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

3 Submission to *HARMFUL ALGAE*, July 2020

4

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10

11

Abstract

12

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

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

26

27

28

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35 Institute, Ireland), and Philipp Hess (Ifremer, France).

36

37

38 1. Introduction

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

54 Looking at HAB events through their economic impacts may complement usefully the ecological
55 approach to design effective warning and remediation measures (Adams et al. 2018). There is a
56 growing literature about the social and economic consequences of HABs, in particular concerning
57 freshwater events. Studies dealing with US data are more abundant than European ones
58 (Sanseverino 2016). Four coastal industries are mostly concerned: fishing, aquaculture, tourism and
59 housing. The methods to evaluate the spillover effects relate to the nature of consequences, either
60 passing through market or non-market values (see Adams et al. 2018 for a survey). Hoagland et al
61 (2002) considered all sectors simultaneously to associate the relevance of estimates as a measure of
62 social costs. Wolf and Klaiber (2017) used hedonic pricing models to estimate the capital loss of
63 houses adjacent to a lake in Ohio.

64 *The economic impact of HABs on shellfish sales*

65 The present research focuses on the shellfish farming industry which is particularly affected by HABs
66 (Basti et al. 2018). In 2018, aquaculture produced 82.1 million tonnes of fish worldwide, where
67 molluscs (mainly bivalves) represented 17.7 million tonnes valuing USD 34.6 billion (FAO 2020).
68 During HAB episodes, sanitary closure of shellfish farms stop or delay commercial activities. Many
69 articles analysed the consequences of trade bans at different scales. Dyson and Hupert (2009) used
70 an Input-Output model to estimate the detrimental impact of beach closures on recreational razor
71 clam fisheries. Diaz et al. (2019) studied the economic loss of the salmon farming industry in South
72 Chile caused by HAB events. The economic damage was deemed particularly strong in case of
73 Paralytic shellfish poisoning (PSP) outbreaks. Red tides are also largely studied through their
74 economic impacts on different industries, using monitoring data (Larkin and Adams 2007, Morgan et
75 al. 2008). Jin et al. (2005) showed an increase of shellfish imports in response to a supply shortage
76 caused by trade bans during the 2005 red tide in New England (USA). They also highlighted a spatial
77 effect on the shellfish market with price movements observed on the Fulton Fish market in New York
78 after that some shellfish closures were implemented in Maine. Wessells et al. (1995) also studied the
79 economic effect of a red tide event in Prince Edward Island (Canada). The authors showed a
80 reduction in the demand for non-affected mussels in the Montreal market, resulting from a change
81 of consumer perception concerning the quality of products, and although the marketed mussels
82 were safe. More recently, Theodorou *et al.* (2020) evaluated the consequences of HAB-related
83 mussel farming site closures through a risk analysis in the Mediterranean sea. They conclude that the

84 risk depends on the season (summertime being the most critical) when it occurs, with a limited
85 financial risk even for closures lasting up to six weeks at certain non-critical periods (Theodorou *et al.*
86 2020). However, beyond a certain duration of closure, the profit loss may range between 4% and
87 38% when harvesting bans last between 6 to 22 weeks (Konstantinou *et al.* 2012).

88 Park *et al.* (2013) studied the economic impact and mitigation strategies of HABs in Korea, where the
89 aquaculture industry suffered a total loss of USD \$121 million from the early 1980s to the early
90 2010s, with a predominance of *Cochlodinium polykrikoides* events since 1990. PSP blooms in Korea
91 almost every year since 1982 and has been monitored and managed since 1980. Authors reported
92 some evolutions of HABs in Korean waters: usually observed during summertime prior to the 1980s,
93 they are now more frequently met in springtime and autumn. The duration of episodes is also
94 elongating. The HAB event duration has increased from less than one week on average in the 1980s
95 to more than a month since 1995. Tang *et al.* (2006) have analysed the spatial and seasonal patterns
96 of HAB outbreaks in the South Yellow Sea and East China Sea between 1933 and 2004. They reported
97 changes in the seasonal patterns (moving from fall to summer and then to spring) with shifting
98 dominant species and nutrient concentration variations in the Yangtze River estuary. In Southern
99 Europe, Rodríguez-Rodríguez *et al.* (2010) looked at mussel cultivation in Galicia in the presence of
100 red tides. They estimated the correlation between the time length of area shutdowns and the
101 quantity of unsold output. They showed that there was no systematic effect: losses depend on
102 specific market circumstances and authors highlighted the importance of organizational solutions to
103 mitigate commercial risks. More recently, Martino *et al.* (2020) used a production function to
104 investigate the effect of HABs on the Scottish shellfish market. They showed a significant but non-
105 linear relationship between DSP and shellfish production. *Regulations and monitoring systems*

106 To protect human health, the aquaculture industry is highly regulated around the world: regional or
107 national laws are implemented within the international legal framework of the 1982 United Nations
108 Convention on the Law of the Sea (van den Bergh *et al.* 2002). The European Union food law impose
109 specific obligations resulting in trade bans and area closures when acceptable biotoxin
110 concentrations are exceeded (O'Mahony, 2018). In some cases, trade bans and industrial shutdowns
111 can last for several months. The regulations are based on monitoring programs that need to be
112 updated to take emergent toxins into account (Silva *et al.*, 2015). Upgrading the monitoring systems
113 with regard to new HAB species is an important issue to improve the management of risk exposure.
114 For example, the ASIMUTH project aimed at developing short term HAB alert systems for Atlantic
115 Europe (Maguire *et al.*, 2016). These systems were applied to shellfish harvesters in Portugal, where
116 *Pseudo-nitzschia*, *Dinophysis*, *Gymnodinium* and more recently *Ostreopsis* and *Karenia* are frequently
117 observed. A weekly bulletin reports the ongoing state of shellfish closures and gives a one-week
118 forecast of closures for all threatening species (Silva *et al.*, 2016). From 27 July 2013 to 17 March
119 2014, this system performed 85% of correct one-week forecasts, with an accuracy depending on
120 specific areas (coastal, estuaries and lagoons).

121 *Central issue and hypothesis*

122 The scientific literature about HABs focuses on the intensity, spatial distribution and drivers of algal
123 blooms, or strives to evaluate their economic consequences. What is missing is a bridge between
124 these two strands of research, by looking simultaneously at the temporal and spatial distribution of
125 HABs through the track records of administrative closures to learn more about their intensity and
126 occurrence, but also to estimate the actual economic vulnerability to HAB events among other risks.
127 Within the 15 research gaps identified by Adams *et al.* (2018), the authors suggested to develop data
128 collection programs in real time. That is exactly what the present article is about, i.e. attempting to
129 inspire a nationwide effort of data collection based on legal decrees regarding the HAB-related

130 closures and trade restrictions. These authors also considered that “few studies have investigated
131 the role of intensity, and none appear to address the potential for a non-linear relationship between
132 economic losses and duration” (Adams et al. 2018, p. 350). Like other authors, we hypothesize that
133 there is no direct link between the presence of HABs resulting in shutdowns lasting for various
134 durations, and the economic loss at stake (Rodríguez-Rodríguez et al. 2010; Rodrigues et al. 2015;
135 Adams et al. 2018; Theodorou et al. 2020). Our hypothesis is that the economic impact of trade bans
136 related to HABs and microbiological pollutions may not be as important as the frequency and
137 duration of closures would predict. We therefore propose a thorough analysis of a possible gap
138 between the spatial exposure to HABs expressed by administrative closures, and the sensitivity of
139 shellfish farmers revealed by an original database of trade bans.

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

148

149 **2. Context, materials and methods**

150

151 **2.1 The regulatory context**

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

167 In France, 351 shellfish zones are followed by this monitoring system. Contaminants are monitored
168 as microbiological contaminants (via the REMI network of Ifremer), phycotoxins (via the REPHY
169 network) and chemical contaminants (via the ROCCH network). The frequency of water sampling and
170 analysis of toxic contaminants vary upon the period and the nature of results. During some more
171 risky periods, tests can increase to a weekly frequency. The results are disseminated in real time via
172 online bulletins and sent to the health authorities and professional organizations. However, there is
173 no direct causal link between the density of HAB cells monitored by such networks and the toxicity of
174 shellfish, as evidenced by previous research (Souchu et al. 2013). This is why it is of major interest to

175 complement the above cited monitoring systems by a look at legal decrees of closure to really assess
 176 the socioeconomic consequences of HAB events. The public decision to authorize shellfish
 177 production is based on the concentration of biotoxins in the shellfish, and not directly to the density
 178 of HAB cells in the water column. Whenever biotoxin or *E. Coli* concentrations exceed a threshold, a
 179 prefectural (state) decree can order the temporary closure of the farming zone or impose restrictions
 180 on sales until new evidence of water quality within acceptable limits is provided¹.

181 Since 2014, in a specific area (Pénestin, by the French Atlantic coast), a mussel farmer trade union,
 182 under the approval of the local health authorities², implemented a self-monitoring system. When the
 183 period at risk is coming or when a trade ban has been implemented, mussel farmers can develop self-
 184 controls in addition to those coordinated weekly by Ifremer. These additional tests are sub-
 185 contracted to certified laboratories and the cost is collectively borne by the union. Such tests avoid
 186 the dispersion of contaminated shellfish and may contribute to put an earlier end to the trade ban.
 187

188 2.2 The data set

189 The analysis was carried out in four French counties: Finistère, Morbihan, Loire-Atlantique and
 190 Vendée. These four counties host 688 shellfish farms ruled by two regional shellfish farming councils
 191 (CRCs): CRC Bretagne Sud (Southern Brittany) and CRC Pays de la Loire. The local industry produces
 192 37,600 tons of shellfish for a value of 141 M€, i.e. representing around 20% of the domestic output.
 193 Two zones were selected within the region because of their particularly high number of trade bans:
 194 Morbihan and Loire-Atlantique.

195 Because no digital database of prefectural decrees was existing so far, we entered manually all data
 196 corresponding to more than 430 prefectural decrees and 5,400 rows³ registered between 2004 and
 197 2018, including different types of information (Table 1).

198 *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 – Toxic alert – Chemical alert
Type of contamination	Microbiological alert, Toxic Alert, Chemical Alert, Pollution Alert
Cause	<i>E. Coli</i> , Norovirus, other, Diarrhetic Shellfish Poisoning (DSP), Paralytic shellfish poisoning (PSP), Amnesic shellfish poisoning (ASP), Oil pollution Group 1: gastropod (whelk, winkle, abalone...), echinoderm (sea urchin, sea cucumber) and tunicate (violet)
Species group	Group 2: burrowing bivalves (clam, cockle,) Group 3: non-burrowing bivalves (oyster, mussel, scallops...)
Particular species	X
Except some species	X

199

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.

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

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

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

220 Once the database was created, some data concerning shellfish hand gathering or fishing were
 221 excluded because the study focused on professional shellfish farmers only. Scallops, donax or more
 222 broadly *pectinidae* were not selected because these species do not pertain to the aquaculture
 223 industry. Finally, some dates of abrogation were not available because extending after the end of
 224 2018 and these decrees were also excluded. From the 148 zones available in the initial database, only
 225 79 were finally kept in the analysis.

226

227 **2.3 A sequential approach by optimal matching analysis**

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

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

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

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

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

265 The typology was also described by their economic characteristics. Some additional information was
266 collected so as to determine whether the closure rate was connected or not with the economic
267 activity spatially distributed within the clusters. Some available information came from the census of
268 2011 and that of 2012 through the leasehold area, the number of farms and the number of jobs by
269 cluster.

270

271

272 **3. Results**

273

274 **3.1 Descriptive statistics of the administrative closure database**

275

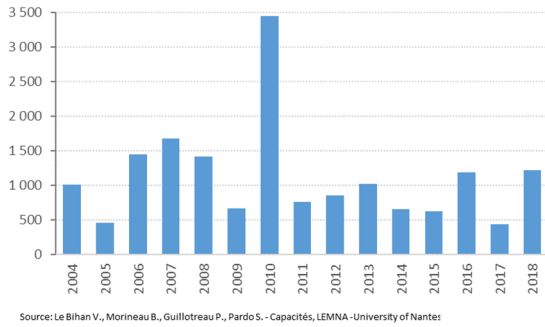
276 *Dynamics throughout the sample period*

277

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

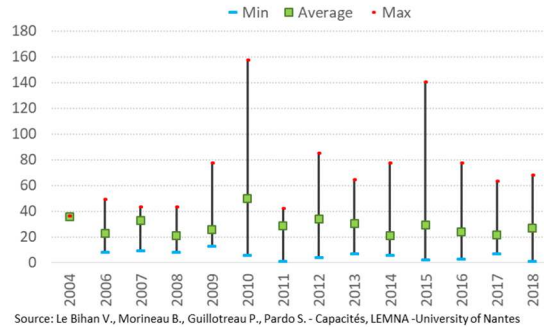
285

⁴ <https://cran.r-project.org/web/packages/TraMineR/index.html>



Source: Le Bihan V., Morineau B., Guillotreau P., Pardo S. - Capacités, LEMNA - University of Nantes

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



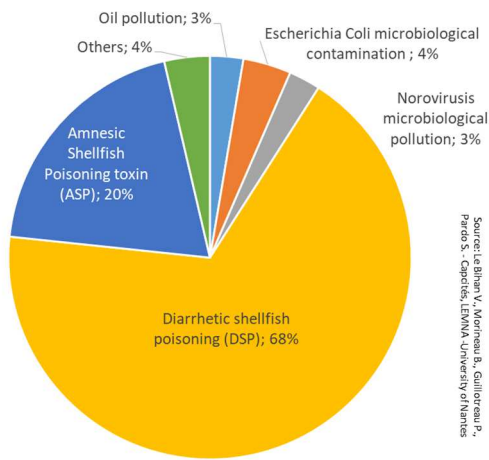
Source: Le Bihan V., Morineau B., Guillotreau P., Pardo S. - Capacités, LEMNA - University of Nantes

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

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287
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289

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.



Source: Le Bihan V., Morineau B., Guillotreau P., Pardo S. - Capacités, LEMNA - University of Nantes

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

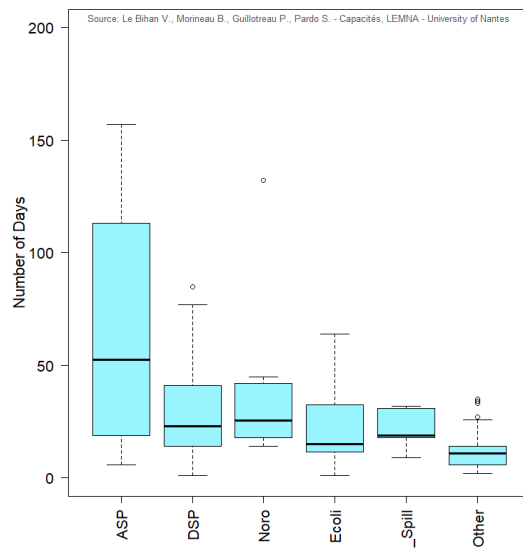


Figure 4 : Number of days of shellfish trade bans by cause (2004-2018) - Q1, Median, Q3 -

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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.

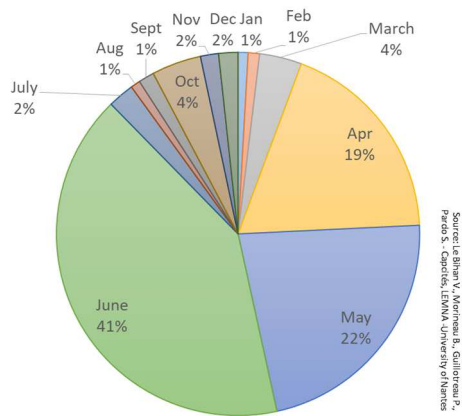


Figure 5 : Distribution of bans by month (average 2004-2018)

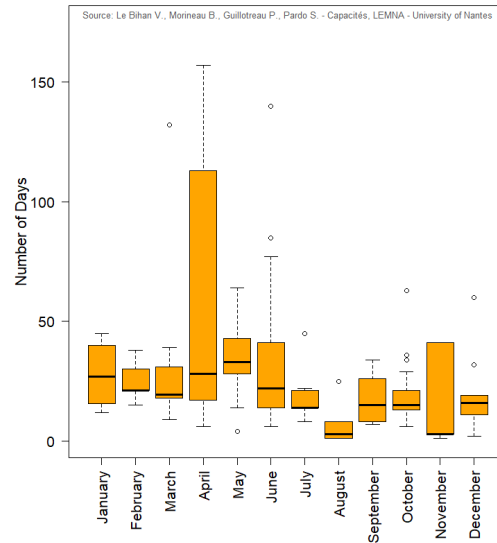


Figure 6 : Number of days of shellfish trade bans per month (2004-2018) - Q1, Median, Q3 -

304

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

309

310 *Geographical distribution*

311

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

316

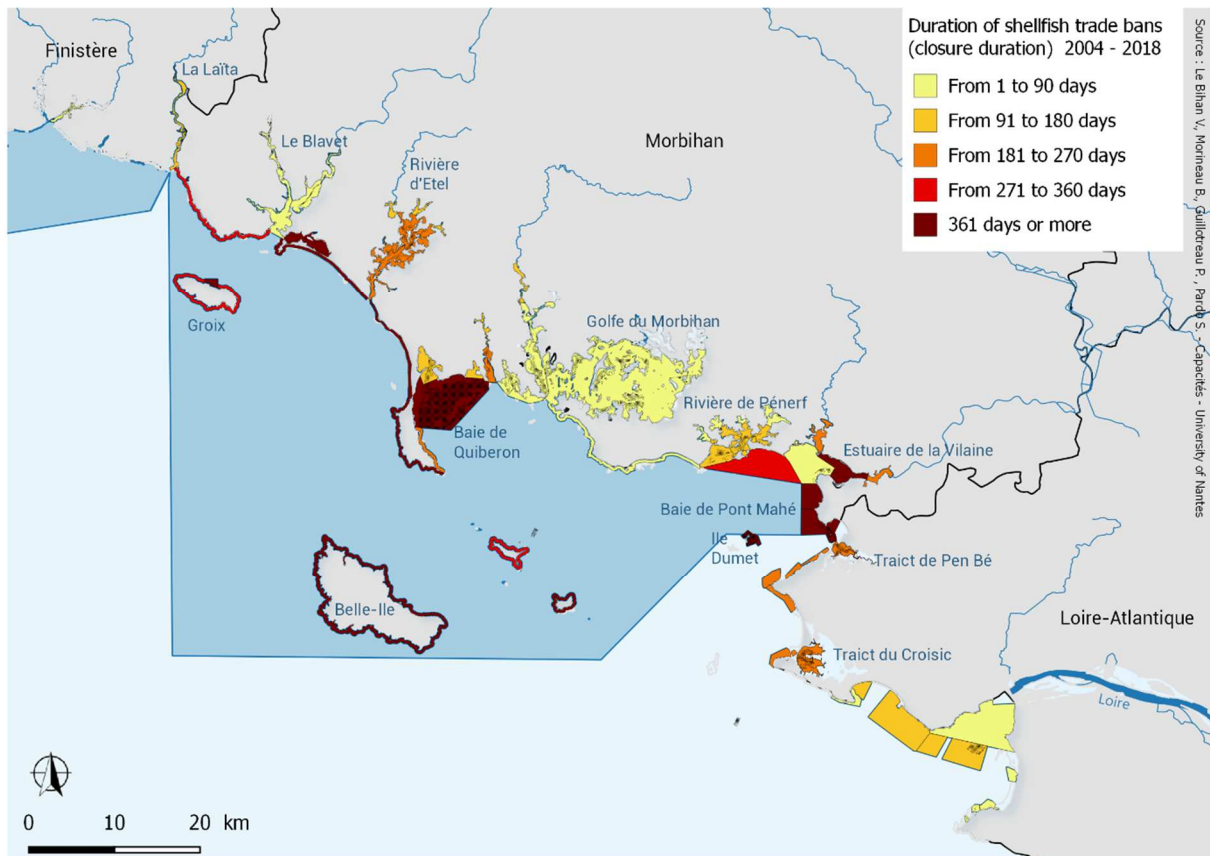


Figure 7 : Map of the number of closure days per shellfish production areas

317

318

319

320 This map shows how some particular geographical zones were more heavily impacted since the early
 321 2000s while others remained relatively protected from any negative environmental impact or
 322 pollution episode. From this map, it is nonetheless hard to draw any conclusion whether semi-
 323 enclosed bay or river mouths were more affected or protected than open areas. The following
 324 analysis attempts to build a spatial typology from the sequential quality states of shellfish zones.

325

326

327

3.2 Typology of trajectories

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

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

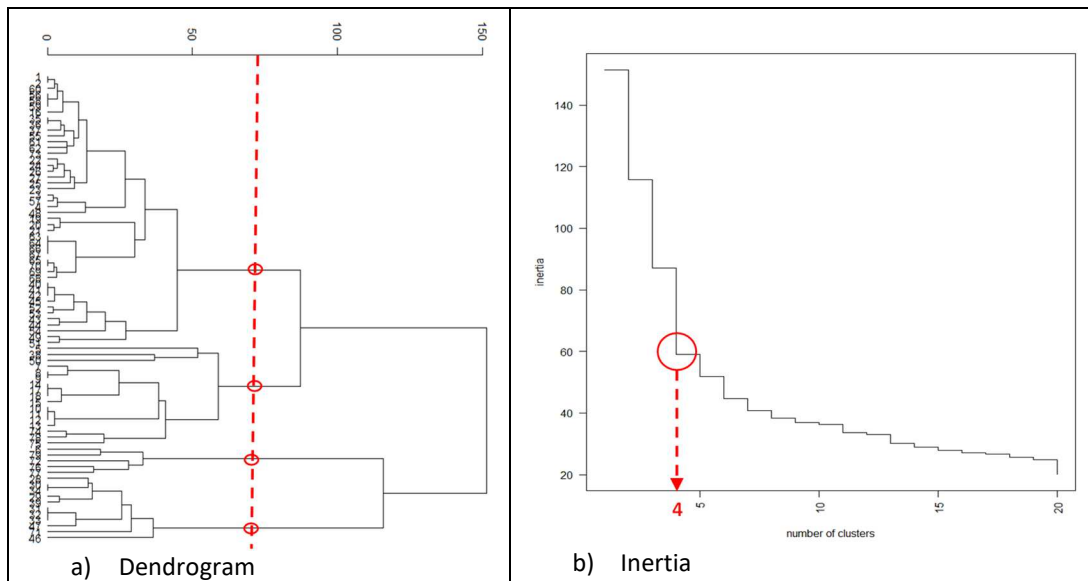


Figure 8 : Dendrogram and inertia (sum of Eigen value) of trajectories

341

342

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

348

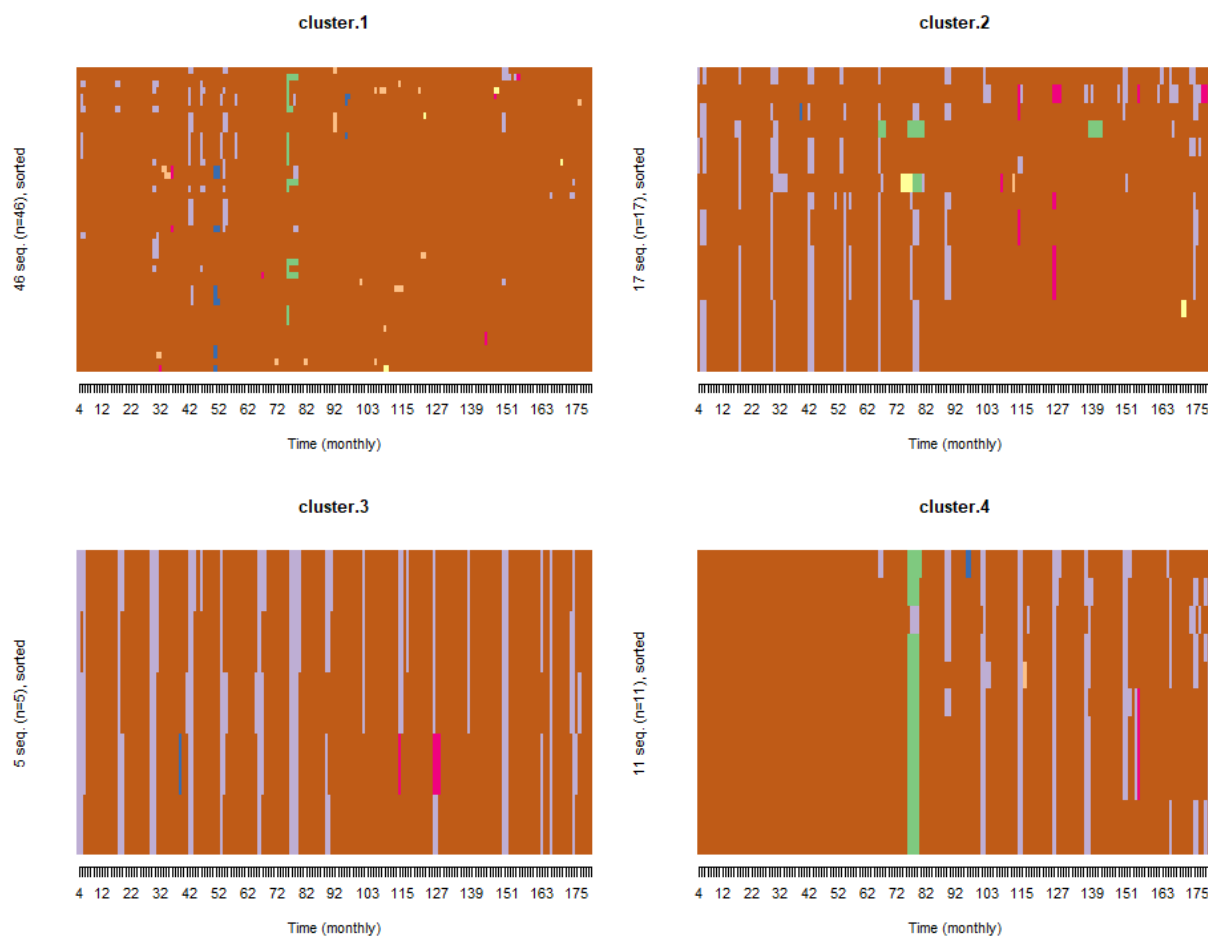
Table 2 : Optimal number of clusters for the typology of sequences

	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

349

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

354



355

356

357

358

Figure 9 : Index plots of the four clusters

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

367 We can give further details about the geographical distribution of area closures (see the Map
 368 in Figure 10). Cluster 1 encompassed 46 shellfish zones which are geographically located in
 369 rivers, estuaries and semi-enclosed bays, such as Aven and Belon rivers, Blavet, Etel river,
 370 the Bay of Morbihan, Penerf river, the Vilaine and Loire estuaries. For the whole sample

371 period, the zones of Cluster 1 were only closed 3% of the time on average (5 months only
372 out of 14 years).

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

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



395

396

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

397

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

406 In the total sample, 57 zones were located in the Morbihan county, whereas 22 were observed in the
 407 Loire-Atlantique county. However, the zones belonging to Morbihan (north of the sample region)
 408 were found over-represented in Clusters 1, 3 and 4, while Loire-Atlantique (south) was over-
 409 represented in Cluster 2 and not at all present in Cluster 4⁵. The same observation was made when
 410 the zones were numbered along a gradient value increasing from North to south. Dividing the sample
 411 between two large areas at the north (36 zones) and south (43 zones) of the Loire estuary, the chi-
 412 squared test demonstrated a non-random distribution, the southern zones being over-represented in
 413 Cluster 2 and 3, and poorly represented in Cluster 4 (Cluster 1 being equally present in both sub-
 414 regions)⁶. Table 3 summarizes some of the findings to characterize the four clusters.

415

416

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

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

417

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

418

** Proportion of factor-related months over the total number of closed months.

419

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

429 Geographically, it seems difficult to emphasize some distinctive features for the four clusters
 430 regarding potential differences of bathymetry, currents, turbidity or distance to the coast. However,
 431 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*

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

437

438 3.3 Economic vulnerability of the clusters

439 In order to check the correspondence between the length and frequency of closures and their
 440 economic consequences, we needed to confront the typology of hazard exposure to the spatial
 441 distribution of shellfish farms. We assumed that the economic impact should be found greater in
 442 clusters where the frequency and length of closures were the highest from the typology. Whatever
 443 the cause, if farmers cannot produce and sell shellfish for several months because of trade bans, this
 444 should affect their economic results. However, if farming is less or not at all present in the affected
 445 zones, the economic consequences should be minor. Additional economic data were therefore
 446 collected from the two censuses of the shellfish aquaculture industry in France published in 2001 and
 447 2012⁷. Some results are summarized in Table 4.

448

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

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

450 * Data collected from the report '*Recensements de la conchyliculture 2001-2012*'.

451 ** Firms which have their headquarter close to the Leaseholds.

452 *** Full-Time Equivalent (FTE) jobs. NB: the number of firms and jobs in Cluster 4 could not be
 453 displayed for statistical secret reasons, the number of farms being less than 3 in this category.

454

455 Several important limits about the assessment of the economic consequences of closures must be
 456 reported. The first one is that trade bans can involve shellfish farms having their headquarters
 457 located far away from where the leaseholds are exploited, sometimes hundreds of miles away. For
 458 example, in the Morbihan County, 84% of the area devoted to shellfish culture are owned and
 459 managed by local farms, but 16% by outsiders. The local ones may also manage leaseholds outside
 460 the area. As a result, the leasehold database does not match exactly the shellfish farm database,
 461 making impossible a comprehensive and accurate economic assessment of clusters. Firms may
 462 compensate a local and temporal loss by higher profits outside the area. A second limit concerns the
 463 lack of knowledge about the type and level of stocks on leasehold beds. The economic impact
 464 depends on which species are cultivated, their output in tonnage and the age structure of stocks
 465 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.

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

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

488 Two Kruskal-Wallis tests were also performed to demonstrate that both variables (closure and
 489 leasehold rates) were not equivalent in the different clusters⁸, this evidence being quite clear from
 490 the mere observation of the figures of Tables 3 and 4. Finally, even in the production zones more
 491 affected by HAB events (e.g. Cluster 3), the regular and seasonal pattern of DSP outbreaks should
 492 allow farmers to anticipate the closing periods in springtime and organize themselves to postpone
 493 their sales and bear no economic loss. We can therefore conclude that the exposure risk is very
 494 unlikely to be correlated with the economic effects of HAB events on the shellfish farming industry in
 495 the southern Brittany and Pays de la Loire regions, as found in another study (Rodríguez-Rodríguez *et*
 496 *al.* 2010).

497

498

499 **4. Discussion**

500 Ecological and economic analyses of HAB events have been usually developed independently. The
 501 drivers of HAB occurrence and diffusion is left to ecological studies (O'Neil *et al.*, 2011; Paerl *et al.*,
 502 2011; Lassus *et al.* 2016; Glibert and Burkholder 2018; Kahru *et al.* 2020, Bresnan *et al.* 2020), while
 503 economists are more interested in assessing the consequences in terms of welfare loss and
 504 employment (Hoagland *et al.* 2002, Sanseverino 2016, Adams *et al.* 2018). The present research aims
 505 at looking at ecological phenomena through the eyes of public decision makers and shellfish farmers.

⁸The 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.

506 The intensity and extent of environmental shocks were estimated by a longitudinal database
507 collecting the legal (Prefectural) decrees restricting the access to the shellfish production zones in
508 Southern Brittany and Pays de la Loire regions (Western part of France) between 2004 and 2018. The
509 sanitary quality of shellfish products is particularly surveyed around the world because of the
510 multiple toxins concentrated in the filter-feeding bivalve molluscs that can be dangerous for human
511 health (Dyson and Hupert 2009, Park et al. 2013, Basti et al. 2018). The economic impact can be
512 tremendous sometimes for the aquaculture industry, although other industries like tourism, housing
513 or fishing can also be dramatically affected (Adams and Larkin 2013; Adams et al. 2018; Diaz et al.
514 2019). However, there might be no direct or linear relationship between the intensity and duration
515 of outbreaks and economic losses (Rodríguez-Rodríguez et al. 2010; Adams et al. 2018), as long as
516 the spatial distribution of blooms does not match the location of the shellfish farming industry. This
517 was the hypothesis we wanted to test for with our original data set.

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

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

⁹ www.mentalfloss.com/

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

555 If HAB outbreaks appear regularly during certain seasons (e.g. in Clusters 3 and 4), this occurrence
556 can be anticipated by farmers. For instance, they can reduce the negative consequences by removing
557 temporarily the molluscs from infected waters and by postponing the sales (Rodríguez-Rodríguez et
558 al. 2010). According to a survey made in France near oyster farmers facing *Dinophysis* outbreaks,
559 producers declared importing shellfish products from non-infected areas during the DSP peak period,
560 re-scheduling the manpower resources through different short-term measures: restriction of working
561 hours, fewer hired seasonal workers, anticipated holidays, and re-organizing the cultivation work on
562 leaseholds (e.g. with more maintenance of equipment) (Souchu et al. 2013). By implementing these
563 simple adaptive strategies, they bear a very limited economic loss, according to this survey, not even
564 mentioning the price response of markets. Other critical issues such as the mass mortality of oysters
565 caused by pathogens (e.g. *OsHV1- μ -var*), far more consequential for farmers although not leading to
566 any closure decree, resulted in a 25% decrease of sales to final consumers between 2008 and 2011,
567 more than fully compensated by a 50% increase in prices because of the market shortage (Le Bihan
568 2015).

569 More generally, Martino et al. (2020) underlined that a difficulty to predict accurately the economic
570 loss caused by DSP is related to the mitigation strategies selected by farmers which may increase
571 costs in the short run but also reduce significantly the profit loss in the long run. It appears in all
572 studies that implementing efficient adaptive strategies is based on the ability of farmers to anticipate
573 HAB events. For Stauffer et al. (2019), one of the key components to solve HAB-related problems is
574 to improve the early detection of toxic events to protect more effectively animal and human health
575 and thus mitigate economic losses. In this respect, the Ecological Forecasting Roadmap program
576 developed by the U.S. National Oceanic and Atmospheric Administration (NOAA) pays greater
577 attention to HAB forecasts both in marine and freshwater systems and should be inspiring for the
578 European management systems¹⁰. In Spain, the ASIMUTH project aimed at developing short term
579 HAB alert systems for Atlantic Europe (Maguire et al. 2016). The information provided by this
580 warning system enabled shellfish farmers to manage more effectively their practices in real time.
581 Thus, a better understanding of complex relationships between HAB outbreaks, environmental
582 factors, seasonal and spatial patterns in connection with the economic activity, remains a top priority
583 of the research agenda to improve forecasting models of HAB and to mitigate economic losses.

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588

589 **Conclusion**

590 Among all the research gaps identified by Adams et al. (2018) in a book dedicated to HABs (Shumway
591 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/>

592 an original database of legal decrees restricting the fishing and shellfish farming activities in the
593 presence of HABs and other microbiological pollutants. This tremendous effort was applied to two
594 important shellfish aquaculture regions in France (Southern Brittany and Pays de la Loire) and on that
595 mere basis, we managed to convince the Ministry of Agriculture about the usefulness of such an
596 endeavour at the national level. The Ministry therefore decided to extend the data collection effort
597 to the whole domestic territory¹¹. Secondly, Adams *et al.* (2018) encouraged scholars to investigate
598 the relationship between the intensity of HAB events (in terms of frequency, duration and spatial
599 extent) and the economic loss for sensitive industries such as fishing, aquaculture, coastal tourism or
600 the housing market. From this gap of knowledge, we built our own hypothesis about a possible non-
601 linear relationship –if not a partial independence– between the degree of spatial exposure and the
602 sensitivity of shellfish farmers to the HAB hazards. HABs may well be intense and emerge seasonally
603 every year, if there is no human activity for the time and space when and where such outbreaks
604 occur, the social and economic consequences will be few.

605 Using the original database of closure decrees by shellfish production zone, we developed an original
606 and longitudinal approach through an Optimal Matching Analysis of water status trajectories in 79
607 shellfish zones between April 2004 and December 2018, borrowing the method from genetics or
608 social sciences dealing with life history traits. We ended up with a typology of trajectories across four
609 zonal clusters. More than half of the zones were pooled in a cluster which was poorly affected by
610 HABs (less than 3% of the time). Another one was struck every springtime by DSP outbreaks. The two
611 others had opposite temporal patterns: one of them faced periodical closures prior to September
612 2011, the other one after this date. HABs prevailed in the causes of administrative closures (in more
613 than 90% of cases), mainly because of DSP, and ASP to a minor extent but with longer average
614 duration by decree. It is important to remind that these are not the only risks faced by shellfish
615 farmers (Le Bihan *et al.* 2013). For instance, the domestic oyster industry has been particularly
616 affected by an Herpes virus (of type *OsHV1- μ -var*) crisis since 2008 onwards, but the farmers
617 managed to cope with this virus which is only killing oysters, and therefore is not deemed to be
618 dangerous for human health. Consequently, this epizooty did not lead to any closure decree from the
619 public authorities.

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

628 Moreover, concluding from this study that shellfish farmers, though exposed, remained weakly
629 sensitive to HAB hazards, does not mean that they will not suffer heavier consequences in the future.
630 Most ecological studies predict an increase of HAB episodes in frequency, spatial coverage and
631 duration in the years to come because of climate changes (e.g. Hallegraeff, 1993; Anderson, 1994;
632 Lassus *et al.* 2016; Glibert and Bulkholder, 2018, Kahru *et al.* 2020). For the last two years in France,
633 changes of HAB events are being observed in traditionally safe shellfish areas. For example in
634 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.

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

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

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- 778

779 **APPENDIX**780 **A1. Optimal Matching Analysis (OMA)**

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

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

798 Example of two lagged DNA sequences:

799 Sequence 1: AAAAGGGG

800 Sequence 2: CCAAAAGG

801 To make both sequences identical, several strategies can be selected: either by inserting two C at the
 802 beginning and deleting two G at the end of sequence 1, or by substituting 2 C for two A and two A for
 803 two G in sequence 1. In most studies, insertion and deletion ("*indel*") are given the same cost value,
 804 while substitution (which combines insertion and deletion) is deemed to be a more costly operation
 805 (representing twice the *indel* cost). In our example, the first (*Indel*) strategy would cost 4, while the
 806 second (substitution) strategy would cost 8. The distance between two sequences is defined as the
 807 minimal cost to make both sequences identical. A distance matrix between sequences is constructed
 808 and further used in a classification analysis to obtain a typology of trajectories (Robette and Thibault
 809 2008).

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

815

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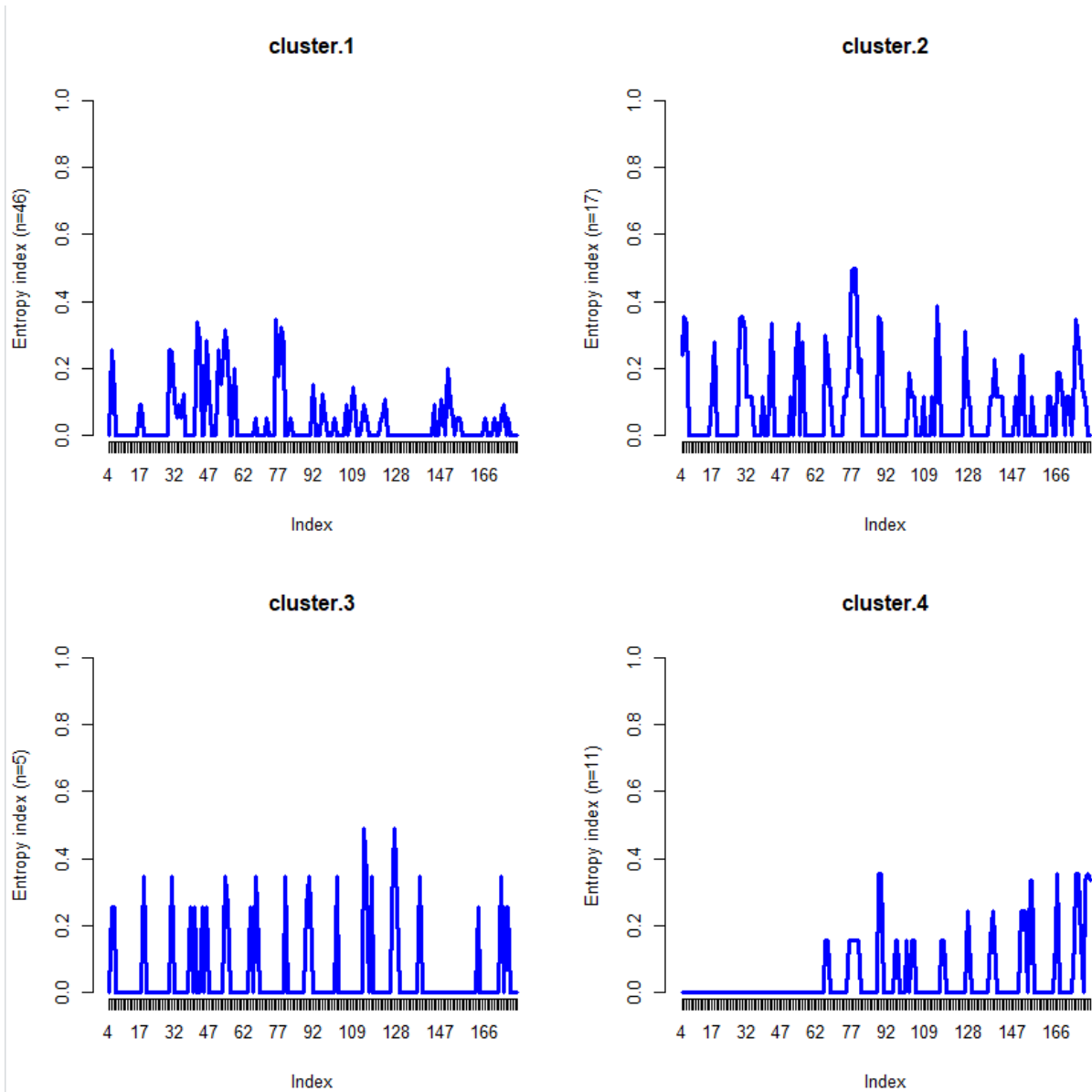
818

819

820 **A2 Entropy index of the four clusters**

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

824



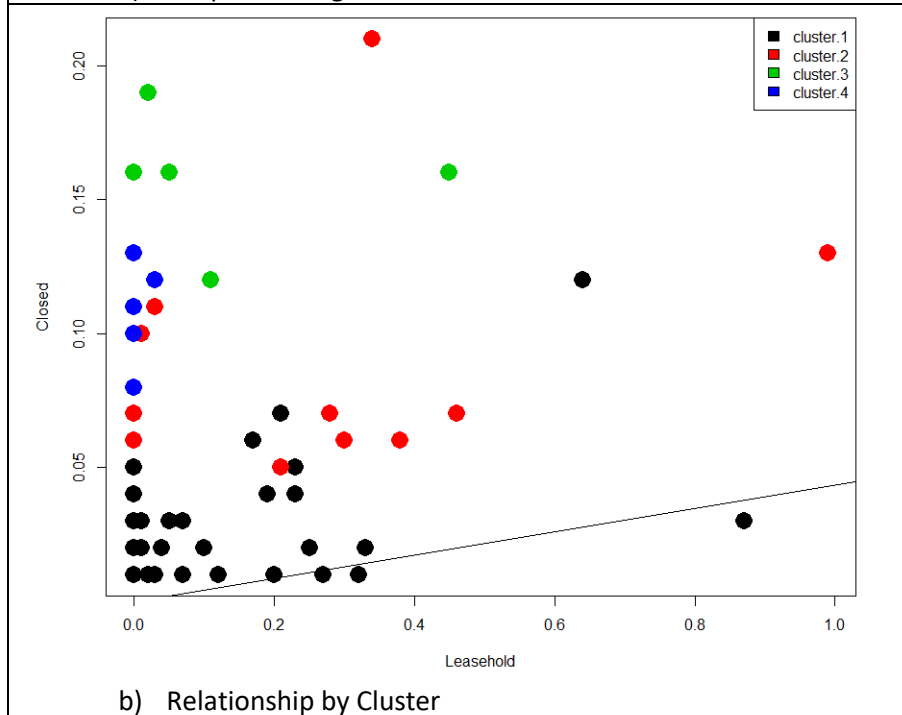
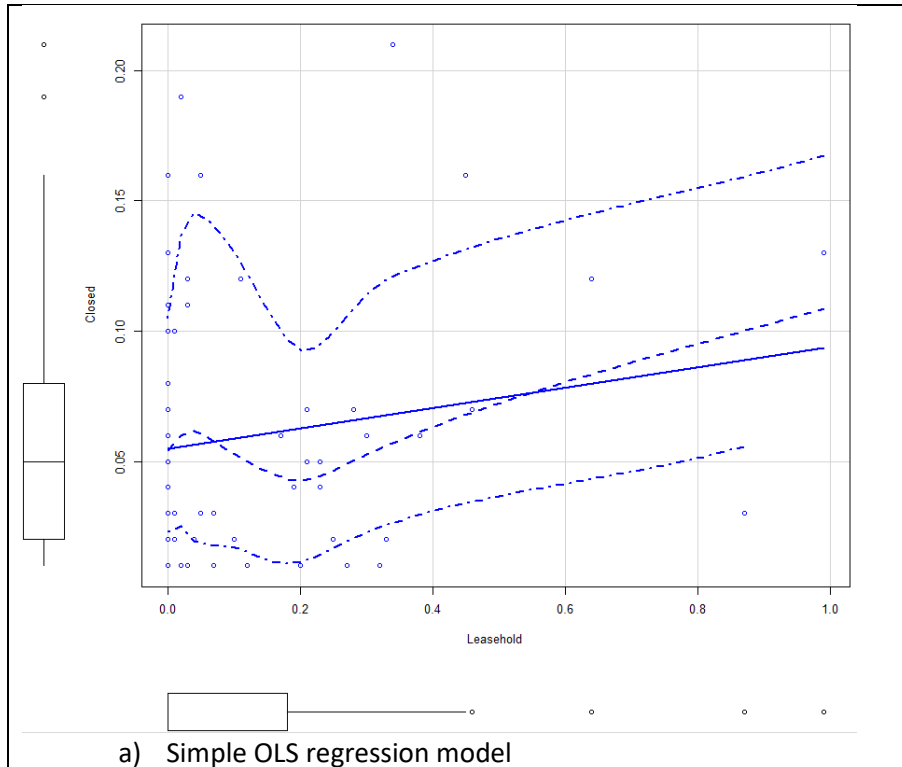
825

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

827

828

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



832

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