The vulnerability of shellfish farmers to HAB events: An optimal matching analysis of closure decrees

Patrice Guillotreau, Véronique Le Bihan, Baptiste Morineau, Sophie Pardo

The vulnerability of shellfish farmers to HAB events: an optimal matching analysis of closure decrees

Submission to *HARMFUL ALGAE, July 2020*

Patrice Guillotreau, Véronique Le Bihan, Baptiste Morineau, Sophie Pardo*

University of Nantes, Lemna, PO Box 52231, 44322 Nantes Cedex 3, France.

* Corresponding author: patrice.guillotreau@univ-nantes.fr

Abstract

Harmful Algal Blooms (HAB) events may have serious economic consequences for shellfish farmers. When toxic algae blooms threaten human health, public authorities may decide to shut down the farming business for a while, i.e. ranging from a few days to several weeks or months, according to the severity of risks. The impact of closures being temporally and spatially distributed, shellfish farmers can avoid the risky zones or develop adaptive strategies to mitigate the economic consequences and therefore reduce significantly their business sensitivity to HABs. A sequential approach by optimal matching analysis is applied to an original data set of shellfish area closure decrees between April 2004 and December 2018 in Southern Brittany and Pays de la Loire (France) to build a typology of 79 aquaculture zones affected by various HAB and microbiological hazards (ASP, DSP, *Norovirus*, *E. Coli*, oil spills). The hypothesis is that the degree of exposure to the HAB hazard assessed by zonal closures may not be correlated to the level of sensitivity revealed by the economic results of the shellfish farming industry which can develop avoidance strategies.

Key-words: shellfish aquaculture, closure, sequence analysis, optimal matching analysis.

Acknowledgement:

The authors acknowledge the financial support of the French research Agency within the ERA4CS /ANR project CoClime (Co-development of Climate services for adaptation to changing marine ecosystems, Grant 690462), coordinated by the Marine Institute, Ireland. They are also grateful to the researchers involved in this project for stimulating discussions, in particular Elisa Berdalet (Institute of Marine Sciences, Spain), Jennifer Joy West (CICERO, Norway), Caroline Cusack (Marine Institute, Ireland), and Philipp Hess (Ifremer, France).

1. Introduction

Harmful Algal Blooms (HABs) result from different microscopic toxic algae or cyanobacteria. They are mostly found in coastal waters and freshwater environments, but can sometimes appear in oceanic waters (Lassus et al. 2016). HABs are hazardous and cause direct and indirect negative impacts to aquatic ecosystems (e.g creating toxicity, oxygen depletion), coastal resources (shellfish or fish mortality) and might also affect human health. HABs produce major economic impacts: damages on commercial fisheries, aquaculture and touristic industries, increasing monitoring and risk management costs, medical expenditure and productivity loss in case of large-scale impact on human health (Hoagland et al. 2002, Sanseverino et al. 2016). Despite increasing research, the extent and intensity of HAB outbreaks remain difficult to predict due to the complexity of processes involving multi-factor and multi-scale causes and effects (Kahru et al. 2020; Bresnan et al. 2020). However, this is of particular importance when considering the vulnerability of coastal industries to HABs. Vulnerability is often defined as a combination of the exposure of groups or individuals to hazards, their sensitivity to these hazards and the lack of adaptive capacity to absorb a shock and recover from losses (Allison et al. 2009, Rodrigues et al. 2015). By this research, we intend to look at the vulnerability of shellfish farmers to HAB events to study separately the components of vulnerability.

Looking at HAB events through their economic impacts may complement usefully the ecological approach to design effective warning and remediation measures (Adams et al. 2018). There is a growing literature about the social and economic consequences of HABs, in particular concerning freshwater events. Studies dealing with US data are more abundant than European ones (Sanseverino 2016). Four coastal industries are mostly concerned: fishing, aquaculture, tourism and housing. The methods to evaluate the spillover effects relate to the nature of consequences, either passing through market or non-market values (see Adams et al. 2018 for a survey). Hoagland et al (2002) considered all sectors simultaneously to associate the relevance of estimates as a measure of social costs. Wolf and Klaiber (2017) used hedonic pricing models to estimate the capital loss of houses adjacent to a lake in Ohio.

The economic impact of HABs on shellfish sales

The present research focuses on the shellfish farming industry which is particularly affected by HABs (Basti et al. 2018). In 2018, aquaculture produced 82.1 million tonnes of fish worldwide, where molluscs (mainly bivalves) represented 17.7 million tonnes valuing USD 34.6 billion (FAO 2020). During HAB episodes, sanitary closure of shellfish farms stop or delay commercial activities. Many articles analysed the consequences of trade bans at different scales. Dyson and Hupert (2009) used an Input-Output model to estimate the detrimental impact of beach closures on recreational razor clam fisheries. Diaz et al. (2019) studied the economic loss of the salmon farming industry in South Chile caused by HAB events. The economic damage was deemed particularly strong in case of Paralytic shellfish poisoning (PSP) outbreaks. Red tides are also largely studied through their economic impacts on different industries, using monitoring data (Larkin and Adams 2007, Morgan et al. 2008). Jin et al. (2005) showed an increase of shellfish imports in response to a supply shortage caused by trade bans during the 2005 red tide in New England (USA). They also highlighted a spatial effect on the shellfish market with price movements observed on the Fulton Fish market in New York after that some shellfish closures were implemented in Maine. Wessells et al. (1995) also studied the economic effect of a red tide event in Prince Edward Island (Canada). The authors showed a reduction in the demand for non-affected mussels in the Montreal market, resulting from a change of consumer perception concerning the quality of products, and although the marketed mussels were safe. More recently, Theodorou *et al.* (2020) evaluated the consequences of HAB-related mussel farming site closures through a risk analysis in the Mediterranean sea. They conclude that the risk depends on the season (summertime being the most critical) when it occurs, with a limited financial risk even for closures lasting up to six weeks at certain non-critical periods (Theodorou *et al.* 2020). However, beyond a certain duration of closure, the profit loss may range between 4% and 38% when harvesting bans last between 6 to 22 weeks (Konstantinou *et al.* 2012).

Park et al (2013) studied the economic impact and mitigation strategies of HABs in Korea, where the aquaculture industry suffered a total loss of USD $121 million from the early 1980s to the early 2010s, with a predominance of *Cochlodinium polykrikoides* events since 1990. PSP blooms in Korea almost every year since 1982 and has been monitored and managed since 1980. Authors reported some evolutions of HABs in Korean waters: usually observed during summertime prior to the 1980s, they are now more frequently met in springtime and autumn. The duration of episodes is also elongating. The HAB event duration has increased from less than one week on average in the 1980s to more than a month since 1995. Tang et al. (2006) have analysed the spatial and seasonal patterns of HAB outbreaks in the South Yellow Sea and East China Sea between 1933 and 2004. They reported changes in the seasonal patterns (moving from fall to summer and then to spring) with shifting dominant species and nutrient concentration variations in the Yangtze River estuary. In Southern Europe, Rodríguez-Rodríguez et al. (2010) looked at mussel cultivation in Galicia in the presence of red tides. They estimated the correlation between the time length of area shutdowns and the quantity of unsold output. They showed that there was no systematic effect: losses depend on specific market circumstances and authors highlighted the importance of organizational solutions to mitigate commercial risks. More recently, Martino et al. (2020) used a production function to investigate the effect of HABs on the Scottish shellfish market. They showed a significant but non-linear relationship between DSP and shellfish production. *Regulations and monitoring systems*

To protect human health, the aquaculture industry is highly regulated around the world: regional or national laws are implemented within the international legal framework of the 1982 United Nations Convention on the Law of the Sea (van den Bergh et al. 2002). The European Union food law impose specific obligations resulting in trade bans and area closures when acceptable biotoxin concentrations are exceeded (O'Mahony, 2018). In some cases, trade bans and industrial shutdowns can last for several months. The regulations are based on monitoring programs that need to be updated to take emergent toxins into account (Silva et al., 2015). Upgrading the monitoring systems with regard to new HAB species is an important issue to improve the management of risk exposure. For example, the ASIMUTH project aimed at developing short term HAB alert systems for Atlantic Europe (Maguire et al., 2016). These systems were applied to shellfish harvesters in Portugal, where *Pseudo-nitzschia, Dinophysis, Gymnodinium* and more recently *Ostreopsis* and *Karenia* are frequently observed. A weekly bulletin reports the ongoing state of shellfish closures and gives a one-week forecast of closures for all threatening species (Silva et al., 2016). From 27 July 2013 to 17 March 2014, this system performed 85% of correct one-week forecasts, with an accuracy depending on specific areas (coastal, estuaries and lagoons).

Central issue and hypothesis

The scientific literature about HABs focuses on the intensity, spatial distribution and drivers of algal blooms, or strives to evaluate their economic consequences. What is missing is a bridge between these two strands of research, by looking simultaneously at the temporal and spatial distribution of HABs through the track records of administrative closures to learn more about their intensity and occurrence, but also to estimate the actual economic vulnerability to HAB events among other risks. Within the 15 research gaps identified by Adams et al. (2018), the authors suggested to develop data collection programs in real time. That is exactly what the present article is about, i.e. attempting to inspire a nationwide effort of data collection based on legal decrees regarding the HAB-related closures and trade restrictions. These authors also considered that “few studies have investigated the role of intensity, and none appear to address the potential for a non-linear relationship between economic losses and duration” (Adams et al. 2018, p. 350). Like other authors, we hypothesize that there is no direct link between the presence of HABs resulting in shutdowns lasting for various durations, and the economic loss at stake (Rodríguez-Rodríguez et al. 2010; Rodrigues et al. 2015; Adams et al. 2018; Theodorou et al. 2020). Our hypothesis is that the economic impact of trade bans related to HABs and microbiological pollutions may not be as important as the frequency and duration of closures would predict. We therefore propose a thorough analysis of a possible gap between the spatial exposure to HABs expressed by administrative closures, and the sensitivity of shellfish farmers revealed by an original database of trade bans.

The article is organized as follows: Section 2 introduces the regulatory context of trade bans and closures in France for shellfish farmers, as well as the database of prefectural decrees between 2004 and 2018, and an original statistical approach by optimal matching analysis to highlight the temporal and spatial distribution of HAB events. In Section 3, the statistical description and analysis of the database is proposed to identify the factors and length of closures in Southern Brittany and Pays de la Loire regions (western France). In Section 4, the results are discussed with respect to the economic consequences for shellfish farmers and show a weak correlation between closures and economic risks.

2. Context, materials and methods

2.1 The regulatory context

To ensure a high level of protection for human health, the European Parliament and the European Council, by Regulation (EC) 853/2004, have adopted general sanitary measures for food business operators. Some food products may present specific risks to human health, requiring specific hygiene rules. This is particularly the case for bivalve molluscs, live echinoderms, live tunicates and live marine gastropods, for which microbiological and chemical issues have frequently been reported. EU member states have to classify production areas to decide whether shellfish harvesting or farming is acceptable and avoid the marketing of any product that would be harmful for human health. Public authorities have developed region-specific management plans for marine toxins that contain details for the sampling sites, frequency and methodology, and all other spatial information necessary to manage effectively the risk of marine poisoning. In France, farmed species are classified differently within the same area: Group 1 concerns gastropods, echinoderms and tunicates, Group 2 the burrowing bivalves (e.g. clams, cockles, razor clams…) and Group 3 the non-burrowing bivalves (oysters, mussels, Pectinidae). Regulation (EC) 854 /2004 also specifies the requirements of all shellfish production areas to be graded according to their microbiological quality (A, B and C). This classification is based on the number of *Escherichia coli* (*E. Coli*)*,* a biomarker of faecal contamination.

In France, 351 shellfish zones are followed by this monitoring system. Contaminants are monitored as microbiological contaminants (via the REMI network of Ifremer), phycotoxins (via the REPHY network) and chemical contaminants (via the ROCCH network). The frequency of water sampling and analysis of toxic contaminants vary upon the period and the nature of results. During some more risky periods, tests can increase to a weekly frequency. The results are disseminated in real time via online bulletins and sent to the health authorities and professional organizations. However, there is no direct causal link between the density of HAB cells monitored by such networks and the toxicity of shellfish, as evidenced by previous research (Souchu et al. 2013). This is why it is of major interest to complement the above cited monitoring systems by a look at legal decrees of closure to really assess the socioeconomic consequences of HAB events. The public decision to authorize shellfish production is based on the concentration of biotoxins in the shellfish, and not directly to the density of HAB cells in the water column. Whenever biotoxin or *E. Coli* concentrations exceed a threshold, a prefectural (state) decree can order the temporary closure of the farming zone or impose restrictions on sales until new evidence of water quality within acceptable limits is provided[1].

Since 2014, in a specific area (Pénestin, by the French Atlantic coast), a mussel farmer trade union, under the approval of the local health authorities[2], implemented a self-monitoring system. When the period at risk is coming or when a trade ban has been implemented, mussel farmers can develop self-controls in addition to those coordinated weekly by Ifremer. These additional tests are sub-contracted to certified laboratories and the cost is collectively borne by the union. Such tests avoid the dispersion of contaminated shellfish and may contribute to put an earlier end to the trade ban.

2.2 The data set

The analysis was carried out in four French counties: Finistère, Morbihan, Loire-Atlantique and Vendée. These four counties host 688 shellfish farms ruled by two regional shellfish farming councils (CRCs): CRC Bretagne Sud (Southern Brittany) and CRC Pays de la Loire. The local industry produces 37,600 tons of shellfish for a value of 141 M€, i.e. representing around 20% of the domestic output. Two zones were selected within the region because of their particularly high number of trade bans: Morbihan and Loire-Atlantique.

Because no digital database of prefectural decrees was existing so far, we entered manually all data corresponding to more than 430 prefectural decrees and 5,400 rows[3] registered between 2004 and 2018, including different types of information (Table 1).

Table 1 : database structure of prefectural decrees

Department	**Finistère - Morbihan - Loire-Atlantique – Vendée**
Name and code area	148 distinct codes
Date of trade bans	DD – MM – YYYY from 2004 to 2018
Modification of prefectural decree	Type of changes
Date of abrogation/repeal	DD – MM – YYYY from 2004 to 2018
Type of event	Microbiological alert – Toxinic alert – Chemical alert
Type of contamination	Microbiological alert, Toxinic Alert, Chemical Alert, Pollution Alert
Cause	E. Coli, Norovirus, other, Diarrhetic Shellfish Poisoning (DSP), Paralytic shellfish poisoning (PSP), Amnesic shellfish poisoning (ASP), Oil pollution
Species group	Group 1: gastropod (whelk, winkle, abalone…), echinoderm (sea urchin, sea cucumber) and tunicate (violet) Group 2: burrowing bivalves (clam, cockle,) Group 3: non-burrowing bivalves (oyster, mussel, scallops…)
Particular species	X
Except some species	X

---

[1] Beyond a few hundred cells (threshold set at 500) per litre, filtered *Dinophysis* can accrue toxins in the flesh of molluscs which are then considered dangerous and analyzed. The time interval between the appearance of Dinophysis in the water and the shellfish toxicity can vary from a few days to several weeks, making it difficult to predict marketing bans.

[2] DDTM Morbihan - Protocol for considering the self-control measures taken by mussel farmers from Pénestin for the sake of health management in the area of Vilaine Bay. Report of the mussel trade union, 24/02/2014 (in French).

[3] There are more rows than the number of decrees because each decree can be attached to several zones and can be modified several times prior to its repeal, thus resulting in several rows for the same decree in the database.

In the database, 148 shellfish production zones were listed, weighting 42% of the national zones. The lag between the date of trade ban and its repeal provides the duration time when shellfish sales are prohibited. Changes in the decree may occur over time in terms of type of event, type of contamination or species, new allowance,… thus bringing additional information into the database.

For each species group, different types of contamination were recorded:

- *E. Coli* (*Escherichia coli*) is a coliform bacterium which is commonly found in the intestine of warm-blooded organisms, like humans or dogs. They may cause food poisoning for their host.
- Norovirus is a group of viruses causing gastroenteritis and diarrhea. They are commonly found in oysters in France.
- DSP (Diarrheic Shellfish Poisoning) is a toxin produced by dinoflagellate microalgae (of *Dinophysis* or *Prorocentrum* types).
- ASP (Amnesic Shellfish Poisoning) is a toxin produced by diatom species (of *Pseudo-nitzschia* type).
- PSP (Paralytic Shellfish Poisoning) is a group of toxins of which the most common is saxitoxin
- Oil Spills can spoil a broad range of the shore after a tanker sinking. In southern Brittany and the Bay of Biscaye, it was the case on December 12th 1999 after the shipwreck of *Erika*, and on November 13th 2002 after the shipwreck of *Prestige*. Other minor oil spills can cause great damages for shellfish farms and may result in trade bans for several weeks.
- Other. They include all other causes of area closures, due to the presence of toxic pathogens, the degraded quality of water, chemical pollution, etc.

Once the database was created, some data concerning shellfish hand gathering or fishing were excluded because the study focused on professional shellfish farmers only. Scallops, donax or more broadly *pectinidae* were not selected because these species do not pertain to the aquaculture industry. Finally, some dates of abrogation were not available because extending after the end of 2018 and these decrees were also excluded. From the 148 zones available in the initial database, only 79 were finally kept in the analysis.

2.3 A sequential approach by optimal matching analysis

Because the status of shellfish farming zones is changing in the course of time, shifting from one state to another, we have chosen to deal with this changing state as for life history traits used in ecology to study the evolution of species (Hamrick and Godt 1996) or in social sciences to analyse biographies and working life trajectories (Abbott and Forrest 1986, Aassven et al. 2007). The optimal matching analysis (OMA) was applied to the sequences of states in the different zones of the studied area (details about the method are given in Appendix A1).

In the present research, seven states related to various quality status of the shellfish farming zones were defined: (1) SAFE, meaning that pumping water, shellfish hand gathering, farming and trading are allowed by the national sanitary authorities represented by the regional Prefecture, (2) DSP (3), ASP (4), *E. Coli* (5), Norovirus (6), Oil Spill and (7) Other. Only state (1) corresponds to an open zone, all other states meaning an administrative closure and a trade ban for farmers.

A sequence is defined as the life history trait of a particular shellfish aquaculture area over a long period of time, with regard to its alternative administrative status (open or closed) characterized by the water quality. Some 79 areas have been selected in this region of Southern Britany and Pays de la Loire. All of them have experienced a closure imposed by the public authorities for sanitary reasons.

The cause of the closure (DSP, ASP, *E. Coli*, *Norovirus*, Oil Spill, Other) is specified on a monthly basis along the trajectory of the zone between April 2004 and December 2018 (177 monthly periods in overall). The closure can affect a zone for less than a month but it has been considered that the full month was impacted whenever a closure was decided within the month and whatever the number of closing days. Other types of analysis can be conducted with a more accurate measurement of time (e.g. survival analysis) but it was not made necessary in the present sequence analysis for which only the change between states mattered.

Concerning the OMA approach, the R-package *TraMineR*[4] was used to create a distance matrix of substitution costs, in which all costs were constant and equal to two for all states. A hierarchical classification was applied to the distance matrix. The optimal number of clusters was decided after using the R-Package WeightedCluster to cross-check the outcomes of ten different statistical tests (Studer 2012). The state distribution was plotted for each cluster of the typology. These plots gave the percent distribution of the seven states for every month of the sample period. Some index plots were designed to complement the state distribution plots in order to emphasize the sequences. Observations (shellfish farming zones) were then ordered to make sequences more visible. Every horizontal segment characterized a sequence, divided into segments corresponding to the sequential states of the area. The average distance of sequences to the centre of gravity of the cluster was calculated to see how homogenous the cluster was. Other indices such as the Entropy index were used to confirm the homogeneity of trajectories belonging to the same cluster (Appendix A2). Pearson's Chi-squared and other statistical tests were also helpful to analyse the linkage between the cluster and some characteristics describing the zones (e.g. the areas belong to one of the two counties of the southern Brittany region).

The typology was also described by their economic characteristics. Some additional information was collected so as to determine whether the closure rate was connected or not with the economic activity spatially distributed within the clusters. Some available information came from the census of 2011 and that of 2012 through the leasehold area, the number of farms and the number of jobs by cluster.

3. Results

3.1 Descriptive statistics of the administrative closure database

Dynamics throughout the sample period

From 2004 to 2018, 432 prefectural decrees of closures concerning shellfish farmers were promulgated. The latter had to face more than 12,400 days of closure. Throughout the 14 years, there was no particular upward or downward trend detected in the number of days of shellfish trade bans. The annual average number of temporary closure of shellfish aquaculture harvesting was 888 days but with an important inter-annual variability: not a single day in 2005 up to 3,400 in 2010 (Figure 1). The average duration per event (decree) is 30 days, with variable closure durations lasting for 1 day only up to 157 days (Figure 2).

[4] https://cran.r-project.org/web/packages/TraMineR/index.html

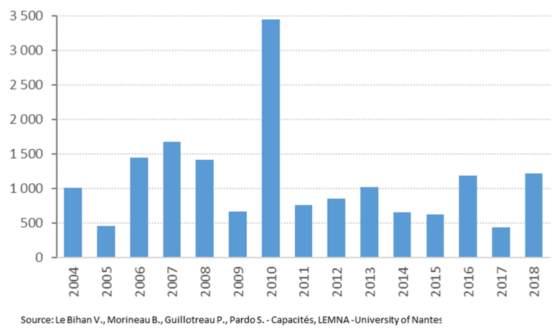


Figure 1 : Total annual number of days of shellfish trade bans

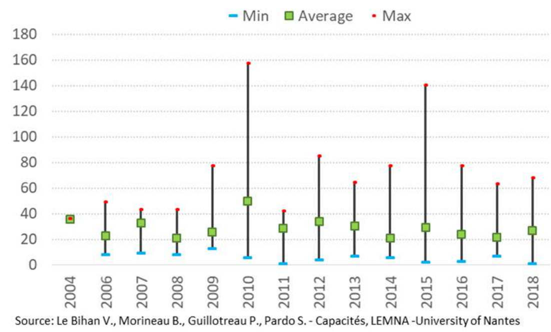


Figure 2 : Number of days of shellfish trade bans per event - Min, Average, Max -

Motives of administrative closures

The largest majority of closing events was explained by seafood toxins like DSP (68% of total decrees) or ASP (20 %), while only a small fraction of microbiological contamination cases was recorded (Figure 3). The analysis by motive also showed that the number of closing days was much longer for ASP-related bans (average of 68 days, median of 52.5) compared to other causes (Figure 4). For example, the mean values for DSP and *E. Coli* were 28 days (median of 23) and 21 days (median of 15), respectively. Figure 4 depicted also revealed a higher dispersion of durations for ASP bans.

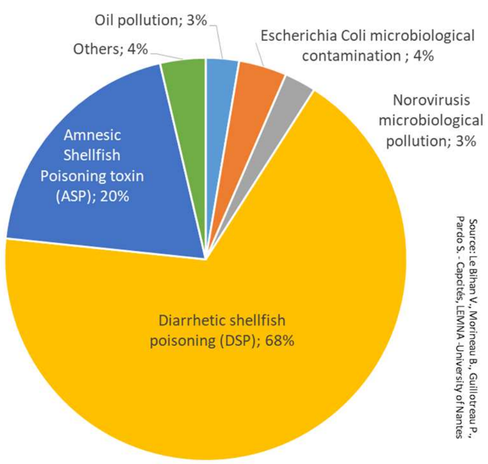


Figure 3 : Distribution of bans by type of event (average 2004-2018)

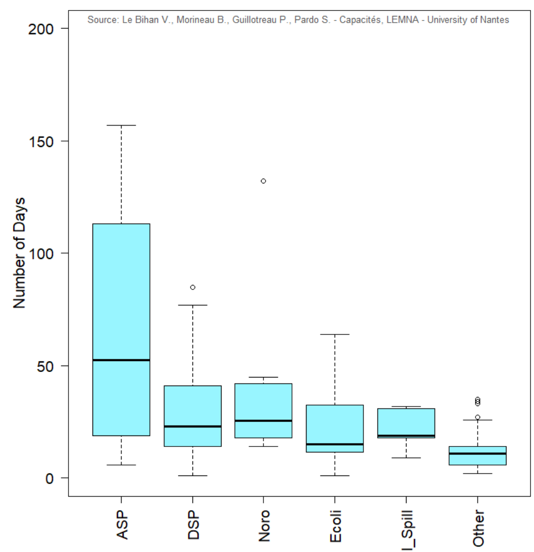


Figure 4 : Number of days of shellfish trade bans by cause (2004-2018) - Q1, Median, Q3 -

Seasonal patterns

Over the sample period, the trade bans were mostly concentrated onto the 3 spring months, April (19%), May (22%) and June (41%) having the greatest number of closures (Figure 5). It does not mean that the spring months aggregated the highest number of closing days, but that closures actually began within these months.

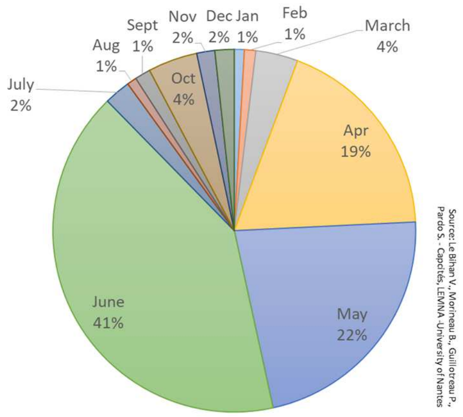


Figure 5 : Distribution of bans by month (average 2004-2018)

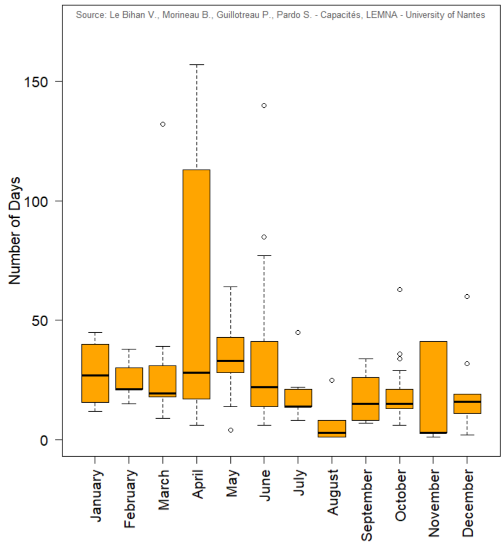


Figure 6 : Number of days of shellfish trade bans per month (2004-2018) - Q1, Median, Q3 -

The number of closing days per starting month varied to a great extent (Figure 6). April was the one characterized by the longest closures recorded between 2004 and 2018, with a maximum of 157 days. The severity of closures measured by the length median was even more important in May, but closures starting in January also proved to last for a month or more.

Geographical distribution

From the database of prefectural decrees, a geographical information system was created to visualize the number of closing days per shellfish production zone over the sample period (Figure 7). Five classes of closure duration were outlined with a colour gradient: light yellow for less than 90 cumulative days of closure in the area to dark brown for more than 361 days of closure.

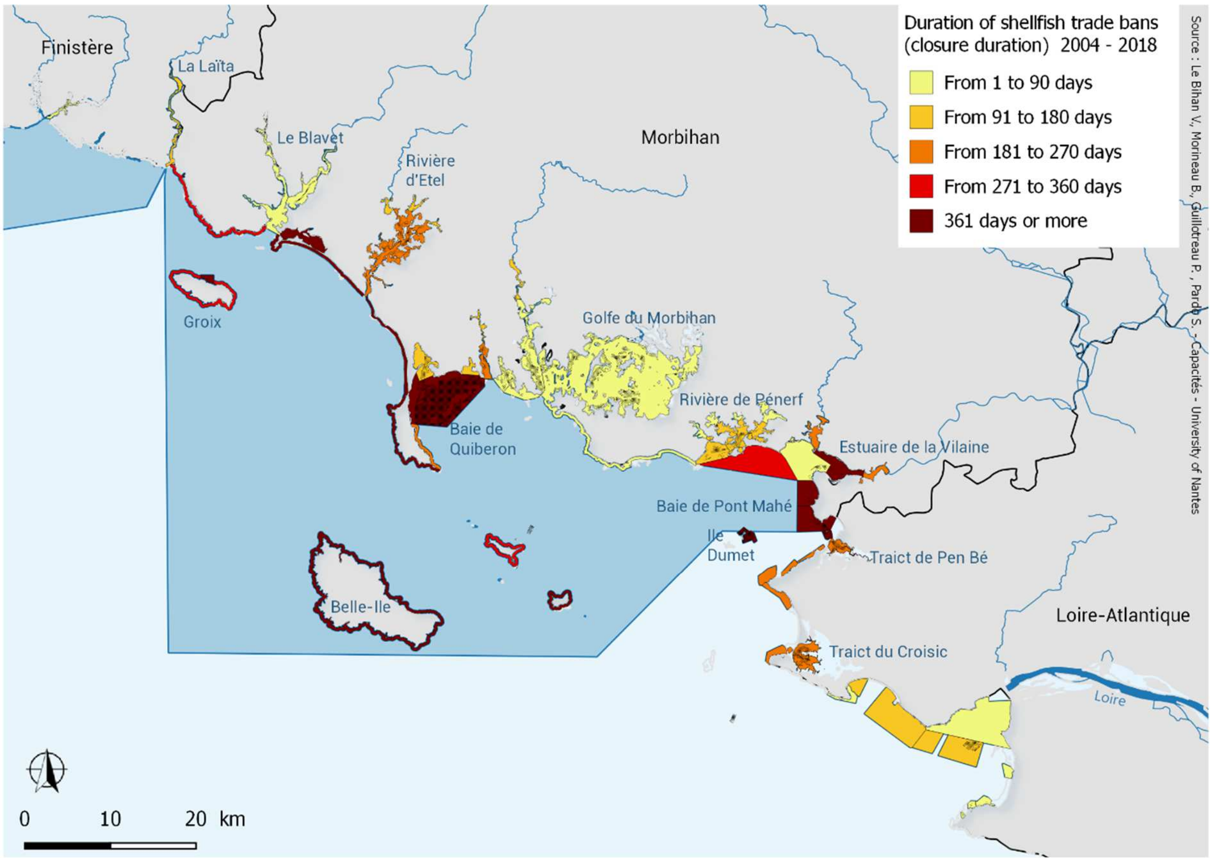


Figure 7 : Map of the number of closure days per shellfish production areas

This map shows how some particular geographical zones were more heavily impacted since the early 2000s while others remained relatively protected from any negative environmental impact or pollution episode. From this map, it is nonetheless hard to draw any conclusion whether semi-enclosed bay or river mouths were more affected or protected than open areas. The following analysis attempts to build a spatial typology from the sequential quality states of shellfish zones.

3.2 Typology of trajectories

A new table was extracted from the original database, crossing 79 rows representing the shellfish farming zones and 180 columns for the months between April 2004 and December 2018. The cells referred to a certain status of water quality among the seven possible states defined above. Two more columns were added: one for the county (Loire-Atlantique or Morbihan) and one for the North or South location of the zone with regard to the Loire estuary limit which can be considered as natural border in terms of turbidity and other physical characteristics (Barillé et al. 2020). The analysis was developed with the R-Package *TraMineR*. In overall, 61 distinct sequences were identified for a maximum length of 177 months (under a 'safe' status), meaning that at least one zone had experienced the entire sample period without being degraded to another state.

A hierarchical ascending classification was developed in order to create a typology of trajectories based on similar sequences, i.e. showing the same temporal pattern in terms of successive states. This classification was plotted on the Dendrogram below (Figure 8). The inertia curve indicated an ideal partition into four clusters.

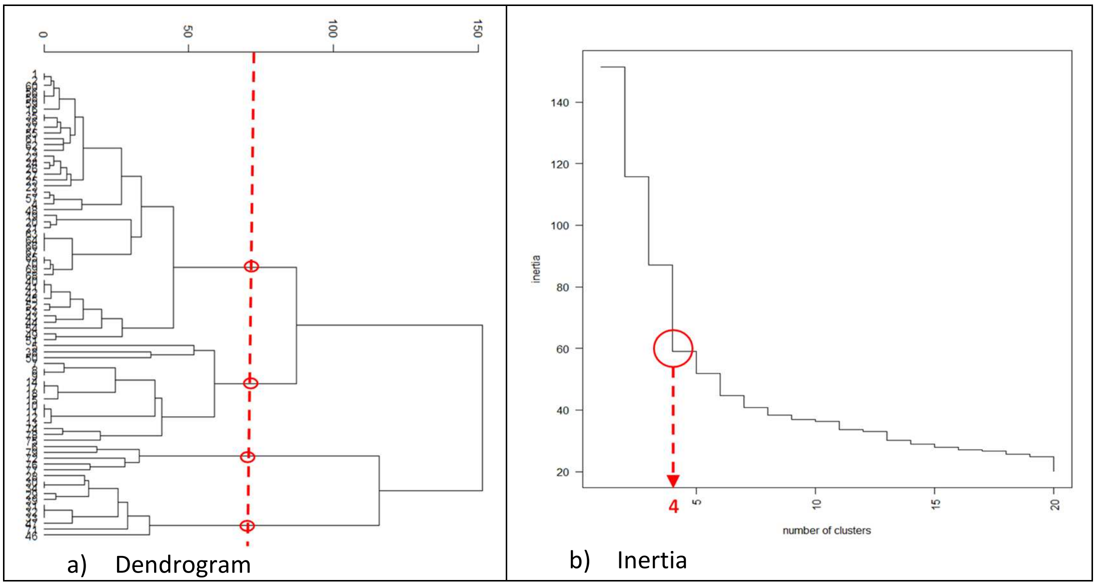


Figure 8 : Dendrogram and inertia (sum of Eigen value) of trajectories

As seen on Fig. 8a, the length of branches offered several possibilities of splitting the observations into a reduced number of clusters by using the *cutree* command in *TraMineR*. The optimal number of clusters was determined by a set of ten statistical tests provided by the R-Package WeightedCluster (Studer 2012) and applied to the partitions into three, four and five clusters (Table 2).

Table 2 : Optimal number of clusters for the typology of sequences

	3 clusters	4 clusters	5 clusters	Criteria	Optimal Nb of clusters
PBC	0.6349	0.7021	0.5965	Max	4
HG	0.7956	0.8898	0.8248	Max	4
HGSD	0.7948	0.8890	0.8236	Max	4
ASW	0.4115	0.4021	0.3173	Max	3
ASWw	0.4344	0.4343	0.3608	Max	3
CH	20.2190	18.7497	16.8248	Max	3
R2	0.3473	0.4286	0.4763	Max	5
CHsq	40.2929	46.3873	39.4658	Max	4
R2sq	0.5146	0.6498	0.6808	Max	5
HC	0.0990	0.0473	0.0726	Min	4

Half of the critical values gave an ideal number of four clusters which was finally selected for the typology. From this partition, the distribution plots of the four clusters gave the structure of state sequences. The distributions were sorted by degree of similarity between sequences and displayed in the following index plots (Figure 9):

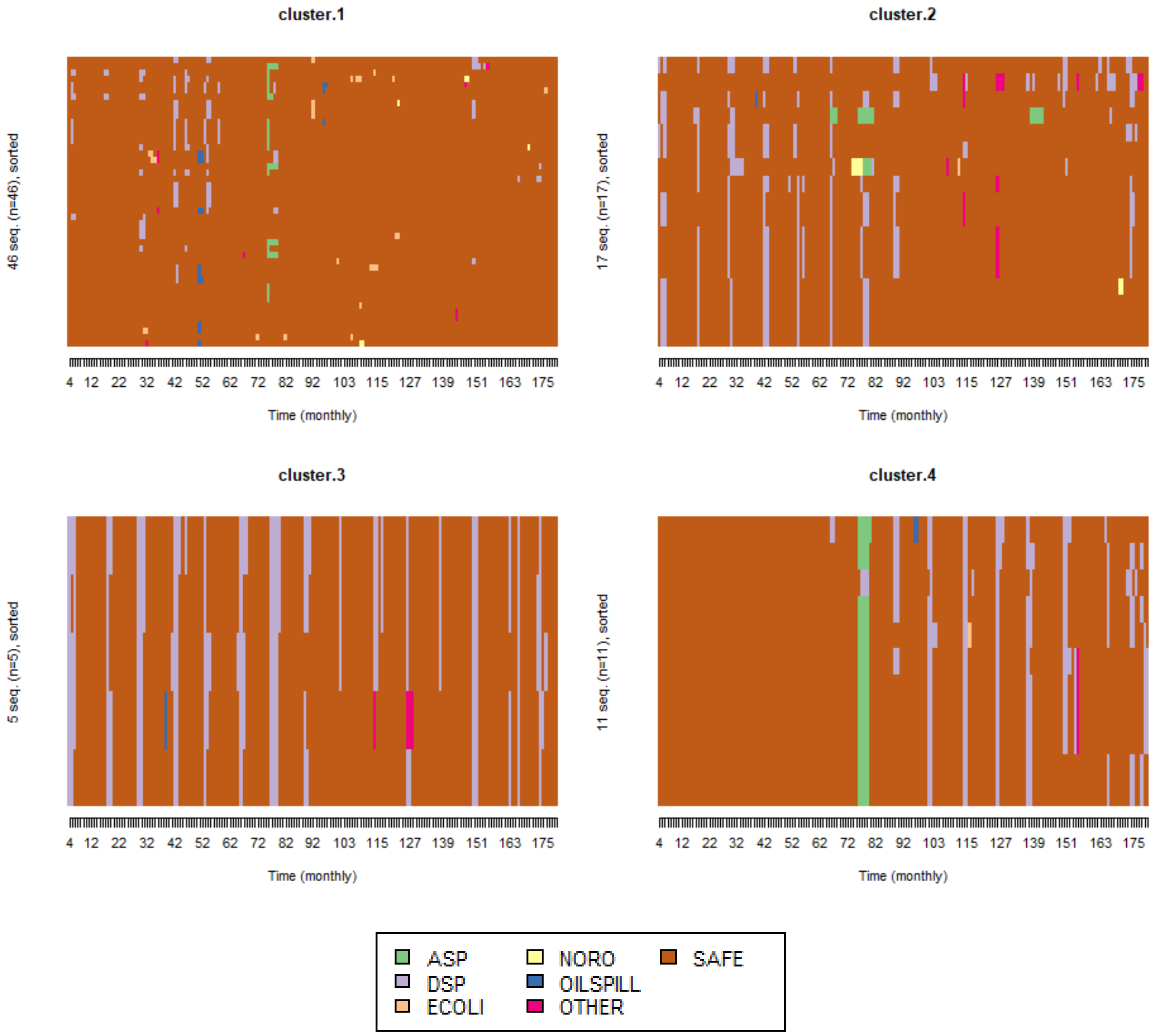


Figure 9 : Index plots of the four clusters

On these index plots, where each colour represents a distinct status, regular seasonal patterns were highlighted, and more findings could be emphasized. Cluster 1 pooled the safest zones, except a few episodes of DSP closures at the beginning of the period, and a short period of ASP closures occurring in April-July 2010 (periods 73-76). At the same period, the zones of Cluster 4 were closed because of this ASP outbreak, prior to be regularly hit by DSP episodes afterwards. The zones belonging to Cluster 2 were less affected by closures during this second half of the sample. The five zones of Cluster 3 remained seasonally shut down because of DSP but with fewer other pathogens or bad microbiological conditions.

We can give further details about the geographical distribution of area closures (see the Map in Figure 10). Cluster 1 encompassed 46 shellfish zones which are geographically located in rivers, estuaries and semi-enclosed bays, such as Aven and Belon rivers, Blavet, Etel river, the Bay of Morbihan, Penerf river, the Vilaine and Loire estuaries. For the whole sample period, the zones of Cluster 1 were only closed 3% of the time on average (5 months only out of 14 years).

Clusters 2 and 4 (17 and 11 zones, respectively) were characterized by their symmetric temporal patterns: the sanitary crises were rather met at the beginning of the period for Cluster 2 (until September 2011 = Month 90) and at the end of the period for Cluster 4 (after September 2011). Cluster 2 pooled the areas located near Gâvres, the Bay of Quiberon, the river mouth of Vilaine, Pen-Bé and Le Croisic. The shellfish zones of Cluster 2 were nonetheless less severely impacted than those of Cluster 4, because they were shut down only for 8% (14 months) of the sample period on average, against 10% (18 months) for Cluster 4. Cluster 4 gathered the offshore areas (Ponant islands, and the offshore zone between the Laïta river in the north and the Bay of Quiberon in its southern limit). The proportion of closed months caused by ASP in this cluster over the period was around 20%, i.e. the same as Cluster 1. Comparatively, the two other clusters were not hit by ASP events. After the severe ASP episode in spring and summer 2010, the area covered in Cluster 4 has been regularly affected by DSP outbreaks every springtime.

Finally, Cluster 3 included 5 zones concentrated in the southern Bay of Pont-Mahé, at the south of the Vilaine river mouth. The shellfish aquaculture zones were seasonally shut down all over the sample period. Cluster 3 pooled the most impacted zones of the whole sample: on average, they were closed 16% of the time (28 months over 177). The motive of closure in this cluster was almost exclusively DSP (96% of cases). Interestingly, activities were prohibited by decree every month of June or so (80% of June months were closed in this cluster), whereas June was only closed 45% of the time for Clusters 2 and 4, and 10% for Cluster 1. This would mean that a closure this particular month is highly predictable for the zones included in Cluster 3.

Figure 10 : Map of the 4 clusters selected from the Sequence typology

To estimate the homogeneity within the 4 clusters, the average distance of trajectories to the centre of the Cluster was calculated with the *disscenter* command of *TraMineR*. The following statistics were obtained: 5.7, 11.2, 9.7 and 7.4 for Clusters 1-2-3-4, respectively. It showed that Cluster 1 was the most homogeneous Cluster in spite of its greater number of observations. An entropy index (whose value is between 0 with full homogeneity and 1 for full heterogeneity) was also calculated and plotted through the *seqHtplot* function of *TraMineR* (diagrams left in Appendix A2 to avoid tedious presentation), confirming the higher homogeneity of Cluster 1 and Cluster 4 at the beginning of the period, entropy increasing seasonally (every spring) for other clusters.

In the total sample, 57 zones were located in the Morbihan county, whereas 22 were observed in the Loire-Atlantique county. However, the zones belonging to Morbihan (north of the sample region) were found over-represented in Clusters 1, 3 and 4, while Loire-Atlantique (south) was over-represented in Cluster 2 and not at all present in Cluster 4[5]. The same observation was made when the zones were numbered along a gradient value increasing from North to south. Dividing the sample between two large areas at the north (36 zones) and south (43 zones) of the Loire estuary, the chi-squared test demonstrated a non-random distribution, the southern zones being over-represented in Cluster 2 and 3, and poorly represented in Cluster 4 (Cluster 1 being equally present in both sub-regions)[6]. Table 3 summarizes some of the findings to characterize the four clusters.

Table 3 – Characteristics of the 4 geographical clusters (79 shellfish zones)

	Number of zones	*Avg Nb closed months*	*% of time**	*%DSP***	*%ASP***
Cluster 1	46	5	3%	51%	19%
Cluster 2	17	15	8%	90%	2%
Cluster 3	5	28	16%	96%	0%
Cluster 4	11	18	10%	76%	21%

* Proportion of closed months over the total number of months (177) in the sample period.
** Proportion of factor-related months over the total number of closed months.

Cluster 1 was the most important by the number of zones (46) but also the least impacted all over the sample period (less than 3% of the 177 months). Conversely, Cluster 3 (5 zones) was the most affected every year (closed 16% of the time), particularly in June because of DSP. The two other intermediate clusters were mostly differentiated because of their yearly pattern: the closed periods in Cluster 2 were mostly met prior to September 2011, those of Cluster 4 after this date. Two factors (DSP and ASP) linked to HABs explained nearly all closure decisions (90%) that were taken by the public authorities during the sample period. This would mean that HABs remain a hot issue for shellfish farmers and public managers, far beyond any other hazard, including oil spills or microbiological pollutants (McGowan 2016; Basti et al. 2018; Bresnan et al. 2020).

Geographically, it seems difficult to emphasize some distinctive features for the four clusters regarding potential differences of bathymetry, currents, turbidity or distance to the coast. However, the analysis showed that some clusters were somehow over-represented by a county and a sub-

[5] *Pearson's Chi-squared value = 20.101, df = 3, p-value = 0.0001618*

[6] *Pearson's Chi-squared value = 21.944, df = 3, p-value = 0.000067*

region (north or south of Loire estuary). When superimposing the two maps of Fig. 7 and Fig 10, we also observed a certain relationship between the duration of trade bans and the clusters. For instance, the zones located in rivers or gulfs were less struck by HAB events and logically belonged to Cluster 1, with the noticeable exception of the Vilaine river mouth where the 5 zones of Cluster 3 were all located in the south of Pont-Mahé Bay.

3.3 Economic vulnerability of the clusters

In order to check the correspondence between the length and frequency of closures and their economic consequences, we needed to confront the typology of hazard exposure to the spatial distribution of shellfish farms. We assumed that the economic impact should be found greater in clusters where the frequency and length of closures were the highest from the typology. Whatever the cause, if farmers cannot produce and sell shellfish for several months because of trade bans, this should affect their economic results. However, if farming is less or not at all present in the affected zones, the economic consequences should be minor. Additional economic data were therefore collected from the two censuses of the shellfish aquaculture industry in France published in 2001 and 2012[7]. Some results are summarized in Table 4.

Table 4 – Economic importance of shellfish aquaculture in the 4 clusters*

	Total Area (km²)	*Leasehold (LH) area (km²)*	*% LH/total area*	*Nb of firms** 2012*	*Nb of jobs*** 2012*	*Species*
Cluster 1	370	52.89	14.01%	485	802	Oysters (mainly), mussels
Cluster 2	49	7.84	16.07%	79	111	Cockles, clams and oysters
Cluster 3	32	2.08	6.44%	36	49	Mussels (mainly), other shellfish spp.
Cluster 4	2,140	0.58	0.03%	-	-	Oysters and mussels

* Data collected from the report '*Recensements de la conchyliculture 2001-2012*'.
** Firms which have their headquarter close to the Leaseholds.
*** Full-Time Equivalent (FTE) jobs. NB: the number of firms and jobs in Cluster 4 could not be displayed for statistical secret reasons, the number of farms being less than 3 in this category.

Several important limits about the assessment of the economic consequences of closures must be reported. The first one is that trade bans can involve shellfish farms having their headquarters located far away from where the leaseholds are exploited, sometimes hundreds of miles away. For example, in the Morbihan County, 84% of the area devoted to shellfish culture are owned and managed by local farms, but 16% by outsiders. The local ones may also manage leaseholds outside the area. As a result, the leasehold database does not match exactly the shellfish farm database, making impossible a comprehensive and accurate economic assessment of clusters. Firms may compensate a local and temporal loss by higher profits outside the area. A second limit concerns the lack of knowledge about the type and level of stocks on leasehold beds. The economic impact depends on which species are cultivated, their output in tonnage and the age structure of stocks along the rearing cycle. Such information is not yet available for a thorough economic analysis.

[7] Recensements de la conchyliculture 2001-2012, Lemna & Capacités, University of Nantes (2019), 122 p.

Thirdly, economic results may vary for many other reasons than closures. For instance, hypoxia or epizooty events do not cause any closure although remaining very detrimental for farming companies. Moreover, economic results are often available on a yearly basis and do not emphasize the seasonal variations whereas closures are only implemented for a limited period of time, from a few days to several weeks. This is why it seems vain to isolate a possible economic loss caused by HAB events from time series of economic results. However, we can still look at the zonal dependence on farming activity to judge the spatial economic sensitivity to closures.

From Table 4, we can see that the total area covered by the most affected zones (Cluster 3) represented only 1.2% of the aggregate surface of the sampled regions. Interestingly, farmers belonging to this cluster cultivate mostly mussels, this species being particularly sensitive to HABs (Theodorou *et al.* 2020). Moreover, 83% of the leaseholds where the shellfish species were cultivated pertained to Cluster 1. The latter therefore concentrated the bulk of the farming activity and full-time equivalent jobs (81% and 83%, resp.). Cluster 4 covered the largest surface with 2,140 km² and we saw that it was particularly affected by HAB-related closures since September 2011. However, this cluster host very few shellfish farms, hence a very low sensitivity to the HAB outbreaks. A simple regression between the proportion of closed periods (Column 4 in Table 3) and the economic importance measured by the relative share of leasehold areas (Column 4 in Table 4) was applied to the 79 zones. The results showed no significant correlation (R^2=0.0127) and the parameter estimate was not significant at the 10% level. Two plots are proposed in Appendix A3 to show how scattered are the observations, with different types of relations between the closure rate and the leasehold rate from cluster to cluster, and many outliers in every cluster. For instance, many zones belonging to the 4 clusters had no farming activity at all (leasehold rate=0).

Two Kruskal-Wallis tests were also performed to demonstrate that both variables (closure and leasehold rates) were not equivalent in the different clusters[8], this evidence being quite clear from the mere observation of the figures of Tables 3 and 4. Finally, even in the production zones more affected by HAB events (e.g. Cluster 3), the regular and seasonal pattern of DSP outbreaks should allow farmers to anticipate the closing periods in springtime and organize themselves to postpone their sales and bear no economic loss. We can therefore conclude that the exposure risk is very unlikely to be correlated with the economic effects of HAB events on the shellfish farming industry in the southern Brittany and Pays de la Loire regions, as found in another study (Rodríguez-Rodríguez et al. 2010).

4. Discussion

Ecological and economic analyses of HAB events have been usually developed independently. The drivers of HAB occurrence and diffusion is left to ecological studies (O'Neil et al., 2011; Paerl et al., 2011; Lassus et al. 2016; Glibert and Burkholder 2018; Kahru et al. 2020, Bresnan et al. 2020), while economists are more interested in assessing the consequences in terms of welfare loss and employment (Hoagland et al. 2002, Sanseverino 2016, Adams et al. 2018). The present research aims at looking at ecological phenomena through the eyes of public decision makers and shellfish farmers.

[8]The Kruskal-Wallis is a non-parametric test designed to compare means or proportions in more than two groups (which is not possible with the Wilcoxon test). The results were a K-W chi-squared value of 55.216 with a p-value of 6.175e-12 for the closure rate, and a K-W chi-squared value of 8.8005 with a p-value of 0.03206 for the leasehold rate.

The intensity and extent of environmental shocks were estimated by a longitudinal database collecting the legal (Prefectural) decrees restricting the access to the shellfish production zones in Southern Brittany and Pays de la Loire regions (Western part of France) between 2004 and 2018. The sanitary quality of shellfish products is particularly surveyed around the world because of the multiple toxins concentrated in the filter-feeding bivalve molluscs that can be dangerous for human health (Dyson and Hupert 2009, Park et al. 2013, Basti et al. 2018). The economic impact can be tremendous sometimes for the aquaculture industry, although other industries like tourism, housing or fishing can also be dramatically affected (Adams and Larkin 2013; Adams et al. 2018; Diaz et al. 2019). However, there might be no direct or linear relationship between the intensity and duration of outbreaks and economic losses (Rodríguez-Rodríguez et al. 2010; Adams et al. 2018), as long as the spatial distribution of blooms does not match the location of the shellfish farming industry. This was the hypothesis we wanted to test for with our original data set.

Starting with a mere statistical description of the 'closure decree' database, we could not observe any significant trend over the past two decades. Some years (like 2010) were particularly affected by HAB hazards but without any regular temporal pattern. Among other factors of area closures (microbiological, oil spills,…), DSP emerged as the main cause of trade bans (68% of cases), although ASP episodes, if more sporadic, were taken very seriously by the public authorities in terms of duration (68 closing days on average, against a period three times shorter for other factors). Decisions concerning the ban of shellfish marketing followed a very seasonal pattern because 82% of shutdowns were issued in spring months. This is of particular importance from an economic perspective because this period comes just before the seasonal peak demand for mussels in summer (because of coastal tourism), and just after the "R-in-the-month" period of oyster sales, 40% of the latter taking place on Christmas holidays (Le Bihan *et al.* 2013). The expression "R-in-the-month" is a food-world and mnemonic adage to define those months from September to April including the letter R in their spelling, unlike the months from May to August. This is an easy way to remember when to avoid eating oysters because of a too milky flesh due to the spring and summer breeding period (release of spat), but also because of algal blooms and toxins: "the idea of not eating oysters during months without an 'R' comes from the fact that the summer months are the prime breeding time for red tides, or large blooms of algae that grow along the coast and have the tendency to spread toxins that can be absorbed by shellfish, including oysters"[9]. This wise tradition of not eating oyster during spring and summer seasons is very ancient and dates back to prehistoric ages (Cannarozzi and Kowalewski, 2019). It is less followed nowadays due to the increasing supply of triploid oysters by hatcheries, also called the "4-season oysters" because they are sterile and do not produce spat (Nell 2002, Le Bihan *et al.* 2013), but could remain useful to remember and avoid the higher toxic period.

Our results from the OMA of closure decrees and the zonal typology showed that the most affected zones revealed by the typology of sequences were those which are rather avoided by farmers. In overall, 83% of the leasehold area covered by the sample is included in Cluster 1, where the zones were only closed less than 3% of the time between 2004 and 2018. This is precisely where the employment, the leasehold surface and the number of farms are concentrated. The lack of spatial correlation between closures (exposure to the hazard) and economic activity (sensitivity) means that farmers have historically settled in the zones where the risk was lower. HAB tides are not the only risks faced by shellfish farmers (Le Bihan et al. 2013), but their spatial strategies show that the managers mitigated partially this type of risk so as to maintain their profitability in the long run. Despite the difficulty to disentangle the factors of variability underpinning the economic results of

[9] www.mentalfloss.com/

shellfish farms, we saw that their earnings were not particularly affected by the HAB outbreaks. Beyond the avoidance strategy highlighted by the typology, farmers can select adaptive strategies to further reduce their vulnerability and become more resilient (Adger 2000, Allison et al. 2009, Guillotreau et al. 2017, Theodorou et al. 2020).

If HAB outbreaks appear regularly during certain seasons (e.g. in Clusters 3 and 4), this occurrence can be anticipated by farmers. For instance, they can reduce the negative consequences by removing temporarily the molluscs from infected waters and by postponing the sales (Rodríguez-Rodríguez et al. 2010). According to a survey made in France near oyster farmers facing *Dinophysis* outbreaks, producers declared importing shellfish products from non-infected areas during the DSP peak period, re-scheduling the manpower resources through different short-term measures: restriction of working hours, fewer hired seasonal workers, anticipated holidays, and re-organizing the cultivation work on leaseholds (e.g. with more maintenance of equipment) (Souchu et al. 2013). By implementing these simple adaptive strategies, they bear a very limited economic loss, according to this survey, not even mentioning the price response of markets. Other critical issues such as the mass mortality of oysters caused by pathogens (e.g. *OsHV1-μ-var*), far more consequential for farmers although not leading to any closure decree, resulted in a 25% decrease of sales to final consumers between 2008 and 2011, more than fully compensated by a 50% increase in prices because of the market shortage (Le Bihan 2015).

More generally, Martino et al. (2020) underlined that a difficulty to predict accurately the economic loss caused by DSP is related to the mitigation strategies selected by farmers which may increase costs in the short run but also reduce significantly the profit loss in the long run. It appears in all studies that implementing efficient adaptive strategies is based on the ability of farmers to anticipate HAB events. For Stauffer et al. (2019), one of the key components to solve HAB-related problems is to improve the early detection of toxic events to protect more effectively animal and human health and thus mitigate economic losses. In this respect, the Ecological Forecasting Roadmap program developed by the U.S. National Oceanic and Atmospheric Administration (NOAA) pays greater attention to HAB forecasts both in marine and freshwater systems and should be inspiring for the European management systems[10]. In Spain, the ASIMUTH project aimed at developing short term HAB alert systems for Atlantic Europe (Maguire et al. 2016). The information provided by this warning system enabled shellfish farmers to manage more effectively their practices in real time. Thus, a better understanding of complex relationships between HAB outbreaks, environmental factors, seasonal and spatial patterns in connection with the economic activity, remains a top priority of the research agenda to improve forecasting models of HAB and to mitigate economic losses.

Conclusion

Among all the research gaps identified by Adams et al. (2018) in a book dedicated to HABs (Shumway et al. 2018), our research attempted to respond at least to two of them. First, we strived to develop

[10] https://oceanservice.noaa.gov/ecoforecasting/

an original database of legal decrees restricting the fishing and shellfish farming activities in the presence of HABs and other microbiological pollutants. This tremendous effort was applied to two important shellfish aquaculture regions in France (Southern Britany and Pays de la Loire) and on that mere basis, we managed to convince the Ministry of Agriculture about the usefulness of such an endeavour at the national level. The Ministry therefore decided to extend the data collection effort to the whole domestic territory[11]. Secondly, Adams *et al.* (2018) encouraged scholars to investigate the relationship between the intensity of HAB events (in terms of frequency, duration and spatial extent) and the economic loss for sensitive industries such as fishing, aquaculture, coastal tourism or the housing market. From this gap of knowledge, we built our own hypothesis about a possible non-linear relationship –if not a partial independence- between the degree of spatial exposure and the sensitivity of shellfish farmers to the HAB hazards. HABs may well be intense and emerge seasonally every year, if there is no human activity for the time and space when and where such outbreaks occur, the social and economic consequences will be few.

Using the original database of closure decrees by shellfish production zone, we developed an original and longitudinal approach through an Optimal Matching Analysis of water status trajectories in 79 shellfish zones between April 2004 and December 2018, borrowing the method from genetics or social sciences dealing with life history traits. We ended up with a typology of trajectories across four zonal clusters. More than half of the zones were pooled in a cluster which was poorly affected by HABs (less than 3% of the time). Another one was struck every springtime by DSP outbreaks. The two others had opposite temporal patterns: one of them faced periodical closures prior to September 2011, the other one after this date. HABs prevailed in the causes of administrative closures (in more than 90% of cases), mainly because of DSP, and ASP to a minor extent but with longer average duration by decree. It is important to remind that these are not the only risks faced by shellfish farmers (Le Bihan et al. 2013). For instance, the domestic oyster industry has been particularly affected by an Herpes virus (of type *OsHV1-μ-var*) crisis since 2008 onwards, but the farmers managed to cope with this virus which is only killing oysters, and therefore is not deemed to be dangerous for human health. Consequently, this epizooty did not lead to any closure decree from the public authorities.

More importantly, our results crossed the legal information of closures with some economic data to show that the shellfish farming industry was not seriously affected economically by HAB events. The major part of the regional activity was concentrated in the clusters where the occurrence and intensity of blooms were the weakest. For those business units located in the more exposed areas, the DSP temporal pattern was so regular seasonally and limited in duration, that the shellfish farmers could organize themselves to reduce significantly their economic loss. A limit to our analysis was that no specific census existed so far to estimate the quantity of shellfish output by leasehold, nor any database to identify the leaseholds attached to one particular company.

Moreover, concluding from this study that shellfish farmers, though exposed, remained weakly sensitive to HAB hazards, does not mean that they will not suffer heavier consequences in the future. Most ecological studies predict an increase of HAB episodes in frequency, spatial coverage and duration in the years to come because of climate changes (e.g. Hallegraeff, 1993; Anderson, 1994; Lassus et al. 2016; Glibert and Bulkholder, 2018, Kahru et al. 2020). For the last two years in France, changes of HAB events are being observed in traditionally safe shellfish areas. For example in southern Brittany, the proliferation of *Lepidodinium chlorophorum* during a *Dinophysis* closure has

[11] A nationwide database of trade bans was created in real-time and makes from now on such data accessible to different stakeholders. This decision came out of several meetings of authors with the Directorate-General for food of the French Ministry of Agriculture (DGAL) and the International Office for Water (OIEau). The database will be available by late 2020.

caused important mussel mortalities in 2019 without any simple solution for farmers. The latter could not use their usual strategy of postponing sales and had to face a net loss of revenue.

The future development of this research will nonetheless attempt to model the duration and extent of economic shocks caused by HAB events by a more accurate analysis of closure lengths. Another avenue for research lies in a future cross-utilization of the REPHY database describing the HAB events in the French coastal waters (spatial and time distribution, type and level of species and toxins…) and the closure decree database, to see whether the administrative shutdown decisions match the intensity and jeopardy of HAB hazards, and whether any forecasting effort of blooms is helpful to reduce their socio-economic impacts.

References

Aassven, A., Billaru, F.C., Piccarreta, R., 2007. Strings of adulthood: a sequence analysis of young British women's work-family trajectories, *European Journal of Population* 23(3-4): 369-388.

Abbott, A., Forrest, J., 1986. Optimal matching methods for historical sequences, *Journal of Interdisciplinary History*, 16(3): 471-494.

Adams, C.M., Larkin, S.L., 2013. Economics of Harmful Algal Blooms: Literature Review. Final report for Gulf of Mexico Alliance Project #00100304, Tallahassee, FL.

Adams, C.M., Larkin, S.L., Hoagland, P., Sancewich B. 2018. Assessing the economic consequences of Harmful Algal Blooms: a summary of existing literature, research methods, data and information gaps. In: Shumway, S.E., Burkholder, J.M., Morton, S.L. (Ed.), Harmful Algal Blooms: A Compendium Desk Reference, First Edition. John Wiley & Sons Ltd, pp 337-354.

Adger, W.N., 2000. Social and ecological resilience: Are they related? *Progress in Human Geography* 24: 347–364.

Allison, E.H., Perry, A.L., Badjeck, M.-C., Adger, W.N., et al. 2009. Vulnerability of national economies to the impacts of climate change on fisheries. *Fish and Fisheries* 10(2): 173-196.

Anderson, D.M., 1994. Red tides, *Scientific American* 271(2): 62-68

Barillé L., Le Bris A., Goulletquer P., Thomas Y., Glize P., Kane F., Falconer L., Guillotreau P., Trouillet B., Palmer S., Gernez P. (2020), Biological, socio-economic, and administrative opportunities and challenges to moving aquaculture offshore for small French oyster-farming companies, *Aquaculture* 521: art. 735045

Basti, L., Hégaret, H., Shumway, S.E. 2018. Harmful Algal Blooms and Shellfish. In: Shumway, S.E., Burkholder, J.M., Morton, S.L. (Ed.), Harmful Algal Blooms: A Compendium Desk Reference, First Edition. John Wiley & Sons Ltd, pp 135-190. Bresnan, E., Baker-Austin, C., Campos, C.J.A, Davidson, K., Edwards, M., Hall, A., McKinney, A. and Turner, A.D., 2020. Impacts of climate change on human health, HABs and bathing waters, relevant to the coastal and marine environment around the UK. *MCCIP Science Review* 2020, 521–545. Doi: 10.14465/2020.arc22.hhe

Cannarozzi, N.R., Kowalewski, M., 2019. Seasonal oyster harvesting recorded in a Late Archaic period shell ring. *PLOS ONE* 14 (11): DOI: 10.1371/journal.pone.0224666.

Díaz, P.A., Álvarez, G., Varela, D., Pérez-Santos, I., Díaz, M., Molinet, C., Seguel, M., Aguilera-Belmonte, A., Guzmán, L., Uribe, E., Rengel, J., Hernández, C., Segura, C., Figueroa, R.I., 2019. Impacts of harmful algal blooms on the aquaculture industry: Chile as a case study. *Perspectives in Phycology*. DOI: 10.1127/pip/2019/0081

Deville, J.-C., Saporta, G., 1980. Analyse harmonique qualitative. In: Diday E. (Ed.), Data Analysis and Informatics, Amsterdam, North Holland Publishing, p. 375-389.

European Union (2004a), Regulation (EC) No 853/2004 of the European Parliament and of the Council of 29 April 2004 laying down specific hygiene rules for on the hygiene of foodstuffs. *Official Journal of the European Union, L139/ 55 April.*

European Union (2004b), Regulation (EC) No 854/2004 of the European Parliament and of the Council of 29 April 2004 Laying down Specific Rules for the Organization of Official Controls on Products of Animal Origin Intended for Human Consumption. *Official Journal of the European Union, L139/30 April*.

FAO, 2020. The State of World Fisheries and Aquaculture 2020. Sustainability in action. Rome.

Glibert, P.M., Burkholder, J.M., 2018. Causes of Harmful Algal Blooms. In: Shumway, S.E., Burkholder, J.M., Morton, S.L. (Ed.), Harmful Algal Blooms: A Compendium Desk Reference, First Edition. John Wiley & Sons Ltd, pp 1-38.Guillotreau, P., Allison, E.H., Bundy, A., Cooley, S.R., Defeo, O., Le Bihan, V., Pardo, S., Perry, R.I., Santopietro, G., Seki, T., 2017. A comparative appraisal of the resilience of marine social-ecological systems to bivalve mass mortalities. *Ecology and Society* 22(1): 46.

Hallegraeff, G.M., 1993. A review of harmful algalblooms and their apparent global increase. *Phycologia* 32 (2): 79–99.

Hamrick, J.L., Godt, M.J.W., 1996. Effects of life history traits on genetic diversity in plant species, *Philosophical Transactions of the Royal Society B* 351(1345), https://doi.org/10.1098/rstb.1996.0112.

Hoagland, P., Anderson, D.M., Kaoru, Y., White, A.W, 2002. The economic effects of harmful algal blooms in the United States: Estimates, assessment issues, and information needs. *Estuaries* 25**,** 819–837 (2002). https://doi.org/10.1007/BF02804908

Jin, D., Thunberg, E., Hoagland, P. (2008). Economic impact of the 2005 red tide event on commercial shellfish fisheries in New England. Ocean and Coastal Management 51: 420-429.

Kahru, M., Elmgren, R., Kaiser, J., Wasmund, N., Savchuk, O., 2020. Cyanobacterial blooms in the Baltic Sea: Correlations with environmental factors. *Harmful Algae* 92. https://doi.org/10.1016/j.hal.2019.101739

Konstantinou, Z. I., Krestenitis, Y. N., Latinopoulos, D., Pagou, K., Galinou-Mitsoudi, S., Savvidis, Y., 2012. Aspects of mussel-farming activity in Chalastra, Thermaikos Gulf, Greece: An effort to untie a management Gordian knot. *Ecology and Society*, 17(1). doi:10.5751/ES-04455-170101

Lassus, P., Chomérat, N., Hess, P., Nézan, E., 2016. Toxic and Harmful Micro-algae of the World Ocean / Micro-algues toxiques et nuisibles de l'océan mondial. Denmark, International Society for the Study of Harmful Algae / Intergovernmental Oceanographic Commission of UNESCO. IOC Manuals and Guides, 68. (Bilingual English/French).

Le Bihan, V., 2015. Analyse économique du risque en conchyliculture. PhD Thesis, University of Nantes.

Le Bihan V., Pardo S., Guillotreau P., 2013. Risk perception and risk management strategies of oyster farmers, *Marine Resource Economics* 28(3): 285-304.

Lemna-Capacités. 2019. Recensements de la conchyliculture 2001-2012 (Survey of the domestic shellfish farming industry in France, 2001 & 2012). Final Report. University of Nantes, 122 p.

Maguire, J., Cusack, C., Ruiz-Villarreal, M., Silke, J., McElligott, D., Davidson, K., 2016. Applied simulations and integrated modelling for the understanding of toxic and harmful algal blooms (ASIMUTH): Integrated HAB forecast systems for Europe's Atlantic Arc, *Harmful Algae* 53: 160-166.

Martino S., Gianella F., Davidson K., 2020. An approach for evaluating the economic impacts of harmful algal blooms: The effects of blooms of toxic Dinophysis spp. on the productivity of Scottish shellfish farms, *Harmful Algae*, 99, https://doi.org/10.1016/j.hal.2020.101912.

McGowan, S., 2016. Algal Blooms, in Biological and environmental hazards, risks, and disasters, R. Sivanpillai ed., Elsevier. pp 5 : 44.

Nell, J.A., 2002. Farming triploid oysters. *Aquaculture* 210(1-4): 69-88.

O'Mahony, M., 2018. EU Regulatory Risk Management of Marine Biotoxins in the Marine Bivalve Mollusc Food-Chain. Toxins*, 10*, 118.

O'Neil J.M., Davis T.W., Burford M.A., Gobler C.J., 2012. The rise of harmful cyanobacteria blooms: The potential roles of eutrophication and climate change, Harmful Algae 14: 313-334.

Paerl, H.W., Paul V.J., 2012. Climate change: Links to global expansion of harmful cyanobacteria, *Water Research* 46(5): 1349-1363, https://doi.org/10.1016/j.watres.2011.08.002

Paerl H.W., Hall N.S., Calandrino E.S., 2011. Controlling harmful cyanobacterial blooms in a world experiencing anthropogenic and climatic-induced change, *Science of the Total Environment* 409(10): 1739-1745, https://doi.org/10.1016/j.scitotenv.2011.02.001.

Park T.G., Lim W.A., Park Y.T., Lee C.K., Jeong H.J., 2013. Economic impact, management and mitigation of red tides in Korea, *Harmful Algae* 30(1): S131-S143.

Robette, N., Thibault, N., 2008. Analyse harmonique qualitative ou méthodes d'appariement optimal ? Une analyse exploratoire de trajectoires professionnelles, Population -Paris, *Institut National D'Études Démographiques*, 2008, 63 (4), pp.621-646. <halshs-01016116>

Rodríguez-Rodríguez, G., Villasante, S., do Carme García-Negro M. 2010. Are red tides affecting economically the commercialization of the Galician (NW Spain) mussel farming? *Marine Policy*, 35: 252-257. doi:10.1016/j.marpol.2010.08.008

Rodrigues, L. C., van den Bergh, J. C. J. M., Massa, F., Theodorou, J. A., Ziveri, P., Gazeau, F., 2015. Sensitivity of Mediterranean bivalve mollusc aquaculture to climate change and ocean acidification: Results from a producers' survey. *Journal of Shellfish Research*, 34(3): 1161–1176. doi:10.2983/035.034.0341

Sanseverino, I., Conduto, D., Pozzoli, L., Dobricic S., Lettieri, T. 2016. Algal bloom and its economic impact; EUR 27905 EN; doi:10.2788/660478.

Shumway, S.E., Burkholder, J.M., Morton, S.L. (Eds.). 2018. Harmful Algal Blooms: A Compendium Desk Reference, First Edition. Wiley Blackwell, John Wiley & Sons, Inc., Chichester, 699 p.

Silva, M.; Pratheepa, V.K.; Botana, L.M.; Vasconcelos, V., 2015. Emergent Toxins in North Atlantic Temperate Waters: A Challenge for Monitoring Programs and Legislation. *Toxins 7* : 859-885.

Silva, A., Pinto, L., Rodrigues, S.M., de Pablo, H., Santos, M., Moita, T., Mateus, M., 2016. A HAB warning system for shellfish harvesting in Portugal, *Harmful Algae* 53: 33-39.

Souchu, P., Oger-Jeanneret, H., Lassus, P., Séchet, V., Le Magueresse, A., Le Bihan, V., 2013. Final Report of the Dinophag program. Research program on Dinophysis in the Pays de la Loire region. https://archimer.ifremer.fr/doc/00172/28368/

Stauffer B. A., Bowers H. A., Buckley E., Davis T. W., Johengen T. H., Kudela R., McManus M. A., Purcell H., Smith G. J., Vander Woude A., Tamburri M. N., 2019. Considerations in Harmful Algal Bloom Research and Monitoring: Perspectives From a Consensus-Building Workshop and Technology Testing. *Frontiers in Marine Science,* 6, 399.

Studer, M., 2012. Étude des inégalités de genre en début de carrière académique à l'aide de méthodes innovatrices d'analyse de données séquentielles, Chapitre : Le manuel de la librairie WeightedCluster : Un guide pratique pour la création de typologies de trajectoires en sciences sociales avec R. Thèse SES777, Faculté des sciences économiques et sociales, Université de Genève.

Tang, D., Di, B., Wei, G., Ni, I-H., Oh, I.S., Wang, S., 2006. Spatial, seasonal and species variations of harmful algal blooms in the South Yellow Sea and East China Sea. Hydrobiologia 568**:** 245–253.

Theodorou, J.A., Moutopoulos, D.K., Tzovenis, I., 2020. Semi-quantitative assessment of Mediterranean mussel (Mytilus galloprovincialis L.) harvesting bans due to harmful algal bloom (HAB) incidents in Greece. *Aquaculture Economics & Management*, DOI: 10.1080/13657305.2019.1708994

van den Bergh, J.C.J.M, Nunes, P.A.L.D, Dotinga, H.M., Kooistra, W.H.C.F, Vrieling, E.G., Peperzak, L., 2002. Exotic harmful algae in marine ecosystems: an integrated biological–economic–legal analysis of impacts and policies, *Marine Policy* 26(1): 59-74.

Wessells, C.R., Miller, C.J., Brooks, P.M., 1995. Toxic algae contamination and demand for shellfish: a case study of demand for mussels in Montreal. *Marine Resource Economics,* 10: 143-159.

APPENDIX

A1. Optimal Matching Analysis (OMA)

Optimal matching is a sequence analysis method used in various fields of research, including social sciences, to assess the similarities and dissimilarities between pairs of time-ordered sequences. Two types of approaches are mostly used to analyse complex trajectories: Qualitative Harmonic Analysis (QHA) and Optimal Matching Analysis (OMA) (Robette and Thibault 2008). The first approach was developed by Deville and Saporta (1980) to analyse the spectral composition of time series. In this approach, the full period covered by the biography of individuals is divided into sub-periods within which the proportion of time spent by every individual in each state during the time interval is measured. A factorial correspondence analysis is then carried out on the basis of time percentages to summarize the information by selecting the most significant factors (i.e. having the highest Eigen values) and a hierarchical ascending classification is applied thereafter to determine the major trajectories of individuals. Because the factorial analysis synthesizes the key factors, some information can be lost, even though the non-used factors can be controlled ex-post in the analysis.

The second approach (Optimal Matching Analysis) relies on a set of dynamic algorithms used in molecular biology to analyse the DNA sequences (sequences of the nitrogenous bases A, T, G, C for Adenine, Thymine, Guanine, Cytosine, respectively). The approach is based on similarities and dissimilarities between pairs of sequences. The similarity is estimated by calculating the cost of transforming one sequence (by inserting, deleting or substituting elements) to match another one.

Example of two lagged DNA sequences:

Sequence 1: AAAAGGGG

Sequence 2: CCAAAAGG

To make both sequences identical, several strategies can be selected: either by inserting two C at the beginning and deleting two G at the end of sequence 1, or by substituting 2 C for two A and two A for two G in sequence 1. In most studies, insertion and deletion ("*indel*") are given the same cost value, while substitution (which combines insertion and deletion) is deemed to be a more costly operation (representing twice the *indel* cost). In our example, the first (*Indel*) strategy would cost 4, while the second (substitution) strategy would cost 8. The distance between two sequences is defined as the minimal cost to make both sequences identical. A distance matrix between sequences is constructed and further used in a classification analysis to obtain a typology of trajectories (Robette and Thibault 2008).

The sequence approach has been imported into social sciences by Andrew Abott in the mid-1980s (Abbott and Forrest 1986), for instance to study the careers of musicians in Germany in the 18th century. In social sciences, sequence analysis is commonly employed to emphasize patterns of life-course development, cycles and life histories (e.g. being at school, internship, working life divided into various types of contracts or jobs, phases of unemployment or retirement, etc.).

A2 Entropy index of the four clusters

The value of entropy indices is obtained by the Command seqHtplot from the R-Package TraMineR. The closer the index value to zero, the more homogenous are the sequences, the closer to 1 and the more heterogeneous they are.

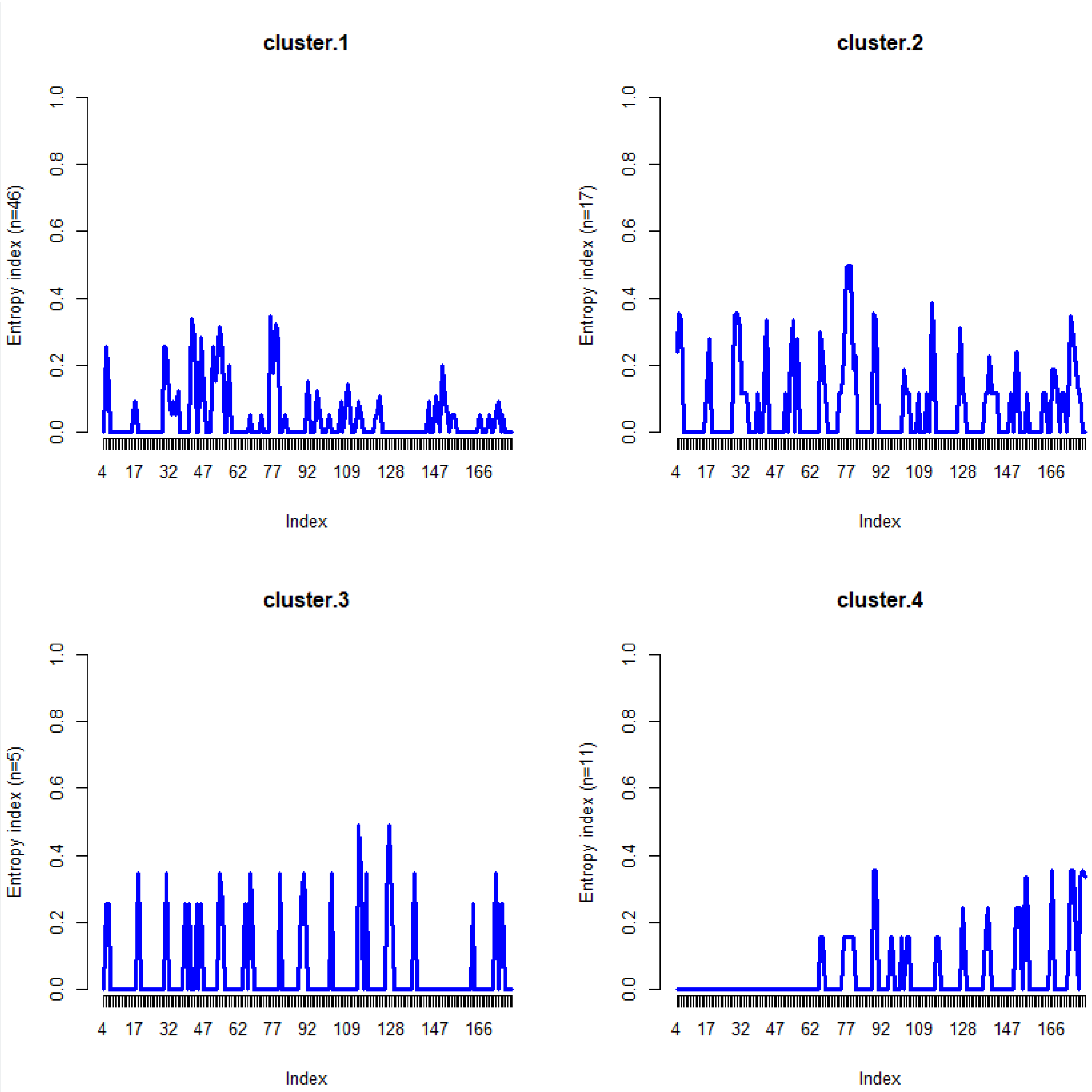
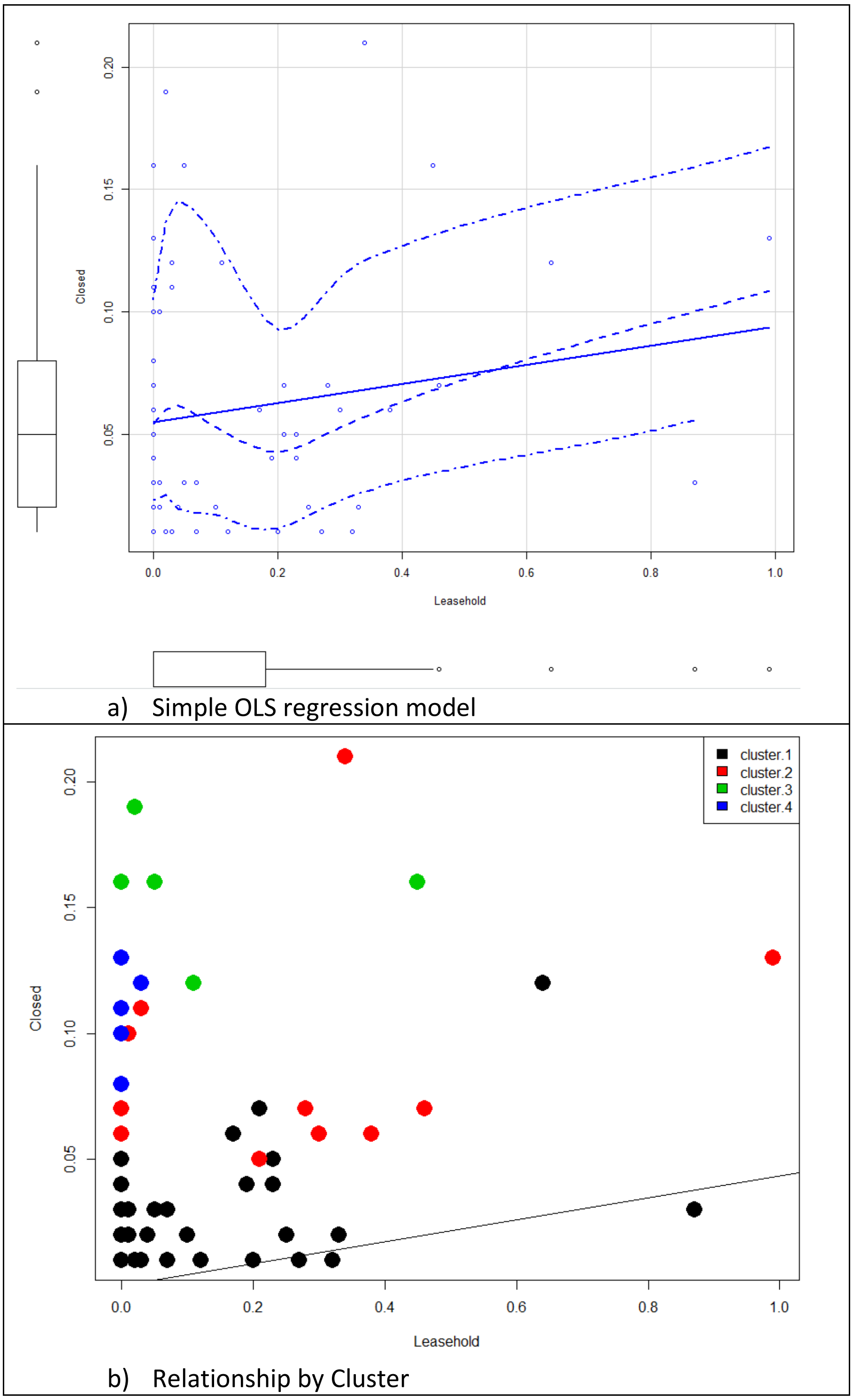


Figure A1a-b-c-d. The heterogeneity of zones within each cluster assessed by the entropy index

A3. Simple OLS regression between the closure rate (% of time closure over the sample period on the Y-axis) and the proportion of leasehold area over the total area (on the X-axis) of the shellfish zone.



a) Simple OLS regression model

b) Relationship by Cluster

NB: we used the R-package Car for Fig. A2.a with the scatterplot command for the OLS simple model, including a nonparametric-regression loess smooth, the smooth conditional spread and a regression line + boxplots in the margins.