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Dinoflagellate composition and environmental conditions in the Xuan Dai Bay, South-Central Vietnam

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ABSTRACT

The dinoflagellate community was investigated in association with environmental factors using a data set in April 2021 and April 2022 in Xuan Dai Bay, South-Central Viet Nam. Environmental variables, including physical parameters and dissolved inorganic nutrients, were measured in April 2022. Seventy-three dinoflagellate taxa were identified for Xuan Dai Bay. There was a significant difference in the number and abundance of dinoflagellates between two parts of the bay, the upper and lower bay. The study showed that dinoflagellates favored an area with good water exchange and were less affected by aquaculture activities. Principal component analysis (PCA) was used to explore the relative abundances of different phytoplankton groups, their diversity indices, and environmental variables at the surface and bottom layers of the two parts of the bay. The results showed that dinoflagellates correlated to physical parameters (e.g., PAR, salinity, temperature) at the surface layer and nutrients at the bottom layer. Dinoflagellates and diatoms are mixotrophic and strongly correlated at the bottom layer in Xuan Dai Bay. This strong relationship in the bay was because of the dominance of a heterotrophic genus, *Protoperidinium*. The present study provided characteristics of the dinoflagellates in Xuan Dai Bay and the possible impacts of environmental parameters on their abundance. The results can be used for further studies and possibly managing of dinoflagellate blooms in coastal waters.

Keywords: Aquaculture, dinoflagellates, mixotrophic dinoflagellates, Xuan Dai Bay.

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INTRODUCTION

Marine dinoflagellates are one of the major groups of marine phytoplankton with different features in morphology, reproduction, toxin production, and nutrient demand in different waters [1–3]. They are important primary producers and indispensable in marine ecosystems, especially in coastal environments [4, 5]. Moreover, dinoflagellates are among the most sensitive phytoplankton to changes in environmental conditions [6, 7]. Their distribution is influenced by different interactions among environmental factors such as sea-surface temperature, salinity, pH, and nutrients [8, 9]. Studies of dinoflagellate physiology have been carried out in various waters, from inshore to offshore waters (e.g., [10–20]). In Vietnam, studies on how dinoflagellate communities respond to the changes in environmental factors were sparse, especially in coastal or aquaculture areas. Recently, there was research on seasonal variations of the potentially toxic benthic dinoflagellates in Bai Lan, Nha Trang Bay [21]. This study analyzed how environmental parameters impact the benthic dinoflagellates and found possible responses of one dinoflagellate group to phosphate and other groups to PAR [21].

As semi-closed coastal waters in Central Vietnam, Xuan Dai Bay harbors rich biodiversity and brings ecological benefits for humans. With a surface area of about 13,000 hectares, aquaculture has developed more widely over the last 15 years. This bay is separated into two parts based on its morphology, the upper bay being relatively closed and shallower and the lower bay deeper and directly connected to open waters (Fig. 1). The upper bay has facilitating conditions to expand aquacultures, such as culturing lobsters, and oysters. Intensive aquaculture can release high nutrients or organic waste and generally cause environmental issues such as eutrophication. However, the changes in coastal environmental quality due to these anthropological activities affecting the dinoflagellate community are still sparse.

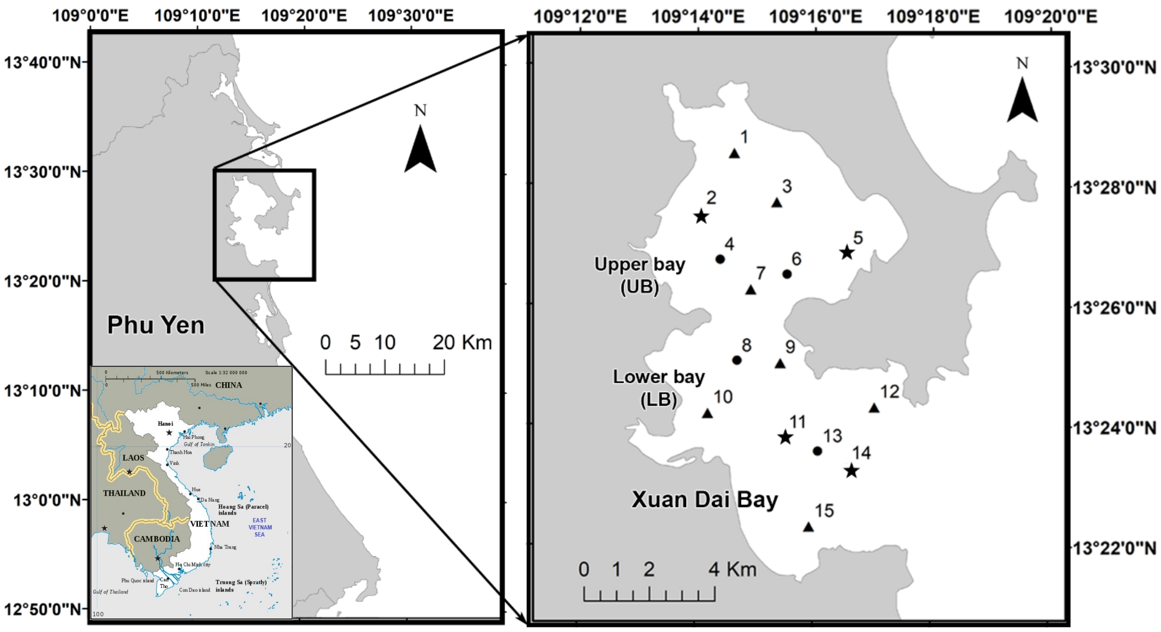

Figure 1. Maps showing location of Xuan Dai Bay and sampling stations in April 2021 and 2022. Solid circles (4, 6, 8 & 13) are stations in 2021, solid triangles are stations in 2022 (1, 3, 7, 9, 10, 12 & 15), and stars (2, 5, 11 & 14) indicate stations were sampling in both years

This study used phytoplankton and environmental data collected in April 2021 and 2022 in Xuan Dai Bay to assess changes in communities and possible impacted factors. It focused on changes in dinoflagellate communities, including species composition, abundance, and effects of environmental factors on them in the survey area.

MATERIALS AND METHODS

Study area

Xuan Dai Bay is in the northern part of Phu Yen Province. The bay is semi-closed with about 4.5 km wide mouth connecting to the open waters. Due to its morphological and bathymetric features, Xuan Dai Bay is divided into two parts, the upper bay (UB) and lower bay (LB), connected through a 2 km narrow channel (Fig. 1). The UB is a closed area and relatively flat. The waters are deeper toward the southeast, with the deepest ca. 9 m. The LB has an average of 14 m depth; the maximum depth at the mouth is 20 m [22].

Phytoplankton samples and environmental parameters were collected at 15 stations in April 2021 and April 2022 in Xuan Dai Bay (Fig. 1). In April 2021; the phytoplankton samples were collected at 8 stations (2, 4–6, 8, 11, 13, 14) with 8 qualitative samples and 16 quantitative samples (at surface and bottom layers). In April 2022, water samples were taken at 11 stations (1–3, 5, 7, 9–15) with 11 qualitative samples and 22 quantitative samples of phytoplankton and environmental parameters, including temperature, salinity, fluorescence, PAR and nutrients.

Sampling and analysis

Phytoplankton

The net samples were taken at 15 stations in April 2021 and April 2022. Qualitative samples were collected using a plankton net with a 25 µm mesh size towing vertically, slowly from the bottom to the surface. Samples were fixed with formalin to a final concentration of 5% and stored in the dark for later analysis. Species were identified, and cell dimensions were measured under the light microscope (Leica LDMB, Germany). A Calcofluor White M2R method [23] was used to identify armored dinoflagellates, and observation was under the epifluorescence microscope (Leica LDMB, Germany).

Identification of the species was based on published descriptions of Graham & Bronikovsky [24], Abé [25], Balech [26], Tomas [27], Larsen & Nguyen Ngoc [28], Nguyen-Ngoc & Larsen [29], Nguyen-Ngoc et al., [30]; Phan-Tan et al., [31]; Phan-Tan et al., [32]; Hoang Quoc Truong [33, 34], Shirota [35], Licea et al., [36]. The scientific names and the nomenclature were updated according to Guiry & Guiry [37]. Mixotrophic dinoflagellates were identified based on publication below: Baek et al. [38], Bockstahler and Coats [39], Bockstahler and Coats [40], Chang & Carpenter [41], Faust [42], Hansen & Tillmann [43], Hansen et al., [44]; Harrison et al., [45]; Horiguchi & Takano [46], Ishimaru et al., [47]; Jacobson & Anderson [48], Jeong et al., [49]; Jeong et al., [50]; Jeong et al., [51]; Leles et al., [52]; Lim et al., [53]; Löder et al., [54]; Nishitani et al., [55]; Norris [56], Park et al., [57]; Qiu et al., [58].

The quantitative samples were taken at 15 stations In two surveys. Quantitative water samples (1 L) were collected using a 5-L Niskin bottle at each station’s surface and bottom layers, stored in PET plastic bottles and fixed with neutral Lugol solution. Samples were concentrated by settling through a few 48 hours-settling steps, from 1,000 mL to the final 3 mL volume, using graded cylinders. A volume of 1,000 µL of each sample was loaded onto the counting chamber Sedgwick-Rafter to enumerate phytoplankton cells following the UNESCO method [59]. One drop of Calcofluor 0.5 mg/mL was added to samples for identification and enumeration of dinoflagellates [28].

The qualitative and quantitative analysis of phytoplankton samples was performed at the Department of Plankton, Institute of Oceanography, Nha Trang.

Environmental variables

The water environmental parameters were collected in April 2022 at 11 sampling samples in Xuan Dai Bay and used for Principal Components Analysis (PCA). All the water samples for nutrient analysis were collected using a 5-liter Niskin bottle at the surface and bottom layers. They were then kept in the dark at a low temperature (ca. 4°C) before transportation to the Department of Hydro-Geochemistry laboratory, Institute of Oceanography, for analysis. Dissolved inorganic nutrients, including phosphate (PO_4^{3-}), nitrite (NO_2^-), nitrate (NO_3^{2-}), and ammonia ($NH_{3,4}$) were measured following standard methods [60]. Temperature, salinity, fluorescence, and Photosynthetically Available Radiation (PAR) were measured *in situ* using a Sea-Bird SBE 19+ CTD (USA) with valid calibration.

Data analyses

Phytoplankton data were extracted from the database of PLANKTONSYS (BioConsult A/S). Excel Microsoft Office 365 was used for data treatment and plotting. Correlations of dinoflagellate community and environmental factors were analyzed and illustrated by Principal Components Analysis (PCA) using RStudio 4.1.1 with packages "FactoMineR" [61] and "factoextra" [62]. ArcMap 10.3 software was used to interpolate nutrient variables with the inverse distance weighted (IDW) interpolation method and plot the abundances of dinoflagellates.

PRIMER software version 6 (PRIMER-E Ltd, Plymouth, United Kingdom) was used for calculating the Margalef and Shannon indices. The following equations were used:

Margalef index:

$$d = (S-1)/\log(N) \text{ [63]}$$

Shannon index:

$$H' = -sum\left(P_i * \log_2\left(P_i\right)\right) \text{ [64]}$$

where: i: the sites; n_i: cell number of species counted on site i; N: a total cell number in a sample; S: a total of the number of species in a sample; P_i: frequency of the i^{th} species in a sample = present probability of the i^{th} species in a sample = n_i/N.

RESULTS AND DISCUSSION

Environmental conditions

Temperature, salinity, PAR, Fluorescence

Water temperature was slightly higher, but salinity was lower at the stations of the UB compared to LB. There was a significant difference in salinity between the surface and bottom layers in the UB due to freshwater runoff from a small spring. Temperature and salinity strongly varied at 3–4 m depth in the UB and at 4–6 m in the LB (Figs. 2 & 3).

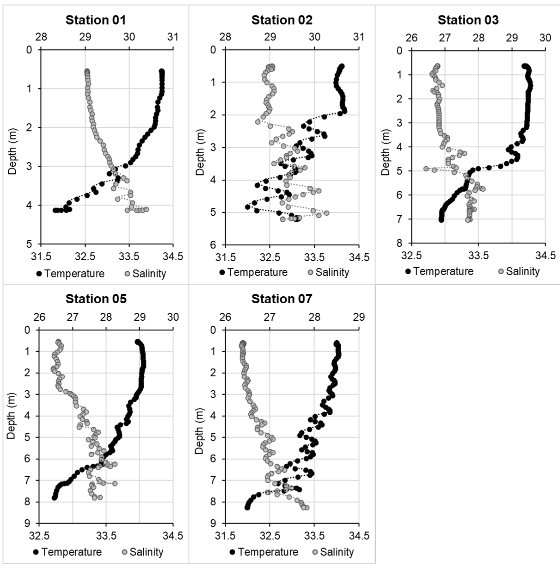

Figure 2. Vertical temperature (°C) and salinity profiles at 5 stations in the UB, April 2022

The PAR in the UB was high at the surface layer (ca. 1,000–2,000 µE.m^{-2}.s^{-1}) from above 2 m depth at most stations, except for station 3, with only 300–500 µE.m^{-2}.s^{-1}. PAR in the LB, however, was lower at the same depth (ca. 300–1,400 µE.m^{-2}.s^{-1}) compared to the UB (Figs. 4 & 5). Regarding fluorescence, there was no significant difference between the UB and the LB. The maximum fluorescence is mainly located at the middle and bottom layers of the water column in the UB and the middle layer (ca. 5–8 m depth) in the LB.

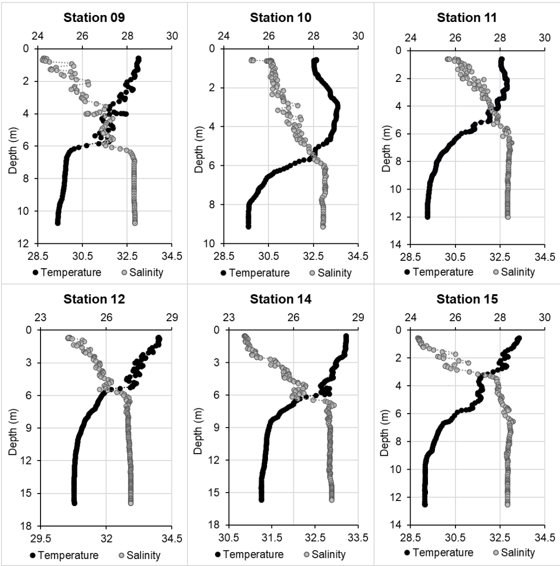

Figure 3. Vertical temperature (°C) and salinity profiles at 6 stations in the LB, April 2022

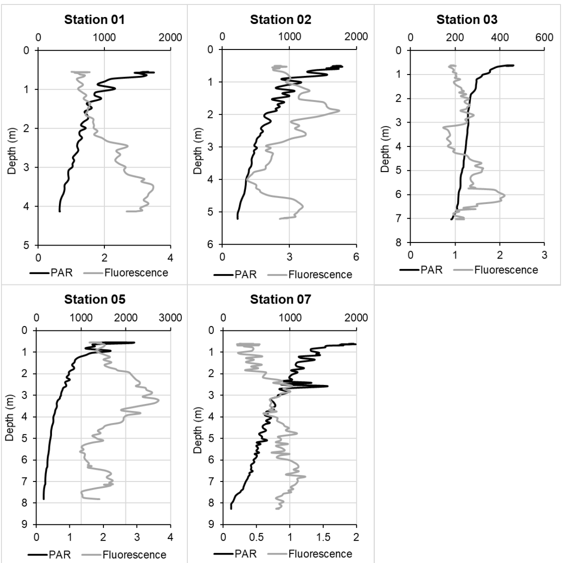

Figure 4. Vertical profiles of Fluorescence (mg Chl-a/m^3) and Photosynthetically Available Radiation (PAR) at 5 stations in the UB, April 2022

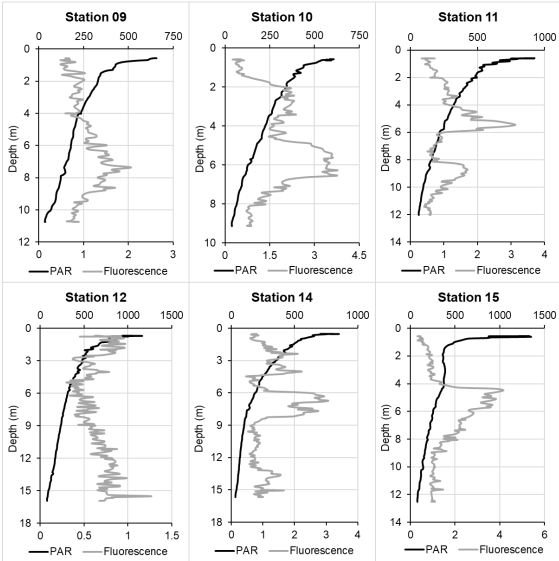

Figure 5. Vertical profiles of Fluorescence (mg Chl-a/m^3) and Photosynthetically Available Radiation (PAR) at 6 stations in the LB, April 2022

Dissolved nutrient concentrations

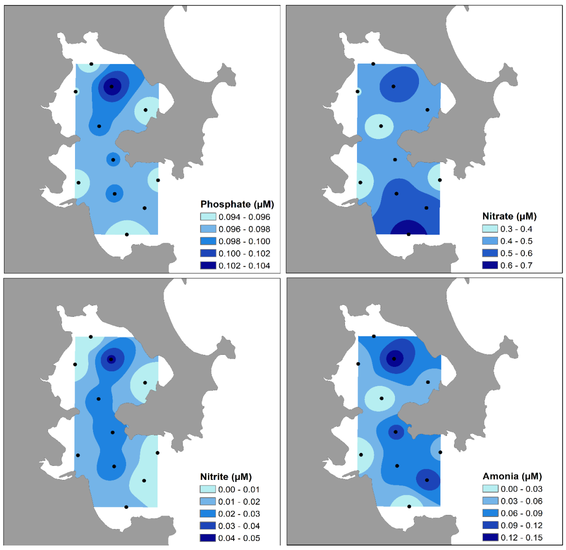

Figure 6. Spatial variability of nutrient concentrations (phosphate, silicate, nitrate, and dissolved inorganic nitrogen) at the surface layer

In April 2022, all nutrient concentrations were relatively low in the bay. However, the nutrient concentrations differed between the surface and bottom layers, with higher concentrations at the bottom layer. Phosphate and nitrite concentrations were higher at both layers' upper area, whereas nitrate was higher at the LB's surface and the UB's bottom layers. Ammonia was evenly distributed at the surface layer in all areas but higher at the bottom layer of the LB (Figs. 6 & 7).

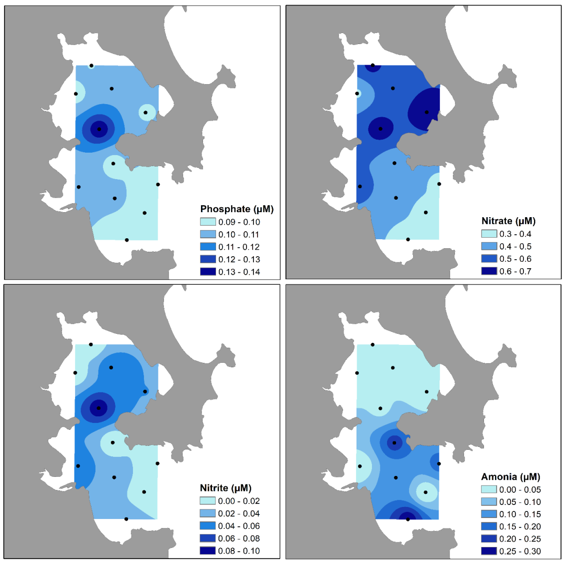

Figure 7. Spatial variability of nutrient concentrations (phosphate, silicate, nitrate, and dissolved inorganic nitrogen) at the bottom layer

Dinoflagellate composition

Regarding species composition, 73 dinoflagellate taxa were identified in two surveys (2021–2022) in Xuan Dai Bay (Table 1). There was no significant difference in the number of species between the two years, with 58 and 61 taxa in April 2021 and April 2022, respectively. The dinoflagellate species number was much lower in the upper bay (26 species), which has a dense density of lobster cages, compared to the lower bay (72 species). There was a bloom formation of centric diatom *Leptocylindrus danicus* with densities of 3–6 × 10^6 cells.L^{-1} at stations 1 and 2 in April 2022, and that could lead to an imbalance of the phytoplankton community.

Dinoflagellate abundance significantly differed between the two surveys, with 445 cells.L^{-1} and 1.235 cells.L^{-1} for April 2021 and April 2022, respectively. However, there was no difference in dinoflagellate abundance between the surface and bottom layer in 2021, while it was higher at the surface layer in 2022 (Fig. 8). Especially in the lower bay, the density of dinoflagellates at all stations at the surface layer was higher with over 1,000 cells.L^{-1}. With the higher species number and abundance of dinoflagellate in the lower bay, dinoflagellates facilitated better in this area. The quality of the water environment in the lower bay was also better (Figs. 6 & 7), with less affected by aquaculture activity and better water exchanged with the open sea compared to the upper bay.

Table 1. List of dinoflagellate species in Xuan Dai Bay in April 2021 and April 2022

Ord.	Species	Stations															Encounter frequency
		Upper bay							Lower bay								
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	
1	*Akashiwo sanguinea*		+	+				+	+	+	+	+	+	+	+	+	11
2	*Alexandrium* sp.									+	+	+	+		+	+	6
3	*Amphisolenia bidentata*									+		+					2
4	*Blixaea quinquecornis*		+		+		+										3
5	*Ceratocorys horrida*														+		1
6	*Dinophysis caudata*							+	+	+	+	+	+	+	+	+	9
7	*Dinophysis fortii*									+	+		+	+	+	+	6
8	*Dinophysis miles*							+		+	+	+	+		+	+	7
9	*Dinophysis* sp.									+		+			+		3
10	*Gonyaulax alaskensis*								+	+		+		+	+	+	6
11	*Gonyaulax fusiformis*							+			+	+			+		4

Ord.	Species	Stations															Encounter frequency
		Upper bay							Lower bay								
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	
12	*Gonyaulax polygramma*						+		+	+	+	+	+	+	+	+	9
13	*Gonyaulax* sp.								+				+			+	3
14	*Gonyaulax spinifera*	+		+				+	+	+	+	+	+	+	+	+	11
15	*Gymnodinium* sp.		+		+					+	+	+	+		+	+	8
16	*Gyrodinium* sp.	+	+		+		+		+	+	+	+	+	+	+	+	12
17	*Lingulodinium polyedra*							+	+	+	+	+	+	+	+	+	9
18	*Noctiluca scintillans*									+	+	+	+		+	+	6
19	*Ornithocercus magnificus*												+			+	2
20	*Ostreopsis* sp.													+			1
21	*Oxytoxum milneri*													+	+		2
22	*Oxytoxum tesselatum*								+			+	+	+	+		5
23	*Oxytoxum laticeps*								+								1
24	*Phalacroma* cf. *rotundatum*								+								1
25	*Phalacroma cuneus*												+			+	2
26	*Podolampas bipes*														+		1
27	*Podolampas palmipes*								+	+		+	+	+	+		6
28	*Prorocentrum* cf. *rhathymum*	+	+	+		+		+		+							6
29	*Prorocentrum micans*			+			+	+	+	+	+	+	+	+	+	+	11
30	*Prorocentrum sigmoides*							+	+	+	+	+	+	+	+	+	9
31	*Prorocentrum* sp.	+	+			+	+	+		+			+	+			8
32	*Protoperidinium angustum*													+	+		2
33	*Protoperidinium brochii*											+	+	+	+	+	5
34	*Protoperidinium claudicans*										+			+		+	3
35	*Protoperidinium conicoides*														+	+	2
36	*Protoperidinium conicum*								+			+		+	+		4
37	*Protoperidinium crassipes*							+	+	+	+	+	+	+	+	+	9
38	*Protoperidinium depressum*								+	+		+	+		+	+	6
39	*Protoperidinium divergens*										+		+		+		3
40	*Protoperidinium elegans*									+			+	+		+	4
41	*Protoperidinium excentricum*											+		+			2
42	*Protoperidinium humile*		+		+									+			3
43	*Protoperidinium inflatum*													+			1
44	*Protoperidinium oceanicum*							+	+	+	+	+	+	+	+	+	9
45	*Protoperidinium ovum*									+		+	+	+	+	+	6
46	*Protoperidinium pellucidum*	+	+	+		+		+	+	+	+	+	+	+	+	+	13
47	*Protoperidinium pentagonum*									+	+	+	+		+	+	6
48	*Protoperidinium sinuosum*									+		+			+		3
49	*Protoperidinium solidicorne*														+		1
50	*Protoperidinium spp.*	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	15
51	*Protoperidinium venustum*								+	+	+	+		+	+	+	7
52	*Protoperidinium yonedae*							+	+	+		+	+	+	+	+	8
53	*Pseliodinium vaubanii*											+	+		+		3
54	*Pyrocystis fusiformis*									+			+			+	3
55	*Pyrophacus horologium*								+	+	+	+	+	+	+		7
56	*Pyrophacus steinii*							+		+	+	+	+	+	+	+	8

Ord.	Species	Stations															Encounter frequency
		Upper bay							Lower bay								
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	
57	*Tripos azoricus*															+	1
58	*Tripos furca*		+	+	+	+	+	+	+	+	+	+	+	+	+	+	14
59	*Tripos fusus*					+		+	+	+	+	+	+	+	+	+	10
60	*Tripos gibberus*											+		+			2
61	*Tripos hexacanthus*											+					1
62	*Tripos inflatus*									+	+	+	+		+		5
63	*Tripos lunula*											+			+		2
64	*Tripos macroceros*									+		+	+		+	+	5
65	*Tripos massiliensis*							+	+	+	+	+	+	+	+		8
66	*Tripos muelleri*		+				+	+	+	+	+	+	+	+	+	+	11
67	*Tripos pentagonus*								+				+		+	+	4
68	*Tripos platycornis*												+				1
69	*Tripos trichoceros*		+				+	+	+	+	+	+	+	+	+	+	11
70	*Tripos candelabrum*										+			+	+		3
71	*Tripos carriensis*														+		1
72	*Tripos longipes*									+		+			+	+	4
73	*Tripos setaceus*									+		+	+		+	+	5
Total		6	12	7	6	6	9	21	29	42	31	46	44	39	53	41	73

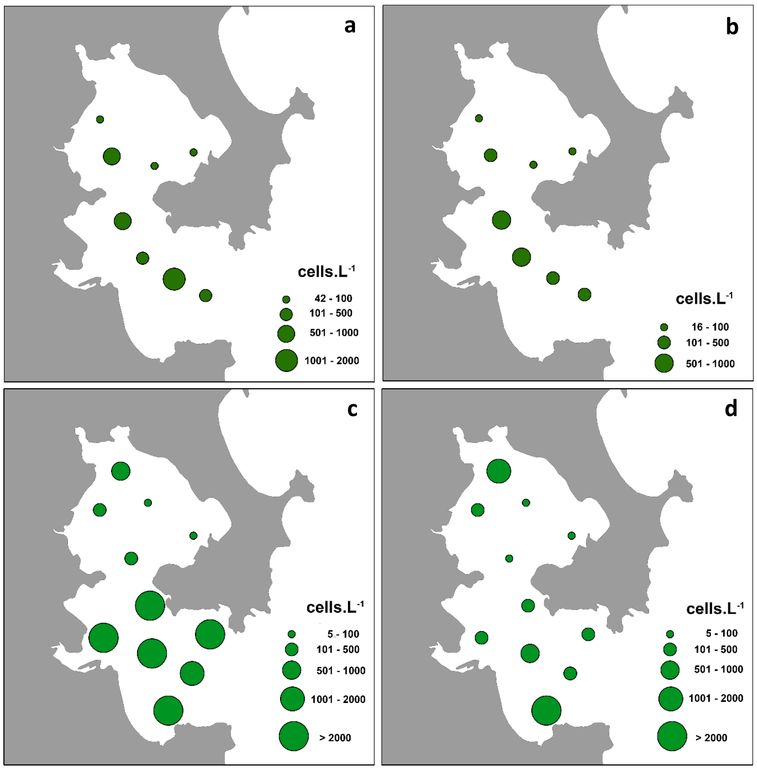

Figure 8. Distribution of dinoflagellate densities (cells.L^{-1}) in Xuan Dai Bay in 2021 and 2022 at the surface and bottom layers (a: surface layer in 2021; b: bottom layer in 2021; c: surface layer in 2022; d: bottom layer in 2022)

Effects of environmental variables on dinoflagellates

Principal component analysis (PCA) using abundances of dinoflagellates (Dino), mixotrophic dinoflagellates (MTD), the number of dinoflagellates' species (S), dinoflagellates' Margalef (d) and Shannon (H) indices, diatoms' abundance (Diat) and environmental variables showed the first two PCA axes explained 55.5% of the variance, with 31.9% and 23.6% for PC1 and PC2, respectively (Fig. 9). The environmental factors were strongly correlated to PC1, including nitrite (0.84), nitrate (0.70), and PAR (-0.61) Salinity was correlated to PC2 (-0.86). Environmental factors had different effects on dinoflagellate abundance, MTD, diatoms, number of species, and Margalef and Shannon indices, and varied among the locations. At the surface layer, these variables are closely correlated with physical conditions (e.g., temperature, salinity, and PAR), ammonia, and fluorescence at the surface layer. At the bottom layers, they had a strong relationship with nutrients (nitrite, nitrate, phosphate, DIN). Especially at the bottom layer of the UB, the abundance of dinoflagellates and diatoms and the Shannon index were negatively correlated with nutrients. There was a strong correlation between the abundance of dinoflagellates and diatoms at the bottom layer.

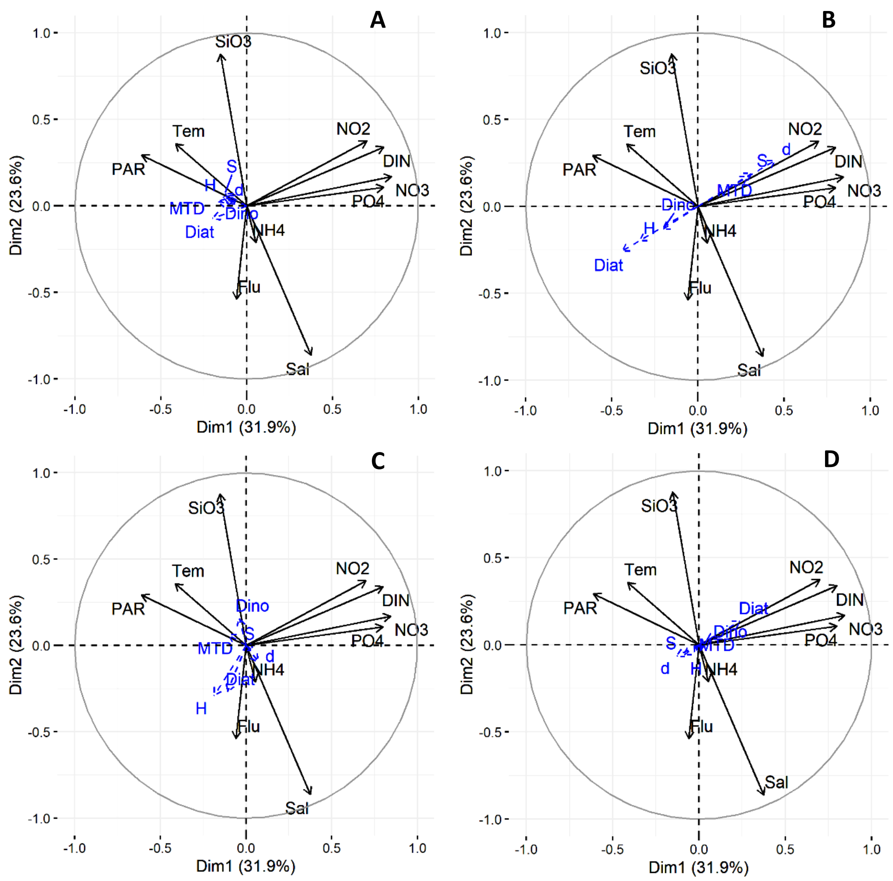

Figure 9. Principle Component Analysis (PCA) for dinoflagellate (Dino) and mixotrophic dinoflagellate (MTD) abundance; diatoms (diat); Shannon index of dinoflagellates (H); Margalef index of dinoflagellates (d); species number of dinoflagellates (S) and environmental factors (Temperature - Tem; Salinity - Sal; Photosynthetically Available Radiation - PAR; Fluorescence - Flu; Phosphate - PO_4; Nitrate - NO_3; Nitrite - NO_2; Ammonia - NH_4; Dissolved inorganic nitrogen - DIN; Silicate - SiO_3) at the UB's surface (A), the UB's bottom (B), the LB's surface (C), and the LB's bottom (D)

Mixotrophic dinoflagellates (MTD) have both phototrophy and phagotrophy [65], making the an excellent adaptive strategy of the group, reflecting changes in environmental factors and the ability to catch prey [66–68]. However, understanding the ecology of mixotrophic dinoflagellates is needed in Vietnamese waters, especially in coastal areas and internationally. Therefore, in the present study, we attempted to estimate the relationship between mixotrophic dinoflagellates and environmental variables, aiming to contribute a more detailed background of dinoflagellates in the survey area. In Xuan Dai Bay, abundance of MTD and dinoflagellates were highly correlated. One exception was for the UB's bottom layer due to mixotrophy being the dominance of total dinoflagellate abundance in this data set. The correlation between dinoflagellate and diatom abundance is well-known, with dinoflagellate being mostly mixotrophic. In Xuan Dai Bay, this strong relationship at the bottom layers was probably because of the dominance of a heterotrophic genus, *Protoperidinum*, which feeds on diatoms or small flagellates [48, 69]. This genus dominated at the bottom layer in most stations of the UB with over 60% of total dinoflagellate abundance.

According to this study, physical and nutrient variables were the main components affecting the dinoflagellate community at the surface and bottom layers. Previously, some studies mentioned temperature as a significant predictor of dinoflagellate abundance [11, 17, 19, 20]. In a model simulation, Zhou et al. suggested that nitrate was crucial in determining the intensity of dinoflagellate blooms. In this simulation, diatoms succeeded before the dinoflagellates [18]. Our results showed that phosphate influenced dinoflagellate less than other nutrients. In real situations, dinoflagellate abundance can be controlled by more than two factors [20] and even interactions among those environmental factors. Besides, dinoflagellates have a strong capacity for phosphorus storage [14], and with their mixotrophic ability, it is not easy to detect the impacts of a single environment variable on them. Evaluating the relationship between dinoflagellates and environmental factors has generally required a spatially and temporally large data series to provide comprehensive results. However, the present study used the data set of the surveys in an embayment, which would reveal a part of the knowledge of the dinoflagellate community in their waters.

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