



HAL
open science

Distribution of Manila clam, *Ruditapes philippinarum*, into Berre Lagoon according to the environmental condition

Mathilde Mahé, Doriane Delanghe, Raphael Grisel, Jean-Christophe Poggiale, Nicolas Mayot

► To cite this version:

Mathilde Mahé, Doriane Delanghe, Raphael Grisel, Jean-Christophe Poggiale, Nicolas Mayot. Distribution of Manila clam, *Ruditapes philippinarum*, into Berre Lagoon according to the environmental condition. *Vie et Milieu / Life & Environment*, 2020. hal-03359303

HAL Id: hal-03359303

<https://amu.hal.science/hal-03359303>

Submitted on 30 Sep 2021

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

DISTRIBUTION OF MANILA CLAM, *RUDITAPES PHILIPPINARUM*, INTO BERRE LAGOON ACCORDING TO THE ENVIRONMENTAL CONDITION

M. MAHÉ^{1,2*}, D. DELANGHE³, R. GRISEL¹, J. C. POGGIALE², N. MAYOT¹

¹ GIPREB Syndicat Mixte, Cours Mirabeau, 13130 Berre l'Étang, France

² Aix Marseille Université, CNRS/INSU, Université de Toulon, IRD, Mediterranean Institute of Oceanography (MIO) UM 110, 13288 Marseille, France

³ Aix-Marseille Université, CNRS, IRD, INRAE, Collège de France, CEREGE, Aix-en-Provence, France

* Corresponding author: mathilde.mahe@gipreb.fr

RUDITAPES PHILIPPINARUM
BERRE LAGOON
FISHERY
STOCK
TEXTURE
HYDROLOGICAL DATA

ABSTRACT. – The Manila clam *Ruditapes philippinarum* (Adams & Reeve, 1850) is one of the most commercially exploited bivalve in the world (Dang *et al.* 2010). Since 2013, it has expanded into Berre lagoon. In 2017, the density was between 41 and 1,264 clams.m⁻², higher than that of other French sites (Mahé 2017, Sanchez *et al.* 2014). In February 2018, the professional clam fishery opened in the Berre lagoon. Starting in July 2018, an ecological crisis occurred and the clam stock was decimated (Mayot *et al.* 2020). Consequently, the fishery was closed. Following this event, the impact assessment was initiated with a clam stock study in spring 2019. During this campaign, 238 stations were sampled where the number and the size of *R. philippinarum* were assessed. To explain the clam distribution into Berre lagoon in relation to environmental conditions, hydrological condition and grain size were analyzed. These parameters are well known to control clam expansion (Le Treut 1986) and are believed to lead the clam distribution. Preliminary results show a total abundance of 552.07 million clams. No clear correlation was found between the hydrological condition, sedimentary data and the clams' distribution at a large scale into Berre lagoon.

INTRODUCTION

The Manila clam (or Japanese carpet shell) *Ruditapes philippinarum* (Adams & Reeve, 1850) is a bivalve mollusk native from the Indo-Pacific province. Nowadays, this is one of the most commercially exploited bivalves mollusks in the world (Dang *et al.* 2010). Manila clam is also 23rd on “the list of the most important 27 aquatic alien species voluntarily introduced in European freshwater and marine coastal waters” (Savini *et al.* 2010). The introduction of species into a new environment is one of the main challenges of global change in marine ecosystems (Cordero *et al.* 2017). In general, these species exhibit invasive behavior that can affect the ecology of ecosystems.

It seems to be the *R. philippinarum* behavior in the Berre lagoon. This area is located South of France, near Marseille urban city (Fig. 1). It covers 155 km² and its maximal depth is found to be at 9.5 m. In the fifties, at the beginning of the industrialization of the Berre coastal zone, two clams species were present in the lagoon: *Pollitapes aureus* (Gmelin, 1791) and *Ruditapes decussatus* (Linnaeus, 1758) (Febvre 1968, Mars 1949). As a result of chemical pollution, which has increased sharply due to increasing industrialization and urbanization, fishing has been forbidden in 1957. In 1966, the hydroelectric power plant installation in the North of the lagoon brought huge freshwater and nutrient inputs into the lagoon (Mayot *et al.* 2020, Roux *et al.* 1985). This perturbation caused the

extinction of many species, like clams (Le Corre & Garcia 1989). Since the 1990s, new laws have regulated the freshwater input volumes. These reductions have led to a significant improvement in the biodiversity of the Berre lagoon ecosystem (Mayot *et al.* 2020). In recent years, the shore benthic macrofauna biodiversity increased and was mainly constituted of Manila clams (Audry 2015; Mayot *et al.* 2020). New studies showed increasing densities in 2017, with an amount varying between 41 and 1,264 clams/m² (Mahé 2017). Note that this result exceeds the densities reported from other French sites but that these sites are exploited by fishing (Sanchez *et al.* 2014). As a result, the clam fishery was opened in February 2018.

In 2018, the occurrence of a massive input of freshwater during spring time (natural and by the hydroelectric power plant via EDF channel), the following high water temperature in summer time (30 °C) and the lack of wind has caused a major ecological crisis into the lagoon which began at the end of July 2018 (Mayot *et al.* 2020). The water column was stratified and O₂ could not reach the bottom layer. Consequently, clams missed O₂ and died. This resulted in a depletion of the clam stock, which ended the fishing activity in September 2018.

With this awareness, it appeared crucial to provide a recovery estimation of the *R. philippinarum* density and abundance after the ecological crisis. This study provides a clear overview of the crisis impact on the shore benthic macrofauna, especially *R. philippinarum*. Environmental

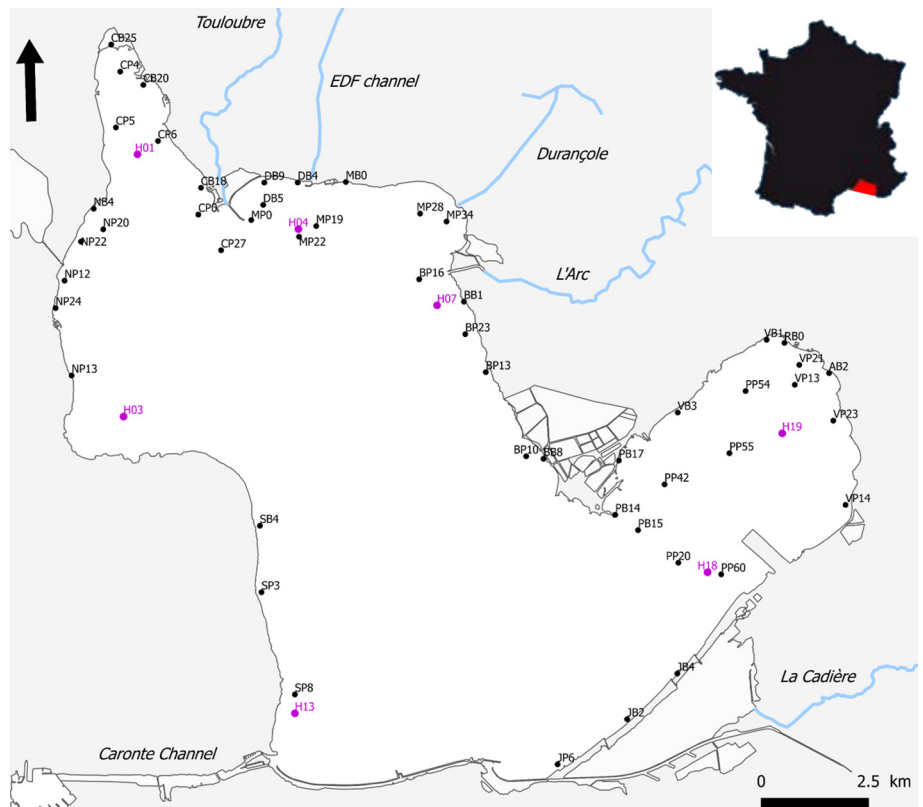


Fig. 1. – Situation of Berre lagoon in the south of France (red) with the localization of sediment station (black) and hydrological station (purple).

and economic officials expect such an ecological inventory from *R. philippinarum* for future decisions. Indeed, the objective of this study is to provide an overview of the distribution of clams in the Berre lagoon according to environmental conditions.

MATERIALS AND METHODS

Sampling campaign: To evaluate the clam distribution and density into Berre lagoon, a field investigation has been performed between the 27th of March and the 27th of July 2019. The lagoon has been divided into 19 layers according to the depth, the grain size *a priori* and the hydrologic conditions (following Berthou *et al.* 1997). Only the first 5 meters of depth were sampled. Indeed, no clams were expected below this depth due to the ecological crisis of 2018 (Mayot *et al.* 2020).

According to Bertignac *et al.* (2001), the sampling rate needs to be at least 10 stations per km² with 2 replicates to have an adequate precision (*i.e.*, 20 stations per km²). This strategy was created for the Arcachon Bay, where the tide plays an important role in clam biology and repartition. Into the Berre lagoon, it is not the case. In this campaign, the sampling rate was different depending on the layer specificity (depth and area) to better adjust the number of stations to the depth clam repartition. For the depth layer (between 2 and 5 meters), the sampling rate was 7 stations per km² with 3 replicates (*i.e.*, 21 stations per km²). For the shore layer (between 0 and 2 meters), two strategies

were chosen (1) for the big shore layer, with an area superior to 1 km², the sampling rate was 10 stations per km² with 3 replicates (*i.e.*, 30 stations per km²) (2) for the shore layer with an area inferior to 1 km², the sampling rate was 20 stations per km² with 3 replicates (*i.e.*, 60 stations per km²). Using three replicates per station allows the data to be considered as normally distributed for statistical analysis.

Stations were randomly distributed inside each layer, with a distance minimal of 200 meters between them. GPS was used for reaching each station. A total of 238 stations were sampled. At each station, 3 replicates were sampled for repeatability estimations.

Biological data: Sampling was done by scuba diving using a 0.25 m² quadrat (0.50 m × 0.50 m). For each replicate, everything inside the quadrat was sampled. On the boat, bivalves were counted and *R. philippinarum* shell length was measured to the nearest 0.01 mm using a caliper. At each station, macrophytes distribution was visually evaluated.

Total abundance has been estimated using the protocol of Berthou *et al.* (1997) for the whole stock, for juvenile and for exploitable clams. According to Caill-Milly *et al.* (2003), clams with a shell of less than 17 mm can be considered as recruitment from the previous year. Into Berre lagoon, the minimum legal size for *R. philippinarum* is the same that for Mediterranean capture: the exploitable stock is all clams with a shell length larger than 30 mm (The Decree of 29 January 2013).

To have an idea of the clam biomass, a relation between shell length and weight, made on 1,347 *R. philippinarum* from Berre lagoon in 2017, was used:

$$\text{Weight} = 0.0002 \times \text{Length}^{3.0579} \quad (R^2 = 0.9627, \text{Mahé 2017})$$

Each observed clam was measured, and weight was calculated using this formula. Then, total biomass has been estimated using the same protocol as for total abundance (Berthou *et al.* 1997).

Hydrological data: For the hydrological parameters (temperature, salinity and dissolved oxygen), a probe (Hydrolab DS5) was used in 7 stations in Berre lagoon every month since 1994 (Fig. 1). Chlorophyll *a* and suspended matter were analyzed on sample taken at the surface and bottom on each station using a Niskin bottle.

Sediment data: During the campaign, sediment was sampled at each station (238 samples) and the visual aspect of the granulometry was estimated (clay, silt, sand, and presence of shell pieces). Analyses were done on a sub-sampling of 50 stations (Fig. 1). These stations were randomly selected in proportion to the number of stations per layer and on the visual aspect of granulometry observed during the fieldwork. These 50 samples were treated using two different protocols: (a) the Loss On Ignition procedure (LOI) was used to estimate the organic content (%MO) and the proportion of carbonates (%CaCO₃) (b) the laser diffraction grain size analysis gives sediment size distribution of each sample. We chose to illustrate the texture using the scale proposed by Blott & Pye (2012).

Loss On Ignition (LOI)

The LOI procedure is a modification of the procedure described by Dean (1974). Each sample was subsampled and weighed to obtain a minimum of 10 g of sediment. The %MO was obtained after heating the sample to 550 °C for a minimum of 6 h. Then, the sediment sample was heated at 925 °C for 12 h to approximate the %CO₂. Regular tests on replicates and carbonates standard made in CEREGE Sedim Laboratory show that there is a mean error of 10 % on carbonates estimations (D. Delanghe, pers comm). To calculate the %CaCO₃ into the sediment, the %CO₂ (with a 10 % error) was multiplied by the molecular conversion factor (2.27).

Laser diffraction grain size analysis

All of the 50 samples granulometry was performed using the laser diffraction grain size Beckman Coulter LS 13,320 laser granulometer (range of 0.04-2,000 microns in 132 fractions). The analytical parameters, procedures and accuracies are detailed in Lepage *et al.* (2019) and Psomiadis *et al.* (2014). All samples were mixed with a dispersing agent (0.3 % sodium hexametaphosphate) to disperse the clay particles. Each sample was subsampled to obtain an obscuration window of the laser between 8 and 16 % and the light polarization between 50 and 70 %. The calculation model (software version 5.01) uses Fraunhofer and Mie theory. Each sample was analyzed 5 times (90 seconds each) and the result was an average of the 4 last

passages because some small bubbles can perturb the integration phase after the rinsing phase.

Berre sediment displays different size distributions with multimodal occurrences from the clays to sand. In some samples, sands were present in weak quantities and clays were numerous. In this case, for statistical reasons (number of particle occurrences) it is difficult to stay within the obscuration intervals and catch the larger particles (sand) signal. Therefore, the sample was separated by sieving at 63 µm and analyzed in two times (one sample clay and silts, one sample sands) following Lepage *et al.* (2019). In this paper accuracies and reproducibility of the Coulter are detailed for standards, natural samples, known mixtures.

RESULTS

Results analysis was performed using Spyder (Python 3.7) and QGIS 2.18.21.

Biological data

During this sampling campaign, the mean *R. philippinarum* density was 33.59 clams.m⁻² (Standard Deviation, SD 73.14) between 0 and 5 meters in depth. This density was very variable depending on the location. Few hotspots can be seen with mean density superior of 250 clams.m⁻²: in the west, in the north and in the east (Fig. 2). Otherwise, clam density was low (around 15-30 clams.m⁻²) or null. In more than 57 % of the stations, clam density was null.

The total abundance of whole stock was estimated at around 552.07 million (SD 75.02) equivalent to a total biomass of 2,903.62 tons (SD 432.68).

The abundance of juveniles has been evaluated to 106.78 million (SD 10.52) corresponding to 19 % of total *R. philippinarum* abundance. Total juvenile biomass has been estimated to 38.13 tons (SD 2.97). Only one hotspot was observed, in the west (the same as for the whole stock) where the mean density is superior to 250 juvenile clams.m⁻². Except for this spot, the juvenile density is quite poor: in 73 % of the stations, the mean density of juvenile was null.

Exploitable clam was found in the same zone as for the whole stock: in the west and in the east (mean density superior to 250 clams.m⁻²). In the rest of Berre lagoon, mean density was very poor: in 79 % of the stations, zero exploitable clams were observed. The total abundance of exploitable *R. philippinarum* was estimated at around 193.05 million (SD 29.63), which corresponds to 35 % of global stock. Total exploitable biomass was evaluated to 1 837.69 tons (SD 270.42) between 0 and 5 meters. Accessible stock for fisherman was between 0 and 2 meters (fishing clams only by walking into the Berre lagoon), this stock was estimated to 582.26 tons (SD 78.21).

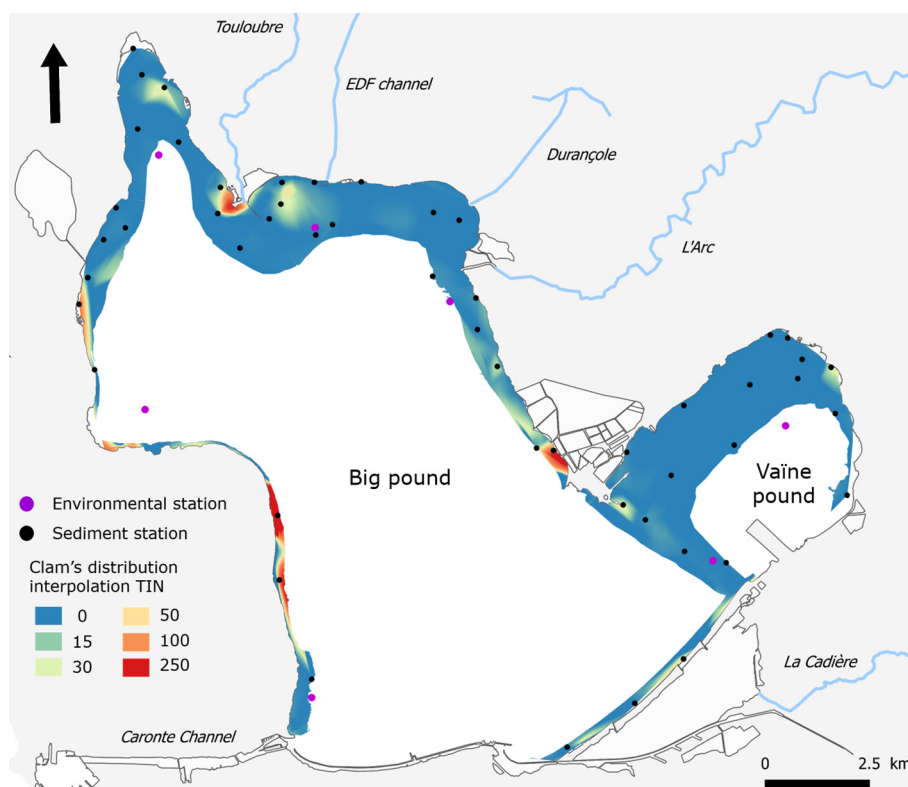


Fig. 2. – Result of clam's distribution by the interpolation from 238 stations (Triangulated Irregular Network with 2,000 columns and cells).

Hydrological data

In this study, 75 % of shell clam measured less than 32.19 mm. According to the von Bertalanffy curve, *R. philippinarum* needs around 3 years to reach 32.19 mm in Berre lagoon (data to be published). This means that these clams became established three years ago, in 2016. To link the hydrological condition to the clam distribution: temperature, salinity, chlorophyll *a*, dissolved oxygen and suspended matter will be studied starting from May 2016 and the average on each parameter on depth was calculated (Table I).

To compare the distribution of hydrological data, stations were studied separately (Fig. 2). Data for each variable at each station do not follow a normal distribution (Shapiro test, p -value < 0.05). Kruskal-Wallis test shows

Table I. – Mean, standard deviation (SD), minimum (min) and maximum (max) of each sediment and hydrological parameters since May 2016.

	Mean	SD	Min	Max
MO (%)	6.29	3.71	0.89	16.33
CaCO ₃ (%)	52.49	10.92	31.07	74.27
Temperature (°C)	16.77	7.16	2.59	30.07
Salinity	23.50	4.73	0	38.08
Dissolved oxygen (mg.L ⁻¹)	8.03	2.42	0	16.42
Suspended matter (mg.L ⁻¹)	5.24	8.29	0	81.50
Chlorophyll <i>a</i> (µg.L ⁻¹)	6.40	8.76	0.24	106.77

no differences between station for the water temperature, salinity and chlorophyll *a* (p -value > 0.09).

Conover's test was used to make multiple comparisons of mean rank sums between each station for dissolved oxygen and suspended matter (p -value < 0.05) but no clear relation with the clam spatial distribution was found.

Sediment data

It should be noted that sediment data from SB4 station was taken off. The SB4 station had a very large number of clams (bigger mean density of 736 clams.m⁻², SD 398.14). The feeling was that the clams were packed like sardines. So far, it has been extremely difficult to sample the sediment compared to the predominance of clams. This point is therefore considered out of the general dynamics of the lagoon and has been removed from our results.

Loss on ignition (LOI)

Into Berre lagoon, the proportion of organic matter (% MO) is found to be quite low according to the vicinity activities, between 0.89 and 16.34 %. The proportion of the CaCO₃ (%CaCO₃) varies between 31.07 % and 74.21 % (± 10 %) (Table I). The dispersion of these values shows a large variation depending on the location in the lagoon, but without showing any particular pattern with the clams abundance.

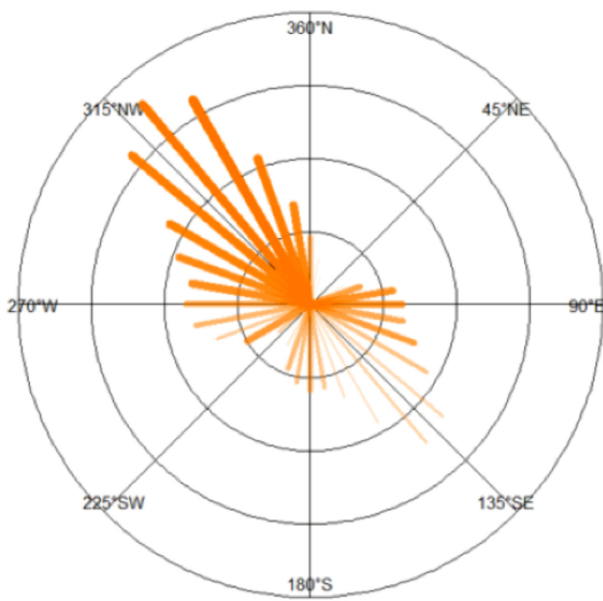


Fig. 3. – Wind direction rose from 2005 to 2019 by frequency (step of 2 %). The wind of 320° is the most frequent in 7.2 % of cases. Color and thickness represent the intensity of the wind. Except for winds from NW sectors, the wind intensity has little correlation with its most frequent direction. Winds from E-NE blow stronger but less frequently than SE winds. The SW wind of fairly strong intensity is infrequent (2 %) and corresponds to summer thermal breezes (from D. Nérini, data to be published).

Laser diffraction grain size analysis

The particle size varies greatly all around the lagoon, from very fine clay to very coarse sand. Well-sorted sands are found along the northwest exposed coastal areas while very fine clays and silts sediments are lying at low depths along the South East orientations coastal zones. The distribution is related to the main wind of the region, the Mistral, from the North-West sector (Fig. 3, Nérini 2000). Another identified pattern is linked with the industrialized and freshwater input zones directly connected to the lagoon or in its vicinity where size fractions display large heterogeneities with multi-modal distributions.

It seems that grain size distributions are influenced by wind directions but with no clear relation with the *R. philippinarum* density (Fig. 4). There is no particular pattern shown in Fig. 4 between the proportion of each texture and the increasing clam density at the stations. However, poor sorting distributions are highlighting anthropogenic areas.

To refine this observation, 4 groups of stations were defined depending on their clam density. The first group merges stations with a poor clams density (0.53 clams.m⁻², SD 0.65): SP8, JP6, JB2, PP60, PP20 (see station coding in Fig. 1 and station density in Fig. 2). The second group includes stations with 5.87 clams.m⁻² (SD 4.43): PB15, BB1, BP16, MP19, CB18. The third group associates AB2, DB5, CB20, which have a mean *R. philippinarum* density of 28.44 (SD 3.33). And then, the last group regroups together stations with the big-

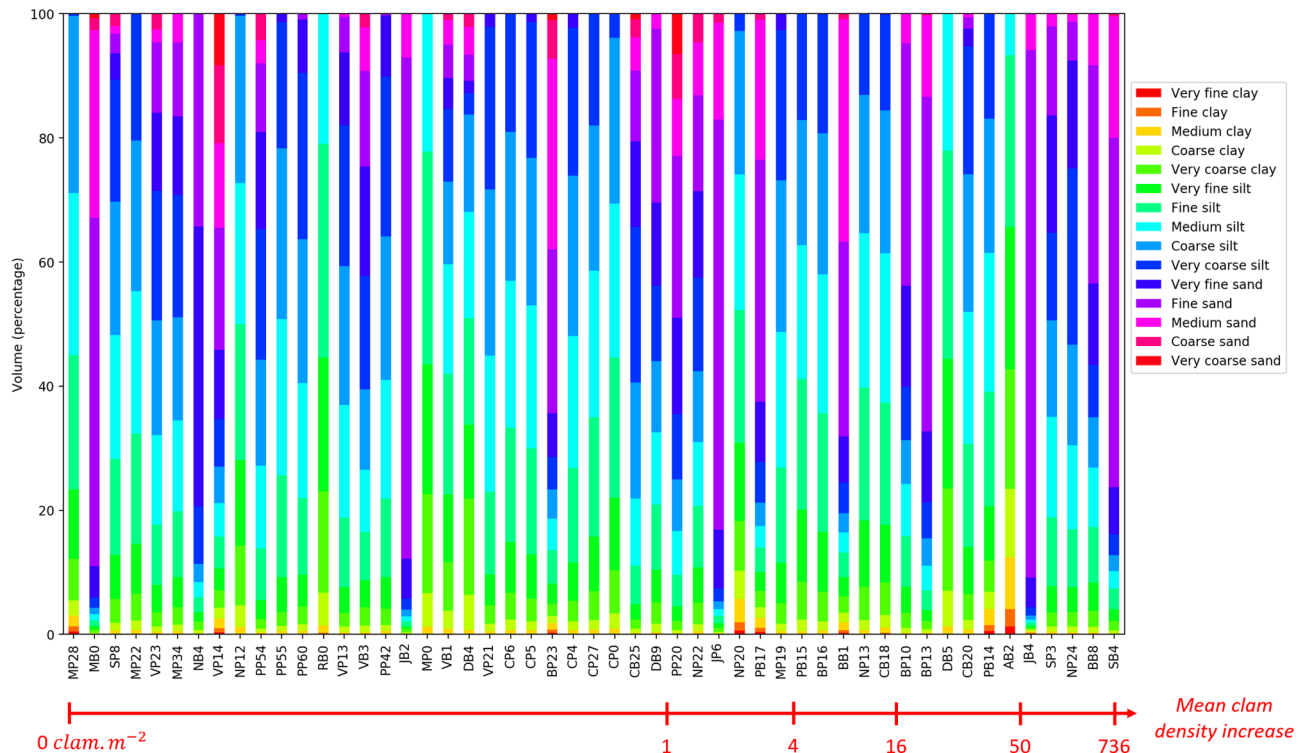


Fig. 4. – Stacked bar plot of sediment texture (scale of Blott & Pye 2012) depending on clam density (without H₂O₂ treatment).

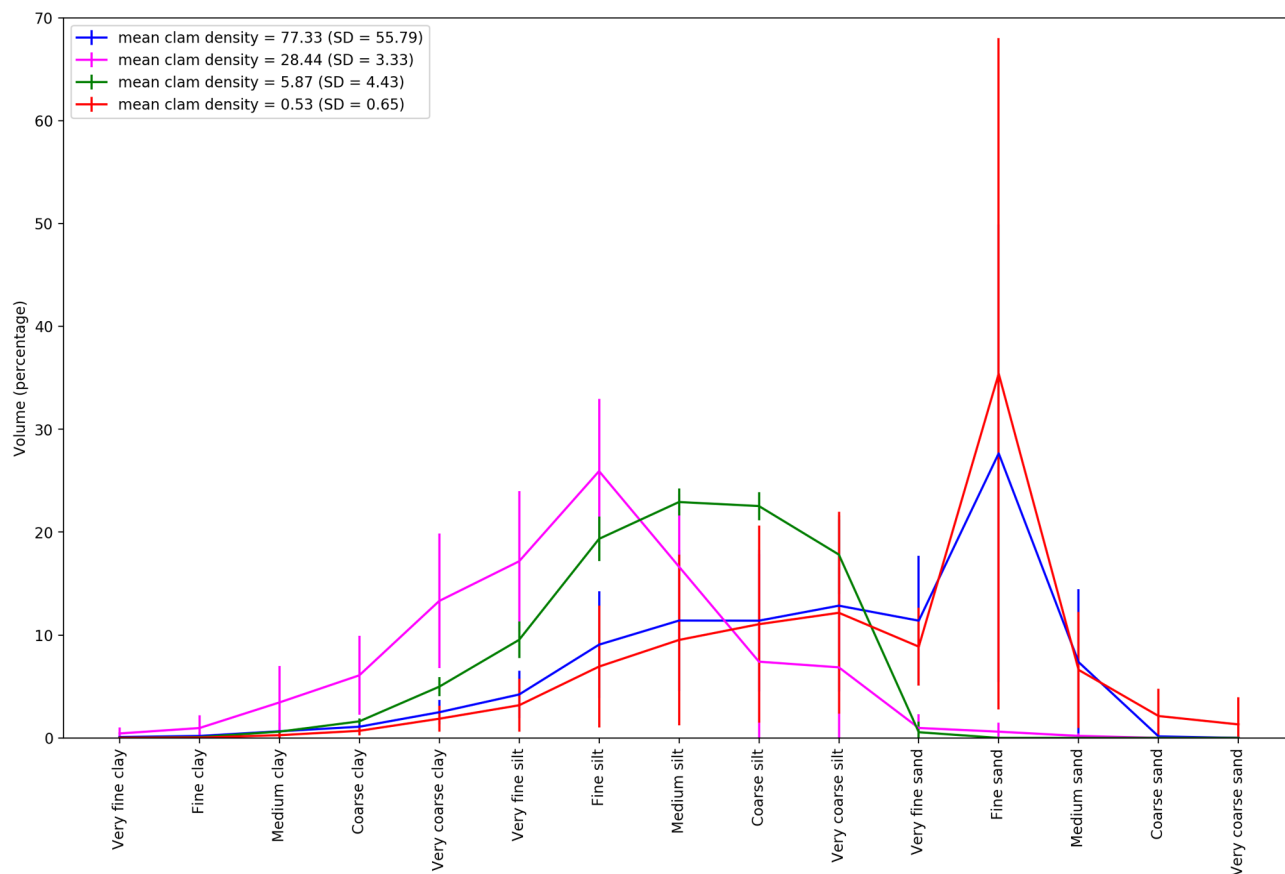


Fig. 5. – Texture of 4 groups of stations, according to the clam density. Number of stations by groups: blue = 6, red = 5, pink = 3 and green = 5.

ger clam density: 77.33 clams.m⁻² (SD 55.79): NP24, SP3, PB14, BB8, BP10, BP13. Fig. 5 shows the texture of each group. Groups with a poor clams density, *i.e.*, group 1, and bigger clams density, *i.e.*, group 4, seem to display almost the same texture pattern. This observation is confirmed by statistical test (Mann-Whitney-Wilcoxon, p-value > 0.15).

No statistical difference between the depth of the group 1 and 4 using the Mann-Whitney-Wilcoxon method with a p-value > 0.39. Also, depth and textures from group 1 and group 4 do not show any particular correlation following this method.

Besides, sediment texture between the big pound and Vaïne pound was analyzed: no pattern between these two parts of the lagoon has been found.

Concerning the lack of consistency between the texture and abundance of clams, we supposed that the behavior of the particles in natural systems could influence the size distributions especially when organic matter and carbonates are present in the system (Slomberg *et al.* 2016). Another series of granulometry was carried out with removal of organic matter (with hydrogen peroxide, following Mikutta *et al.* 2005), but no pattern could be found.

DISCUSSION

An ecological inventory of a commercially exploited species such as *R. philippinarum* is important in a sustainable stock management principle for human exploitation (Caill-Milly 2012). Preliminary results show a total abundance of 552.07 million clams (SD 75.02) between 0 and 5 meters into Berre lagoon in 2019. Regarding the comparable results of Sanchez *et al.* (2014), since they have estimated their abundances using the same protocol during the year 2014 (Berthou *et al.* 1997). The Berre lagoon clam's stock is found to represent the second French stock, behind the Arcachon Bay (2,264 million), and in front of the Gulf of Morbihan (61 million).

The first objective of this study was to provide a snapshot of the density and abundance of clams after the ecological crisis of 2018 (Mayot *et al.* 2020). Historically, only data of accessible stock for fishermen has been estimated. The accessible stock was on clam with a shell length superior to 30 mm into the coastal zone (between 0 and 2 meters, regarding the Decree of 29 January 2013). According to the GIPREB data, in 2017 (before the opening fishing of *R. philippinarum* into Berre lagoon), the accessible stock was estimated to 2,200 tons. In this study, a sampling campaign was made in 2019, accessible stock

was evaluated to 582.26 tons (SD 78.21). This reduction of more than 73 % of the accessible stock is found to be related to the anoxic crisis that occurred in the summer 2018 (Mayot *et al.* 2020).

This study establishes a “zero state” of the *R. philippinarum* stock after this ecological crisis. In the perspective of the reopening of the fishery, it would be interesting to follow a few layers of this campaign every six months to estimate the recolonization of the stock. This survey would allow monitoring the dynamics of the *R. philippinarum* population in a context of recolonization.

The second objective of this study was to understand the distribution of clams in the Berre lagoon as a function of the environmental conditions. Like all species, *R. philippinarum* requires optimal hydrological conditions to live. Water temperature needs to stands between 12 and 18 °C for the reproduction period and between 18 and 25 °C for optimal living conditions (Kang *et al.* 2016, Le Treut 1986). Salinity is another important environmental factor that controls the distribution of marine species, in particular through sudden changes in salinity that can have sub-lethal effects on the organisms (Nie *et al.* 2017). Salinity into Berre lagoon ranges between 12 and 32 – which allows optimal living conditions for *R. philippinarum* (Le Treut 1986). Oxygen is in normoxic condition, so clam can breathe normally. The suspended matter must remain as low as possible otherwise, the clam will stop filtering and be affected for reproduction or growth (Jones *et al.* 1993). According to Vincenzi *et al.* (2006), chlorophyll *a* can be used as a proxy of clam food and its optimal concentration for *R. philippinarum* biology is between 2 and 12 µg.L⁻¹. As shown in Table I, each hydrological parameter followed into Berre lagoon seems to be in the optimal range for clam biology all stations combined. This study does not show a link between abiotic conditions and clam distribution. This was quite surprising because according to Caill-Milly (2012), in the Arcachon bay, there is a strong link between the concentration of chlorophyll *a* (*i.e.*, food availability) and the stock state. Temperature also seems to play a role in the distribution of the stock into Arcachon Bay. These two parameters do not seem to be sufficient to explain the distribution of clams in the Berre pond.

With the preliminary results found in this study on a 50 sub-samples of the 238 stations, no clear relation is found between sediment data (texture from Blott & Pye 2012) and clams density. This result is unexpected compared to previous studies that showed a preference for *R. philippinarum* in sandy rather than silty environments (Le Treut 1986, Vincenzi *et al.* 2011). These studies seemed to highlight that with sand sediment, clams have a greater growth rate, higher maximum shell length and more successful juvenile settlement. On the contrary, into Berre lagoon, *R. philippinarum* densities do not seem related to the proportion of clay neither of sands (Fig. 4). For example, in AB2 station, a relatively high mean clam density (32

clams.m⁻²) was observed with a high proportion of clay and silt (42.70 % of clay and 57.30 % of silt). Besides, the textures of stations with high clam densities show the same pattern as stations with low clam densities (Fig. 5). There is no statistical difference between these groups in texture and in depth. Our study may indicate that other environmental conditions have a predominant influence on clam growth, as shown by Sakamoto et Hirai (1984 in Artigaud *et al.* 2014), where no influence of sediment was observed with a salinity of 30 and a water temperature above 20 °C. In this lagoon, sediment composition and/or physicochemical conditions may have a greater influence on clam growth than grain size distribution. Overall, in the Berre lagoon, this study suggests that sediment texture does not appear to be a key factor in the distribution of *R. philippinarum*.

It should be stressed out that with the laser diffraction grain size analysis, the specter of grain size between 0.04 and 2,000 microns in analyses in made in one time. Often, coarse sediment (coarse sand and very coarse sand) are underestimated with this method (Lepage *et al.* 2019). According to Le Treut (1986), *R. philippinarum* can live in a habitat with very coarse sediment with rocks and shell pieces. Again, into Berre lagoon, it seems that with coarse sediment, no clam was found (Figs 4, 5) but this hypothesis needs to be confirmed by a mechanical sieving study. The question of the grain sizes and clam abundance possible relation remains therefore almost entire or local-dependent with winds directions and currents directions into the lagoons for nutrient-availability.

It's well known that *R. philippinarum* has an aggregated spatial distribution with a fine-scale (< 130 m, Beninger & Boldina 2014) but this analysis was made to try to understand the global repartition of clams at a large scale into Berre lagoon depending on hydrological and sediment data. Preliminary results submitted in this study do not show any correlation between environmental data and *R. philippinarum* distribution. The analysis is still in progress and another environmental factor can explain clam distribution into Berre lagoon.

The hydrodynamic regime can play a key role on the *R. philippinarum* biology, in the regulation of growth by the resuspension of food and on the reproduction by the transport of eggs and larvae (Abe *et al.* 2015, Kuwahara *et al.* 2016, Melià *et al.* 2004). However, the power of water current needs to be not too high because it can avoid the larvae settlement and cause their death (Le Treut 1986). The wind drives the resuspension of suspended matter than can feeds *R. philippinarum* according to the wind power, depth and also water current (Gouletquer 1989). Abe *et al.* (2015) show a significant relationship between current speed and growth rate of clam: with a water current of 0.15 m.s⁻¹ the growth is higher than with a water current of 0.043 m.s⁻¹. They explain this difference by the role of current speed into the resuspension of suspended

matter (such as microphytobenthos) as food sources for *R. philippinarum*.

Due to its shallow depth, the hydrodynamics into Berre lagoon is only caused by the wind that affects the entire water column and causes currents and wind waves (Alekseenko *et al.* 2013, Paquier 2014). The two principal winds that affect the Berre lagoon are strong northwest wind, called Mistral, and southeast winds (Paquier *et al.* 2014). This lagoon is almost always under wind stress, with a wind speed more than 2 m.s⁻¹ (Alekseenko *et al.* 2013). Strong wind, with a speed higher than 10 m.s⁻¹, is more common in winter and spring but still present in the other season (27.6 % from January to March, 26.6 % from April to June, 22.7 % from July to September and 23.1 % from October to December) (Paquier *et al.* 2014). Alekseenko *et al.* (2013) have shown the presence of a strong coastal jet into the Berre lagoon, which develops along the shore and under the wind in the big pound. This coastal jet creates a random bottom velocity near the shore. Depending on the wind, and the currents resulting from it, the clams are probably transported into the Berre lagoon in refuge areas, sheltered from hydrodynamics. These hypotheses must be confirmed by future studies.

In this study, only abiotic parameters were apprehended, but the distribution of clams may also depend on the biotic environment. A study is underway to look for traces of main clam diseases: the Brown Muscle Disease (BMD), the Brown Ring Disease (BRD), and the parasites *Perkinsus* (Dang 2009, De Montaudouin *et al.* 2016). The results of these experiments may be able to explain the distribution of clams. As far as predators are concerned, the best known predators of *R. philippinarum* are birds (such as gulls, seagulls and oystercatchers), fish (such as plaice, sea bream and triggerfish), crabs (especially green crabs) and starfish (Le Treut 1986). In the Berre lagoon, the amplitude of the tide is low (5-25 cm maximum, Nérini (2000)), so birds do not have access to clams. The main species fished in the Berre lagoon are European eels, mullet, sea breams and sea bass (GIPREB 2019), but so far, no evidence of predation has been found on *R. philippinarum* (GIPREB pers comm).

Finally, it is important to take into account that this study follows a major ecological crisis (Mayot *et al.* 2020). The distribution of clams in 2019 is therefore the consequence of this crisis of 2018. As no pattern of distribution is clearly obtained according to sediment structure or hydrological parameters, the survival (or refuge) zones should probably be linked to very local hydrodynamic force that could have preserved these zones from anoxic conditions. The future recolonization of Berre lagoon will be based on these high-density zones and the global hydrodynamic to disperses the larva. The continuous observation of the lagoon recolonization until stabilization would therefore be of high interest for the hypotheses tested in our study.

This work is part of a global project on *Ruditapes philippinarum* into Berre lagoon (GEPEPA). Many experiments on clam's biology are in progress (growth, reproduction, mortality, fishery). The purpose is to create a management model to find a sustainable way of exploitation for clams using DEB theory.

ACKNOWLEDGMENTS. – This study was financed by the European funding: “European Maritime and Fisheries Fund” (EMFF: FEAMP in French) in the project GEPEPA. Many thanks are due to P Raimbault, D Nérini, S Moureau and V Mahé for their help. We thank the reviewers for their constructive comments on the manuscript.

REFERENCES

- Abe H, Hasegawa N, Yoon S, Kishi MJ 2015. Evaluation of Manila clam *Ruditapes philippinarum* growth and microphytobenthos resuspension in a subarctic lagoon in Japan. *Hydrobiologia* 758 1: 87-98.
- Alekseenko E, Roux B, Sukhinov A, Kotarba R, Fougere D, 2013. Coastal hydrodynamics in a windy lagoon. *Comput Fluids* 77: 24-35.
- Artigaud S, Lacroix C, Pichereau V, Flye-Sainte-Marie J 2014. Respiratory response to combined heat and hypoxia in the marine bivalves *Pecten maximus* and *Mytilus* spp. *Comp Biochem Physiol A: Mol Integr Physiol* 175: 13-40.
- Audry E 2015. Évaluation du stock des bivalves fouisseurs sur la bordure côtière de l'étang de Berre. Mémoire de fin d'étude – Master 2. Université Blaise Pascal, Clermont-Ferrand.
- Beninger PG, Boldina I 2014. Fine-scale spatial distribution of the temperate infaunal bivalve *Tapes* (= *Ruditapes*) *philippinarum* (Adams & Reeve) on fished and unfished intertidal mudflats. *J Exp Mar Biol Ecol* 457: 128-34.
- Berthou P, Huet J, Noël P, Jezequel M, Fifas S 1997. Étude de la pêcherie de Palourdes du golfe du Morbihan. IFREMER.
- Bertignac M, Auby I, Foucard J, Martin S, De Montaudouin X, Sauriau PG 2001. Évaluation du stock de Palourdes du bassin d'Arcachon. DRVIRHIRST/2001/05. IFREMER.
- Blott SJ, Pye K 2012. Particle size scales and classification of sediment types based on particle size distributions: review and recommended procedures. *Sedimentology* 59(7): 2071-96.
- Caill-Milly N 2012. Relations entre l'état d'une ressource et son exploitation via la compréhension et la formalisation des interactions de socio-écosystèmes. Application à la Palourde japonaise (*Venerupis philippinarum*) du bassin d'Arcachon. Université de Pau et des Pays de l'Adour.
- Caill-Milly N, de Casamajor MN, Lissardy M, Sanchez F, Morandeau G 2003. Évaluation du stock de Palourdes du bassin d'Arcachon. IFREMER.
- Cordero D, Delgado M, Liu B, Ruesink J, Saavedra C 2017. Population genetics of the Manila clam (*Ruditapes philippinarum*) introduced in North America and Europe. *Sci Rep* 7: 39745.
- Dang C 2009. Dynamique des populations de Palourdes japonaises (*Ruditapes philippinarum*) dans le bassin d'Arcachon : conséquences sur la gestion des populations exploitées. Bordeaux 1.

- Dang C, De Montaudouin X, Gam M, Paroissin C, Bru N, Caill-Milly N 2010. The Manila clam population in Arcachon Bay (SW France): can it be kept sustainable? *J Sea Res* 63(2): 108-18.
- De Montaudouin X, Arzul I, Caill-Milly N, Khayati A, Labrousse JM, Lafitte C, Paillard C, Soudant P, Goulletquer P 2016. Asari clam (*Ruditapes philippinarum*) in France: history of an exotic species 1972-2015. 42: 35-42.
- Dean WE 1974. Determination of carbonate and organic matter in calcareous sediments and sedimentary rocks by loss on ignition; comparison with other methods. *J Sedim Res* 44(1): 242-48.
- Febvre J 1968. Étude biomique des substrats meubles dans l'étang de Berre. Station Marine d'Endoume, Division du Benthos Marseille.
- GIPREB 2019. Les pêcheries professionnelles et de loisirs de l'étang de Berre. Rapport d'études. <https://etangdeberre.org/>
- Goulletquer P 1989. Étude des facteurs environnementaux intervenant sur la production de la palourde japonaise d'élevage *Ruditapes philippinarum*. Université de Bretagne Occidentale.
- Jones GG, Sanford CL, Jone BL 1993. Manila Clams: Hatchery and Nursery Methods. Innovative Aquaculture Products Ltd.
- Kang HY, Lee YJ, Choi KS, Park HJ, Yun SG, Kang CK 2016. Combined effects of temperature and seston concentration on the physiological energetics of the Manila clam *Ruditapes philippinarum*. *PLoS ONE* 11(3): e0152427.
- Kuwahara H, Nambu R, Higano J, Watanabe S, Hasegawa N, Fujioka Y, Ishihi Y, Hanyu K, Miyawaki D, Tanaka Y, Saito M, Kudo T, Okamoto H 2016. An a-priori evaluation model for restoration of fisheries population of the Manila clam and a countermeasure example in Ise Bay. *Bull Jpn Fish Res Edu Agen* 42: 67-73.
- Le Corre G, Garcia F 1989. Les ressources halieutiques de l'étang de Berre. IFREMER.
- Le Treut Y 1986. La Palourde : Anatomie. Biologie. Élevage. Pêche. Consommation. Inspection sanitaire. École National Nantes Atlantique (Vétérinaire, Agroalimentaire et de l'Alimentation).
- Lepage H, Masson M, Delanghe D, Le Bescond C 2019. Grain size analyzers: results of an intercomparison study. *SN Appl Sci* 1(9): 1100.
- Mahé M 2017. Les Palourdes japonaises dans l'étang de Berre : amélioration des connaissances et mise en place d'indicateurs de gestion de la pêche. GIPREB.
- Mars P 1949. Contributions à l'étude biologique des étangs méditerranéens – Faune malacologique de l'étang de Berre. *Bull Mus Hist Nat Marseille* 9(2): 65-116.
- Mayot N, Grisel R, Faure V, Mahé M 2020. An ecosystemic approach of an ecological crisis in Berre lagoon. *Vie Milieu* 70(3-4): 77-82.
- Melià P, De Leo G, Gatto M 2004. Density and temperature-dependence of vital rates in the Manila clam *Tapes philippinarum*: a stochastic demographic model. *Mar Ecol Progr Ser* 272: 153-64.
- Mikutta R, Kleber M, Kaiser K, Jahn R 2005. Review: organic matter removal from soils using hydrogen peroxide, sodium hypochlorite, and disodium peroxodisulfate. *Soil Sci Soc Am J* 69(1): 120-35.
- Nérini D 2000. Analyse statistique de processus physiques et chimiques en océanologie côtière à l'aide d'une méthode de régression et de classification par arbre décisionnel : application à l'étude d'un milieu fortement perturbé : l'Étang de Berre. Thèse de doctorat, Aix-Marseille 2.
- Nie H, Chen P, Huo Z, Chen Y, Hou X, Yang F, Yan X 2017. Effects of temperature and salinity on oxygen consumption and ammonia excretion in different colour strains of the Manila clam, *Ruditapes philippinarum*. *Aquaculture Res* 48 (6): 2778-2786.
- Paquier AÉ 2014. Interactions de la dynamique hydro-sédimentaire avec les herbiers de phanérogames, Étang de Berre. Thesis, Aix-Marseille.
- Paquier AÉ, Meulé S, Anthony EJ, Bernard G 2014. Sedimentation and erosion patterns in a low shoot-density *Zostera noltii* meadow in the fetch-limited Berre lagoon, Mediterranean France. *J Coast Res* 70: 563-67.
- Psoimiadis D, Ghilardi M, Demory F, Sabatier D, Bloemendal J, Yiu C 2014. Late Pleistocene to Mid Holocene landscape reconstruction in the western part of the Thessaloniki Plain (Greece): evidence for environmental changes, and their consequences for the settlement history. *Ann Géomorph / Zeitsch Geomorph* 58(2): 67-87.
- Roux RM, Nodot C, Rodier M, Stora MG, Bellan D, Liorzou B 1985. Étang de Berre : bilan des connaissances écologiques. IFREMER, Marseille.
- Sanchez F, Caill-Milly N, Lissardy M, Bru N 2014. Campagne d'évaluation du stock de Palourdes du bassin d'Arcachon. IFREMER.
- Savini D, Occhipinti-Ambrogi A, Marchini A, Tricarico E, Gherardi F, Olenin S, Gollasch S 2010. The top 27 animal alien species introduced into Europe for aquaculture and related activities. *J Appl Ichthyol* 26(s2): 1-7.
- Slomberg DL, Ollivier P, Radakovitch O, Baran N, Sani-Kast N, Miche H, Borschneck D, Grauby O, Bruchet A, Scheringer M, Labille J 2016. Characterisation of suspended particulate matter in the Rhone River: insights into analogue selection. *Environ Chem* 13(5): 804-15.
- Vincenzi S, Caramori G, Rossi R, De Leo GA 2006. Estimating clam yield potential in the Sacca di Goro lagoon (Italy) by using a two-part conditional model. *Aquaculture* 261(4): 1281-1291.
- Vincenzi S, Zucchetta M, Franzoi P, Pellizzato M, Pranovi F, De Leo GA, Torricelli P 2011. Application of a Random Forest algorithm to predict spatial distribution of the potential yield of *Ruditapes philippinarum* in the Venice lagoon, Italy. *Ecol Model* 222(8): 1471-1478.

Laws

Par le ministère de l'Écologie, du Développement Durable et de l'Énergie. Arrêté du 29 janvier 2013 modifiant l'arrêté du 26 octobre 2012 déterminant la taille minimale ou le poids minimal de capture des poissons et autres organismes marins (pour une espèce donnée ou pour une zone géographique donnée) effectuée dans le cadre de la pêche maritime de loisir. NOR : TRAM1240353A. JORF n°0045 du 22 février 2013 page 3024 texte n° 28 [en ligne] Disponible sur : <https://www.legifrance.gouv.fr/affichTexte.do?cidTexte=JORFTEXT000027093867&categorieLien=id> (consulté le 24 janvier 2017).

