 this marine park is composed of representatives of territorial authorities, officials,
227 professional fishermen and recreational users, scientists, environmental NGOs... It defines
228 and implements the park policy, within the framework of its management guidelines and its
229 management plan. This natural marine park have tree main objectives: knowledge of the
230 marine environment, its protection and the sustainable development of marine activities
231 (MPAs Agency, 2015).

232 **4. Requirements and relevant issues for clams management**

233 The exploitation of this resource began in the 1990s. Following a decrease in yields in the late
234 90s raising fears of an overexploitation of the stock, professional fishermen asked scientists to
235 carry out a first study of the deposit in order to assess the Manila clam stock (Bertignac et al.,
236 2001). A first study was undertaken on part of the deposit (~ 24 km²) in order to test the
237 sampling method. It demonstrated its applicability but partially answered the questioning. The
238 whole area (~ 47 km²) was prospected from 2003. This date constitutes the period of
239 acceptance of the method by most fishermen.

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

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

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

254 **5. Stakeholders collaboration**

255 Many experiments associating fishermen and scientists in a collaborative fisheries research
256 highlight the benefits of a mutual partnership (Johnson & van Densen, 2007; Yochum et al.,

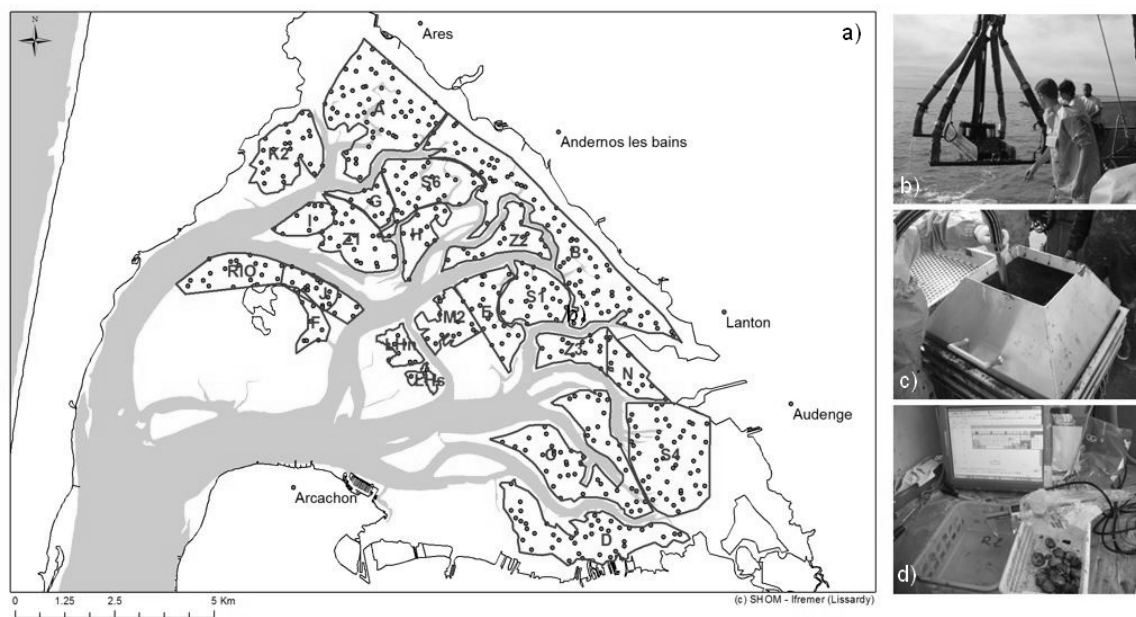
257 2011; Massé et al., 2016). By involving fishermen in each phase of the research project
258 (sampling, logistics, collecting data...), they become “actors of science” and they have more
259 confidence in the data and the results (Yochum et al., 2011; Massé et al., 2016). In the case of
260 Manila clam of Arcachon Bay, exchanges between fishermen and scientists take the form of
261 working groups (before and after the campaigns – see 5.1.), systematic partnership to carry
262 out monitoring surveys from 2003 and support in carrying out certain field experiments.
263 Whereas the initial objective of these monitoring surveys was to assess the Manila clam stock,
264 they generated data to conduct research programs with specific questions and hypotheses. The
265 discussions during the working groups also made it possible to identify gaps in knowledge
266 essential for management. They were then the subject of specific work.

267 5.1. Clam monitoring survey

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

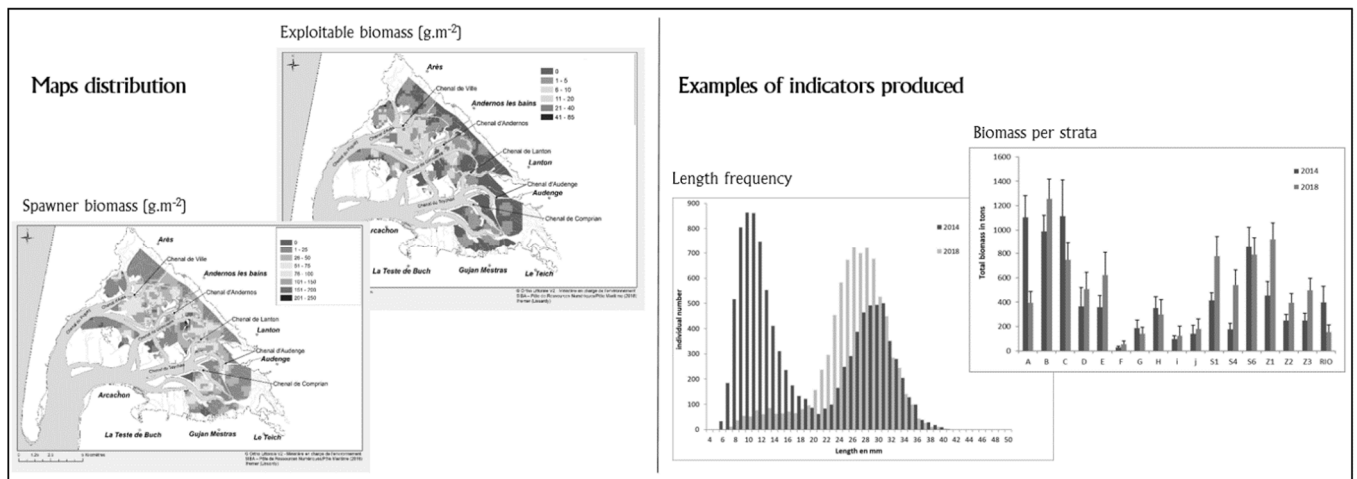
278 A stratified random sampling was applied dividing the study area into 16 reference strata,
279 based on expert knowledge (Fig. 4). These strata are homogeneous in terms of hydrology,
280 sediment particle size characteristics and current patterns (Kermorvant et al., 2017). Over time
281 new strata in adjacent areas have been added. This mainly concerns the addition of fishing

282 restricted areas or other areas of interest for fishermen. For sampling protocol, see details in
283 Sanchez et al., 2018; Kermorvant et al., 2017; Kermorvant et al., 2019a).



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

289 These surveys provide a dataset of indicators such as abundance indices (number.m⁻² and
290 g.m⁻²), length-frequency histograms, total abundance and biomass (number and weight),
291 fraction of juveniles (individuals measuring less than 17 mm), spawners (individuals
292 measuring more than 25 mm) and exploitable stock (individuals measuring more than
293 35 mm) (%), as well as their abundance (number and weight) and maps of clam densities (Fig.
294 5). The dataset includes 7 years of monitoring (2003, 2006, 2008, 2010, 2012, 2014 and
295 2018). The 2016 survey could not take place for financial reasons. After each campaign, the
296 results of the survey are presented to the working group and to all the fishermen. The
297 evolution of those indicators constitutes essential knowledge to make recommendations or
298 advices from scientists to professional organizations in charge of Manila clam management.



299

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

301 monitoring.

302 5.2. Progression in the knowledge of population dynamics

303 5.2.1. Growth/diseases

304 Size-structure histograms of Manila clams, including those obtained in the framework of
 305 stock-assessment surveys (see § 5.1), revealed a lack of large individuals, i.e. > 40 mm shell
 306 length. Monitoring of growth and searching the main involved drivers (natural and anthropic)
 307 became rapidly a priority. Using a capture-tagging-recapture method, shell growth rates were
 308 determined in four different areas, and at four different tidal levels. Surprisingly for a
 309 suspension feeder, tidal level poorly explained growth performance (Dang et al., 2010b). The
 310 main scheme was a “normal” growth until a size of approx. 30 mm, and a strong reduction
 311 after leading to a relatively small asymptotic size. In the same time, condition index (CI)
 312 (flesh weight/shell weight) displayed low values compared to other sites throughout the
 313 world. Professional fishermen proposed a genetic impoverishment as an explanation, due to
 314 the semi-enclosed status of Arcachon Bay. This hypothesis was discarded, since these Manila
 315 clams, when transplanted in a site where growth is reputed to be high for oyster (Banc
 316 d’Arguin), displayed rapidly high growth rate and elevated asymptotic shell length (Dang,
 317 2009). The hypothesis that fishing may have an effect on the selection of slower-growing

318 individuals in Arcachon Bay cannot be totally ruled out. However, Manila clam cross-
319 transplant experiments between contrasted areas highlight the strong relationship between
320 growth and environment features (phenotypic plasticity). Moreover, in situ capture-tagging-
321 recapture experiments enabled the assessment of the Von Bertalanffy growth function
322 parameters. For Arcachon Bay, mean growth parameter K is 0.72 year^{-1} (Dang et al., 2010)
323 which is relatively high in comparison with other geographical areas such as Canada, England
324 and Turkey [values between 0.14 and 0.54 year^{-1} (Bourne, 1982; Çolakoğlu and Palaz, 2014;
325 Clarke et al., 2019)]. Regarding environmental conditions, growth is mainly influenced by
326 seawater temperature (Toba, 1987 in Nakamura et al., 2002; Fan et al., 2007). For Jiaozhou
327 Bay (China), the temperature range of $18\text{-}23^{\circ}\text{C}$ was determined to be the most suitable for
328 shell growth (Fan et al., 2007). Growth was also described for the Manila clam in Thau
329 lagoon (Maitre-Allain, 1982): no growth occurs below 6°C and optimal growth is expected
330 between 12 and 20°C . Considering the temperature conditions prevailing in the Arcachon
331 Bay, this factor may not explain the observed growth deficit. In addition, scanning different
332 pathogens and diseases in Manila clams highlighted their detrimental effects on CI with
333 possible knock-on effect on shell growth parameters. Trematode parasites, at the stage of
334 metacercariae (i.e. larvae with generally small interaction with host tissues), were present at
335 low intensity and are certainly innocuous at that infection level (Dang et al., 2009a).
336 Perkinsosis, a disease related with different protozoan parasite species belonging to *Perkinsus*
337 genus and responsible of most infectious pathologies in bivalves worldwide (Soudant et al.,
338 2013), were present in Arcachon Bay. Its prevalence (% of infected individuals) was 93% and
339 mean infection abundance was $96 \times 10^3 \text{ cells g}^{-1}$ wet weight gill tissues (Dang et al., 2010a,
340 Dang et al., 2013). At this level of infection, the population of Manila clams must be
341 impacted. Besides, Manila clams suffered from another disease, the Brown Muscle Disease
342 (BMD) (Dang et al., 2008), only reported in Arcachon Bay, lethal for individuals and causing
343 moderate population mortality as long as the prevalence remains low (Dang & de

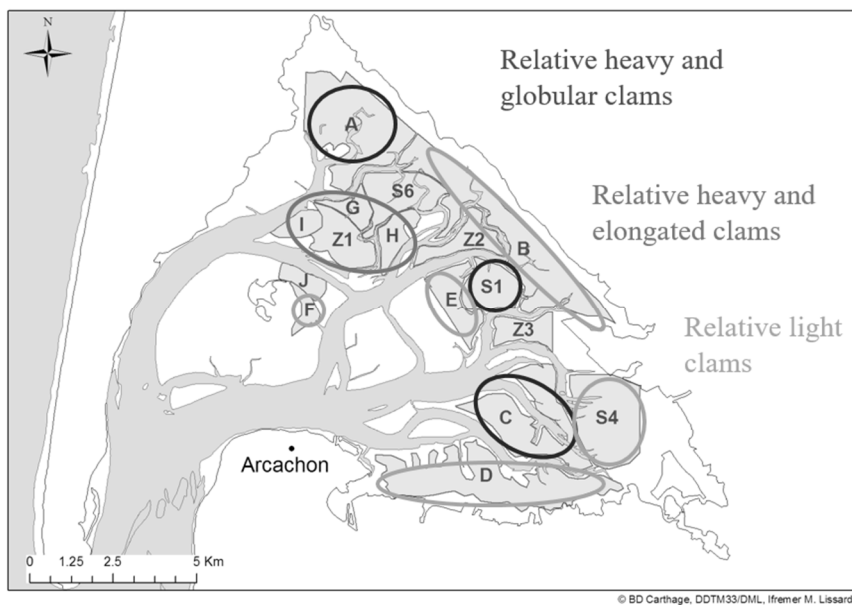
344 Montaudouin, 2009; Binias et al., 2014). The infectious agent of BMD is supposed to be a
345 virus (Dang et al., 2009b; Binias, 2013; Pierron et al., 2019) but supplementary studies should
346 be envisaged to confirm the aetiology and understand this emergent disease. Finally, Brown
347 Ring Disease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

355 5.2.2. Morphometrics variability and links with geographical or environmental
356 considerations

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

360 So, morphometric studies were conducted to consider intra-site (at the Arcachon Bay scale)
361 and inter-site phenotypic variabilities of Manila clam (on four deposits distributed along the
362 French Atlantic coasts). They concerned conventional shape analysis based on metric (length,
363 ventral length, height, width, lateral and ventral areas) and weight (shell mass) measurements.
364 The first study (Caill-Milly et al., 2012) was conducted on 2070 sub-sampled shells from the
365 Arcachon Bay monitoring survey of 2010. It established allometric relationships between
366 pairs of descriptors that were specific to the lagoon. A significant change in morphology was
367 highlighted from a length close to 16-20 mm which corresponds to the second year of life
368 [with reference to the work of Dang (2009)]. From this size, the growth rates of the height and

369 weight of the valve are therefore greater than that of the length. Intra-site phenotypic
370 variability study led to the identification of three morphological patterns among adult clams
371 within the Arcachon basin, which differed in particular by their distance to the ocean
372 connection (Fig. 6). Relative heavy and globular clams were associated with low density and
373 the specific local pathology (BMD). The results converge to indicate that certain intra-basin
374 areas seem unfavorable for the development of individuals (strata A, S1 and C, Fig. 6).
375 Conversely, they identify the north central part of the Basin as favorable for their good
376 development (Strata I, G, H and Z1, Fig. 6). In addition, clams in the Arcachon Bay appear to
377 be much less elongated (elongation index) and more globular (compactness index) than in other
378 sites including Europe confirming poor conditions for some individuals (Caill-Milly et al.,
379 2012).



380

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

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

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

397 5.2.3. Knowledge regarding clam habitat

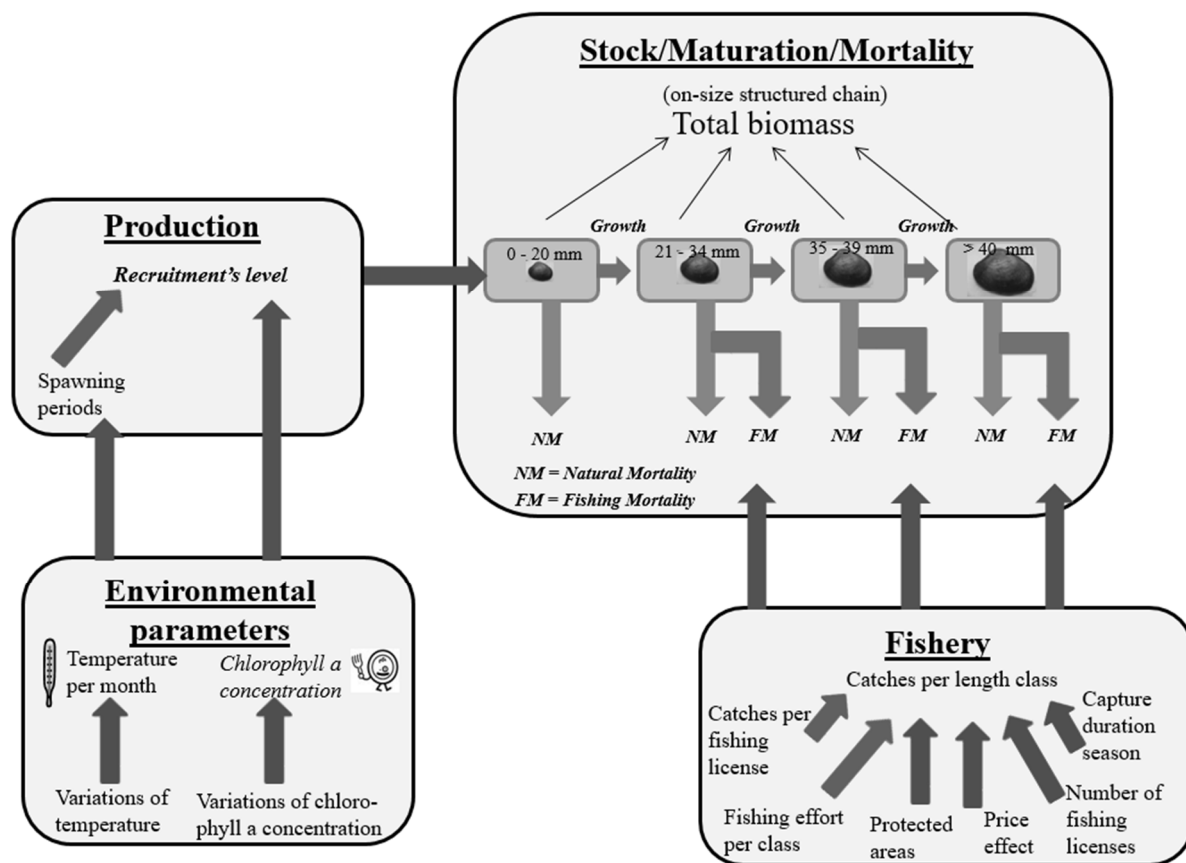
398 Since the beginning of the clam survey, some intertidal habitats have drastically changed.
399 Indeed, an important seagrass decline has been reported in years 2003-2007 (Plus et al.,
400 2010). Concurrently, some modifications of the sediment dynamics within the Bay have been
401 observed by both local scientists and stakeholders: increase in suspended sediment
402 concentrations (ARCHYD hydrological network, Ifremer 2017), infilling of secondary
403 channels or grain-size changes (Blanchet et al., 2005), important mud deposits on north-
404 eastern sandy beaches, mudflat erosion in the center of the Arcachon Bay where seagrass
405 disappeared. Recent studies based on field experiments, decadal analysis of morphological
406 changes and numerical hydrodynamics modelling demonstrated that such modifications of
407 sediments dynamics within the Arcachon Bay can be mainly explained by the direct
408 consequences of the seagrass regression on tidal propagation and associated current velocities,
409 leading to a self-amplification of the seagrass regression (Cognat, 2019 ; Ganthy et al., 2018;
410 Mütterlein et al., 2016). Current research is attempting to forecast possible future evolutions

411 of intertidal habitats regarding present environmental conditions and potential local
412 consequences of the global changes.

413 5.3. A management tool to support the decision-making process

414 In order to help management decision, a tool adapted to the Manila clam population of the
415 Bay was developed by gradually integrating knowledge specific to Arcachon Bay (Bald et al.,
416 2009; Dang, 2009; Caill-Milly, 2012). It is a deterministic type simulation model based on a
417 dynamic systems approach. It was structured into four shell length size classes (0-20 mm, 21-
418 34 mm, 35-39 mm and greater than 40 mm). On the one hand the
419 “Stock/Maturation/Mortality” block is fueled by the “Recruitment” block itself influenced by
420 “Environmental parameters”. On the other hand, the “Stock/Maturation/Mortality” block is
421 also influenced by the “Fishery” block that defined the fishing mortality according to the
422 different size classes (Fig. 7). This tool was implemented under Vensim ©. It allowed to
423 envisage various combinations of management measures or environmental conditions and to
424 compare differences in biomass trends in response to these various *scenarii*.

425



426

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

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

435 5.4. Optimization of the monitoring survey

436 Recent development in statistics and geostatistics allows survey designs theory and
 437 implementation to be more and more efficient. Spatially balanced sampling (SBS) designs are
 438 a newly developed family of survey designs (Kermorvant et al., 2019b). For a survey design,

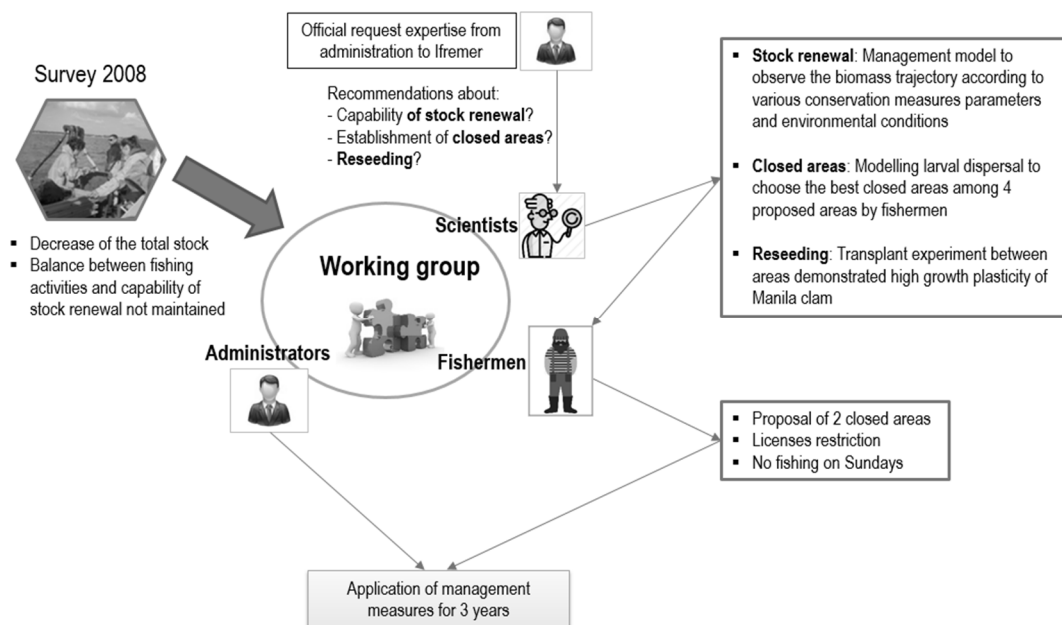
439 efficiency means a lower sampling size and/or a higher precision reached on final estimates.
440 Spatially balanced sampling (SBS) designs are one of these newly developed survey designs.
441 SBS provides a good sampling coverage of the study area thought balancing samples
442 geographically. They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

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

451 5.5. Co-management process between fishermen/scientists/administration

452 The co-management Manila clam process has been really in place since 2003, including
453 biomass monitoring, research and exchanges in working groups in response to fishermen
454 issues. Different steps were performed in response to a decrease of the Manila clam stock
455 occurring in 2008 (Fig. 8). The questioning mainly concerned the capability of the Manila
456 clam stock renewal, the establishment of closed areas and the reseeded. Several sources of
457 knowledge and capacities were considered and shared between the actors to make proposal
458 actions to address this decline such as the approach described by Léopold et al. (2019) in
459 small-scale fisheries of Vanuatu and New Caledonia (South Pacific). Scientists used different
460 tools as a specific compartmental single-species model developed to assess different
461 management strategies (Bald et al., 2009), a numerical hydrodynamics modelling (Plus et al.,
462 2009) to study larval dispersion to choose the best closed areas and transplant experiments
463 (Dang, 2009). All stakeholders then meet together during working groups to discuss about the

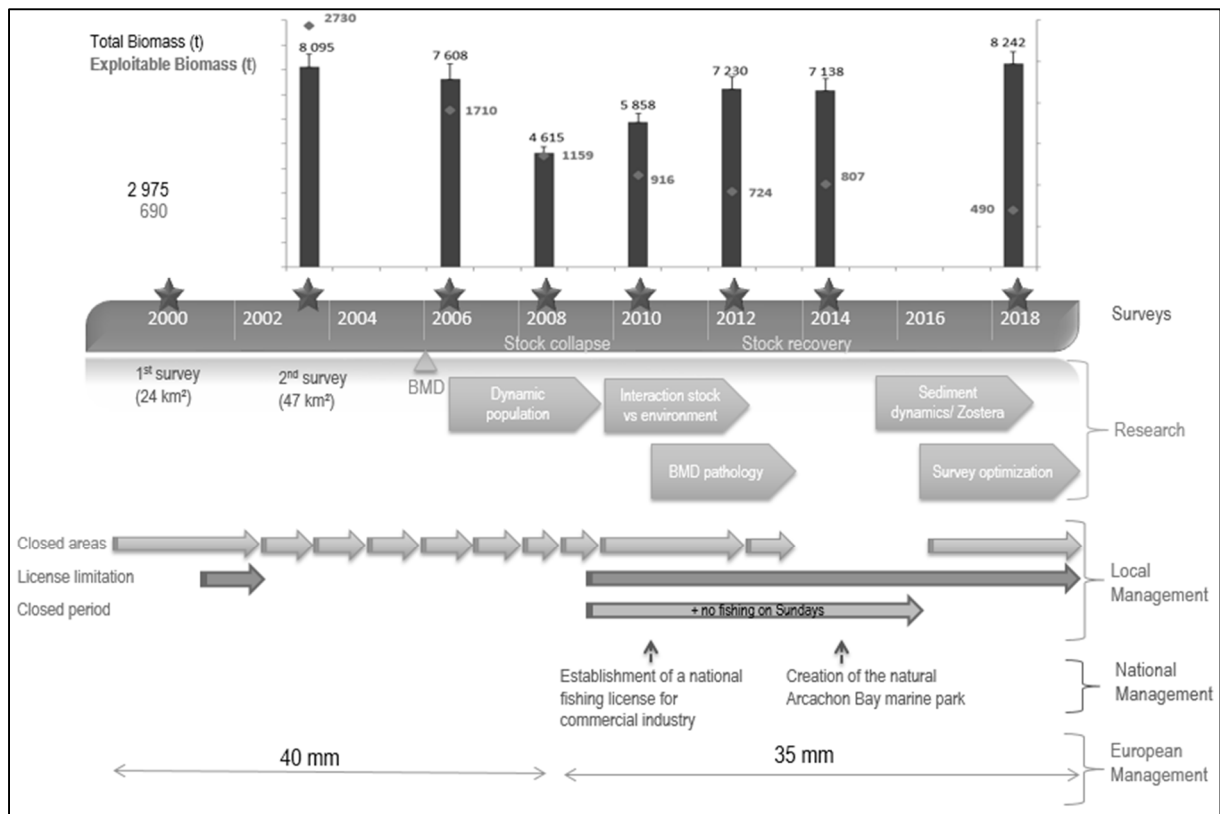
464 results and to take decisions. The use of mapping tools is particularly implemented during
 465 exchanges.



466

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

469 Since the first study in 2000, the co-management process for the Manila clam fisheries was
 470 established and improved gradually. The strong willingness to maintain sustainable Manila
 471 clam fisheries has led to all stakeholders to interact with each other. This collaborative
 472 process to manage this resource takes the form of various collective actions such as co-
 473 organized monitoring surveys, research programs that have been intensified since 2006 and
 474 working groups to have discussion and make decisions. Figure 9 shows the chronology of
 475 developed actions since 2000 with the realized monitoring surveys, the research undertaken
 476 and the different management levels and their applications. As highlighted by Léopold et al.
 477 (2019), the implementation of cooperative co-management in small-scale fisheries is a slow
 478 process lasting several years. It is an illustration of the adaptive ability of management mode
 479 at a local scale.



480

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

483 The role of the actors in this process is different, some roles are shared equally, others are not
 484 (Table 1). Regarding the “animation/exchanges organization”, there is no real stakeholder
 485 leader. The interactions take place mainly during the working groups or during research
 486 projects. They can be intense on these occasions but apart from that, they remain infrequent.
 487 Some tasks are formalized (by conventions), but most of them are not. Mackinson et al.
 488 (2011) wrote about it that prescribed or mandated participation is rarely effective for fisheries
 489 and marine research.

490 Table 1. Roles of the stakeholders in the collaboration with regard to the nature of the
 491 participation to the Manila clam studies (H: high contribution; M: medium contribution; L:
 492 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

493



494 **6. Discussion**

495 6.1. Success and failure

496 The Manila clam case study in Arcachon Bay demonstrates that a collaborative process
497 between stakeholders in the present case is a real success to monitor species abundance in
498 small case areas (Table 2). The investment of the fishermen in the monitoring survey
499 indicates a successful collaboration. It increased and encouraged mutual understanding raising
500 new research questions considering fishermen local knowledge and taking advantage of their
501 experience because they are well placed to perceive fine-scale changes in the environment
502 (Daw et al., 2011; Yochum et al., 2011; Massé et al., 2016). Orensanz et al. (2014) perceived
503 a collaborative engagement as an intellectual partnership between fishermen, scientists and
504 managers. In our case, the approach can be considered as collaborative due to fishermen
505 involvement in the monitoring survey, the holding of working groups involving several actors
506 (administration, scientists, fishers, managers) to discuss and exchange about specific issues or
507 scientific objectives. The different questions raised have taken the form of research programs
508 (Dang et al., 2009; Caill-Milly et al., 2012; Montaudouin et al., 2016b; Kermorvant et al.,

509 2019a) that assembled scientists from several disciplines. According to Dutra et al. (2015), the
 510 success of natural resources management depends on both improving the knowledge about
 511 resource dynamics, governance and the stakeholder engagement in the management decision.
 512 However, some difficulties are to be highlighted such as the available funds to schedule
 513 regular surveys (with a financial contribution supported by the professionals which is the
 514 structure carrying out the campaign from funders) and available funds for research programs
 515 applied to local issues (Table 2). It also revealed the discrepancy between the outcomes of
 516 research for a global management vision and the individual expectations of professionals, the
 517 difficulty in maintaining sufficient contact due to other individual activities and the turnover
 518 of State and fishermen representatives *etc.* This last difficulty is consistent with the roles of
 519 the fishermen organization representatives described by Marín and Berkes (2010): they are
 520 the “gatekeepers” of the co-management process and the links between fishermen and the
 521 organizational environment. The term “gatekeepers” (or “sentinel”) also has a meaning in
 522 terms of environmental monitoring. Indeed, it is the daily presence of professional fishermen
 523 that has made it possible to detect abnormal localized mortalities which have proven to be
 524 linked to a hitherto unknown disease.

525 Table 2. Positive and negative outcomes identified in the collaborative process in this case
 526 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
Scientific findings (applied research) used to a better management process	
Recognition of the approach and the developed competencies (requests from	

other sites)	(short term enterprise vision)
Sentinel role of the fishermen regarding environmental quality	Difficulties to assert local characteristics of the resources (growth) to adapt European legislation

527

528 This type of collaboration between scientific and professional structures exists for numerous
529 other local French deposits or resources such as bivalves (Manila clam, scallop, mussel ...),
530 crustaceans (spiny lobster) or algae, mainly in Brittany and in Normandy (Picault et al., 2014;
531 D’Hardivillé and Bouché, 2018; ICES, 2018). Spatial extents of those stocks are generally
532 restricted and well delimited (little or no mobile resources). In addition, the number of
533 stakeholders involved in the management is also relatively limited (due to local and regional
534 level). Those two aspects must have favoured this type of collaboration. For resources such as
535 fish and when they are shared between States, such collaborations seem to be more recent.
536 Collaborations regarding inshore fisheries are often the subject of technical reports and not
537 scientific papers; thus, they are poorly disseminated and not always well identified by the
538 scientific community and by managers.

539 6.2. Lessons and perspectives

540 The co-management process looks like a perpetual search for balance (*i.e.* stay connected
541 between stakeholders, acts, ensure medium and long-term financing, be available to explain
542 the ins and outs when changing representatives...) but it is worthwhile. In the case of small-
543 scale artisanal fisheries in Chile, Schumann (2007) identified four social benefits of co-
544 management initiatives involving fishermen organizations: improving relationships between
545 fishermen and the State; increasing fishermen sensitivity regarding ecology and management;
546 cooperation between fishermen and scientists; and approach promoting a feeling of unity
547 between fishermen in particular regarding management interest. This current work is in
548 agreement with this analysis for the 2nd and 3rd points. For the first one, information is missing

549 on the relations between fishermen and the State apart from those with the presence of
550 scientists. For the last one, the question is inherent in fishermen. From the moment when it
551 was the fishermen who mobilized the scientists at the start of year 2000 to have factual
552 elements to manage the local resource, it can be considered that the local committee
553 CDPMEM Gironde already created the conditions of unity among fishermen. One could ask
554 the question of the unity between professional fishermen and recreational fishermen.
555 Nonetheless, as explained previously, recreational fishing is considered to have a negligible
556 impact on the stock compared to that of professional fishing.

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

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

584 Defined roles for each of the stakeholders in the decision support process should be explicit.
585 This is a key issue identified for the success of this process (Röckmann et al., 2017 in Macher
586 et al., 2018). In this study, roles of the stakeholders are already well defined (with high
587 involvement of some) and shared, but for some roles, there are no leader. For example,
588 regarding “animation/exchange organization”, nothing formal exists outside working groups
589 and it would be more efficient if a structure supports it. In any case, it is crucial to keep a
590 clear separation between decision-support and decision making process. Otherwise, confusion
591 may occur between stakeholders’ involvement in decision support and consultation for
592 decision making (Macher et al., 2018). Such deviance may lead to instrumentalization of
593 science in the decision process and is often cited. But a certain instrumentalization of
594 producers may also be a source of fear. Finally, the communication between stakeholders is
595 also a point to improve. Exchanges take place during working groups and dissemination of
596 results is done through technical reports. All monitoring survey campaign reports are also
597 available online (<https://w3.ifremer.fr/archimer/>) as well as reports and scientific papers. But
598 are they really consulted by non-scientists (even if some of them are in French)? Would a
599 specific Internet site as the one developed for the Canadian Northern Gulf sentinel programs

600 on groundfish fisheries (Gillis, 2002) be better to inform? A reflection on other forms of
601 communication should be carried out. For example, would a dashboard on the main results of
602 the survey (using selected indicators) be of interest to better share observations on the state of
603 the stock with professional fishermen? To reinforce the links between the stakeholders outside
604 the highlights of campaigns and some specific research, would it be appropriate to set up a
605 dedicated half day of exchanges between scientists, fishermen on this resource with a large
606 place for discussion? Such possible initiatives will be discussed soon among the stakeholders.

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

615

616 **Acknowledgments**

617 All the structures involved in the decision-support process regarding Manila clam case study
618 in Arcachon Bay are thanked: first, the local fishing committee CDPMEM Gironde and the
619 regional committee CRPMEM Nouvelle-Aquitaine, and also the French Administration and
620 the Arcachon Bay natural marine park. Recognition is also addressed to all the fishermen who
621 contributed to the monitoring surveys or to specific experiments with a special thanks to
622 Céline Laffitte for her involvement in logistic and administrative support regarding the

623 campaigns since 2003. A special acknowledgement for the late Jean-Michel Labrousse,
624 former chairman of the local fishing committee.

625 Thanks are also addressed to the two anonymous reviewers and the editor for their useful
626 comments on the submitted manuscript.

627 All studies were supported from National, Regional and European funds and relied on a
628 partnership with Ifremer, fishing professional organizations and academic institutes. For more
629 detail about financial support, see the different papers in bibliography.

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