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***Pseudo-nitzschia* sp. diversity and seasonality in the southern North Sea, domoic acid levels and associated phytoplankton communities**

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Abstract :

The diversity, toxicity and seasonality of *Pseudo-nitzschia* sp. were investigated from February to November 2012 in the southern Bight of the North Sea (SBNS) along the French coast. The identification of *Pseudo-nitzschia* species in this area was addressed for the first time in this study. Our results revealed a low species richness (3 distinct species) in association with moderate (102 pg mL⁻¹) to high (263 pg mL⁻¹) domoic acid (DA) levels in autumn and spring, respectively.

Pseudo-nitzschia succession corresponded to the dominance of *P. delicatissima* in April–May (86% of total diatoms) as a co-occurring species of the *Phaeocystis globosa* bloom. Following the *Phaeocystis* bloom (May–September), *P. pungens* dominated markedly over *P. fraudulenta* and *P. delicatissima* and was the only species present in autumn, although at low abundance (<1000 cell L⁻¹). The results of this study support the idea that *Pseudo-nitzschia* seasonality in the SBNS relies principally on temperature and nutrient availability (DIN and silicates), which, in turn, depend on locally fluctuating environmental conditions (rainfalls and winds). This study highlights the potential for the SBNS to be a potential risk area in regard to the possible impacts of DA on marine resources and the DA transfer through marine food webs. This is of particular concern since DA concentration in seawater was not systematically correlated to potentially toxic *Pseudo-nitzschia* abundance.

Highlights

► Low *Pseudo-nitzschia* sp. diversity (three species) in the southern North Sea. ► Domoic acid levels reached 263 pg mL⁻¹ in May 2012, 83% as dissolved DA. ► Strong species seasonality driven by temperature and nutrient availability (DIN and silicates). ► Autumnal DA concentrations could be attributed to *P. pungens*. ► DA concentration was not systematically correlated to *Pseudo-nitzschia* spp. abundance.

Keywords : *Pseudo-nitzschia*, Southern North Sea, Domoic acid, *Phaeocystis globosa*, Harmful algal blooms (HAB)

1 Introduction

The cosmopolitan diatom genus *Pseudo-nitzschia* sp. comprises more than 50 species amongst which 24 are known to produce Domoic Acid (DA; Gai et al., 2018; Lundholm, 2018), a potent neurotoxin responsible for Amnesic Shellfish Poisoning (ASP). Since the first reports of ASP in 1987 at Prince Edward Island, shellfish stocks have been systematically monitored to prevent any outbreaks of ASP among humans. Since then, alert indicators such as DA concentration and/or *Pseudo-nitzschia* sp. abundance monitoring have been shown to be efficient tools, as no human poisoning has ever been reported (Trainer et al., 2012). However, DA poisoning of marine mammals and seabirds can still occur when they feed on DA-contaminated planktivorous prey (e.g. anchovies and sardines; Du et al., 2016; Gible et al., 2018; Jensen et al., 2015; Lefebvre et al., 2002; Louw et al., 2018; Scholin et al., 2000; Sierra-Beltran et al., 1997; Stauffer et al., 2012). The trend of increasing abundance of *Pseudo-nitzschia* over the past decade has raised scientific awareness and concerns about public health (e.g. Hernández-Fariñas et al., 2014; Lefebvre et al., 2014; Lundholm et al., 2010; Parsons et al., 2002; Trainer et al., 2012) emphasizing the need to assess its dynamics, and investigate potential DA production in exploited coastal areas. In the English Channel, occurrence of DA in king scallop (*Pecten maximus*) has been reported several times from south western regions such as the Bay of Seine and the Bay of Brest (Husson et al., 2016). In the Eastern English Channel-North Sea (EEC-NS), reported ASP events were mainly concentrated in the northern regions (Scotland, Norway, Denmark; Trainer et al., 2012) although *Pseudo-nitzschia* sp. cells are present year-round in the southern regions (Bresnan et al., 2015; Hernández-Fariñas et al., 2014; Schapira et al., 2008; Seuront et al., 2006). Thus, reports of DA and shellfish closures were not recorded in the EEC-NS until 2014, when king scallop stocks off the Bay of Somme (France) were contaminated with DA, which represented the northernmost ASP alert of France (Lefebvre A., pers. com.). Existing studies and

monitoring surveys often limit the detection of *Pseudo-nitzschia* sp. to the genus level or to morphological features measurable by optical microscopy, *i.e.* valve width, distinguishing large species (width > 3 μm , *Pseudo-nitzschia* complex *seriata*), from narrow ones (width < 3 μm , *P. delicatissima* complex). This distinction by size categories has already made possible seasonal studies within this genus (Bresnan et al., 2015; Brown and Bresnan, 2008; Fehling et al., 2004; Thorel et al., 2017) as well as allowing for analysis of the short and long-term changes in *Pseudo-nitzschia* with regard to environmental parameters (Díaz et al., 2014; Husson et al., 2016; McKibben et al., 2015).

In the Eastern English Channel and Southern Bight of the North Sea, phytoplankton studies have largely focused on spring bloom periods, revealing that diatoms and the prymnesiophytes *Phaeocystis globosa* form the bulk of phytoplankton biomass (Bonato et al., 2015; Schapira et al., 2008; Seuront et al., 2006). However, there is still a clear lack of knowledge in this region regarding *Pseudo-nitzschia* species diversity and seasonality in relation to environmental parameters and DA levels. Finally, studies defining *Pseudo-nitzschia* species nutrient and physical requirements and biotic interactions at the regional scale are scarce but crucial to predict proliferation and associated toxicity. Recently, Husson et al. (2016) identified the environmental niche of *Pseudo-nitzschia* sp. in six distinct bays from Brest to the Seine estuary. In this study, additional data focusing on *Pseudo-nitzschia* seasonality and diversity in the EEC-NS ecosystem over an annual cycle is provided. The aim is to define their importance in the seasonal phytoplankton succession and to estimate associated DA concentrations with regard to environmental forcing and hydro-biological conditions.

2 Material and Methods

2.1 Sampling strategy

The sampling station (~ 10 m depth) was located along the French coast of the southern North Sea, in Dunkirk harbor (51°1'12'' N, 1°9'0''E, Figure 1). The inner part of this harbor forms a small semi-enclosed embayment where semi-diurnal macrotidal tides prevail and enable important water exchanges with coastal waters of the southern North Sea. Sampling was conducted fortnightly from February 22 to November 14 2012 during flood (within 2 hours before high tide) to consider only neritic plankton communities although benthic communities could be re-suspended during high mixing periods.

Temperature (°C) and salinity were measured with an Aanderaa Instruments probe, turbidity (Turb) with an Eutech instruments waterproof probe, pH with a HANNA pH probe, and dissolved oxygen (dO₂, mg L⁻¹) with a Handy Polaris Oxyguard probe at each sampling date. Seawater samples were collected at one meter depth using a Niskin bottle. For inorganic nutrients, seawater samples (frozen at -20 °C until analysis) were analyzed by either fluorimetry (NH₄⁺; Trilogy, Turner Designs; Holmes et al., 1999) or by the use of an autoanalyzer (Alliance Integral Futura) for NO₂⁻, NO₃⁻, HPO₄²⁻, Si(OH)₄ following standard protocols (Bendschneider and Robinson, 1952; Mullin and Riley, 1955; Murphy and Riley, 1962). The surface solar irradiance (ssi) was derived from the bi-directional reflectance measured by MSG (METEOSAT Second Generation) and provided by the OSI SAF (Le Borgne et al., 2006). Winds (hourly measurements) and rainfall (daily) data were obtained from the Dunkirk Meteo France station (www.meteofrance.fr).

2.2 Phytoplankton standing stock and community composition

Phytoplankton biomass was assessed from chlorophyll *a* and pheopigment concentrations. Seawater samples (250 to 500 mL) were filtered on glass fiber filters (Whatman GF/F) under low vacuum and frozen at -20 °C until analysis (within 2 months after collection). Pigments were extracted in 90 % acetone overnight at 4°C and chlorophyll *a*, and pheopigments concentrations were estimated following Lorenzen (1966) using a pre-calibrated (chlorophyll

113 *a* from *Anacystis nidulans*, Sigma) fluorometer (Trilogy, Turner designs). For phytoplankton
114 community analyses, 250 mL samples were preserved in the field with lugol/glutaraldehyde
115 fixative (2 % final concentration, Verity et al., 2007) and stored at 4 °C in the dark until
116 analysis (within 3 months after collection). At the laboratory, 5 to 10 mL subsamples were
117 settled in Hydrobios counting chambers. Phytoplankton cells were identified and enumerated
118 using an inverted microscope (Nikon Eclipse TE2000-S, magnification $\times 200$, $\times 400$) under
119 phase contrast illumination. On average 942 ± 568 cells per sample were identified and
120 counted. For *Phaeocystis globosa*, total cells were enumerated without stage distinction (i.e.
121 isolated, colonial stages). Under optical microscopy, *Pseudo-nitzschia* cells were categorized
122 on the basis of cell width. More specifically, *Pseudo-nitzschia* cells with frustule width up to
123 $3\mu\text{m}$ were placed in the *P. delicatissima* complex while those with frustules above $3\mu\text{m}$ were
124 placed in the *P. seriata* complex as was done in several studies (Bresnan et al., 2015; Fehling
125 et al., 2004; Hasle and Syvertsen, 1997; Thorel et al., 2017).

126 When *Pseudo-nitzschia* sp. cell concentrations were higher than 10^3 cell L^{-1} , Scanning
127 Electron Microscopic (SEM) analyses were carried out for species identification, covering the
128 whole study period (April 4, May 2, May 16, June 1, September 5, October 3). In short, 10 to
129 100 mL of homogenized preserved samples were filtered on polycarbonate filters (24 mm
130 diam.; $0.8 \mu\text{m}$ porosity) and rinsed with Milli-Q water to eliminate salts. Filters containing
131 diatom frustules were acid cleaned (2 - 3 mL HCl 37%) in Teflon beakers overnight at room
132 temperature and rinsed in a Milli-Q water bath. Acid and water baths were filtered once again
133 using same filter to limit cell loss during the acidification and rinsing steps. Thereafter, filters
134 were placed on aluminium stubs with double sticky carbon tabs and air-dried during 12 h
135 under laminar flow. Lastly, dried filters were metallized under argon flow with Au/Pd during
136 90 s (Polaron SC 7620). Quantified measures based on literature review (e.g., valve length
137 and width, number of fibulae and of interstriae in $10 \mu\text{m}$) allowed for the discrimination of the

species within *Pseudo-nitzschia seriata* complex (width > 3 µm) and *P. delicatissima* complex (width < 3 µm; see Table 1), but species variety could not be inferred from our study. At least 50 *Pseudo-nitzschia* sp. cells per sample were identified via SEM analyses. When present in lower numbers, the entire filter was scanned for *Pseudo-nitzschia* frustules and identification was carried out on available material. Dissolved and particulate domoic acid (DA; pg mL⁻¹) concentrations were measured using ASP ELISA kits (Biosense, Bergen, Norway) following the provided procedure. Total DA concentration (tDA *i.e.*, dissolved + particulate DA) was measured from 5 mL of natural seawater samples stored at -20 °C until analysis. For dissolved DA, collected seawater samples (5 mL) were filtered under low vacuum pressure (< 50 mm Hg) on 0.2 µm cellulose acetate filters before being frozen (-20 °C). On the day of the analysis, samples were thawed at 4 °C and dissolved DA samples were directly processed. For total DA samples, sonication on ice was carried out in order to disrupt cells, and samples were filtered on 0.2 µm cellulose acetate before the assay. Particulate DA was obtained by subtracting dissolved DA from total DA. Given the limit of *Pseudo-nitzschia* cell counts via microscopy, DA cell quota were computed only when *Pseudo-nitzschia* cell abundance reached 10³ cell L⁻¹ (*i.e.* at least 5-10 *Pseudo-nitzschia* cells were counted).

2.3 Data analyses

In order to efficiently synthesize the environmental context of the survey and identify forcing parameters, a Principal Component Analysis (PCA) was applied to the environmental data matrix (11 parameters x 16 dates, Legendre and Legendre, 1998). Wind speed data from three days before the sampling date were averaged. Rainfalls were summed over 3 days before the sampling date in order to take into account watershed run-offs.

Nutrients concentrations of DIN (*i.e.* the sum of NH₄⁺, NO₂⁻ and NO₃⁻ concentrations), HPO₄²⁻ and Si(OH)₄ concentrations were depicted in the PCA plots as N, P and Si, respectively.

Nutrient ratios (S/P, Si/N and Si/P) were considered as illustrative variables to highlight

potential nutrient limitations. Prior to the analysis, all data were tested for normality (Shapiro test) and $\log(x+1)$ transformed.

Pseudo-nitzschia complex raw abundances were plotted on each PCA graph to give a picture of species seasonality. Only variables significantly correlated to at least one principal component (PC) of the PCA are presented and discussed (Spearman test, p -value <0.05). Correlation coefficients will be referred to as r'_{PC1} , r'_{PC2} , r'_{PC3} for the first three principal components of the PCA (Table 2). Additionally, correlations between *Pseudo-nitzschia* complexes abundances and domoic acid concentrations have been assessed. Since data did not fit the normality, correlations were tested using Spearman test (significance threshold was set at p -value <0.05). Statistics were performed using R software packages (R Core Team, 2012)

3 Results

3.1 Environmental conditions

The present study began in the cold snap of February 2012 (temperature of minus 10°C) that had not occurred in the area since 1991 (MeteoFrance data; regional bulletin, www.meteofrance.fr). The following spring was cooler (-1.0 °C) and drier (half as much rainfall) than average (Figure 2A, 2C). Stormy weather dominated the summer months (June-July) and autumn. Autumn 2012 was characterized by strong southwestern and northeastern winds (up to 100 km h⁻¹), excess precipitations (+30%) and a rapid drop in temperature. Seawater surface temperature followed a typical seasonal evolution increasing from 4.9 °C in February to 19.0 °C in August. By contrast, as measured by flood tide, salinity remained stable with an average of 34.2 ± 0.3 (min: 33.4, max = 35.0; Figure 2A). The mean annual pH value was 8.1 ± 0.3 and decreased continuously over the study period from February (8.6) to November (7.6; Figure 2B). The mean annual dissolved oxygen concentration (dO₂) was 8.1 ± 1.3 mg L⁻¹ with the highest values recorded in winter and late autumn, and the lowest (6.4 mg L⁻¹) in late summer (Figure 2B). A slight increase in dO₂ concentrations coincided with the

spring bloom development in May. Turbidity averaged at 6.9 ± 3.2 NTU (Figure 2C). The lowest turbidity values were measured in April and June (2.9 NTU) and the highest in May and September (14.3 and 12.1 NTU, respectively). With the exception of NH_4^+ , all concentrations of nutrients decreased rapidly to reach their annual minima of 0.01, 0.35 and $0.30 \mu\text{mol L}^{-1}$ for $\text{NO}_2^- + \text{NO}_3^-$, HPO_4^{2-} and $\text{Si}(\text{OH})_4$, respectively, in April (Figure 3). Thereafter, HPO_4^{2-} concentration varied between 0.5 and $1.0 \mu\text{mol L}^{-1}$ and the maximal values followed storm events (July and November). $\text{NO}_2^- + \text{NO}_3^-$ concentrations remained stable below $5 \mu\text{mol L}^{-1}$ from April to October and increased to high values at the end of the survey ($11.7 \mu\text{mol L}^{-1}$) although they did not reach the previous winter maxima of $22.5 \mu\text{mol L}^{-1}$. Silicate concentrations decreased from 7.5 to 0.3 between February and late March. A second minimal value ($0.2 \mu\text{mol L}^{-1}$) was recorded in June. The silicate concentrations increased continuously during summer and reached $7.5 \mu\text{mol L}^{-1}$ at the end of the survey. NH_4^+ concentrations were highly variable from February to June ranging between 1.0 and $3.8 \mu\text{mol L}^{-1}$. Thereafter, concentrations remained between 2.0 to $4.0 \mu\text{mol L}^{-1}$.

3.2 Phytoplankton standing stock, seasonality and domoic acid levels

The phytoplankton bloom, started at the end of February 2012 and lasted until early June. It was characterized by three successive peaks in chlorophyll *a* concentrations (from 4.0 to $9.5 \mu\text{g chl}a \text{ L}^{-1}$; Figure 4A), and phytoplankton abundance (from 8.2×10^5 to $3.6 \times 10^6 \text{ cells L}^{-1}$; Figure 4B). From July to November, chlorophyll *a* concentrations ($2.3 \pm 0.7 \mu\text{g L}^{-1}$) along with phytoplankton abundance ($1.9 \pm 0.7 \times 10^5 \text{ cells L}^{-1}$) remained relatively stable and low. Pheopigment concentrations followed the same pattern as chlorophyll *a* (Figure 5A) and represented 22 to 49 % of total pigments. Four periods could be identified based on phytoplankton community composition (Figure 4C): Period 1 (P1, February 20 – April 5) was characterized by the dominance of small diatoms (5-20 μm in width/length; *Thalassiosira* sp., *Skeletonema costatum*, *Asterionellopsis glacialis* and *Chaetoceros* sp.), either as isolated cells

or in forming colonies, and phytoplankton abundance peaked at 8.2×10^5 cells L⁻¹. Period 2 (P2, April 5 to May 20) corresponded to the *P. globosa* bloom with abundances ranging from 1.8 to 3.6×10^6 cells L⁻¹ (Figure 4B). This bloom co-occurred with high abundances of *Chaetoceros* sp. (8.7×10^4 cells L⁻¹, 64 % of the diatom community at the beginning of P2), and *Pseudo-nitzschia* sp. (2.1×10^5 cells L⁻¹ equivalent to 25% and 86% of the phytoplankton and the diatom communities, respectively; at the end of P2). Period 3 is the post-bloom period (P3, from May 20 to September 8). Both fine walled summer diatoms such as *Guinardia* sp. (*i.e.* *G. delicatula*, *G. flaccida*, and *G. striata*), and highly silicified spring diatoms such as *Chaetoceros* sp. and *Thalassiosira* sp. composed the bulk of the diatom community in association with small Cryptophytes. Period 4 (P4, from September 8 to November 16) revealed the occurrence of intermediate sized diatoms (30 - 40 µm in length/width; *Delphineis* sp.) as well as diatoms in forming colonies (e.g., *Thalassiosira* sp.) which remained in low number ($1.2 \pm 0.5 \times 10^5$ cells L⁻¹).

SEM analyses revealed a low diversity of *Pseudo-nitzschia* sp. in the area with three distinct species namely *P. delicatissima* (belonging to the *P. delicatissima* complex), *P. fraudulenta*, and *P. pungens* (both belonging to the *P. seriata* complex, see Table 1 and Figure 5). No overlap between the two complexes was found in terms of species morphological features since the width of *P. delicatissima* width was below 2 µm, and the widths of *P. pungens* and *P. seriata* were above 2.7 µm (Table 1). *P. delicatissima* represented up to 99 % of SEM-identified frustules during the *P. globosa* bloom period (P2, Mid-May) and outnumbered other diatoms. By contrast, at the beginning of the post-bloom period (P3), the percentage of *Pseudo-nitzschia* sp. to total diatoms decreased to 10 % of total diatoms. *P. pungens* markedly dominated (54 % of the SEM-identified frustules) over *P. fraudulenta* and *P. delicatissima* (33 % and 13 %, respectively). In autumn (P4), all the identified *Pseudo-nitzschia* sp.

frustules belonged to the *P. pungens* species ($< 10^3$ cells L⁻¹ representing $< 1\%$ of total diatoms). Domoic acid was mostly present as dissolved DA throughout the survey averaging $83 \pm 16 \%$ of the total DA (tDA). Particulate domoic acid (pDA) was detected in May (end of P2) and was still measurable at the end of P4. pDA punctually represented 10 to 40 % of tDA (Figure 6). tDA concentration followed *Pseudo-nitzschia* sp. dynamics, particularly during the *P. globosa* bloom and post-bloom periods (P2 and P3, Figure 7). tDA maxima (263 pg mL^{-1}) corresponded to the co-occurrence of *P. seriata* complex and *P. delicatissima* complex, reaching 2.8×10^4 and 7.5×10^5 cells L⁻¹ in early May (P2), respectively. Thereafter, tDA decreased to 118 and 110 pg mL⁻¹ at the end of P2 and beginning of P3, which coincided with the highest abundance of *P. delicatissima* complex and *P. seriata* complex, respectively. In autumn, tDA concentrations remained high ($102 \pm 39 \text{ pg mL}^{-1}$) despite low abundances of *P. seriata* complex (*i.e.* *P. pungens*), as suggested by the absence of correlation between tDA and *Pseudo-nitzschia* abundances. When measurable, DA cell quota ranged between 0.016 pg cell⁻¹ in May and 7.9 pg cell⁻¹ in September.

3.3 Abundance of *Pseudo-nitzschia* in relation to environmental factors

PCA confirmed the clear seasonal pattern of environmental variables and allowed to synthesize their relation with the temporal variability of *Pseudo-nitzschia* (Figure 7). The first three principal components (PC) explained 75.82 % of the total variance (PC1: 35.01 %, PC2: 28.77 %, PC3: 12.04 %). Considering coefficients in the linear combination of variables, period P1 was mainly characterized by high DIN ($r'_{\text{PC1}} = 0.88$) and dO₂ ($r'_{\text{PC2}} = -0.75$) concentrations, high N/P ratios ($r'_{\text{PC1}} = 0.66$; $r'_{\text{PC2}} = -0.50$) and low temperature and salinity ($r'_{\text{PC2}} = 0.73$ and 0.64, respectively; Table 2). P2 (bloom period) was more related to high ssi ($r'_{\text{PC1}} = -0.74$), pH ($r'_{\text{PC2}} = -0.64$), and increases in temperature and salinity ($r'_{\text{PC2}} = 0.73$ and 0.64), low nutrient stocks, particularly Si(OH)₄ and HPO₄²⁻ ($r'_{\text{PC1}} = 0.69$ and 0.87), and to a

lesser extent low Si/P ratio ($r'_{PC2}=0.44$, Table 2). Additionally, punctual storm events in May characterized by high rainfalls ($r'_{PC3}=0.61$) and by strong winds ($r'_{PC3}=0.43$) led to a prompt increase in turbidity (Figures 3 and 7B). High temperature, DIN limitations illustrated by low N/P, and increasing Si/P ratio and Si(OH)_4 concentrations characterized periods P3 and P4 (Table 2).

The plotting of *Pseudo-nitzschia* abundance on the PCA graphs illustrated the importance of high rainfall, increasing pH, ssi in the initiation of the *P. delicatissima* complex bloom (Figures 7A and 7B). The seasonality of the *P. seriata* complex was essentially shown by their high abundance in June (beginning of P3) and their disappearance in August and September (end of P3; Figures 7C and 7D). The highest abundance of *P. seriata* complex was observed at low nutrient levels (particularly DIN and Si(OH)_4), increasing surface solar irradiance and high pH. From September to November 2012 (P4), rainfalls and wind speed decreased, and *P. seriata* complex persisted at low abundance in increasing concentrations of Si(OH)_4 , decreasing pH and concentrations of dO_2 . Finally, as illustrated by the distribution of abundance values on the PCA plots, both complexes were present under Si(OH)_4 limitation and the *P. seriata* complex seemed to tolerate higher variable environmental conditions (e.g. nutrients) as compared to the *P. delicatissima* complex.

4 Discussion

4.1 Specificity of the 2012 spring bloom

In the southern North Sea - Eastern English Channel ecosystem, the phenology of phytoplankton communities is generally characterized by a phytoplankton spring bloom dominated by *Phaeocystis globosa* (Gentilhomme and Lizon, 1998; Lefebvre et al., 2011; Schapira et al., 2008). In 2012, the spring bloom appeared to be of low magnitude and short duration compared to other studies ($\sim 20 \mu\text{g L}^{-1}$ in Breton et al., 2000 and Kesaulya et al., 2008 ; $\sim 50 \mu\text{g L}^{-1}$ in Lefebvre et al., 2011; Seuront et al., 2006), as exemplified by low

chlorophyll *a* values ($9.5 \mu\text{g L}^{-1}$, Figure 4A). This small bloom magnitude was confirmed by the low *P. globosa* abundance (between 0.019 and $3.7 \times 10^6 \text{ cell L}^{-1}$ in this study vs 5.5 to $100 \times 10^6 \text{ cell L}^{-1}$ in Gómez and Souissi, 2008; Seuront et al., 2006; Widdicombe et al., 2010) and its low contribution to total phytoplankton abundance (50% vs $74\text{-}90\%$ between 1992 and 2011, Hernández-Fariñas et al., 2014). *P. globosa* dynamics can exhibit high interannual variability (Lamy et al., 2006; Lefebvre et al., 2011) and the year 2012 appeared as a low *Phaeocystis* year. The co-occurrence of the *P. delicatissima* complex and *P. globosa* development (Figure 4; Period P2) is often described: *P. delicatissima* complex is a co-occurring species of *P. globosa* bloom (Grattepanche et al., 2011; Hernández-Fariñas et al., 2014; Monchy et al., 2012; Sazhin et al., 2007) and may serve as solid substrate during the transitional phase from free-living cells to colonial stages (Peperzak and Gäbler-Schwarz, 2012; Rousseau et al., 2007; Verity et al., 2007).

4.2 Environmental factors drive *Pseudo-nitzschia* diversity and seasonality.

Three species of *Pseudo-nitzschia* were identified in 2012 in the Southern North Sea (*P. delicatissima*, *P. pungens* and *P. fraudulenta*) by using SEM imagery and measurements. These results are congruent with recent published data from adjacent areas (Eastern English Channel - Thorel et al., 2017, Northern North Sea - Bresnan et al., 2015). Identification was based on a literature review and best matches with species morphometric issues are specified in Table 1. The identification of *Pseudo-nitzschia* species is a tricky issue since some species can have very similar morphological characteristics (e.g. *P. delicatissima* with *P. dolorosa*, *P. decipiens* or *P. fraudulenta* with *P. subfraudulenta*, Amato et al., 2007; Orsini et al., 2004; Quijano-Scheggia et al., 2009). Further studies are therefore needed to confirm these identifications using molecular tools (e.g. Pugliese et al. 2017). The seasonality of *Pseudo-nitzschia* species within the Eastern English Channel – North Sea (EEC-NS) ecosystem resulted in two distinct periods of abundance (spring and autumn)

312 during which a very small number of *Pseudo-nitzschia* species was observed. The three
313 identified species (*P. delicatissima*, *P. pungens*, and *P. fraudulenta*) are considered to be
314 cosmopolites (see Table 3; Hasle 2002 and Lelong et al. 2012 for reviews). They are also
315 known to have different but variable hydrological preferences depending on their ecosystem
316 inhabited, and genetic strains. Temperature and salinity values recorded in 2012 (4.9-19.0°C
317 and 33.6-35.0, respectively; Figure 2A) are consistent with the euryhaline features of *Pseudo-*
318 *nitzschia* spp. Most species are indeed able to grow at salinities comprised between 1 and >
319 30, occurring and growing more efficiently at high salinity (Cho et al., 2001; Husson et al.,
320 2016; Thessen et al., 2005). Prior studies have also demonstrated a wide temperature range for
321 *Pseudo-nitzschia* spp. (Dortch et al., 1997; Louw et al., 2016; Tas and Lundholm, 2016). In
322 particular, *P. delicatissima*, which was dominant in May (P2, 86% of the diatom community
323 and 99 % of identified frustules) seemed to better grow at temperatures ranging between 10-
324 12 °C (Table 3; Fehling et al. 2006). *P. pungens* and *P. fraudulenta* were commonly present
325 in summer (June) and autumn (October) when days were longer and temperatures higher
326 (Table 3). However, *P. pungens* seems to have a wider environmental tolerance than *P.*
327 *fraudulenta* (Klein et al., 2010) as it can peak at temperatures up to 21.0 °C (Terenko and
328 Terenko, 2012). The increasing relative contribution of *P. pungens* to *Pseudo-nitzschia*
329 species between June (54 %) and October (100 %) may be explained by two non-conflicting
330 hypotheses. Firstly, the *P. pungens* population may comprise different varieties exhibiting
331 different temperature preferences (e.g. Kim et al. 2015). Secondly, it can present varying
332 responses to temperature increases (Thessen et al., 2009).

333 *P. delicatissima* development began in February (P1) under high DIN concentrations, high
334 N/P ratios and low temperature (i.e. late winter conditions; Figure 7A, 7B). It is well known
335 that high abundances of *Pseudo-nitzschia* spp. are found in areas enriched with nutrients
336 (Parsons et al., 2002; Tas et al., 2016) which can originate from upwelling (Díaz et al., 2014),

337 mixing events and riverine inputs (Trainer et al., 2012). Paradoxically, the highest abundance
338 of *P. delicatissima* in May (P2) occurred after a decrease in DIN concentrations and rather
339 suggested nutrient limiting conditions. Pulses of DIN (Figure 3A) following rainfall events in
340 May (Figure 2C) could have favored the species rapid growth and bloom, a phenomenon
341 which has already been shown in estuarine systems (Tas et al., 2016; Tas and Lundholm,
342 2016). The results of this study also demonstrated that the maximum abundance of the *P.*
343 *delicatissima* complex occurred at high pH levels and dO₂ concentrations (P2, Figure 7).
344 Lundholm et al. (2004) suggested that high pH values (8.7 - 9.1) can inhibit the growth of
345 most *Pseudo-nitzschia* species. Such high values were never recorded during our study (7.6 to
346 8.6; Figure 3) and no significant relationships could be established between pH values and
347 *Pseudo-nitzschia* abundance. Rather than being associated solely with the *P. delicatissima*
348 complex, variability in dO₂ is likely associated with the photosynthetic activity of the whole
349 phytoplankton community including the *Phaeocystis* sp. bloom (P2).
350 High amount of particulate matter (i.e., high turbidity) linked to water mixing and river inputs
351 can limit light availability and consequently inhibit photosynthesis and growth. This light
352 attenuation can result in the limitation of both the spatial and temporal distribution of *Pseudo-*
353 *nitzschia* as demonstrated in estuarine and coastal systems (Dursun et al., 2016; Tas et al.,
354 2016). These studies are consistent with the *P. seriata* complex distribution pattern in the
355 Southern Bight of the North Sea (SBNS), the species being abundant when turbidity was low
356 (e.g. in June, Figure 2C, 7D). *P. delicatissima* could have benefited from the storm event
357 (high wind and rainfall) which occurred in May and particularly from the subsequent pulses of
358 DIN and Si(OH)₄ (Figures 3A and 7B).
359 The *P. seriata* species complex was the most abundant (beginning of P3) in low DIN and
360 SiOH₄ concentrations resulting in low Si/N ratios (figure 7C). These conditions may have
361 been caused by the lag effect of *P. delicatissima* and the associated *P. globosa* bloom having

already drawn down the nutrients. The *P. seriata* species complex was still persisting at low abundance in the area from the end of the summer to the fall (end of P3 and P4). PCA plots suggest that the growth of the *P. seriata* complex may benefit from nutrient pulses of silicate, phosphate and DIN but that it tends to be limited at that time of the year by decreasing temperature and irradiance (Figure 7C, 7D).

Silicate limitations were already proven to increase *Pseudo-nitzschia* abundance and toxicity (Anderson et al., 2010; Thorel et al., 2017). For instance, *P. multiseriata* was able to outcompete other phytoplankton species when silicate was low compared to nitrogen (Sommer, 1994). Laboratory culture conditions conducive to DA production generally include limitation by silicate or phosphate during the stationary phase (reviewed by Bates et al., 1989; Trainer et al., 2012, 2008). This could explain this study findings of the high domoic acid concentration in spring (P2, May, Figure 6) which coincided with low Si and DIN concentrations along with low Si/P ratios (Figure 7A- C). However, no significant correlation could be demonstrated between nutrients stocks and DA concentrations. Consequently, more targeted studies (e.g., nutrient uptake experiments) are required in order to properly evaluate the nitrogen nutritional status and nitrogen preference (i.e., $\text{NO}_2^- + \text{NO}_3^-$ vs NH_4^+ vs urea) for *Pseudo-nitzschia* populations, and thus the potential influence of nitrogen on bloom dynamics and toxicity in the EEC-NS.

4.3 Domoic acid concentrations and *Pseudo-nitzschia* species

The existence of toxigenic and non-toxigenic strains of the same species has been mentioned recurrently for several *Pseudo-nitzschia* species (e.g. Sahraoui et al. 2011; Thessen et al. 2009; Villac et al. 1993) Sahraoui et al., 2011; Thessen et al., 2009; Villac et al., 1993). Total DA concentrations measured during this study (max. 263 pg mL^{-1}) were higher than several published values in the EEC-NS ecosystem (up to 7 pg mL^{-1} ; Downes-Tettmar et al. 2013; Klein et al. 2010) but remained lower than recent measurements in the Bay of Seine (1.4×10^3

387 pg mL⁻¹, Thorel et al. 2017), and other ecosystems such as Monterey Bay (10×10³ pg mL⁻¹;
388 Walz et al. 1994), the Gulf of Mexico (3.3×10³ pg mL⁻¹, Liefer et al. 2013) or Luanda Bay,
389 Angola (1.4×10³ pg mL⁻¹, Blanco et al. 2010).

390 Although *Pseudo-nitzschia* abundance matched high DA concentration in spring, this
391 observation did not hold for the end of summer and autumn periods (Figure 6). Other species
392 (i.e. *Nitzschia navis-vargnica* and *N. bizertensis*) are known to produce DA in south-east Asia
393 and Tunisia, respectively (Bouchouicha-Smida et al., 2015; Kotaki et al., 2000; Lundholm and
394 Moestrup, 2000; Tan et al., 2016). Since neither species has been detected in North Atlantic
395 waters (including the English Channel and the North Sea) or been observed during this 2012
396 survey, it is likely that DA originate exclusively from *Pseudo-nitzschia* species.

397 Consequently, this result supports other studies where DA concentration in seawater
398 (particulate and dissolved) or in shellfish does not always depend on *Pseudo-nitzschia*
399 abundance (e.g. Bates et al. 1998; Bresnan et al. 2017; Klein et al. 2010; Lelong et al. 2012;
400 Walz et al. 1994). During P2 and P3, high tDA concentrations coincided with the co-
401 occurrence of two or three *Pseudo-nitzschia* species (i.e., *P. delicatissima* and *P. pungens*
402 during P2 and *P. delicatissima*, *P. pungens* and *P. fraudulenta* during P3). Since these three
403 species have been proven at least once to produce DA (Lelong et al., 2012), the formal
404 identification of the species responsible for DA concentration cannot be addressed with
405 certainty. Consistent with Downes-Tettmar et al. (2013), *P. pungens* was certainly toxic as it
406 was the only *Pseudo-nitzschia* sp. present in autumn when DA concentrations reached 101 pg
407 mL⁻¹. *P. delicatissima* and *P. fraudulenta* were demonstrated to be weakly toxigenic in
408 different ecosystems (Almandoz et al., 2017; Parsons et al., 2012; Rhodes et al., 1998).

409 Additionally, in the northern North Sea, *P. delicatissima* cells have not been observed to
410 produce DA (Scottish Waters, (Fehling et al., 2006, 2004). The DA cell quotas estimated for
411 the three samples in which particulate DA was associated with *Pseudo-nitzschia* abundance >

10³ cell L⁻¹ ranged between 0.016 and 7.9 pg. cell⁻¹. These DA cell quotas are comparable to values obtained for batch cultures of *P. fraudulenta* (0.03 pg.cell⁻¹, Rhodes et al. 1998; 0.16 pg.cell⁻¹, Thessen et al. 2009) and *P. pungens* (0.2 to 10 pg. cell⁻¹; Lelong et al. 2012). They are also congruent with DA cell quotas inferred from *in situ* surveys for *P. fraudulenta* (0.002 to 0.120 pg. cell⁻¹; Almandoz et al. 2017) and *P. delicatissima* (1.52 to 5.54 pg. cell⁻¹, Parsons et al. 2012).

4.4 DA implications in the ecosystem and challenges for future surveys

In this study, the high proportion of dissolved domoic acid year round (~83%) may have two main implications regarding phytoplankton communities succession and marine resources. Dissolved domoic acid can indeed act as an effective Fe chelator, increasing its bioavailability and providing a competitive advantage to *Pseudo-nitzschia* sp. over other phytoplankton species for Fe assimilation (Prince et al., 2013; Rue and Bruland, 2001; Trick et al., 2010; Zabaglo et al., 2016). Other studies suggest that DA synthesis requires available Fe (e.g. Sobrinho et al. 2017). In both cases, accumulated iron in the polysaccharidic matrix of *P. globosa* (Schoemann et al., 2005) could have benefitted *Pseudo-nitzschia* sp. growth and DA production and could well explain its appearance every year, during and after the *P. globosa* bloom.

Regarding marine resources, dissolved DA is reported to alter bivalve larvae growth (Liu et al., 2007) and immunity (De Rijcke et al., 2015) and these effects could spread to population recruitment and picking activities. Dissolved DA is also reported to inhibit herbivorous feeding as shown for krill (Bargu et al., 2006) and copepod species (Tammilehto et al., 2015) modifying matter and energy fluxes within the trophic web. These elements suggest the potential for dissolved DA to impact marine resources throughout the year and to trigger long-term effects regarding growth and recruitment.

Despite its absence in spring, particulate DA appeared at significant level (10-40%) over a wide temporal window (May to December). During this period, *Pseudo-nitzschia* sp. could provide a non-negligible food source from which particulate DA could be directly transferred to higher trophic levels such as exploited filter feeders namely mussels or king scallops in the EEC-NS (Ambiaud and Lefebvre, 2017). Phytoplankton consumers such as *Noctiluca scintillans* and copepods could act as DA vectors/inducers (Escalera et al., 2007; Fock and Greve, 2002; Leandro et al., 2010; Maneiro et al., 2005; Tammilehto et al., 2015) and were shown to dominate the zooplankton community when particulate DA reached 40% of total DA in the summer. Our data suggest that the SBNS could be an at-risk area regarding DA contamination and/or exposure of marine resources to dissolved DA: the phytoplankton abundance alert threshold was reached at least once for the *P. delicatissima* complex during the 2012 survey (i.e. $>300\,000\text{ cells L}^{-1}$, (EC) No 853/2004 2004; (EC) No 854/2004 2004) concomitantly with significant DA concentrations in seawater. However, high domoic acid concentration was not always associated with high *Pseudo-nitzschia* abundance. This study at the seasonal scale allowed the identification of risky periods regarding species diversity and DA forms and concentrations in the SBNS ecosystem. Given the inter-annual variability of *Pseudo-nitzschia* species occurrence (e.g. Thorel et al. 2017), long term monitoring is fundamental to assess whether the species seasonality persist over years and whether it is always associated to the same toxigenic species and environmental parameters.

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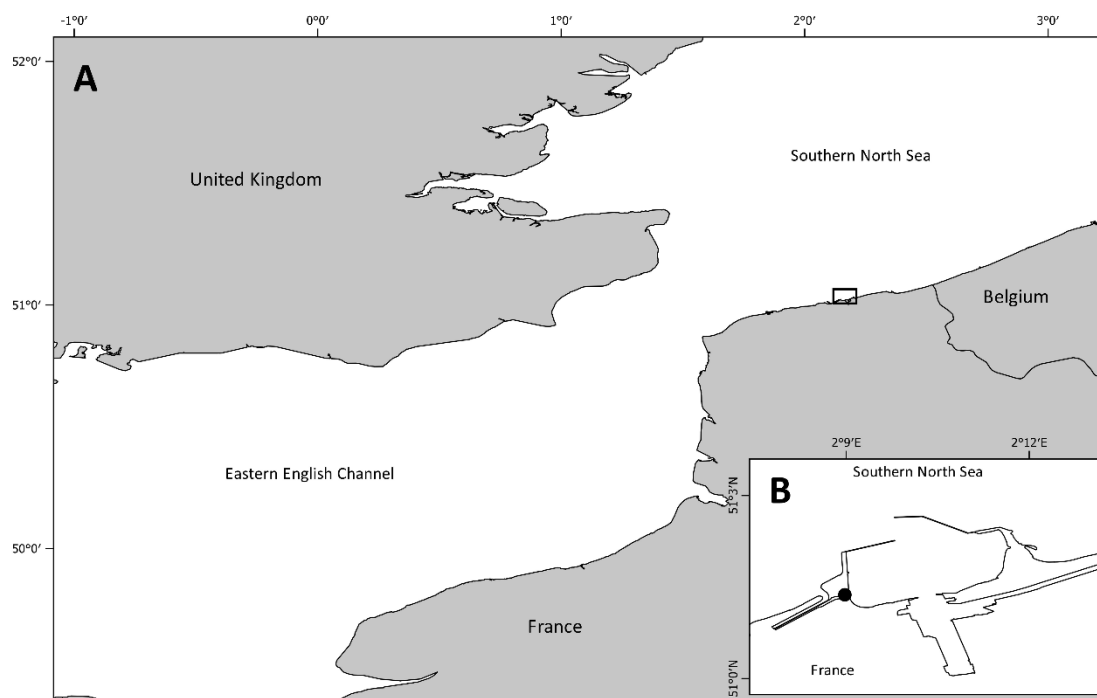


Figure 1. A – Location of the study area. B – Location of the sampling station (black dot) in Dunkirk harbor (Southern Bight of the North Sea).

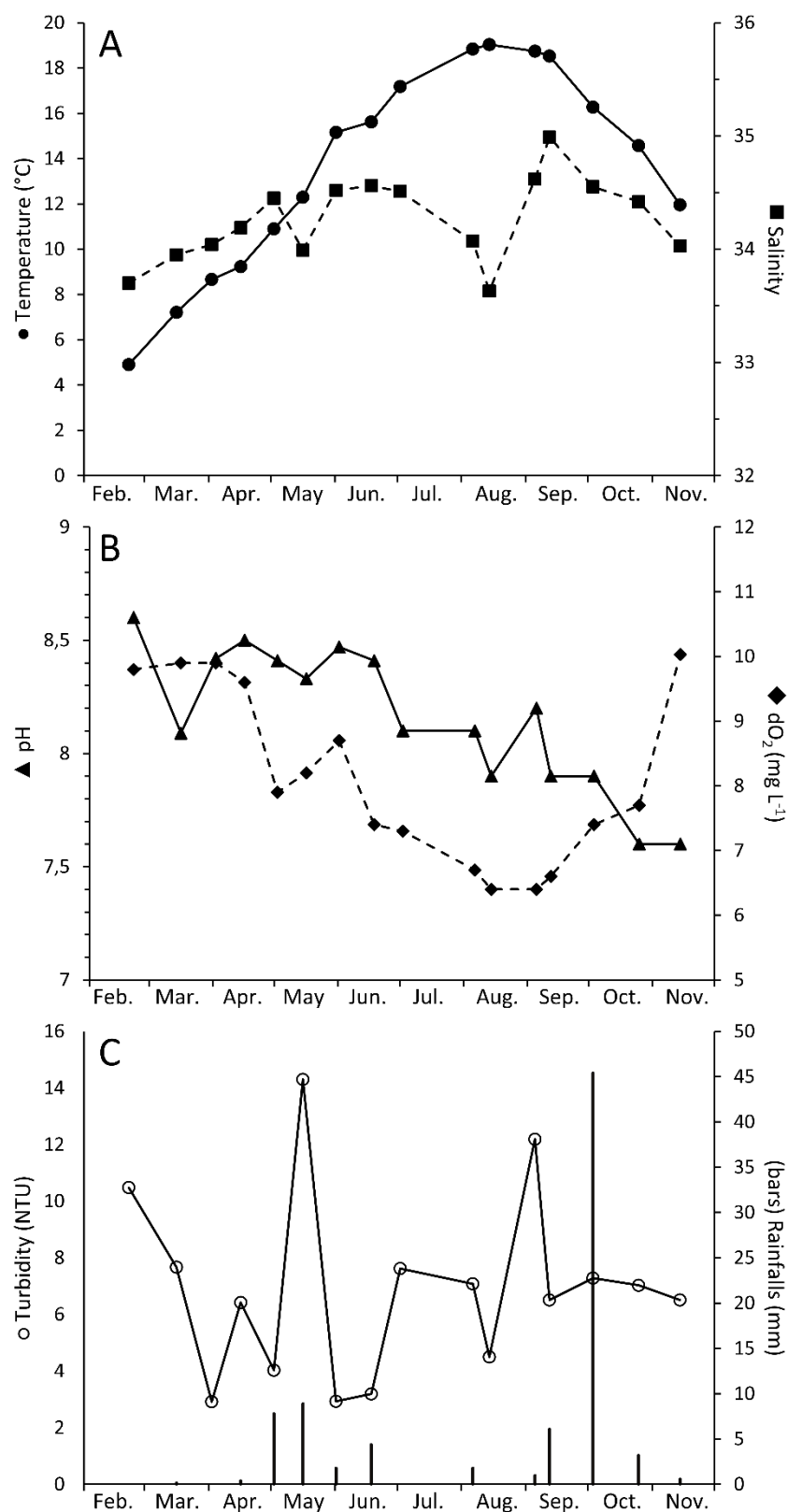


Figure 2. Time series of meteorological and hydrological parameters. A. Temperature (°C) and salinity, B. pH and dO₂ (mg L⁻¹), C. Turbidity (NTU) and cumulated rainfalls over three days (bars, mm) during the 2012 survey.

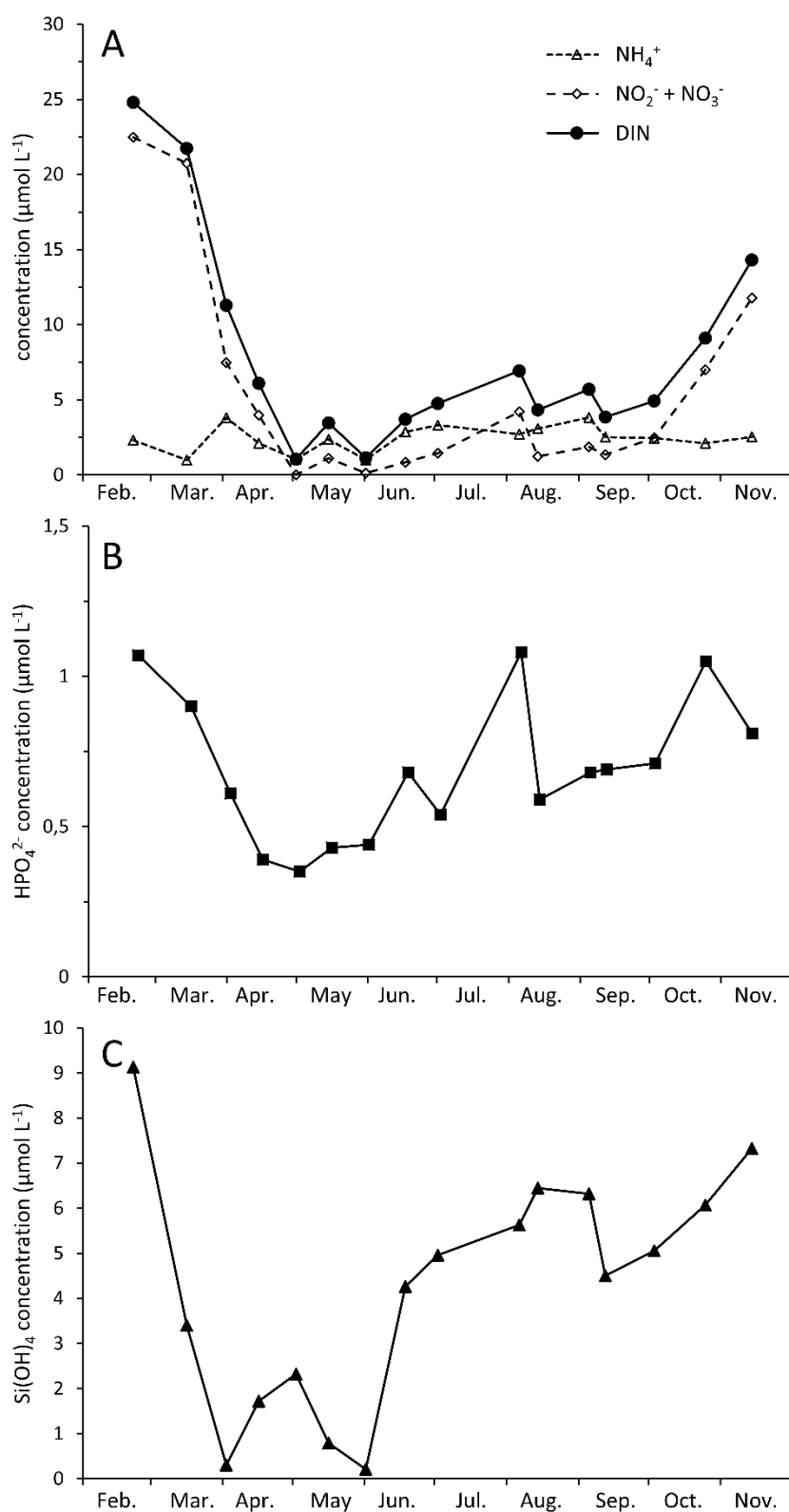


Figure 3. time series of nutrient concentrations ($\mu\text{mol L}^{-1}$). A. $\text{NO}_2 + \text{NO}_3$, NH_4^+ and total dissolved inorganic nitrogen ($\text{DIN} = \text{NO}_2 + \text{NO}_3 + \text{NH}_4^+$). B. HPO_4^{2-} . C. Si(OH)_4 , during the 2012 survey.

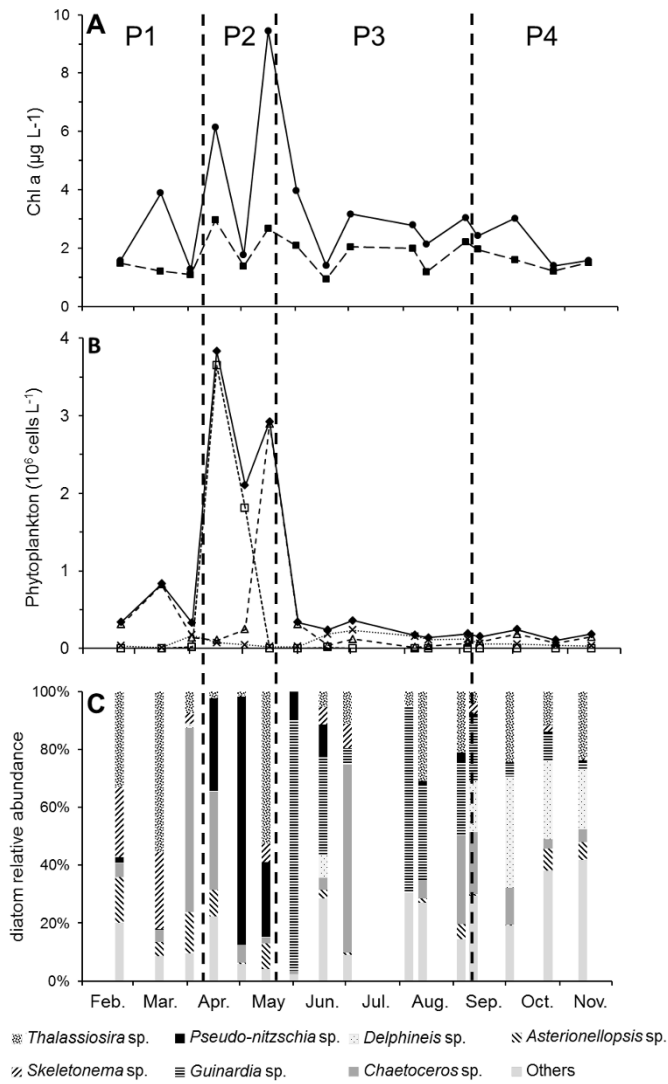


Figure 4. Time series of A. Chlorophyll *a* (●) and pheopigment (■) concentrations ($\mu\text{g L}^{-1}$);
 B. Abundance (cell L^{-1}) of total phytoplankton (◆), diatoms (Δ), *Phaeocystis globosa* (□) and
 other phytoplankton groups (×); and C. relative abundance of diatom genus (%) during the
 2012 survey.

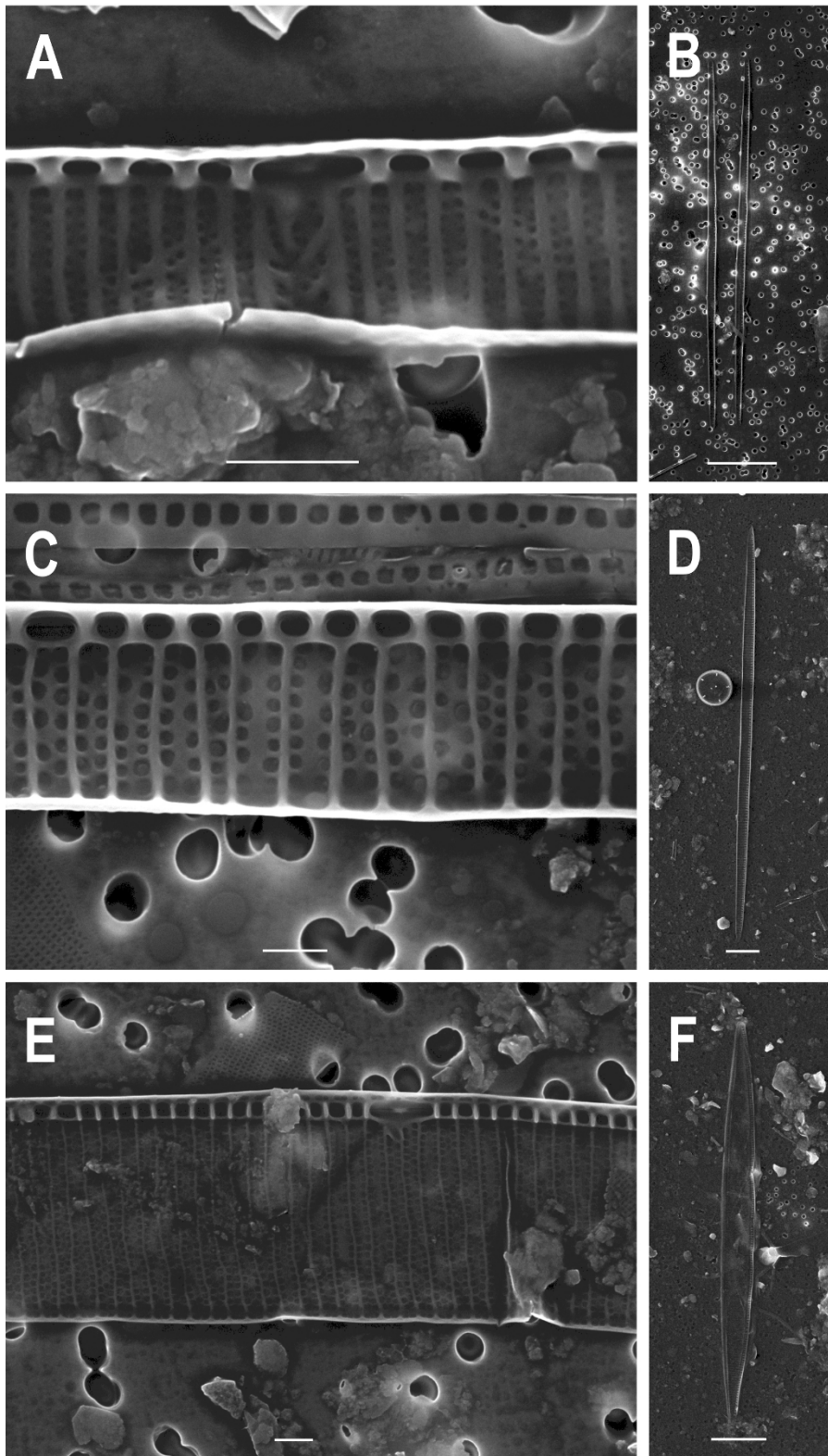


Figure 5. SEM micrographs of the three identified *Pseudo-nitzschia* species. A-B: *Pseudo-nitzschia delicatissima*; C-d: *Pseudo-nitzschia pungens*; E-F: *Pseudo-nitzschia fraudulenta*. Scale bars: A, C, E = 1µm, B, D, F = 10µm.

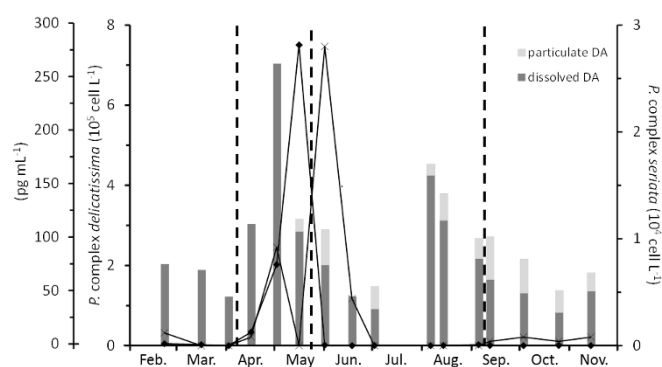


Figure 6: Time series of *Pseudo-nitzschia* complex *delicatissima* (◆) and *P. complex seriata* (×) abundances (cell L⁻¹), and particulate and dissolved domoic acid (DA, pg mL⁻¹) during the 2012 survey. Stars below the x axis indicate the dates of SEM analyses for *Pseudo-nitzschia* sp. diversity.

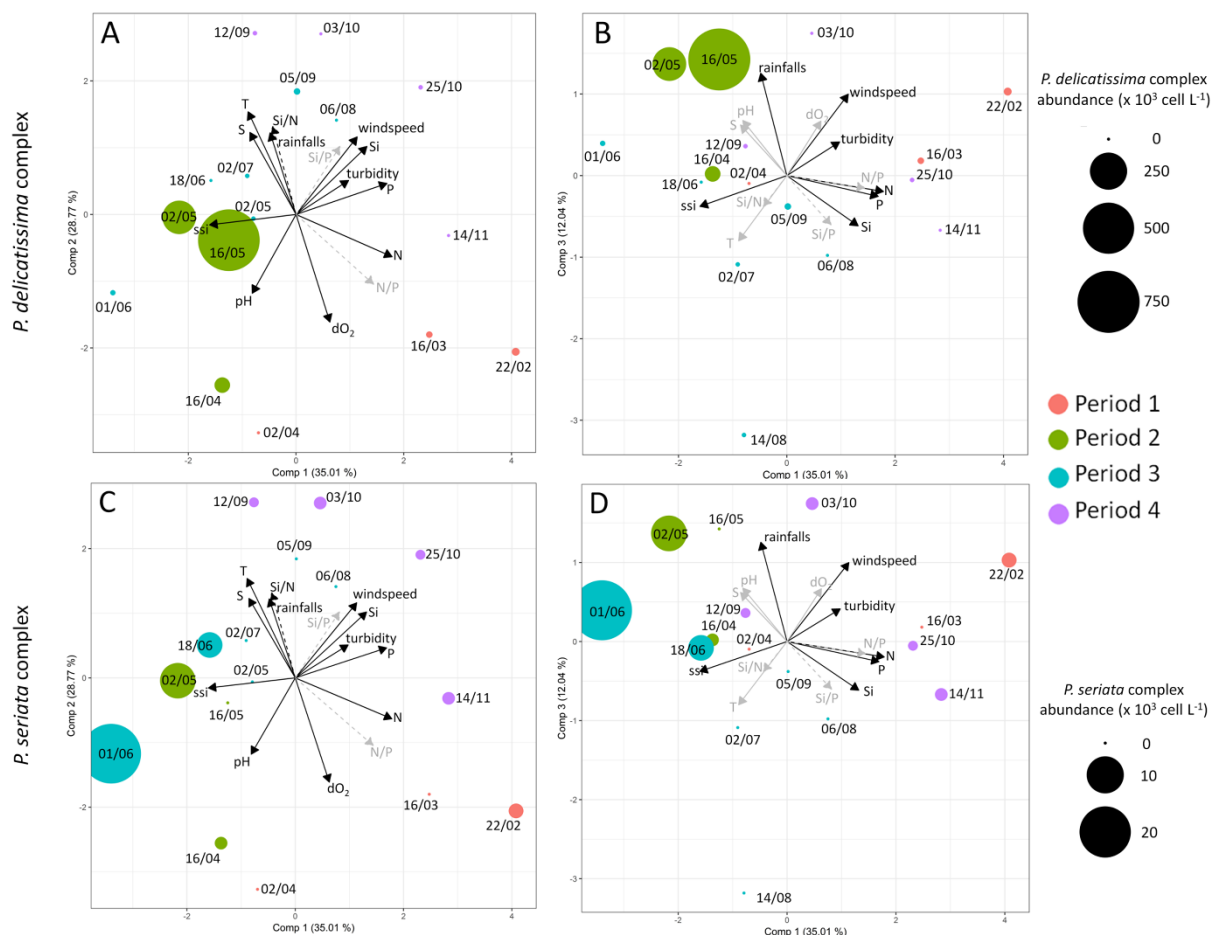


Figure 7: PCA plots of environmental variables. A and C. Plane defined by the two first axes of the PCA (PC1 and PC2) B and D. plane defined by the first (PC1) and third axis (PC3) of the PCA (B and D). Points correspond to sampling dates. The colors of the circles correspond to the periods (P1 to P4) determined from phytoplankton communities composition. Circles size is proportional to *Pseudo-nitzschia* abundance (cell L⁻¹) for *P. complex delicatissima* (A and B) and *P. complex seriata* (C and D). Black arrows represent variables significantly correlated to at least one represented PC.

Table 1. Morphological features of *Pseudo-nitzschia* species and comparison with literature values (min-max). * correspond to one frustule analysed and presenting outliers in poroids features (among >300 identified frustules)

Species	Width µm	Length µm	Central Interspace	Fibulae 10 µm ⁻¹	Interstriae 10 µm ⁻¹	Rows of poroids	Poroids 1 µm ⁻¹	Reference
<i>P. delicatissima</i>	1.3-2	N/A	+	22-29	33-43	2	8-11	Amato et al., 2005
	1.7-2.8	N/A	+	20-27	24-40	2	8-14	Fehling et al., 2006
	1.1-2	40-78	+	19-25	36-40	2	10-12	Skov et al., 1999
	1.0-1.5	42-66	+	20-23	env 40	2	10-12	Hasle et al., 1996
	1.7-2.3	17-48	+	18-36	37-44	2	7.5-13.4	Kaczmarska et al., 2008
	1.3-1.6	48-49	-	22-23	36-40	2	8-9	Klein et al., 2010
	1.5-2.0	19-76	N/A	19-26	35-40	2	12	Lundholm et al., 2006
	1.3-1.6	34-46	+	24-28	41-45	2	7-11	Moschandreou and Nikolaidis, 2010
	1.0-2.4	19-78	+	19-30	33-42	2	8-12.5	Quijano-Scheggia et al., 2010
	1.4-2.6	31-48	+	20-28	38-41	2	8-12	Fernandes et al 2014
	1.1-1.7	40.7-67.1	+	18-27	34-44	2(3*)	10-14(18*)	This study
<i>P. fraudulenta</i>	4.3-5.1	N/A	+	20-24	22-26	2-3	5-6	Fehling et al., 2006
	4.5-10	50-119	+	12-24	18-24	2-3	5-7	Skov et al., 1999
	5-6	73-117	+	19-23	19-23	2-3	4-5	Hasle et al., 1996
	3-4.5	63-99	+	15-17	14-15	2	N/A	Hernández-Becerril, 1998
	5.1-5.6	56.8-81	-	21-22	22-24	2-3	6-7	Klein et al., 2010
	4-7	71-101	N/A	18-30	19-28	2-3	6-7	Ljubešić et al., 2011
	4.4-5.8	48-80	+	22-24	21-24	2	5-6	Moschandreou and Nikolaidis, 2010
	2.9-7.1	38.9-131.5	+	12-24	18-24	2	4-7	Quijano-Scheggia et al., 2010
	5.2-6.2	64-84	+	20-23	22-23	2	5-6	Fernandes et al. 2014
	5.2-6.1	75.0-98.8	+	19-23	17-23	2-3	6-7	This study
<i>P. pungens</i>	3.1	N/A	-	12	12	2	3-4	Fehling et al., 2006
	2.4-5.3	74-174	-	9-16	9-16	1-2	3-4	Skov et al., 1999
	2.9-4.5	74-142	-	9-15	9-15	2	3-4	Hasle et al., 1996
	3-4	94-109	-	10-11	10-12	2	N/A	Hernández-Becerril, 1998
	2.9-3.3	61-106	-	11-13	11-14	2-3	2-4	Klein et al., 2010
	3.9-5.7	88-105	-	10-17	8-15	2	2-4	Ljubešić et al., 2011
	2.5-3.6	77-101	-	11-13	11-13	2	2-4	Moschandreou and Nikolaidis, 2010
	2-4.8	37-156	-	9-13	9-15	2	1-5	Quijano-Scheggia et al., 2010
	4-4.5	75-130	-	9-13	N/A	2	3-4	Stonik et al., 2001
	3.0-4.1	72-149	-	11-13	10-12	2	3-4	Fernandes et al 2014
	2.7-4.7	95.9-135.5	-	10-15	10-15	2-3	2-4	This study

Table 2. Spearman correlation coefficient between principal components (PCx), environmental parameters, *Pseudo-nitzschia* complexes abundances and domoic acid concentration.

Parameters	PC1	PC2	PC3
<i>Main variables</i>			
Temperature (T)	-0.18	0.73**	-0.45 ⁺
Salinity (S)	-0.39	0.64**	0.13
pH	0.43 ⁺	-0.64**	0.29
dO ₂	0.22	-0.75***	0.26
Turbidity	0.498*	0.22	0.15
Rainfalls	-0.29	0.55*	0.61*
Windspeed	0.61*	0.51*	0.47
Surface Solar Irradiance (ssi)	-0.74**	-0.06	-0.15
DIN	0.88***	-0.29	-0.25
PO ₄ ²⁻	0.87***	0.28	-0.15
Si(OH) ₄	0.69***	0.37	-0.38
<i>Supplementary variables</i>			
Si/P	0.26	0.44	-0.38
Si/N	-0.23	0.69**	-0.19
N/P	0.66**	-0.50*	-0.20
<i>Pseudo-nitzschia and DA</i>			
<i>P. delicatissima</i> complex	-0.27	-0.33	0.47 ⁺
<i>P. seriata</i> complex	-0.31	-0.07	0.50*
tDA	-0.30	0.12	0.20
(* p-value < 0.05, ** p-value < 0.01, *** p-value < 0.001)			

Table 3. Environmental features of *Pseudo-nitzschia* spp. identified during the 2012 survey and literature values.

Species	Location	Temperature °C	Salinity	DIN μmol L ⁻¹	PO4 μmol L ⁻¹	Si μmol L ⁻¹	Abundance cells L ⁻¹	DA	Reference
<i>P. delicatissima</i>	Southern Adriatic Sea	8.79-29.91, R<0	R>0	no significant pattern			nd	nd	Caroppo et al., 2005
	Western Scotland	~8°C	nd	~3μM	~0.3μM	~2.5μM	1.6·10 ⁵	nd	Fehling et al., 2006
	Louisiana	nd	nd	no significant pattern			1·10 ⁶	5.5pg cell ⁻¹	Parsons et al., 2013
	NE Spanish Coast	R>0	36.8±1.1, R<0	R>0	nd	nd	17.6±5.2·10 ⁵	nd	Quijano-Scheggia et al., 2008
	Bay of Fundy	nd	nd	R>0	no significant correlation		nd	nd	Kaczmarek et al., 2007
	Gulf of maine	nd	nd	nd	nd	nd	nd	111-390 pg mL ⁻¹	Fernandes et al., 2014
	Black Sea	16-17.5	14.5-15.7	nd	nd	nd	1.5-3.1·10 ⁶	nd	
<i>P. delicatissima</i> complex	Western English Channel	déc-15	34.9±0.4, R>0	nd	R<0	nd	2,5·10 ⁵	0.2-0.4 pg mL ⁻¹	Downes-Tettmar et al., 2013
	Galicia – Spain	~ 13.1	~35.6	~2.1	~0.22	~3	6.6·10 ⁵	not detected	Díaz et al., 2014
	Southern Bight of the North Sea	9-12	34.2±0.2	3.5±2.5 decreasing	0.39±0.04	1.6±0.8	33·10⁵-7.5·10⁶	92-229pg mL⁻¹	This study
<i>P. pungens</i>	Louisiana	nd	nd	R<0	R>0	no corr	50000	nd	Parsons et al., 2013
	NE Spanish Coast	nd	nd	no pattern	nd	nd	nd	nd	Quijano-Scheggia et al., 2008
	Gulf of Maine	nd	nd	Nd	nd	nd	nd	40-1100 pg mL ⁻¹	Fernandes et al., 2014
	Bay of Fundy	nd	nd	R<0	R>0	nd	nd	nd	Kaczmarek et al., 2007
	Western English Channel	12-16	34.9±0.4	R<0	R<0	R<0	25000	0.2-0.4 pg mL ⁻¹	Downes-Tettmar et al., 2013
	Sea of Marmara,Turkey	11.6-22.8	21.6	nd	nd	1.8	4.8·10 ⁵	nd	Tas and Lundholm, 2016
	Sea of Marmara,Turkey	7.4-26.3	15.9-19.9	Nd	Nd	Nd	1.6-1.7·10 ⁴	1.0pg mL ⁻¹	Tas et al., 2016
<i>P. fraudulenta</i>	California	18.5-26.5	nd	0-3	nd	2.9-35.5	5-13 10 ⁵	detected	Gárate-Lizárraga et al., 2007
	North Western Mediterranean Sea	nd	R>0	R<0	nd	nd	nd	nd	Quijano-Scheggia et al., 2008
<i>P. seriata</i> complex including <i>P. pungens</i> , <i>P. fraudulenta</i>	Western Scotland	12-13	nd	~0.3	~0.25	~3	110000	nd	Fehling et al., 2006
	Southern Bight of the North Sea	15.4±0.3	34.50±0.03	2.4±1.8 decreasing	0.56±0.17	2.2±2.8 increasing	9.2·10⁵-2.8·10⁶	82-108pg mL⁻¹	This study

Min-max, mean ± standard deviation, R<0 and R>0: negative and positive correlation with diatom abundance, respectively., nd = no data

