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► **To cite this version:**

Catherine Belin, Dominique Soudant, Zouher Amzil. Three decades of data on phytoplankton and phycotoxins on the French coast: Lessons from REPHY and REPHYTOX. *Harmful Algae*, 2021, 102, 101733 (12p.). 10.1016/j.hal.2019.101733 . hal-04203153

HAL Id: hal-04203153

<https://hal.science/hal-04203153v1>

Submitted on 22 Jul 2024

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1 **Three decades of data on phytoplankton and phycotoxins on the French coast:**
2 **lessons from REPHY and REPHYTOX.**

3

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5

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9

10 **Abstract**

11 In France, REPHY (Observation and Surveillance Network for Phytoplankton and Hydrology
12 in coastal waters) and REPHYTOX (Monitoring Network for Phycotoxins in marine
13 organisms) have been contributing to long-term time series on ocean health for more than 30
14 years. The aim of this paper is to describe these networks and to highlight their key results.
15 Over the last 20 years, phytoplankton flora analysis on French coasts from the Channel to
16 Mediterranean has shown that the five "emblematic" taxa are *Chaetoceros*, *Skeletonema*,
17 Cryptophyceae, *Leptocylindrus* and *Pseudo-nitzschia*. The latter, together with the taxa of
18 interest *Dinophysis* + *Phalacroma*, *Alexandrium*, and *Karenia*, have been consistently
19 recorded along the entire French coastline. However, when taking into account frequency of
20 occurrence some taxa exhibit more distinct geographical distributions. In particular, the
21 occurrence of *Phaeocystis* appeared to be strongly specific to the northern coasts of the
22 Channel. French coasts have been regularly affected since the 1980s by the presence of
23 toxins in bivalve molluscs, leading to bans on fishing and sale of shellfish during periods of
24 varying duration. Three categories of toxins were involved. PST and AST were absent from
25 the French coasts, respectively before 1988 and 2000. DST (Diarrhetic Shellfish Toxins) have
26 affected many areas along the whole coast every year since 1987. For PST (Paralytic
27 Shellfish Toxins), only a few areas have been affected, sometimes sporadically, since 1988 in
28 the Channel, 1993 in the Atlantic, and 1998 in the Mediterranean. Many areas have been

29 impacted since 2000 by AST (Amnesic Shellfish Toxins) episodes, mainly affecting scallops
30 in the Channel and on Atlantic coasts. The patterns of change of shellfish toxicity episodes
31 showed no real trend in any province over the entire period 1987-2018.

32

33 **Keywords**

34 Monitoring network; Phytoplankton time-series; Dominant species; DST-Diarrheic Shellfish
35 Toxins; PST-Paralytic Shellfish Toxins; AST-Amnesic Shellfish Toxins

36

37 **Terminology**

38 Taxonomic Units (TU): taxa clusters, most often groups of genera and / or groups of species,
39 described to allow data processing.

40 Dominant taxa: the taxa most present on the French coast, calculated by a method derived
41 from the Sanders index (1960).

42 Emblematic taxa: some of the most dominant taxa + some toxic or harmful taxa that are not
43 dominant. These taxa are considered emblematic either on the whole French coast or in one
44 of the three provinces (Channel, Atlantic, Mediterranean).

45

46 **1 Introduction**

47 Phytoplankton provide key ecosystem services in terms of the functioning of the biological
48 pump, regulation of climate, generating half of the oxygen in our atmosphere, and as the
49 base of marine food webs. Numerous global changes since the beginning of the industrial
50 era, such as eutrophication, warming, acidification and deoxygenation of the ocean,
51 represent key stressors for marine ecosystems. Phytoplankton responses to these include:
52 (i) increase in phytoplankton biomass and oxygen depletion in bottom waters (Diaz and
53 Rosenberg, 2008); (ii) changes in structure of phytoplankton communities in response to
54 changes in nitrogen / phosphorus / silica ratios (Philippart *et al.*, 2000); (iii) increased
55 frequency of harmful algal blooms (Hallegraeff, 1993; Anderson *et al.*, 2002; Anderson, 2009;
56 Wells *et al.* 2015); (iv) alteration of the phenology of phytoplankton communities (Leterme *et*

57 *al.*, 2008). Human health can be impacted by species that produce toxins that are dangerous
58 for humans who consume seafood, as well as environmental impacts from species that are
59 toxic or harmful for the marine fauna and flora. For all these reasons, knowledge of
60 phytoplankton dynamics is essential. Most natural ocean processes vary on annual to
61 decadal timescales and to identify shifts resulting from climate change, observations need to
62 span at least 30 or preferably 50 years or more (Koslow and Couture, 2013). In this context,
63 the acquisition of long-term series of phytoplankton species has become a priority in the
64 monitoring of the marine environment, knowing that long-term series on phytoplankton are
65 not common worldwide. The study of these issues is already benefiting from the availability of
66 long-term time series from coastal sites subject to contrasting environmental and human
67 pressures at a global scale. For example: (i) plankton observation data produced since 1931
68 by the Continuous Plankton Recorder (CPR), initially deployed in the North Sea and then
69 extended to the North-East Atlantic and now globally, (ii) the data series since 1962 on
70 plankton 'Helgoland Roads', located in a German archipelago in the southeast of the North
71 Sea.

72
73 In France, the creation in 1984 of the monitoring network REPHY-REPHYTOX by Ifremer
74 was part of this process. The objective of REPHY is to acquire data of the biomass,
75 abundance and composition of marine phytoplankton in coastal and lagoon waters, as well
76 as the associated hydrological parameters. These data cover in particular the spatio-
77 temporal distribution of phytoplankton species, and the identification of exceptional blooms.
78 The objective of REPHYTOX is the detection and monitoring of the three categories of toxins
79 that can accumulate in bivalve molluscs, which are regulated at European level: lipophilic
80 toxins (including DST), PST and AST, which are respectively responsible for the following
81 human syndromes: DSP (Diarrheic Shellfish Poisoning), PSP (Paralytic Shellfish Poisoning)
82 and ASP (Amnesic Shellfish Poisoning). The two networks are closely associated, since the
83 monitoring of toxic phytoplankton by REPHY is used for triggering toxin analysis by
84 REPHYTOX and for a better understanding of shellfish contamination. REPHY is divided into

85 three components: Observation, Surveillance and Health (Belin and Soudant, 2018). The aim
86 of the Observation component is to seek answers to research questions such as: (i) what are
87 the responses of phytoplankton communities to environmental changes (e.g. Hernández-
88 Fariñas *et al.*, 2014); (ii) participate in the definition of phytoplankton ecological niches
89 (Hernández-Fariñas *et al.*, 2015); (iii) detect variations in phenology (Guallar *et al.*, 2017); (iv)
90 participate in the characterization of traits and functional groups (David *et al.*, 2012). The
91 main aim of the Surveillance component is to participate, in addition to the Observation
92 component, in the assessment of the quality of the coastal waters through indicators, in
93 particular those described that meet the requirements of the European directives WFD
94 (Water Framework Directive) and MSFD (Marine Strategy Framework Directive). The
95 purpose of the Health component is to participate in the triggering of shellfish sampling
96 carried out within the framework of REPHYTOX network, by supplementing the results
97 already acquired on the toxic species by the two other components. REPHYTOX monitoring
98 applies to shellfish harvested for professional purposes in their natural environment i.e. in
99 production areas and natural populations, and in professional fishing zones. In addition to
100 providing the necessary information to the authorities responsible for managing the public
101 health risk, this monitoring system makes it possible to acquire scientifically interesting data.

102

103 The purpose of this article is to present a comprehensive review of the data acquired since
104 1987: (i) on the phytoplankton of the French coast, with respect to the most dominant taxa
105 and a survey of the geographical distribution of some toxic or harmful species; (ii) on the
106 three categories of phycotoxins most widespread in France, with the temporal patterns of
107 change of episodes of toxicity, and their geographical distribution. Data presented here do
108 not include those from the French overseas departments/areas.

109

110 **2 Material and methods**

111 The REPHY and REPHYTOX monitoring networks were set up by Ifremer in 1984, with the
112 first data available from 1987. All operations relating to REPHY and REPHYTOX, from

113 sampling to analysis, were carried out using a quality approach, the main components of
114 which were: a general quality assurance process, the accreditation or official approval of
115 laboratories, documents and methods standardized at national level, regular performance
116 testing of measuring equipment, intercalibration and inter-laboratory comparability tests.
117 Methodological support, expertise and organization of training for staff were provided by
118 experts qualified in the relevant fields.

119

120 *2.1 Sampling strategies*

121 REPHY and REPHYTOX spread over the whole French coastline. The three marine
122 provinces of France are: the Atlantic Ocean, the Channel and the Mediterranean (see Fig. 1).
123 The Channel is an epicontinental sea of the Atlantic Ocean, located in North-West Europe
124 and separating France from the United Kingdom; the Eastern Channel is one of the busiest
125 maritime areas of the globe; the water of this zone is, because of the currents among most
126 important in the world, very turbid, while remaining oxygenated. The Mediterranean Sea is an
127 almost entirely closed intercontinental sea, bordered by the coasts of Southern Europe,
128 North Africa and West Asia; its opening to the Atlantic Ocean by the Strait of Gibraltar is 14
129 kilometers wide.

130 For REPHY, the Observation component comprised 36 sampling stations (Fig. 1). The
131 Surveillance component complemented this system with another 116 stations distributed in
132 water bodies not covered by the Observation component. The Health component included 71
133 additional stations with strictly health objectives, but also used data from 41 stations related
134 to the Observation or Surveillance components. The sampling strategy consisted of *in situ*
135 measurements, and water samples for microscopic analysis of phytoplankton and for
136 selected additional analyses. Sampling and measurements were carried out under specific
137 conditions, particularly at 1 m below the surface (dissolved oxygen was also measured at the
138 bottom) and within 2 hrs either side of high tide in the Channel and the Atlantic. The sampling
139 periods and frequencies, as well as the parameters to be measured, were different
140 depending on the REPHY component, and the type of water body. For REPHY Observation,

141 sampling was done all year round, once a fortnight. The mandatory parameters were: *in situ*
142 measurements (temperature, salinity, turbidity, dissolved oxygen), microscopic analysis of all
143 phytoplankton ('total flora'), chlorophyll *a*, pheopigments and nutrients. Dissolved oxygen was
144 only measured in Summer from June to September. Phytoplankton pigments were also
145 analyzed on samples from a selection of stations spread along the whole coastline. For
146 REPHY Surveillance, sampling was generally done all year round, once a month. For most
147 stations, the mandatory parameters were: *in situ* measurements, microscopic analysis of a
148 selection of phytoplankton species ('targeted flora'), chlorophyll *a*, pheopigments and
149 nutrients. However, some analyses were limited to one period of the year: (i) for Channel and
150 Atlantic coasts, chlorophyll *a* and nutrients were measured respectively from March to
151 October, and from November to February, (ii) dissolved oxygen was measured from June to
152 September. Otherwise, for a few stations in Channel or Atlantic transitional water bodies, only
153 *in situ* measurements and nutrient analysis were performed. In the Mediterranean lagoons,
154 an estimation of nano- and pico-phytoplankton by flow cytometry was made in addition, from
155 June to August. For REPHY Health, the sampling period at strictly health-related stations was
156 dependent on the context: all year round, or over a limited period. The frequency was once a
157 week. The only mandatory parameter was the microscopic identification of toxic
158 phytoplankton species ('toxic flora'). At the Observation and Surveillance components
159 stations identified as being useful for the Health component, sampling could possibly be
160 carried out for additional toxic flora during the weeks without scheduled sampling.

161 For REPHYTOX, nearly 300 shellfish sampling stations could potentially be used, with
162 mussels at almost half of the stations, as well as oysters, scallops, clams, cockles or various
163 other shellfish. REPHYTOX sampling stations were in some cases in common with those of
164 REPHY. Alert thresholds, based on historical data, were defined for the phytoplankton toxic
165 species currently occurring on French coasts. Their detection by the REPHY network above
166 these thresholds triggered toxin monitoring in shellfish on a weekly basis. These alert
167 thresholds were: (i) for diarrhetic shellfish toxin producing species: as soon as *Dinophysis*
168 was present, whatever the species, 10,000 cells per liter for *Gonyaulax spinifera*,

169 *Lingulodinium polyedrum*, *Protoceratium reticulatum* or *Prorocentrum lima* (when present in
170 the water column); (ii) for paralytic shellfish toxin producing species: 10,000 cells per liter in
171 areas usually affected by *Alexandrium minutum*, between 1,000 and 5,000 cells per liter in
172 areas usually affected by *Alexandrium pacificum* according to the zone, 10,000 cells per liter
173 for unidentified *Alexandrium* species; (iii) for amnesic shellfish toxin producing species:
174 300,000 cells per liter for the less toxic *Pseudo-nitzschia* species, 100,000 cells per liter for
175 the most toxic; the difference between these two groups of species was made from their
176 general form: broad or slender for the most toxic (including e.g. *P. australis*, *P. fraudulenta*, *P.*
177 *multiseriata*, *P. pungens*), thin or sigmoid for the least toxic (including e.g. *P. delicatissima*, *P.*
178 *multistriata*); the notion of 'more or less toxic' is deduced from the history observations made
179 in France, and is subject to evolution. However, there were two cases where the monitoring
180 of toxic phytoplankton was not reliable enough to ensure the absence of toxins in shellfish.
181 Firstly, lipophilic toxins were sometimes observed in shellfish before the presence of
182 *Dinophysis* was detected; the search for these toxins was therefore systematically carried out
183 in the 'risk zones' and during 'risk periods' defined using the history of results over the last
184 three years. Secondly, offshore and deep-sea shellfish deposits were systematically
185 monitored for all three toxin categories every fortnight, one month before and during the
186 entire shellfish harvesting period. Mussels (*Mytilus edulis*, *M. galloprovincialis*) were
187 considered as sentinels for lipophilic toxins, since historical data showed that they were
188 always contaminated earlier than all other shellfish. If they were present in a production area,
189 the mussels were analysed first, and the other shellfish as soon as the mussels became
190 toxic. This was not the case for PST and AST episodes: all shellfish species were then
191 monitored simultaneously.

192 2.2 Measured parameters and methods

193 For REPHY, the identification and count of phytoplankton cells under an optical microscope
194 was performed at most REPHY sampling stations, with the exception of: (i) those located in
195 turbid waters or too far upstream in a river, (ii) some stations located in Mediterranean
196 lagoons for which phytoplankton was measured by flow cytometry. Phytoplankton data was

197 grouped into three different categories: (i) 'total flora' corresponded to the identification and
198 count of all phytoplankton taxa identified using light microscope; (ii) 'targeted flora'
199 corresponded to the identification and count of a targeted list of species, including those in
200 high concentrations and those which were known to be toxic or harmful; (iii) 'toxic flora'
201 corresponded to the identification and count of the few species that produced toxins that
202 could accumulate in shellfish. The method used was that of Utermöhl (1931). The
203 identification of phytoplankton was based on the WoRMS (World Reference Marine Register)
204 and had to be at the most precise taxonomic level (species or genus) if possible, and if not,
205 at a higher taxonomic level (family, class, etc.). The analysis by flow cytometry, according to
206 the Vaquer *et al.* (1996) method, provided functional groups for nano- and pico-
207 phytoplankton. Chlorophyll *a* and pheopigments were essentially analyzed by
208 monochromatic spectrophotometry or fluorimetry (Aminot and K  rouel, 2004). The measured
209 nutrients were: ammonium (NH_4^+), nitrate (NO_3^-), nitrite (NO_2^-), phosphate (PO_4^{3-}), silicate
210 (SiOH_4). The ammonium concentration was determined by flow fluorimetry, and the
211 concentration of the other four nutrients by flow spectrophotometry (Aminot and K  rouel,
212 2007). In addition to phytoplankton observations, the measurement of physical and chemical
213 parameters (i.e. temperature, salinity, turbidity and dissolved oxygen) were generally
214 measured *in situ* using sensors, with a multi-parameter probe.

215 For REPHYTOX, detection and quantification of phycotoxins was carried out on the total
216 flesh from live shellfish according to the official European methods. These also describe
217 regulatory safety thresholds not to be exceeded for shellfish to be considered consumable.
218 Lipophilic toxins including DST have been measured by Liquid Chromatography coupled to
219 tandem Mass Spectrometry (LC-MS / MS) since early 2010 (Anonymous, 2015). They had
220 been previously detected by mouse bioassay according to the method of Yasumoto *et al.*,
221 (1984 modified). These results were therefore qualitative until 2009, and expressed in terms
222 of 'favorable' or 'unfavorable'. The results were quantitative from 2010 and included
223 quantification for each of the molecules of the groups of regulated toxins. The regulatory
224 thresholds were (expressed per kg of shellfish flesh): (i) 160 μg of OA equivalent for the

225 OA+DTX+PTX group (okadaic acid + dinophysistoxins + pectenotoxins); (ii) 160 µg of AZA
226 equivalent for AZA (azaspiracids); (iii) 3750 µg of YTX equivalent for YTX (yessotoxins). Each
227 of the constitutive toxins in these groups was corrected by a TEF (Toxic Equivalent Factor) to
228 account for its potential toxicity. The quantification of PST was carried out by mouse
229 bioassay, calibrated and validated to give a quantitative result (Anonymous, 2014). The
230 regulatory threshold was 800 µg STX (saxitoxin) equivalent per kg of shellfish flesh. AST
231 were measured by High Performance Liquid Chromatography with Ultra Violet detection
232 (HPLC/UV) (Anonymous, 2008). The regulatory threshold was 20,000 µg DA (domoic acid)
233 equivalent per kg of shellfish flesh. For PST and AST, the results recorded in the REPHYTOX
234 data did not include detailed results for each constitutive toxin.

235

236 **2.3** *Data: storage, availability, communication*

237 All REPHY and REPHYTOX results have since 1987 been recorded in the national
238 'Quadrigé' database, in compliance with a quality process, the main characteristics of which
239 are: administration of the database by a dedicated data management team, mandatory
240 training and agreement for the use of Quadrigé, entering the results according to a user
241 manual, compulsory checks and validation of the data entered, a quality process
242 implemented *a posteriori* on the data in order to provide, for each result, information on the
243 quality (good, doubtful or erroneous). Access to the raw data of Quadrigé is restricted to
244 authorized users, but the validated data are public, associated with a DOI (Digital Object
245 Identifier), and accompanied by user manuals in English: REPHY (2017), REPHYTOX
246 (2017), with the respective DOI: doi.org/10.17882/47248, doi.org/10.17882/47251. The
247 datasets used for the presentation of the results below were all extracted from the Quadrigé
248 database.

249

250 **2.4** *Data presented and processing*

251 Results presented at national scale were always aggregated geographically according to
252 Quadrigé's internal 'marine areas' reference system. This defines 123 contiguous marine

253 areas: 38 for the Channel, 54 for the Atlantic and 31 for the Mediterranean. Phytoplankton
254 taxa were always grouped in 'Taxonomic Units' (TU). The REPHY data were composed of
255 more than 500 different taxa over the entire period 1987-2018, including more than 200
256 species or groups of species, more than 200 genera or groups of genera, and about 40
257 families. To partially address the difficulty of processing such heterogeneous data,
258 Hernández-Fariñas *et al.* (2014) proposed using taxa clusters and described them as
259 Taxonomic Units, which were most often groups of genera and / or groups of species. The list
260 was thus reduced to less than 250 TU.

261 Two characteristics of phytoplankton data for the last 20 years (1999-2018) are presented
262 here: dominance and abundance. For the determination of 'dominant' TU, only 'total flora'
263 data were taken into account for this calculation. The dominance measure used here was
264 derived from the Sanders index (1960). This is determined by classifying the species from 1
265 to 10 by abundance in each sample. A rank of 1 receives a value of ten points, a rank of 2
266 nine points, etc. A rank of 10 receives one point. The points are summed on all samples: the
267 higher the sum of points, the more dominant is the species. This approach consisted on the
268 one hand of taking abundance into account by using relative numerical abundance of
269 species in samples instead of points, and on the other hand considering all species and not
270 only the ten most abundant ones. The summary of results for TU abundance was based on
271 the 90th percentile, encompassing the spread of data omitting highly skewed values (Devlin
272 *et al.*, 2014), computed with TU occurrence abundance during the considered period and
273 marine area. These values were represented on a map as disks with a diameter proportional
274 to their abundance class on a log 10 scale. The number of TU occurrences was taken into
275 account through the transparency of the disk color varying linearly from transparent (i.e.
276 1 occurrence) to opaque (i.e. 240 occurrences, that is, identified each month during 20
277 years). Six TU were chosen according to their toxicity or harmfulness. Three of these TU
278 included species that produced toxins that were dangerous to shellfish consumers
279 (*Dinophysis + Phalacroma*, *Alexandrium* and *Pseudo-nitzschia*). The other three TU
280 contained species that already led to mortalities of marine fauna in France: (i) *Karenia*

281 *mikimotoi*, a producer of hemolytic ichthyotoxins; (ii) *Phaeocystis*, via mechanical action with
282 production of foams; (iii) *Lepidodinium chlorophorum* which, by its capacity to develop rapidly
283 in abundant quantities, has regularly led to anoxia in the marine environment .The results on
284 toxins were summarized, on the one hand temporally, and on the other hand spatially. For
285 the temporal dimension, a toxicity episode of a given toxin (i.e. DST, PST or AST) was
286 defined by its occurrence in shellfish above the European regulatory threshold. For each
287 given year and toxin, a marine area was considered affected by the given toxin if at least one
288 toxicity episode was recorded. Then, to compare the number of affected areas by province,
289 year and toxin, sums were divided by the number of marine areas of the corresponding
290 province and plotted as stacked bar charts. For the spatial dimension, three maps were
291 produced (one per toxin) showing for each marine area the number of years affected by at
292 least one toxic episode in the year. In order to achieve more relevant comparison between
293 the respective impacts of the three categories of toxins, the focus for these maps was on the
294 period 2000-2018 (the PST and AST being less or not present before 2000). Data
295 processing, tables and maps were made with R (2018) and QGIS (2018).

296 **3 Results**

297 Most of the location names cited in the text appear in Fig. 1.

298 *3.1 Phytoplankton*

299 Table 1 details the most dominant TU for the period 1999-2018. It shows that five TU can be
300 considered as the most emblematic of the French coastline as a whole: *Chaetoceros*,
301 *Skeletonema*, Cryptophyceae, *Leptocylindrus*, *Pseudo-nitzschia*. These always belong to the
302 group of the ten most dominant TU, whatever the geographical region. Among the target TU,
303 *Phaeocystis* was also an element of interest although it has never been detected on
304 Mediterranean French coast. It reached the 64th dominance rank in the Atlantic, but was the
305 second most dominant TU on the French coast of the Channel. *Lepidodinium*, which is
306 another harmful TU of interest, has also never been observed on the Mediterranean French
307 coasts. Unlike *Phaeocystis*, it is more dominant on the Atlantic coasts than in the Channel.
308 The three other toxic or harmful TU of interest, i.e. *Dinophysis* + *Phalacroma*, *Alexandrium*

309 and *Karenia*, are towards the bottom of the ranking, respectively, 47th, 49th and 61st. Over the
310 same period of 20 years, Fig. 2 provides a summary of the geographical distribution of some
311 of these TU, chosen because they include toxic or harmful species. The geographical
312 distribution of *Pseudo-nitzschia* shows that it was regularly present along the entire coastline
313 at high concentrations. *Dinophysis + Phalacroma*, *Alexandrium* and *Karenia* have been
314 observed in all marine provinces. *Dinophysis + Phalacroma* occurred mostly in the Bay of
315 Seine, in western and southern Brittany, and in the lagoons of the western Mediterranean or
316 Corsica. *Alexandrium* appeared more frequently in Brittany and in the lagoons of the western
317 Mediterranean. *Karenia* was observed everywhere, but its regular presence was only
318 observed in certain areas, especially in western and southern Brittany, in low concentration.
319 *Phaeocystis* was observed mainly in the Channel and in southern Brittany, with the highest
320 concentrations along the northern parts of the French coasts. *Lepidodinium* was very little
321 present in the Channel and was absent in the Mediterranean. It was mainly present in
322 southern Brittany and around the Loire estuary.

323 3.2 Toxins

324 Fig. 3 shows that on the Atlantic coast, the percentage of affected areas was almost always
325 greater than in the other provinces. The appearance of AST episodes was observed on this
326 coast since the mid-2000s. This pattern is also found in the Channel, on a smaller scale. DST
327 episodes do not seem to have increased or decreased over these 32 years, regardless of the
328 province. PST episodes occurred on all three provinces, but the percentage of affected areas
329 has not increased significantly since their appearance respectively in 1988 in the Channel,
330 and 1998 in the Mediterranean. Fig. 4 shows the geographical distribution and the
331 recurrence of episodes of toxicity during the last 19 years, by toxin, and by area. It shows
332 that many areas were regularly affected by DST episodes, especially in Normandy, in
333 western and southern Brittany and in several regions of the Atlantic coast, on the
334 Mediterranean coast, and in lagoons of the western Mediterranean and Corsica. Conversely,
335 whole regions were spared from DST episodes, especially along the northern coast of
336 France, and along the Channel. With regard to PST episodes, a few areas were affected

337 over the period, sometimes sporadically. The two most frequently affected areas were: Brest
338 harbor in western Brittany, and Thau lagoon in the Mediterranean. The AST episodes
339 showed a pattern that was different from that of DST and PST, with a large number of
340 affected areas but fewer than for DST. The most frequently affected areas over the period
341 were: the Bay of Seine in Normandy, and the western and southern coasts of Brittany.
342 Table 2 summarizes the information on the relative weight of the shellfish affected by the
343 episodes of toxicity. In some cases, the different species of a genus are grouped, either
344 because some species hybridise with each other or because they are difficult to identify. This
345 is the case of: (i) *Mytilus*, the species occurring in France being *M. edulis* (in Channel and
346 Atlantic), *M. galloprovincialis* (rather Mediterranean), or a hybrid of the two; (ii) *Donax*, which
347 includes *D. trunculus* and *D. vittatus*; (iii) *Ruditapes*, which includes *R. decussatus* and *R.*
348 *philippinarum* or their hybrids; (iv) *Mimachlamys* which includes the species *M. varia*. Table 2
349 shows that: DST episodes regularly affected a wide variety of shellfish especially in the
350 Atlantic, PST episodes affected only a few species of shellfish, while AST episodes mainly
351 affected scallops, especially in the Channel. This inventory should be qualified by the fact
352 that the small number of areas affected by PST reduced the range of shellfish species
353 impacted.

354 **4 Discussion**

355 *4.1 Phytoplankton*

356 The following are examined and discussed: the most dominant TU (see Table 1), then the TU
357 with toxic or harmful species, some of which are mapped in Fig. 2.

358 The TU *Chaetoceros*, *Skeletonema*, Cryptophyceae and *Leptocyldrus* exhibited
359 approximately the same geographical pattern as that of *Pseudo-nitzschia* (and are therefore
360 not mapped in Fig. 2): in terms of presence on all marine areas of the coast, at high or very
361 high concentrations. *Chaetoceros* included species with barbs on their setae likely to cause
362 lesions on fish gills and therefore mortalities: in France this was the case in 2010 in western
363 Brittany (Lassus *et al.*, 2016). *Skeletonema* and *Leptocyldrus* are not known to be harmful
364 in France. The REPHY data showed that in terms of annual maxima per marine area: (i)

365 *Chaetoceros* regularly exceeded 10 million cells per liter, particularly in the Channel; (ii)
366 *Skeletonema* often exceeded 1 million cells per liter, and often 10 million in the
367 Mediterranean, and even reached 550 million in northwestern Brittany in 2000; (iii)
368 Cryptophyceae quite often exceeded 1 million; (iv) *Leptocylindrus* often exceeded 1 million
369 cells per liter, in all provinces. Blooms greater than 1 million for these four TU were generally
370 observed from March to October in the Channel and Atlantic, and in all seasons in the
371 Mediterranean. For the TU containing toxic or harmful species, and mapped in Fig. 2, they
372 systematically include all species belonging to the TU, regardless of their harmful potential.
373 However, the geographical distribution of these TU provides in most cases interesting
374 information in terms of risk.

375 For *Pseudo-nitzschia*, which was regularly present everywhere (Fig. 2), the pattern was
376 similar from one year to the next, with annual maxima per marine area often greater than 1
377 million cells per liter, sometimes 10 million, in all provinces. Blooms over 1 million were
378 observed from March to November in the Channel and Atlantic, all year round in the
379 Mediterranean. The national record was reached in 2010 in the western Mediterranean with
380 60 million cells per liter. Several *Pseudo-nitzschia* species occurred in France. The species
381 *P. australis* and *P. pseudodelicatissima* have been formally identified as the cause of AST
382 episodes (Amzil *et al.*, 2001, Nézan *et al.*, 2006). It should also be noted that the following
383 toxigenic species were present: *P. delicatissima*, *P. fraudulenta*, *P. multiseriata*, *P. multistriata*,
384 *P. pungens* (Lassus *et al.*, 2016). Given the difficulty of identifying species of this genus
385 under the light microscope, the identifications in the REPHY data were mostly related to
386 species groups called "complex": for example the *delicatissima* / *pseudodelicatissima*
387 complex, the *seriata* complex, etc. It was therefore not possible to quantify the percentage of
388 the contribution of toxic species in blooms compared to that of non-toxic species. However,
389 some groups contain more toxic species, and the alert thresholds defined in the REPHY for
390 triggering AST analysis takes this into account. The REPHY and REPHYTOX data showed
391 that shellfish only became toxic after the development of at least several 100,000 cells per
392 liter. Husson *et al.* (2016) used the REPHY data to characterize the seasonal dynamics and

393 interannual variability of *Pseudo-nitzschia* blooms associated with scallop (*Pecten maximus*)
394 contamination in six Channel and Atlantic coastal areas. They have shown that: (i) the extent
395 and characteristics of blooms, as well as the frequency of associated toxicity episodes,
396 varied widely by area; (ii) contamination of shellfish by AST was always preceded by
397 significant blooms; (iii) irradiance and temperature played a major role in the initiation of
398 blooms in the spring; (iv) AST episodes tended to be more frequent in bays strongly
399 influenced by nutrient inputs.

400 Table 1 and Fig. 2 consider the two *Dinophysis* + *Phalacroma* genera together in the TU of
401 the same name. Data from the three provinces for this TU were almost exclusively
402 *Dinophysis* species. Otherwise, some *Phalacroma* species may also be toxic (Lassus *et al.*,
403 2016). The geographical distribution of these two genera together provided therefore relevant
404 information in terms of risk. If this TU was present in all provinces, the concentrations were
405 never high, or it was not present in all seasons, as evidenced by its weak dominance rank,
406 especially in the Channel and Atlantic, respectively 57th and 58th (Table 1). The maximum
407 annual concentrations were generally < 10,000 cells per liter, and were always < 100,000
408 cells per liter with the exception of Normandy, for which higher concentrations were recorded,
409 e.g. 803,000 cells per liter on the coast of Calvados (south of Seine Bay) in 2006. If
410 *Dinophysis* could be present in all seasons, it was generally observed from March-April in
411 western and southern Brittany, and from July-August in Normandy. While it was rarely
412 observed in winter on the Channel and Atlantic coasts, *Dinophysis* was present year round in
413 the Mediterranean. In France, it was mainly *Dinophysis acuminata* and *D. sacculus* species
414 that were responsible for DST episodes. But more episodic or more localized presence of the
415 following potentially toxigenic species, could be observed: *D. acuta*, *D. caudata*, *D. fortii*, *D.*
416 *norvegica*, *D. tripos*. Shellfish could become toxic even when *Dinophysis* was observed at
417 very low concentration (sometimes < 100 cells per liter).

418 The dominance ranks of *Alexandrium* are very different according to the province (Table 1). It
419 could be observed along the whole coastline, but showed a preference for certain areas
420 (Fig. 2), in which the observed concentrations were high: on the north coast of Brittany, the

421 annual maxima in the areas concerned often exceeded 1 million cells per liter, sometimes 10
422 million (always between June and August). The very regular presence of *Alexandrium* in
423 Thau lagoon, all year round, but especially in autumn and winter, made it more dominant in
424 the Mediterranean (29th) than on the other provinces. In France, the two toxic species that led
425 to PST episodes were: *A. minutum* in the Channel and Atlantic (Lassus *et al.*, 2016);
426 *A. pacificum* in Thau lagoon (Masselin *et al.*, 2001; John *et al.*, 2014). REPHY and
427 REPHYTOX data showed that shellfish became toxic only after significant development of a
428 toxic species of *Alexandrium* (several thousand or tens of thousands of cells per liter,
429 depending on regions and species), which explains why *Alexandrium* was an excellent
430 indicator of future PST contamination. The areas most frequently affected by blooms greater
431 than 100,000 cells per liter were located in northern and western Brittany, as well as in Thau
432 lagoon. The maximum concentration recorded since 1999 was 41 million cells per liter in
433 Brest harbor in 2012, and significant blooms have been recorded in this area since (Chapelle
434 *et al.*, 2015). Guallar *et al.* (2017) showed that temperature was a key factor for bloom
435 initiation, and river flow for the maximum abundance. However, this second factor was local,
436 favoring growth through the supply of nutrients and limiting abundance by dilution. They also
437 showed that *Alexandrium* has dynamic characteristics of an invasive species: an introduction
438 period with low abundance, then a period with high abundance blooms and, finally, a period
439 of presence but at lower abundance (because controlled by parasites or predators or
440 competition). In the Mediterranean, the most prolific blooms of *A. pacificum* occurred in Thau
441 lagoon. The fact that the strain of this species in this lagoon was related to a Japanese strain
442 (Lilly *et al.*, 2002) has supported the hypothesis of an accidental introduction of *A. pacificum*.
443 The cysts transported in the deballasting waters of Asian ships possibly contaminated the
444 shellfish of the Spanish Mediterranean coast, leading to the introduction into Thau lagoon
445 and the subsequent distribution of contaminated shellfish between France and Spain in the
446 years 1980-1990. The *Alexandrium* blooms at Thau required special hydroclimatic
447 conditions, combining temperature and wind factors (Laanaia *et al.*, 2013). The species

448 *A. minutum* was also observed in another lagoon of western Mediterranean, Salses-Leucate,
449 but generally at low concentrations.

450 While it does not appear to be a dominant TU (Table 1), *Karenia*, essentially represented in
451 the data by *K. mikimotoi*, remained associated with significant harmful effects in France, by
452 its hemolytic toxins acting directly on the marine fauna and flora, even if the events in
453 question were not recent. The regular presence of *Karenia* was only found in certain areas,
454 especially in western and southern Brittany, in low concentration. Over the period 1999-2018,
455 the maximum observed was 136 million cells per liter for *K. mikimotoi*, in Brest harbor in
456 2002. In the years 1970-1980, *K. mikimotoi* was associated with harmful impacts on scallops
457 (*Pecten maximus*): mortalities, growth inhibition, etc. in western Brittany (Lassus *et al.*,
458 2016). In June-July 1995, it caused massive mortalities of marine animals along the French
459 Atlantic coast; this episode reached a considerable scale, never repeated since, by its
460 geographical extension from western Brittany to south of the Loire river; the biological and
461 economic impacts of these blooms were wide-ranging. It is worth remembering that the
462 REPHY results were for near-shore waters, and could not be representative of phenomena
463 that would have appeared offshore. This point is crucial for *K. mikimotoi*, whose near
464 monospecific blooms were observed by satellite each year in July at the western entrance to
465 the Channel (Ménèsquen *et al.*, in revision), while Fig. 2 shows that the concentrations were
466 not high in inshore coastal zones. The presence of *K. mikimotoi* offshore was particularly
467 noted in the frontal zones and in the stratified waters where it could have access to high
468 levels of ammonium (its preferred nitrogen nutrient form) resulting from the bacterial
469 remineralization of the previous diatom blooms having sedimented at the bottom (Le Corre *et*
470 *al.*, 1993, Ménèsquen *et al.*, in revision). Worth noting is the presence in France, but rarely
471 and always at low or very low concentration, of another species of *Karenia*, potentially
472 producing brevetoxins: *K. papilionacea*. Because of the low concentrations observed, no
473 harmful effect has ever been observed in France.

474 Another toxic species is worth mentioning: *Ostreopsis*, even if it does not appear in the first
475 40 dominant TU of Table 1. Present in the REPHY data since the 1990s, *Ostreopsis* has

476 been particularly closely monitored since 2006, following respiratory disorders in bathers in
477 the Marseille region (east Mediterranean). Only one species could be identified on a
478 morphological and molecular basis, *O. cf. ovata* (Penna *et al.*, 2005), producer of palytoxins
479 and ovatoxins, which release into the air in the form of aerosols can lead to irritation of the
480 skin, eyes and respiratory system. *Ostreopsis* was observed almost every year in the French
481 Mediterranean, particularly in more eastern areas not monitored by REPHY, where it
482 regularly formed major blooms in summer (Amzil *et al.*, 2012; Lemée *et al.*, 2012; Brissard *et*
483 *al.*, 2014).

484 Among the toxic species of recent appearance in France are: *Karlodinium*, *Vulcanodinium*
485 *rugosum* and *Azadinium*. It should be noted that not all of them are currently identified as
486 such in the database, but most often under a higher level taxon (family, order, class, etc.), at
487 least until a certain period of time. For example, *Karlodinium*, of which several species are
488 known to be toxic to fish, has been present in the data only since 2008. However, fish
489 mortalities observed in 1994 in Diana lagoon (Corsica), following a proliferation of
490 *Gyrodinium corsicum*, known since as *Karlodinium corsicum* (Lassus *et al.*, 2016), proved
491 that this genus was really present in French waters. *Vulcanodinium rugosum*, described by
492 Nézan and Chomérat (2011), was present in the data from 2013 and identified as the source
493 of pinnatoxin production in shellfish of Ingril lagoon on the Mediterranean west coast (Hess *et*
494 *al.*, 2013). Its presence has been known since 1996, but it was only in 2009 with its massive
495 proliferation at Ingril that it was possible to describe it. *Azadinium*, recognized as a producer
496 of azaspiracids (Tillmann *et al.*, 2009) was present in the REPHY data from 2013 in the
497 Atlantic. Azaspiracids were detected in France in small quantities as early as 2002 (Lassus *et*
498 *al.*, 2016), then in 2008 (Amzil *et al.*, 2008): so, *Azadinium* was probably already present in
499 France before 2013, but was not registered as such in the database.

500 *Phaeocystis*, ranked 2nd in dominance in the Channel (Table 1), was almost exclusively
501 specific to this province, essentially along the northern part of the French coast, as shown in
502 Fig. 2. It was present every year in this region, of which the coastal waters are among the
503 most enriched in nutrients of the French coasts (Belin and Soudant, 2018). The annual

504 maxima of *Phaeocystis* (which could be observed at all seasons) often exceeded 10 million
505 cells per liter and almost always 1 million, commonly forming spectacular foams. Blooms
506 were also observed in the Bay of Mont-Saint-Michel (at the border between Normandy and
507 Brittany): up to several million cells per liter in the 2000s.

508 At the 12th rank of dominance in the Atlantic (Table 1), *Lepidodinium* was mainly present in
509 southern Brittany and around the Loire river estuary (Fig. 2). The annual maxima of
510 *Lepidodinium* often exceeded 10 million cells per liter, the record since 1999 being 100
511 million in northern Brittany in 2001. Blooms greater than 1 million cells per liter could be
512 observed from March to November. The TU was entirely represented by the species
513 *L. chlorophorum*, which colored the waters a very intense green. Although non-toxic, its
514 proliferation regularly led however to significant anoxia, possibly resulting in mortalities of
515 marine animals. The links between *L. chlorophorum* blooms and anoxia were described in
516 Sournia *et al.* (1992), and could be found in REPHY data for more recent data: e.g. in Vilaine
517 Bay (southern Brittany) in July 2018, 30 million cells per liter of *L. chlorophorum* were
518 associated with three dissolved oxygen values below 2.9 mg/L, hypoxia threshold defined by
519 Diaz and Rosenberg (2008). Green waters recorded on the Atlantic coast since 1982 could
520 also be attributed retrospectively to this same species (Sournia *et al.*, 1992). Having a
521 typically coastal distribution, its proliferation seemed to correlate with the river Loire inputs.

522 In addition to the results presented here, REPHY phytoplankton data sets (REPHY, 2017),
523 have also been used to answer scientific questions, and have provided valuable information
524 on phytoplankton biodiversity, spatial distribution and temporal variations of the various taxa
525 along the French coastline (Beliaeff *et al.*, 2001; Gailhard *et al.*, 2002; 2003). More recently,
526 David *et al.* (2012) analyzed the variability of phytoplankton groups in relation to climatic and
527 environmental indices in the Bay of Biscay. Hernández-Fariñas *et al.* (2014) have shown
528 modifications in species diversity over the last twenty years in the eastern Channel, in
529 relation to hydroclimatic changes. Studies have also examined the conditions of the
530 appearance of toxic species, e.g. Husson *et al.* (2016) for *Pseudo-nitzschia*, Chapelle *et al.*
531 (2015) and Guallar *et al.* (2017) for *Alexandrium*. Hernández-Fariñas *et al.* (2015), analyzing

532 the positions occupied by 35 phytoplankton taxa, have shown that several environmental
533 variables could be considered as key factors controlling phytoplankton dynamics and
534 influencing the structure of the community.

535

536 4.2 Toxins

537 The French coast has been regularly affected by the harmful effects of toxins for more than
538 30 years, the main problem being related to the contamination of bivalve molluscs, leading to
539 bans on the fishing and sale of these shellfish during periods of variable duration.

540

541 4.2.1 History of toxic episodes in France

542 Shellfish farming is a historical activity in France for centuries. The two main shellfish
543 exploited are oysters and mussels, with currently about 130,000 tons of oysters and about
544 65,000 tons of mussels produced each year, for a total production of about 200,000 tons all
545 shellfish combined ([http://coquillages.com /statistics/](http://coquillages.com/statistics/)). These tonnages have been similar
546 from year to year for decades (Buestel *et al.*, 2009). It should be noted that all French areas
547 exploited by shellfish farmers or fishermen, in production areas, natural populations, and
548 professional fishing zones, have always been monitored, except in two cases. The first case
549 concerned scallop (*Pecten maximus*) fishing areas until 2004 for all categories of toxins; this
550 has little impact on the interpretation of the evolution of the toxic episodes for DST and PST,
551 the scallops being mainly concerned by AST. The second case concerned oysters
552 (*Crassostrea gigas*) until 2001, which were not monitored as first-line for DST; given that
553 DST data indicate that mussels have always been toxic prior to oysters over the 2001-2018
554 period, it is likely that the lack of oyster DST data prior to 2001 has a relatively small impact
555 on overall interpretation DST data.

556 DST episodes have been regularly observed in all provinces since 1987 (Fig. 3). In fact, the
557 first toxic episodes clearly associated with diarrhetic toxins date back to 1983, when about
558 3,000 cases of diarrhetic intoxication were reported in western France. But it is very likely that
559 diarrhetic toxins had contaminated shellfish long before that date: intoxications observed

560 previously could have been confused with bacterial or viral poisoning (Caruana and Amzil,
561 2018). Lipophilic toxins incriminated in shellfish contamination were always OA (most often)
562 or DTX (Amzil and Mathias, 2006; Amzil *et al.*, 2007; REPHYTOX, 2017). The REPHY and
563 REPHYTOX data showed that these toxins were always present in association with the
564 phytoplankton *Dinophysis*. Two other groups of lipophilic toxins were sometimes present in
565 France, but always at very low concentration: AZA and YTX. Their presence could not be
566 formally associated with their potential producers, although these were sometimes observed
567 in water samples, respectively *Azadinium* for AZA, *Lingulodinium polyedrum* and
568 *Protoceratium reticulatum* for YTX.

569 The first observation of PST dates from 1988 in northwestern Brittany, following the detection
570 of significant concentrations of *Alexandrium minutum*. The Mediterranean province was
571 affected ten years later, in 1998, in Thau lagoon. The presence of PST in France before 1988
572 is highly unlikely, given the following considerations: (i) the first observations of PST in
573 Europe were made only in 1987 (Norway, Sweden, Denmark, Spain, Portugal) (information
574 from: <http://haedat.iode.org/index.php>), (ii) in 1988, the monitoring was in place in France for
575 4 years, (iii) from 1988 to 1990, PST were observed only in the same two marine areas. The
576 toxin profile of *A. minutum* was composed mainly of gonyautoxins-2,-3 (carbamate toxins)
577 (Lassus *et al.*, 2004) and toxins-C1,-2 (N-sulfocarbamoyl toxins), while that of *A. pacificum*
578 was composed mainly of gonyautoxins-1, -4, -5 and toxins C-2, C-4 (Masselin *et al.*, 2001).
579 In the majority of cases, the presence of PST above the regulatory threshold was associated
580 with significant developments of *Alexandrium*. The case of the Arcachon Bay episode in
581 2002-2003 remains the only one unsolved, since the presence of *Alexandrium* was not
582 observed in the phytoplankton flora: no alternative explanation could be found for the
583 presence of PST above the regulatory threshold, even if it was very low (864 µg STX
584 equivalent per kg of shellfish flesh). With this exception, the *Alexandrium* / PST episode
585 relationship cannot be called into question in the light of available 32-year data, and confirms
586 the relevance of the PST surveillance strategy based on a phytoplankton indicator.

587 The first observation of AST dates back to 2000 in western Brittany (Amzil *et al.*, 2001;
588 Nezan *et al.*, 2006). These toxins have been monitored along the entire coast only since
589 1999. It is therefore conceivable that occurrences of AST have not been detected before this
590 date, but this assumption is unlikely. Indeed, the first observations of AST in Europe were
591 made in 1992 (Sweden), then in 1995 (Spain, Portugal) and 1998 (UK) (information from:
592 <http://haedat.iode.org/index.php>), showing slow progression of AST toxin occurrences across
593 Europe. In addition, a study conducted by LeDoux *et al.* (1996) on several areas of the
594 French coast showed that these toxins were then absent from those areas, at least in the
595 mussels. Finally, the system of control of food poisoning by the French authorities would
596 have highlighted a problem related to the contamination of shellfish, which was not the case.
597 The increase in AST episodes recorded since 2004 in the Channel and the Atlantic (Fig. 3)
598 clearly corresponds to the beginning of the obligation to monitor scallops (*Pecten maximus*)
599 in the European context, since these were previously excluded from the toxin monitoring
600 system in France. In the different AST episodes, the toxin profile was mainly composed of
601 domoic acid, and its epidomic acid analogue in small amounts, both produced by the toxic
602 species of *Pseudo-nitzschia*. REPHY and REPHYTOX data showed that AST episodes were
603 always associated with the genus *Pseudo-nitzschia* in coastal areas for which phytoplankton
604 sampling could be performed at a depth close to that of toxins. Based on the REPHY-
605 REPHYTOX available data over 32 years, the *Pseudo-nitzschia* / AST episodes relationship
606 confirms the relevance of the AST surveillance strategy based on a phytoplankton indicator.
607 In offshore areas (mainly scallop fishing areas), the association between phytoplankton and
608 AST could not be evidenced from REPHY-REPHYTOX data alone, phytoplankton sampling
609 not being carried out on deep scallops beds. But various *in situ* studies have shown the
610 correspondence between the accumulation of AST in shellfish and the proliferation of toxic
611 *Pseudo-nitzschia* species (Husson *et al.*, 2016; Thorel *et al.*, 2017).

612

613 *4.2.2 Affected areas and shellfish*

614 The geographical distribution of DST episodes (Fig. 4) highlights areas that were always
615 spared (e.g. northern France and northern Brittany). This could partly be explained by a
616 lower frequency of *Dinophysis* occurrences in these areas (REPHY, 2017). In northern
617 Brittany in particular, the hydrodynamics would not favor *Dinophysis* accumulation. In
618 regularly affected areas, the periods of toxicity were clearly different according to the region.
619 In the Channel, toxic episodes were generally observed between July and October. In the
620 Atlantic, they were: (i) from May, or even March-April, in western and southern Brittany, until
621 August, sometimes until October-November; (ii) generally from May to July-August between
622 the Loire and Gironde rivers; (iii) between April and August in the Arcachon Bay. In the
623 Mediterranean: (i) in the open sea zones, toxic episodes were generally spread between
624 March and October; (ii) in the lagoons, they could be observed all year long. The shellfish
625 contaminated during the presence of DST were very varied (Table 2), especially in the
626 Atlantic because the diversity of exploited shellfish was much greater than on the other
627 provinces. Mussels were systematically contaminated before other shellfish and often at
628 higher concentrations. The periods and duration of shellfish contamination-decontamination
629 of offshore beds were most often different from those of shellfish close to the coast. The
630 results prior to 2010 being qualitative (bioassay), the different toxic episodes could not be
631 compared in terms of toxin concentrations for this period. The highest toxin concentration
632 over the period 2010-2018 (expressed in μg of OA equivalent per kg of shellfish flesh) was
633 recorded in the Arcachon Bay in April 2012: 37,296 $\mu\text{g}/\text{kg}$ for *Mytilus* sp.; in this zone, at the
634 same time, the following shellfish also reached their record, with 11,755 $\mu\text{g}/\text{kg}$ for
635 *Cerastoderma edule* and 2,278 $\mu\text{g}/\text{kg}$ for *Ruditapes philippinarum*. The maxima observed for
636 other species were: 4,792 $\mu\text{g}/\text{kg}$ for *Donax trunculus* in western Brittany in June 2013,
637 2,621 $\mu\text{g}/\text{kg}$ for *Politapes rhomboides* in southern Brittany in June 2010, 2,305 $\mu\text{g}/\text{kg}$ for
638 *Pecten maximus* off the eastern Channel coast in September 2014, 1,067 $\mu\text{g}/\text{kg}$ for
639 *Aequipecten opercularis* in Jersey-Guernesey (Channel) in July 2018, 1,041 $\mu\text{g}/\text{kg}$ for
640 *Crassostrea gigas* in Salses Leucate lagoon in December 2012. For *Spisula solida*,
641 *Glycymeris glycymeris*, *Mimachlamys varia*, the maxima were less than 500 $\mu\text{g}/\text{kg}$. During

642 this period 2010-2018, the maximum concentrations of azaspiracids and yessotoxins were
643 both observed in southern Brittany mussels, respectively: 53 µg of AZA equivalent in June
644 2017 and 1720 µg of YTX equivalent in July 2018.

645 Only two areas were affected for at least 5 years by PST episodes over the period 2000-
646 2018 (Fig. 4), and were still so in recent years. The first was Brest harbor for which the first
647 PST episodes were recent (2012), and recurred very regularly, the last having taken place in
648 2017. The second was Thau lagoon in the Mediterranean, for which the PST episodes were
649 common between 1998 and 2007, and occurred again in 2015, 2016 and 2017. The three
650 areas of the north coast of Brittany were mostly affected in the 1990s, with some sporadic
651 episodes in the 2000s in one or other of these areas. For other areas (Arcachon Bay and
652 Mediterranean areas except Thau lagoon), there were only very isolated episodes, dating
653 back at least 10 years. The periods of PST episodes were very different between the Brittany
654 areas and those of the Mediterranean. In Brittany, PST episodes have always been observed
655 between June and August-September. In Thau lagoon, the PST episodes were
656 systematically observed between September and December. The shellfish contaminated
657 during the presence of PST were always among the following (Table 2): mussels, oysters,
658 cockles, clams. This was partly explained by the fact that the areas concerned only contained
659 these shellfish. But the wide range of data acquired with the systematic search for PST
660 during fishing periods on various offshore shellfish of the Channel and the Atlantic (*Pecten*
661 *maximus*, *Aequipecten opercularis*, *Mimachlamys varia*, *Callista chione*, *Glycymeris*
662 *glycymeris*, *Polititapes rhomboides*, *Spisula*, *Venus verrucosa*, *Ostrea edulis*), attest that
663 these shellfish have never been contaminated by PST, at least during fishing periods. The
664 highest concentration of PST (expressed in µg STX equivalent per kg of shellfish flesh) over
665 the period 1987-2018 was recorded in Brest harbor in July 2012: 11,664 µg/kg for *Mytilus* sp.
666 The maxima observed for the other shellfish species were: 7,360 µg/kg for *Crassostrea gigas*
667 in northern Brittany in August 2001, 5,740 µg/kg for *Ruditapes decussatus* in Thau lagoon in
668 November 2001, 3,300 µg/kg for *Cerastoderma edule* in northern Brittany in June 1998.

669 The areas and shellfish most affected by AST episodes over the period 2000-2018 (Fig. 4
670 and Table 2), and which were still so in recent years, were: (i) in Normandy, exclusively
671 scallops (*Pecten maximus*) off the Bay of Seine; (ii) in western and southern Brittany, mostly
672 *Pecten maximus*, but also *Donax* or *Polititapes rhomboides*, and sometimes *Mytilus edulis*,
673 *Crassostrea gigas*, *Callista chione*, *Aequipecten opercularis*. On the Atlantic coast, between
674 the rivers Loire and Gironde, the year 2010 was an atypical year: while AST were observed
675 for the first time in this region, the variety of contaminated shellfish (mussels, oysters, clams,
676 scallops, etc.) has never been found in later episodes. The hypothesis of a link between
677 these episodes and the storm Xynthia which passed over much of France at the end of
678 February 2010 is very likely. The conjunction of the storm with high tidal coefficients did
679 indeed lead to the flooding of many coastal areas to the south of the Loire estuary (Bertin *et*
680 *al.*, 2012). The marine waters, which were then loaded with nutrients, were probably the
681 trigger of *Pseudo-nitzschia* blooms (Nézan *et al.*, 2010; Husson *et al.*, 2016), with
682 concentrations never observed before or since 2010 in this region. On the Mediterranean
683 coast, AST episodes affected *Mytilus galloprovincialis* or *Donax* from several areas of the
684 west coast in the early 2000s; since 2006, no more AST episodes have been observed. If
685 whole regions were spared the presence of AST, this is not explained by lower frequencies or
686 concentrations of *Pseudo-nitzschia* in these areas; in fact the year-by-year maps of
687 developments of this taxon show significant blooms every year along the entire French coast
688 (Fig. 2). The most plausible explanation remains that these blooms were often composed of
689 several *Pseudo-nitzschia* species, whose toxic potential might be very different. Almost all
690 AST episodes were observed between March and May including in the Mediterranean, over
691 the entire period 2000-2018, and for all shellfish apart from scallops. This information
692 corroborates the observations relating to *Pseudo-nitzschia*, of which proliferations in high
693 concentration began most often in March-April. Conversely, scallops (*Pecten maximus*) could
694 be contaminated all year round in the Channel (Amzil *et al.*, 2009) or the Atlantic, with the
695 fishing periods extending most often from October to March. The highest concentration of
696 AST (expressed in $\mu\text{g DA equivalent per kg shellfish flesh}$) was recorded in Brest harbor in

697 April 2014: 861,000 µg/kg for *Pecten maximus*. The maxima observed for the other shellfish
698 species were: 221,000 µg/kg for *Mytilus* sp. in Brest harbor in April 2014, 133,000 µg/kg for
699 *Donax trunculus* in western Brittany in April 2017, 123,000 µg/kg for *Ruditapes philippinarum*
700 in southern Brittany in April 2010, 110,000 µg/kg for *Crassostrea gigas* in Brest harbor in April
701 2014. For the other shellfish, the maxima were less than 100,000 µg/kg.

702

703 **5 Conclusions**

704 REPHY phytoplankton data contains gems of knowledge regarding the temporal and spatial
705 distribution of species in terms of presence, abundance and biodiversity. The elementary
706 data analysis used here has enabled us to pick only the low hanging fruits. Among them,
707 dominant Taxonomic Units of the French coast during the last 20 years were *Chaetoceros*,
708 *Skeletonema*, Cryptophyceae, *Leptocylindrus* and *Pseudo-nitzschia*. Occurrences and
709 frequencies of occurrence of 6 toxic and harmful TU showed different spatial patterns,
710 suggesting a mosaic of phytoplankton ecological niches and of coastal ecosystems. The
711 long-term information gathered over the years enabled the investigation of abundance time
712 series, unusual events and conditions of appearance of these species. The patterns of
713 change of shellfish toxicity episodes over 32 years appeared as a growing trend on the
714 Atlantic coast in the overall number of toxic episodes since 1987; the appearance of AST
715 episodes and the beginning of the obligation to monitor scallops, especially since 2005,
716 explains this upward trend. It should be noted that PST and AST were very probably absent
717 from the French coasts, respectively before 1988 and 2000. In addition, even by roughly
718 estimating the number of occurrences of DST before the 1980s, a projection over 40 or 50
719 years would undeniably show that the presence of toxins in shellfish became, in the years
720 1980-1990, a priority public health concern and a major issue for shellfish farmers and
721 fishermen in France. It was to be feared that other toxins could also appear: For this reason,
722 in parallel with the monitoring carried out under REPHY-REPHYTOX, a shellfish watch is
723 also undertaken by Ifremer for toxic micro-algae and toxins known in other countries, but not
724 yet listed in France. This complementary system should make it possible to tailor the official

725 surveillance process to enable it to keep up with new events as far as possible. For 30 years,
726 the REPHY-REPHYTOX networks have fulfilled their objectives of scientific observation,
727 regulatory surveillance and health controls. Among the major challenges that remain to be
728 faced are ensuring sustainability through continuous adaptation to the objectives and to the
729 enhancement of measurement methods, and to developing analysis strategies to deal with
730 the extensive and complex data they involve.

731 **6 Acknowledgements**

732 Financial support for the implementation of REPHY and REPHYTOX was provided by,
733 respectively: the Water Management Agencies (Artois-Picardie, Seine-Normandie, Loire-
734 Bretagne, Adour-Garonne and Rhône-Méditerranée-Corse), the General Directorate for Food
735 of the Ministry of Agriculture and Food. Many thanks to: the staff of Ifremer coastal
736 laboratories without whom these data would not exist, REPHY-REPHYTOX national
737 coordination team, those who created and maintain the Quadrige database, the experts who
738 contribute to the quality of the data and to their processing, the researchers increasingly
739 using these data. Thanks are due to Philippe Gros and Cedric Bacher for their contribution to
740 the Introduction.

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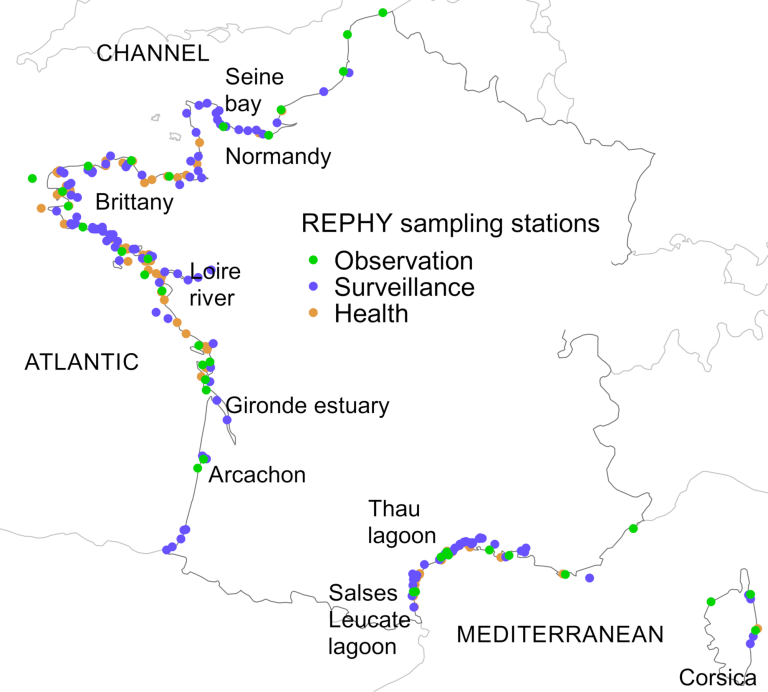
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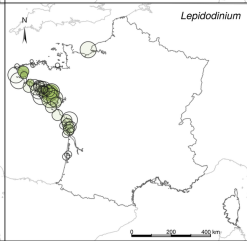
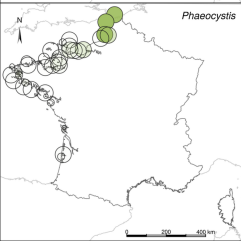
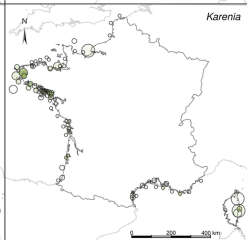
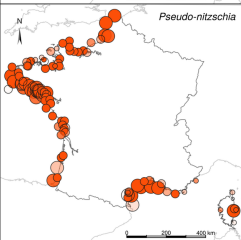
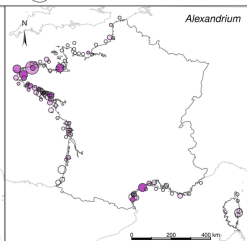
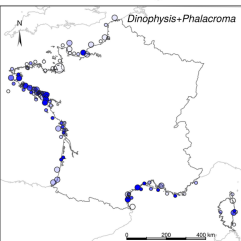
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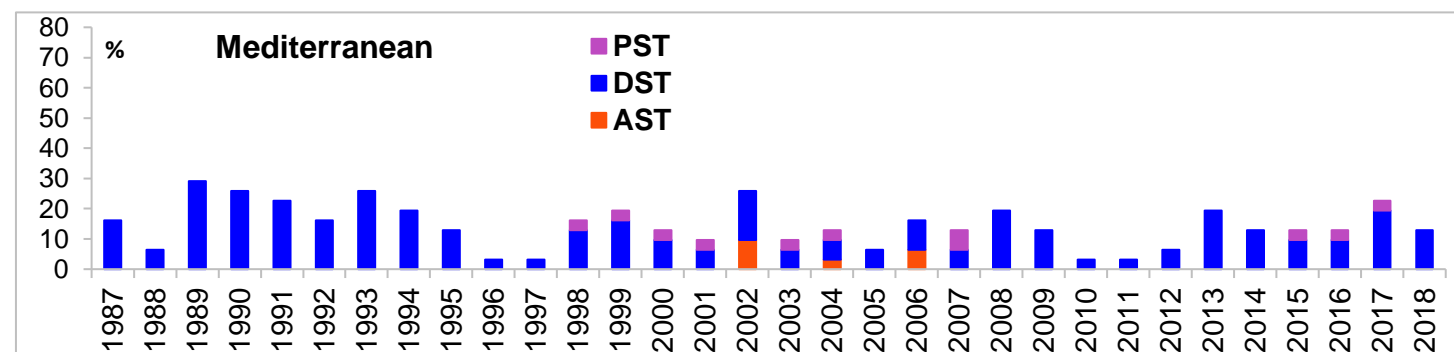
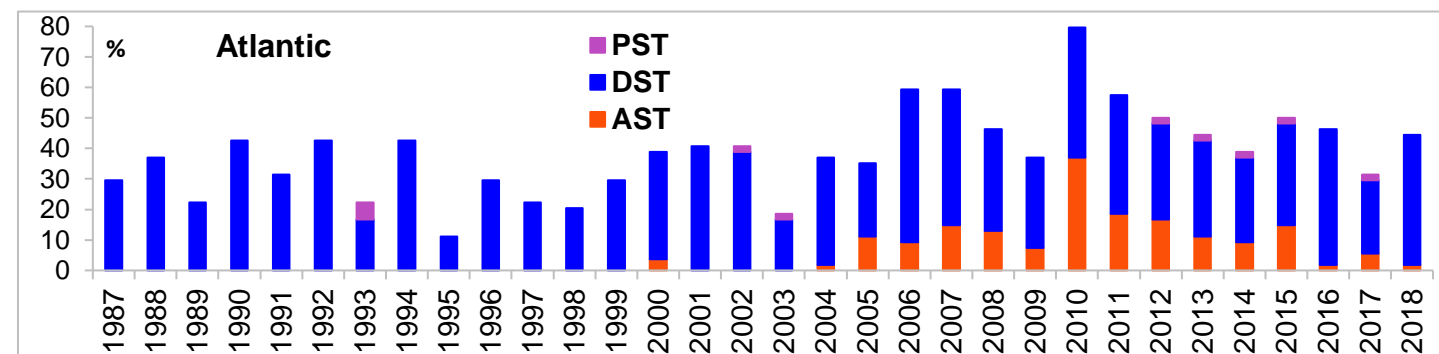
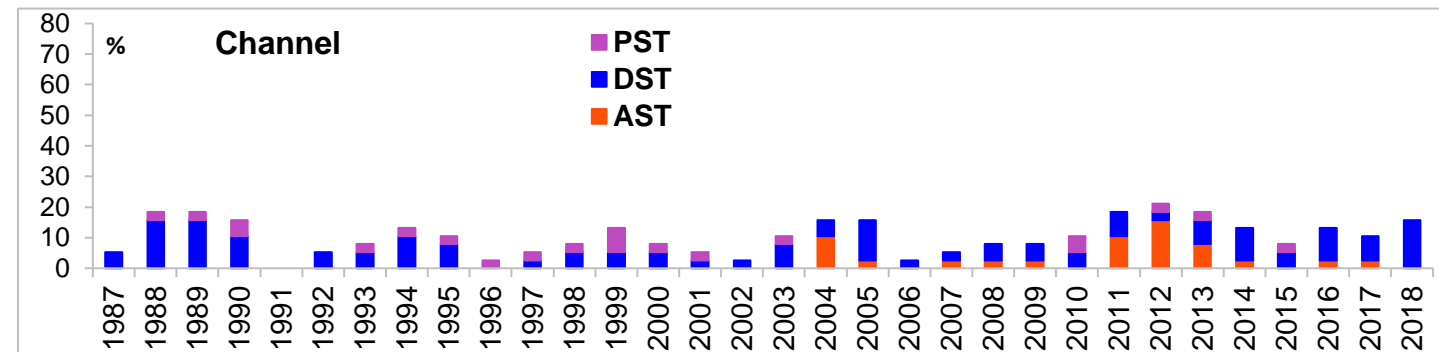
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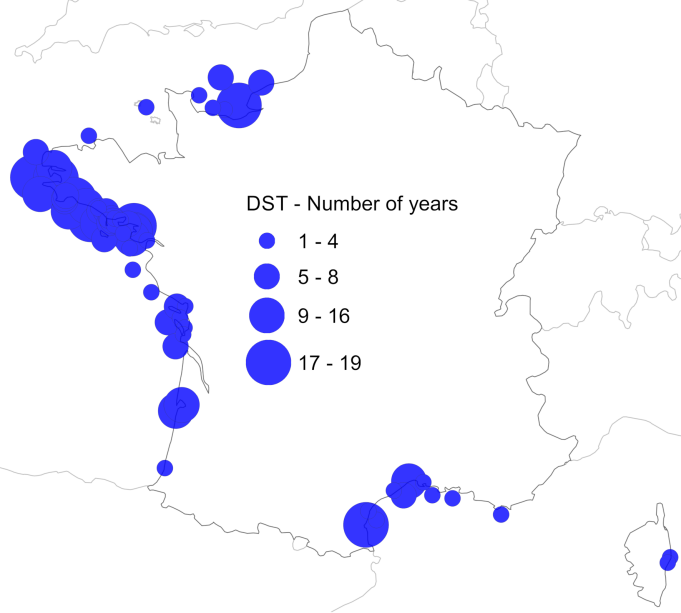


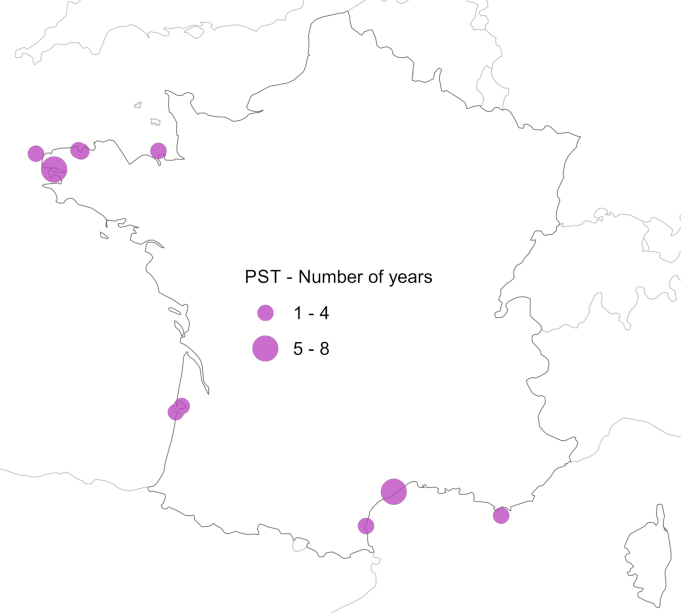
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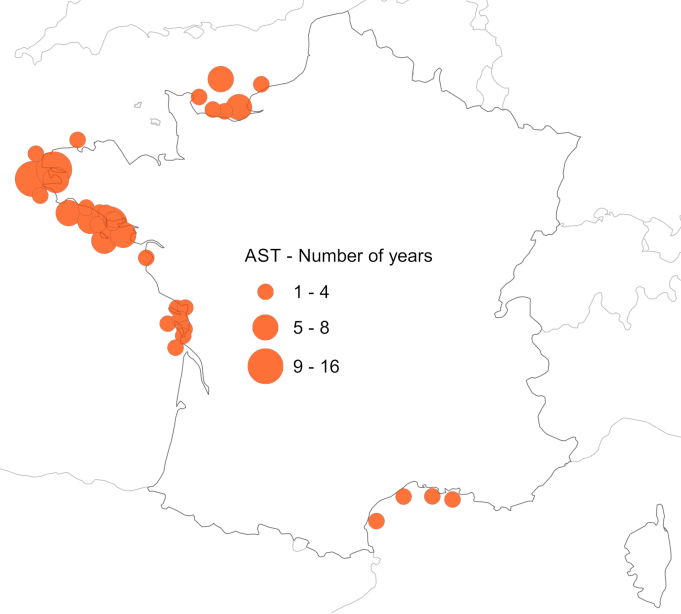
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Channel	DST	5.26	15.79	15.79	10.53	0.00	5.26	5.26	10.53	7.89	0.00	2.63	5.26	5.26	5.26	2.63	2.63	7.89	5.26	13.16	2.63	2.63	5.26	5.26	5.26	7.89	2.63	7.89	10.53	5.26	10.53	7.89	15.79	
	PST	0.00	2.63	2.63	5.26	0.00	0.00	2.63	2.63	2.63	2.63	2.63	2.63	7.89	2.63	2.63	0.00	2.63	0.00	0.00	0.00	0.00	0.00	0.00	5.26	0.00	2.63	2.63	0.00	2.63	0.00	0.00		
	AST	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	10.53	2.63	0.00	2.63	2.63	2.63	0.00	10.53	15.79	7.89	2.63	0.00	2.63	2.63	0.00	
Atlantic	DST	29.63	37.04	22.22	42.59	31.48	42.59	16.67	42.59	11.11	29.63	22.22	20.37	29.63	35.19	40.74	38.89	16.67	35.19	24.07	50.00	44.44	33.33	29.63	42.59	38.89	31.48	31.48	27.78	33.33	44.44	24.07	42.59	
	PST	0.00	0.00	0.00	0.00	0.00	0.00	5.56	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.85	1.85	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.85	1.85	1.85	1.85	0.00	1.85	0.00	
	AST	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.70	0.00	0.00	0.00	1.85	11.11	9.26	14.81	12.96	7.41	37.04	18.52	16.67	11.11	9.26	14.81	1.85	5.56	1.85
Mediterranean	DST	16.13	6.45	29.03	25.81	22.58	16.13	25.81	19.35	12.90	3.23	3.23	12.90	16.13	9.68	6.45	16.13	6.45	6.45	6.45	9.68	6.45	19.35	12.90	3.23	3.23	6.45	19.35	12.90	9.68	9.68	19.35	12.90	
	PST	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.23	3.23	3.23	3.23	0.00	3.23	3.23	0.00	0.00	6.45	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.23	3.23	3.23	0.00
	AST	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	9.68	0.00	3.23	0.00	6.45	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00









	By geographic region			
	All	Ch	Atl	Med
<i>Chaetoceros</i>	1	1	3	1
<i>Skeletonema</i>	2	3	1	4
Cryptophyceae	3	6	4	3
<i>Leptocylindrus</i>	4	8	2	5
<i>Pseudo-nitzschia</i>	5	9	5	2
<i>Thalassiosira</i> + <i>Porosira</i>	6	5	6	22
<i>Guinardia</i>	7	4	11	19
<i>Cylindrotheca</i> + (1)	8	12	8	6
<i>Paralia</i>	9	7	7	41
<i>Phaeocystis</i>	10	2	64	n.o.
<i>Asterionella</i> + <i>Asterionellopsis</i> + <i>Asteroplanus</i>	11	11	9	12
Other Gymnodiniaceae	12	16	10	8
<i>Prorocentrum</i>	13	25	13	7
<i>Thalassionema</i> + <i>Thalassiothrix</i> + <i>Lioloma</i>	14	13	20	9
<i>Neocalyptrella</i> +(2)	15	10	15	16
<i>Navicula</i> + <i>Fallacia</i> + <i>Haslea</i> + <i>Lyrella</i> + <i>Petroneis</i>	16	17	17	11
<i>Scrippsiella</i> + <i>Ensiculifera</i> + <i>Pentapharsodinium</i>	17	28	14	10
<i>Dactyliosolen</i>	18	14	24	14
Other (Cymatosiraceae + Plagiogrammaceae)	19	15	18	86
<i>Protoperidinium</i> + <i>Peridinium</i>	20	29	21	17
Other (Euglenoidea + ...) (3)	21	22	27	20
<i>Lepidodinium</i>	22	65	12	n.o.
Ciliophora	23	18	22	n.o.
<i>Cerataulina</i>	24	26	19	28
<i>Dictyocha</i> + <i>Octactis</i>	25	39	30	18
Other Fragilariaceae + Toxariaceae	26	47	16	115
<i>Licmophora</i>	27	54	63	13
<i>Pleurosigma</i> + <i>Gyrosigma</i>	28	30	28	23
<i>Cocconeis</i>	29	91	72	15
<i>Heterocapsa</i>	30	35	34	24
"Pennate" diatoms	31	21	33	34
<i>Melosira</i>	32	37	23	49
<i>Ceratium</i> + <i>Neoceratium</i> + <i>Tripos</i>	33	81	41	21
<i>Biddulphia</i> + ... (4)	34	20	38	58
<i>Lauderia</i> + <i>Detonula</i>	35	23	35	47
<i>Rhaphoneis</i> + <i>Delphineis</i>	36	19	56	n.o.
"Centric" diatoms	37	38	26	78
<i>Ditylum</i>	38	27	32	54

- (1) *Cylindrotheca* + *Ceratoneis* + *Nitzschia* + *Hantzschia*
(2) *Neocalyptrella* + *Proboscia* + *Rhizosolenia* + *Pseudosolenia*
(3) *Euglenoidea* + *Euglenia* + *Euglenida* + *Eutreptiida* + *Eutreptiales*
(4) *Biddulphia* + *Odontella* + *Trigonium* + *Trieres* + *Isthmia*
(5) *Euglenaceae* + *Euglena* + *Eutreptiaceae* + *Eutreptia* + *Eutreptiella*
(6) *Diplopsalis* + *Diplopelta* + *Diplopsalopsis* + *Preperidinium* + *Oblea*

	By geographic region			
	All	Ch	Atl	Med
Other Chaetocerotaceae	39	n.o.	25	n.o.
<i>Katodinium</i>	40	40	42	32
Other Thalassionemataceae	41	43	36	33
<i>Coscinodiscus</i> + <i>Stellarima</i>	42	45	29	60
Chromista incertae sedis	43	24	59	n.o.
Other Thalassiosiraceae	44	32	37	n.o.
<i>Grammatophora</i>	45	53	47	30
Euglenaceae + ... (5)	46	36	45	50
<i>Dinophysis</i> + <i>Phalacroma</i>	47	57	58	25
Other Peridinales	48	52	31	95
<i>Alexandrium</i>	49	48	66	29
Other Bacillariaceae	50	34	48	116
<i>Eucampia</i> + <i>Climacodium</i>	51	31	52	62
<i>Oxytoxum</i> + <i>Corythodinium</i>	52	131	103	26
<i>Diploneis</i>	53	50	70	31
<i>Bacteriastrum</i>	54	83	54	35
<i>Actinocyclus</i>	55	108	160	27
Other Cymatosiraceae	56	105	39	n.o.
<i>Bacillaria</i>	57	42	51	65
"Phytoflagellates except dinoflagellates"	58	79	40	n.o.
<i>Lithodesmium</i>	59	69	43	108
<i>Torodinium</i>	60	56	55	46
<i>Karenia</i>	61	63	65	37
<i>Scenedesmus</i>	62	49	57	53
<i>Diatoma</i> + <i>Fragilaria</i>	63	76	46	71
Other Entomoneidaceae	64	n.o.	44	n.o.
<i>Gonyaulax</i> + <i>Protoceratium</i>	65	60	67	42
<i>Synedra</i> + <i>Toxarium</i>	66	74	49	56
<i>Mesodinium</i>	67	51	53	74
<i>Dinobryon</i>	68	72	50	61
<i>Diplopsalis</i> + ... (6)	69	66	76	40
<i>Amphidinium</i>	70	55	77	45
Other Chlorophyceae	71	33	110	80
<i>Hemiaulus</i>	72	110	102	36
<i>Lingulodinium</i>	73	126	123	38
Other Ceratiaceae	74	41	88	91
Other Naviculales	75	n.o.	n.o.	39

- 1st to 10th rank
11th to 20th rank
21st to 30th rank
31st to 40th rank

Toxin	DST (since 1987)			PST (since 1988)			AST (since 2000)		
	Ch.	Atl.	Med.	Ch.	Atl.	Med.	Ch.	Atl.	Med.
Maritime province									
<i>Mytilus</i>	30	32	32	12	8	10		5	2
<i>Crassostrea gigas</i>	1	17	16	10	2	5		2	
<i>Donax</i>	5	32	11					9	2
<i>Cerastoderma edule</i>		23		4					
<i>Ruditapes</i>		10	6			2		1	
<i>Pecten maximus</i>	9	6					11	15	
<i>Aequipecten opercularis</i>	3	3						1	
<i>Mimachlamys</i>		2							
<i>Politapes rhomboides</i>		20						2	
<i>Glycymeris glycymeris</i>		12						1	
<i>Callista chione</i>		2						1	
<i>Spisula</i>		5							