



# Dinoflagellate cyst assemblages from the northern shelf sediments of the East China Sea: An indicator of marine productivity

So-Young Kim<sup>a</sup>, Dhong-Il Lim<sup>b,\*</sup>, Hyun-Jin Cho<sup>c</sup>

<sup>a</sup> Division of Polar Climate Research, Korea Polar Research Institute, Get-pearl Tower, Songdo Techno Park, 12 Gaetbeol-ro, Yeonsu-gu, Incheon 406-840, South Korea

<sup>b</sup> Library of Marine Samples (LIMS), South Sea Research Center, Korea Ocean Research and Development Institute, 391 Jangmok-ri, Jangmok-myun, Geoje, 656-830, South Korea

<sup>c</sup> Marine Pollution Response Department, Korea Coast Guard, 3-8 Songdo-dong, Yeonsu-gu, Incheon, 406-741, South Korea

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## ABSTRACT

The dinoflagellate cyst assemblages from the northern shelf of the East China Sea were examined to assess their potential use as indicators of marine productivity in shelf environments. A characteristic disparity in the species compositions of dinoflagellate cysts between coastal sediments and outer-shelf sediments was observed. Coastal areas affected by fluvial freshwater input adjacent to the Changjiang River mouth were dominated by protoperidinioid species, whereas open sea shelf areas were dominated by gonyaulacoid species. The rarity of protoperidinioid cysts in the shelf sediment is primarily attributable to the deficit of silicate in the waters overlying the northern East China Sea shelf, associated with low supplies of suspended particulate matter from the adjacent continent. This would limit the growth of the protoperidinioid species, which feed on diatoms. In contrast, a constant supply of nitrogen generated by microbial nitrogen fixation appeared to have played an important role in supporting the production of gonyaulacoid species in this shelf region. Thus it was determined that dinoflagellate cyst assemblages in marine sediments are closely linked to significant changes in nutrient composition, leading to a selective advantage for the growth of favored taxa. This result suggests that gonyaulacoid dinoflagellate cysts are a potentially useful proxy indicator for low nutrient concentration levels, especially of silicate, in the shelf environment.

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## 1. Introduction

Dinoflagellates constitute a major part of the phytoplankton and are commonly found in fresh water, brackish and marine habitats. They include autotrophs, which utilize inorganic compounds and sunlight to manufacture their own food, and heterotrophs that require organic compounds for growth and reproduction (Taylor, 1987; Tiselius and Kuylenstierna, 1996). Many dinoflagellate species produce cysts as a benthic resting stage, which are extremely resistant to physical, chemical, and biological breakdown (e.g., Wall et al., 1977; Versteegh and Blokker, 2004). Dinoflagellate cyst distributions in recent sediments may be used as proxies of certain environmental parameters (e.g. sea surface temperature, salinity, coastal versus oceanic waters and productivity), which are potentially useful for paleoenvironmental interpretations (Marret and Zonneveld, 2003; Marret and Kim, 2009). Therefore, dinoflagellate cysts in marine sediments have been successfully utilized as tools for understanding changes in marine environments, particularly in areas where other microfossil remains (i.e., foraminiferal tests, diatom frustules, and coccoliths) are scarce due to the dissolution of opaline silica

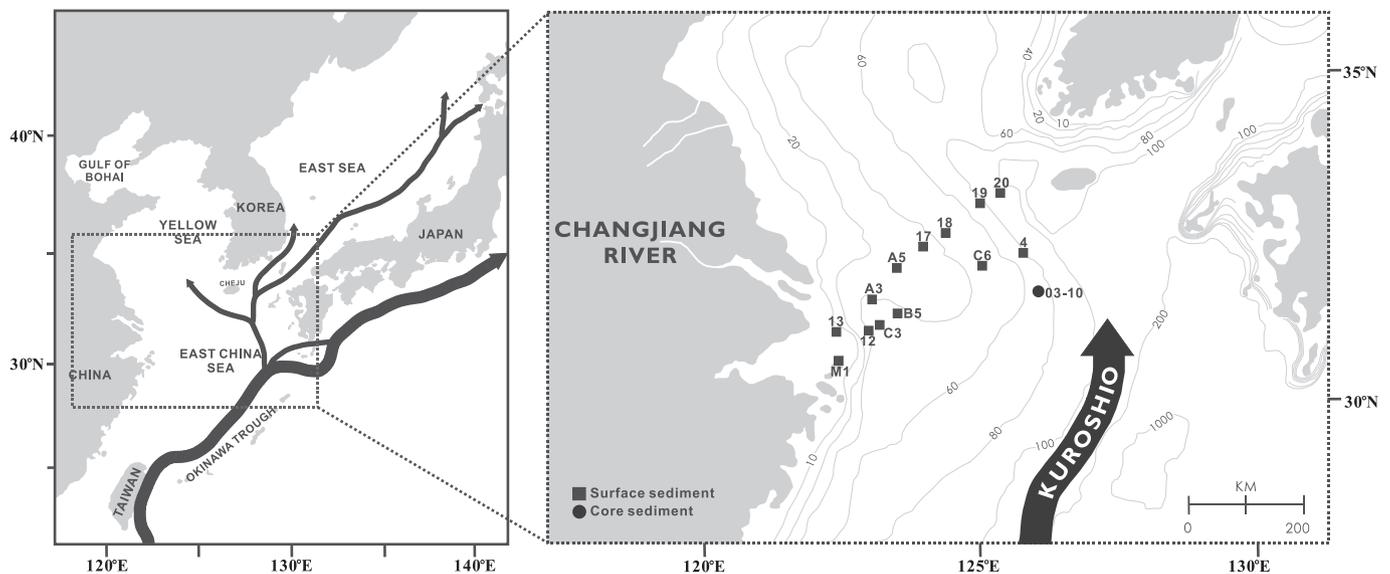
or calcium carbonate (Fischer and Wefer, 1999; Wefer et al., 1999; Huber et al., 2004).

The use of dinoflagellate cysts for reconstructing past oceanic conditions has increased during the last two decades in conjunction with an improved understanding of the distribution of modern dinoflagellate cysts in relation to various environmental parameters (e.g., de Vernal et al., 2001; Marret and Zonneveld, 2003; Marret et al., 2008; Marret and Kim, 2009). For example, *Operculodinium aguinawense* (Marret and Kim, 2009), found in marine sediments from the Gulf of Guinea in the Atlantic Ocean, showed an affinity for lower salinity conditions and thus may be a good indicator of paleosalinity changes. In addition, fluxes or changes in the relative abundances of heterotrophic dinoflagellate cysts have been used to estimate late Quaternary primary production or upwelling associated with changing nutrient conditions (e.g., Radi et al., 2007; Mertens et al., 2009; Kim et al., 2010).

Shelf sediments in temperate regions contain a relatively higher abundance of dinoflagellate cysts than sediments from open marine environments (McMinn, 1992; Dale, 1996). Of particular interest is the high representation of autotrophic dinoflagellate cysts (e.g., *Operculodinium centrocarpum*, and *Spiniferites* spp.) in shelf sediments from the northeast North Atlantic and North Pacific (Voronina et al., 2001; Novichkova and Polyakova, 2007; Radi et al., 2007; Radi and de Vernal, 2008). However, comprehensive studies of environmental factors that would cause such

\* Corresponding author. Tel.: +82 55 639 8580; fax: +82 55 639 8589.

E-mail address: [oceanlim@kordi.re.kr](mailto:oceanlim@kordi.re.kr) (D.-I. Lim).



**Fig. 1.** Map of the study area with locations of sediment samples, as well as the Kuroshio Current system on the northern shelf of the East China Sea : piston core 03–10 (31°37'N, 125°53'E; circle) and surface sediments (squares). After Ujiie et al., 2003.

a strong signal in the dinoflagellate cyst records of shelf sediments have been lacking.

The semi-enclosed East China Sea (ECS) is one of the largest marginal seas bordering the western Pacific, consisting of a broad continental shelf and the Okinawa Trough (Fig. 1). It receives tremendous input from runoff from the Changjiang (the third longest river in the world) with an annual mean freshwater discharge of about  $9 \times 10^{11} \text{ m}^3$  (Tian et al., 1993). The plume from the Changjiang disperses up to approximately  $85 \times 10^3 \text{ km}^2$  of sediment over the ECS area, and during summer the plume spreads farther eastward, reaching as far as Cheju Island and the shelf-break (Zhang et al., 2007). The annual sediment load carrying nutrients into the sea is about  $0.5 \times 10^9$  tons, half of which is deposited and accumulates in the Changjiang estuary (Milliman and Meade, 1983). A large part of the remaining material is likely transported southward and accumulates along the coast of China and the adjacent inner shelf (Shen et al., 1993; Liu et al., 2007; Lim et al., 2007). According to Edmond et al. (1985), annual nitrate, phosphate, and silicate levels from the Changjiang to the ECS are approximately  $6 \times 10^{10}$ ,  $1.3 \times 10^9$ , and  $12 \times 10^{10}$  mol, respectively. Away from the river mouth, there is an extensive exchange of waters and nutrients between the ECS and the Kuroshio, which flows northeastward along the eastern margin of the continental shelf (Chen, 1996; Liu et al., 2000).

Cho and Matsuoka (2001) previously showed the spatial distribution of dinoflagellate cysts in surface sediments of the Yellow Sea and East China Sea regions. However, the relationship between dinoflagellate cysts and nutrient concentrations in the shelf region has not been discussed, although it is of primary importance to understand the mechanisms responsible for the characteristic dinoflagellate cyst distributions in bottom sediments in relation to the nutrient status

of the overlying waters. The present study assessed the characteristics of dinoflagellate cyst assemblages and their potential use as indicators of marine productivity in shelf environments on the basis of gravity and piston core samples from the northern ECS shelf. To discern the relationship between coastal and shelf productivity, spatial variations of dinoflagellate cyst assemblages along cross-shelf transects are discussed.

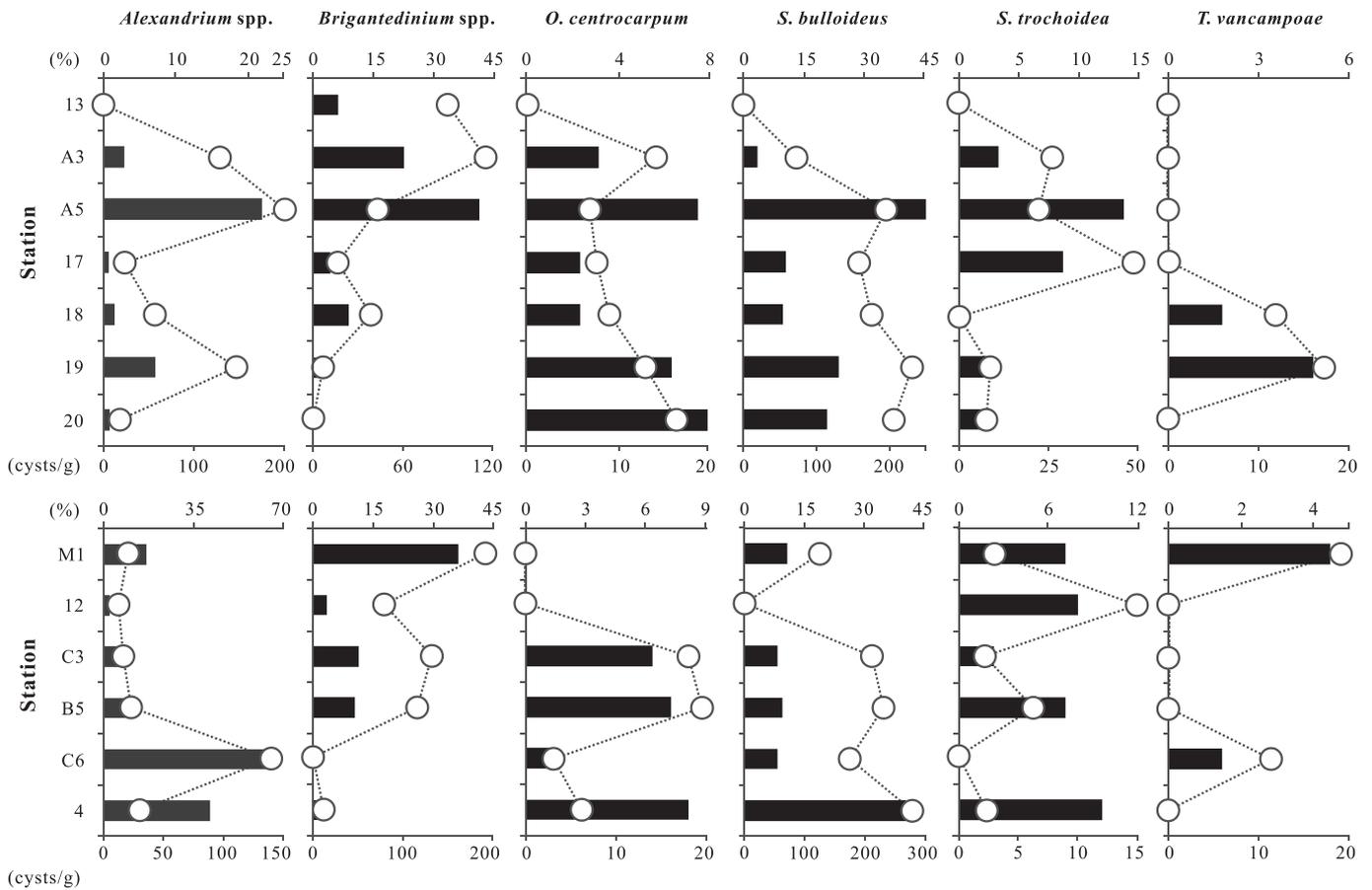
## 2. Materials and methods

For this study, surface sediment samples (the top 3 cm of gravity cores) from 13 sites were selected along two cross-shelf transects from the coastal zone around the Changjiang River mouth to the ECS shelf area in order to examine coastal and shelf productivity, and spatial variations of dinoflagellate cyst assemblages along the cross-shelf transect (Fig. 1). The original data of dinoflagellate cysts in these surface sediments are from Cho and Matsuoka (2001).

To analyze the vertical variations of dinoflagellate cysts in the shelf sediments, a piston core 03–10 (360 cm in length) was collected at 65 m water depth from the muddy bottom of the northern ECS (Fig. 1). Approximately 5 g of subsamples of core 03–10 was taken and treated by the following method. To prevent the dinoflagellate cysts from being damaged by the oven-drying process, the original sample was divided into two parts: one for measuring water content and the other for microscope analysis. The first was weighed wet and oven dried at 70 °C for a day to measure water content. The second was also weighed wet and then treated with ca. 50 ml of 10% hydrochloric acid (HCl) to remove calcium carbonate. To remove siliceous materials, the samples were also processed with ca. 50 ml of

**Table 1**  
AMS<sup>14</sup>C age data for piston core 03–10.

Core no.	Depth (cm)	Measured <sup>14</sup> C age (yr BP)	Error (years)	Conventional <sup>14</sup> C age (yr BP)	Error (years)	Dating material	Laboratory Ref. no.
03-10	20	500	40	890	40	Benthic foraminifera	Beta204935
	80	1240	40	1630	40	Benthic foraminifera	Beta204936
	200	1470	40	1860	40	Benthic foraminifera	Beta204937
	250	1780	40	2160	40	Benthic foraminifera	Beta221825
	298	2070	40	2470	40	Benthic foraminifera	Beta204938



**Fig. 2.** Relative abundances (%; open circle) and concentrations (cysts/g of dry sediment; black bar) of selected dinoflagellate cysts that occurred in the surface sediments along the cross-shelf transect.

47% hydrofluoric acid (HF) for about 24 h. After decanting and neutralizing with distilled water, the chemically treated samples were sonicated for 30 s and passed through stainless steel mesh sieves with 125 and 20  $\mu\text{m}$  pore sizes. The use of a 20  $\mu\text{m}$  pore size mesh sieve might cause loss of dinoflagellate cysts during preparation. However, given that most dinoflagellate cysts are in the size range of 30–65  $\mu\text{m}$  as shown in previous studies on the ECS shelf sediments (Cho, 2000; Cho and Matsuoka, 2001), the loss of dinoflagellate cysts due to the use of a 20  $\mu\text{m}$  mesh sieve would be negligible. Where possible, 300 dinoflagellate cysts were counted and identified from each sample with an inverted microscope (Olympus IX70) at 400 and 600 times magnification. The dinoflagellate cyst concentration in each sample was calculated as cysts/g dry weight of sediment:  $N/W(1-R)$ , where  $N$  is the number of counted cysts,  $W$  is the weight of the observed sediment, and  $R$  is the ratio of water content of the sediment. Microscope observation was carried out on 1 ml aliquot of the 10 ml refined sample, and  $N$  (observed cyst number) was obtained by multiplying the counted cyst number by 10 so that the number of cysts in 10 ml could be calculated.

Accelerator mass spectrometry (AMS)  $^{14}\text{C}$  dating was conducted on benthic foraminiferal tests (mixed species) due to the very low abundance of planktonic foraminifera. The dating materials were selected from nine horizons in piston core 03–10 (Table 1).  $^{14}\text{C}$  measurements were conducted at Beta Analytic, Inc. (Miami, FL, USA). All dates were calculated using the Libby half-life of 5568 years and a reference of 1950 A.D.

### 3. Results

Dinoflagellate cysts in surface sediments along the cross-shelf transect were classified into 16 genera and 22 species. They were divided into six

groups of gonyaulacoid, tuberculodinioid, calciodinellid, protoperidinioid, diplopsalid, and gymnodinioid taxa (Fig. 2). Gonyaulacoid and protoperidinioid groups were relatively abundant at all stations. Major species included *Alexandrium* spp. (relative abundance: 0–65.1%), *Brigantedinium* spp. (0–43%), *O. centrocarpum* (0–8.8%), *Spiniferites bulloideus* (0–42%), *Scrippsiella trochoidea* (0–15%), and *Tuberculodinium vancampoe* (0–5%). The total dinoflagellate cyst concentration ranged from 51 (St. 13) to 695 cysts/g of dry sediment (St. A5).

Dinoflagellate cysts in subsamples of piston core 03–10 were classified into 14 genera and 23 taxa categorized into four groups: gonyaulacoid, tuberculodinioid, protoperidinioid, and gymnodinioid taxa (Table 2; Figs. 3 and 4). The dominant species, with a relative abundance of > 10% in at least one sample were *S. bulloideus* (maximum abundance: ~67%), *Spiniferites* spp. (~47%), *O. centrocarpum* (~25%), *Spiniferites delicatus* (~12%), *Nematosphaeropsis labyrinthus* (0–26%), and *T. vancampoe* (~13%). *Brigantedinium* spp., *Lingulodinium machaerophorum*, and *Selenopemphix nephroides* also occurred at mostly less than 5%. Total dinoflagellate cyst concentrations in subsamples of core 03–10 ranged from 1648 to 8557 cysts/g of dry sediment. The radiocarbon ages of core 03–10 at sediment depths of 20, 200, 250, and 300 cm were  $890 \pm 40$ ,  $01,860 \pm 40$ ,  $2160 \pm 40$ , and  $2470 \pm 50$  years B.P., respectively, indicating that the sediments were deposited during the late Holocene.

The most notable observation made in this study was a predominance of gonyaulacoid species in the dinoflagellate cyst species composition in the shelf sediments. In core 03–10 from the outer shelf area, the gonyaulacoid group ranged from approximately 83 to 99% (94% on average), while the protoperidinioid group was less than 7% throughout the core subsamples (Fig. 5). Results of surface sediment analysis show a prominent disparity in dinoflagellate cyst species composition between coastal and shelf sediments. As shown in

**Table 2**  
Species composition and concentration (cysts per gram) of dinoflagellate cysts in piston core 03–10 from the northern ECS.

Species/depth (cm)	0	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	
<b>Gonyaulacoid group</b>																			
<i>Nematospaeropsis labyrinthus</i>	329	66	55	173	24	118	0	68	835	81	35	65	320	496	194	61	77	11	
<i>Lingulodinium machaerophorum</i>	6	19	0	14	24	0	10	0	79	16	17	11	0	25	0	12	13	11	
<i>Spiniferites bentorii</i>	11	19	18	43	47	0	69	15	32	0	26	33	20	50	43	61	0	22	
<i>Spiniferites bulloideus</i>	698	1088	893	1240	1544	1936	1512	942	898	1457	1416	2373	2218	4613	2797	2875	1929	3053	
<i>Spiniferites delicatus</i>	195	38	120	115	204	43	227	98	173	16	79	163	60	422	65	195	64	66	
<i>Spiniferites hyperacanthus</i>	33	19	37	29	133	96	69	45	32	81	44	293	100	446	32	97	26	110	
<i>Spiniferites membranaceus</i>	6	0	9	0	31	0	0	0	0	0	0	22	0	0	11	24	0	0	
<i>Spiniferites mirabilis</i>	56	47	18	115	47	107	89	90	63	130	52	130	120	124	86	122	39	55	
<i>Spiniferites ramosus</i>	73	47	28	43	16	139	69	23	221	81	44	217	60	0	32	24	13	44	
<i>Spiniferites</i> spp.	352	747	497	1182	384	1562	474	1175	378	1376	682	1365	899	2183	925	816	977	1113	
<i>Operculodinium centrocarpum</i>	128	104	111	159	180	96	296	105	268	178	184	184	260	0	151	219	51	121	
<i>Impagidinium</i> spp.	0	0	0	0	0	21	0	8	0	16	0	0	0	0	22	0	0	0	
<b>Gymnodinioid group</b>																			
<i>Polykrikos</i> sp.1 (rod-like)	17	9	0	14	0	11	20	0	0	16	0	11	0	0	22	12	0	55	
<i>Polykrikos</i> sp.2 (reticulum)	6	0	0	0	0	0	0	0	0	0	9	0	0	50	11	0	0	0	
<b>Tuberculodinioid group</b>																			
<i>Tuberculodinium vancamptoeae</i>	61	47	46	72	63	182	119	121	142	113	105	33	20	0	118	97	129	55	
<b>Protoperidinioid group</b>																			
<i>Brigantedinium</i> spp.	73	19	28	72	16	32	20	8	32	97	17	22	60	99	22	49	116	22	
<i>Quinquecuspid concretum</i>	0	0	9	0	0	0	10	0	0	0	0	0	0	0	0	0	0	0	
<i>Stelladinium</i> spp.	0	0	9	14	0	0	10	0	0	0	0	11	0	0	0	24	0	22	
<i>Selenopemphix nephroides</i>	6	0	0	0	0	21	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Selenopemphix quanta</i>	0	28	0	0	16	0	10	15	0	16	35	0	0	50	22	12	13	11	
<i>Trinovantedinium applanatum</i>	0	38	0	0	0	0	0	0	47	0	17	0	0	0	11	0	13	11	
<i>Votadinium calvum</i>	6	0	0	0	0	0	0	0	0	16	0	0	0	0	0	0	0	0	
<i>Xandarodinium xanthum</i>	0	0	0	0	0	0	0	15	0	0	0	0	0	0	11	0	0	0	
Total cysts per gram	2054	2336	1879	3287	2728	4364	3004	2728	3198	3691	2762	4930	4136	8557	4571	4702	3460	4783	

Fig. 6, higher occurrences of the heterotrophic dinoflagellate cysts (mainly protoperidinioid group) were mainly found in the vicinity of the mouth of the Changjiang, whereas the autotrophic dinoflagellate cysts (mainly gonyaulacoid group) showed a gradual increase toward the outer shelf area. The predominance of gonyaulacoid species in dinoflagellate cyst assemblages have been reported from the northeast North Atlantic and North Pacific shelf regions (Voronina et al., 2001; Novichkova and Polyakova, 2007; Radi et al., 2007; Radi and de Vernal, 2008). It should be noted that dinoflagellate cyst assemblages in marine sediments can be affected by differential preservation. Several studies have inferred that protoperidinioid dinoflagellate cysts were highly susceptible under oxidizing conditions (Zonneveld et al., 1997, 2001). However, given that the water depth of this region is shallow and dissolved oxygen levels in the bottom waters of the ECS shelf are generally low (Li et al., 2007; Chen, 2008), we consider that a species-selective degradation is negligible in our results.

#### 4. Discussion

During the last few decades, the use of dinoflagellate cysts for reconstructing paleoceanographic and paleoenvironmental conditions has been notably increased in parallel to an improvement in our understanding of modern dinoflagellate cyst distributions in relation to environmental parameters (de Vernal et al., 2001; Marret and Zonneveld, 2003; Matthiessen et al., 2005; de Vernal and Marret, 2007). Of particular interest is a close linkage between heterotrophic dinoflagellate cysts (mainly protoperidinioid group) and high nutrient conditions, where bottom sediments of highly productive regions with enriched nutrient concentrations and upwelling are characterized by the dominance of protoperidinioid cysts (e.g., Hamel et al., 2002; Marret and Zonneveld, 2003; Radi and de Vernal, 2004). In nutrient-enriched coastal environments, diatoms in particular benefit from the nutrients supplied and, as a consequence, heterotrophic dinoflagellates that feed on the diatoms can be more abundant than

autotrophic dinoflagellates (Kim et al., 2009). In deep-sea regions, the assemblage shifts between heterotrophic (protoperidinioid cysts) and autotrophic (gonyaulacoid cysts) taxa have been utilized as tracers for long-term variations of productivity changes in relation to upwelling intensity (Mertens et al., 2009; Kim et al., 2010). Based on these studies, we can reasonably assume that the low concentration of protoperidinioid cysts in the shelf sediments from the study area suggests unfavorable nutrient conditions in the upper water for these species. Supporting this notion, in the eastern part of the dilution zone off Changjiang River, the primary production in summer decreased from 1500 to 200 mg cm<sup>-2</sup> d<sup>-1</sup> in the outer continental shelf due to the influence of the oligotrophic Kuroshio Current (Guo, 1991). Kim et al. (2006a) also reported that nutrient concentrations in the upper 50 m of the northern ECS shelf waters at about 126°E were very low under the influence of the Kuroshio Current.

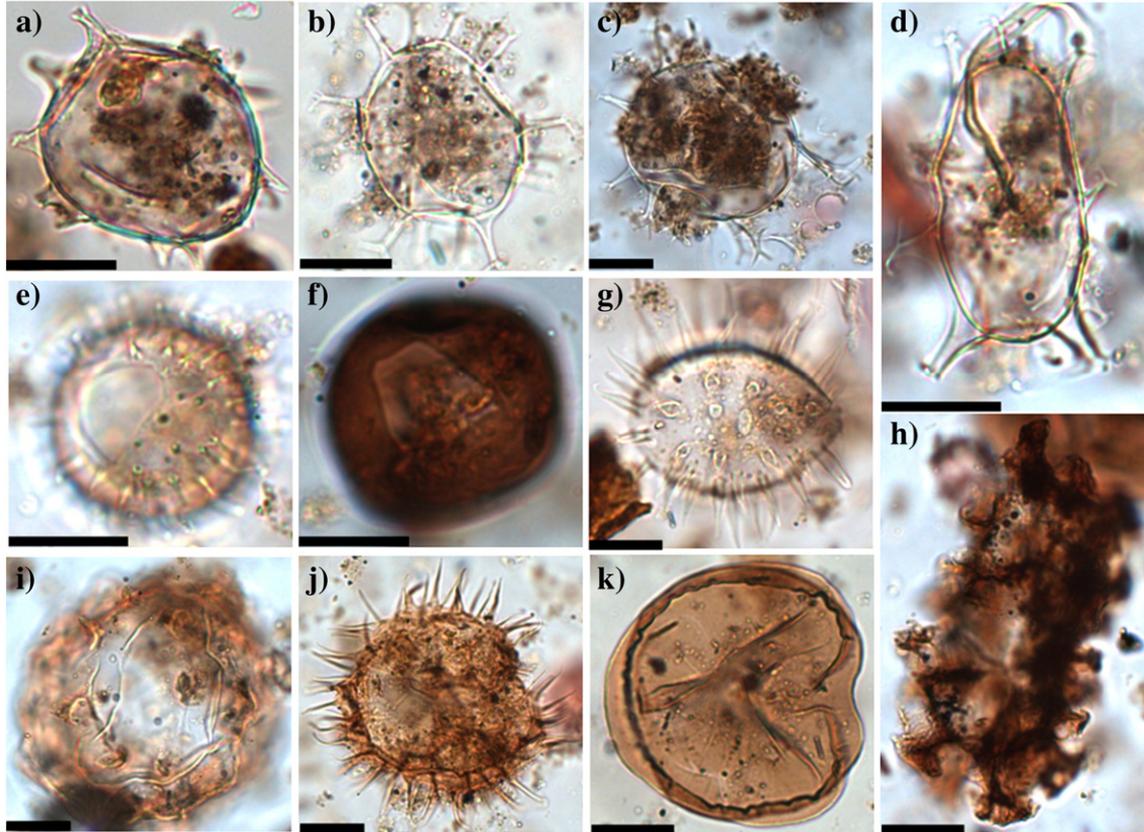
Another possible interpretation is that the disparity between gonyaulacoid and protoperidinioid groups in the northern ECS shelf sediments might be linked to the nutrient composition of the water affecting which dinoflagellate species are favored. Major nutrients dissolved in seawater include nitrate, phosphate, and silicate, which are usually required in large quantities and have the potential to control the growth of different types of algae (Pedersen and Borum, 1996). For instance, diatoms use silicon for their cell wall construction and therefore, diatom growth can be critically determined by the availability of silicate in seawater (Allen et al., 2005). Since diatoms are a food source for the heterotrophic dinoflagellates (Falkowski et al., 1985; Langdon, 1987; Tang, 1995), high diatom abundances in the upper water often result in higher accumulations of heterotrophic (i.e., protoperidinioid) and lower accumulations of autotrophic (i.e., gonyaulacoid) dinoflagellate cysts in the bottom sediments (Matsuoka, 1999; Kim et al., 2009).

Studies of variation in nutrient concentration across the ECS shelf show that in surface waters, nutrient concentrations gradually decrease from eutrophic coastal waters to oligotrophic open shelf waters (Chang et al., 2003; Asanuma et al., 2008). In particular, nitrate

180	190	200	210	220	230	240	250	260	270	280	290	300	310	320	330	340	350	360
48	453	111	224	35	29	81	45	69	100	109	63	8	128	8	60	118	21	117
10	4	18	11	17	0	0	18	0	19	0	38	0	0	0	12	0	0	0
48	22	55	11	17	14	0	45	28	13	39	0	0	0	0	6	17	0	16
2532	2873	2274	2093	1249	1629	1364	1729	1606	1381	1431	428	902	922	1337	883	465	970	749
68	435	37	139	35	0	97	323	42	151	178	138	157	43	128	138	101	52	31
19	67	92	43	26	43	32	125	69	100	79	0	41	34	40	12	42	21	0
0	13	0	0	0	0	16	9	0	13	10	0	0	0	0	0	8	0	0
39	94	111	43	52	72	65	81	194	44	59	38	8	102	40	66	17	41	62
48	54	148	11	17	43	32	54	14	44	20	0	8	51	8	12	8	41	8
1247	1136	1137	748	515	721	1218	564	789	684	1086	893	505	461	408	378	600	413	725
145	189	176	43	122	130	162	287	111	301	227	88	166	111	128	78	93	103	148
0	13	0	0	0	0	0	0	0	0	10	0	0	9	0	12	0	0	0
39	36	28	11	26	14	0	45	0	0	0	0	25	9	0	6	0	10	0
0	4	0	0	0	29	32	0	0	0	0	13	0	0	0	6	0	0	8
58	49	55	43	70	43	32	125	97	119	168	126	149	111	128	72	93	93	226
39	81	55	85	9	14	0	18	28	19	30	0	25	94	32	18	42	10	101
0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	4	0	11	0	0	0	0	14	13	10	0	0	9	8	0	0	21	0
0	0	0	0	0	14	0	0	28	0	0	0	0	26	8	12	17	0	8
29	9	28	53	0	0	16	0	0	13	20	63	0	17	0	12	17	21	31
0	18	0	11	9	0	0	9	0	0	10	13	33	17	8	6	8	10	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4369	5562	4326	3578	2202	2797	3151	3476	3088	3013	3484	1899	2028	2144	2281	1790	1648	1826	2230

and silicate concentrations in the shelf area were much lower than in both the Changjiang estuary and plume due to dilution by the input of Kuroshio water (Chen, 2008). According to Koshikawa et al. (2007), as

the Changjiang water flows eastward into the northern ECS and mixes with seawater, suspended particulate matter (SPM) that is enriched with silicate rapidly decreases in the shelf area (below 5–10 mg/l)



**Fig. 3.** Dinoflagellate cysts found in core 03–10 from the northern East China Sea shelf. (a) *Spiniferites bentorii*, (b) *Spiniferites bulloideus*, (c) *Spiniferites mirabilis*, (d) *Spiniferites elongatus*, (e) *Operculodinium centrocarpum*, (f) *Brigantedinium simplex*, (g) *Lingulodinium machaerophorum*, (h) *Polykrikos kofoidii*, (i) *Tuberculodinium vancampoeae*, (j) *Selenopemphix quanta*, (k) *Selenopemphix nephroides*. All scale bars are 20  $\mu$ m.

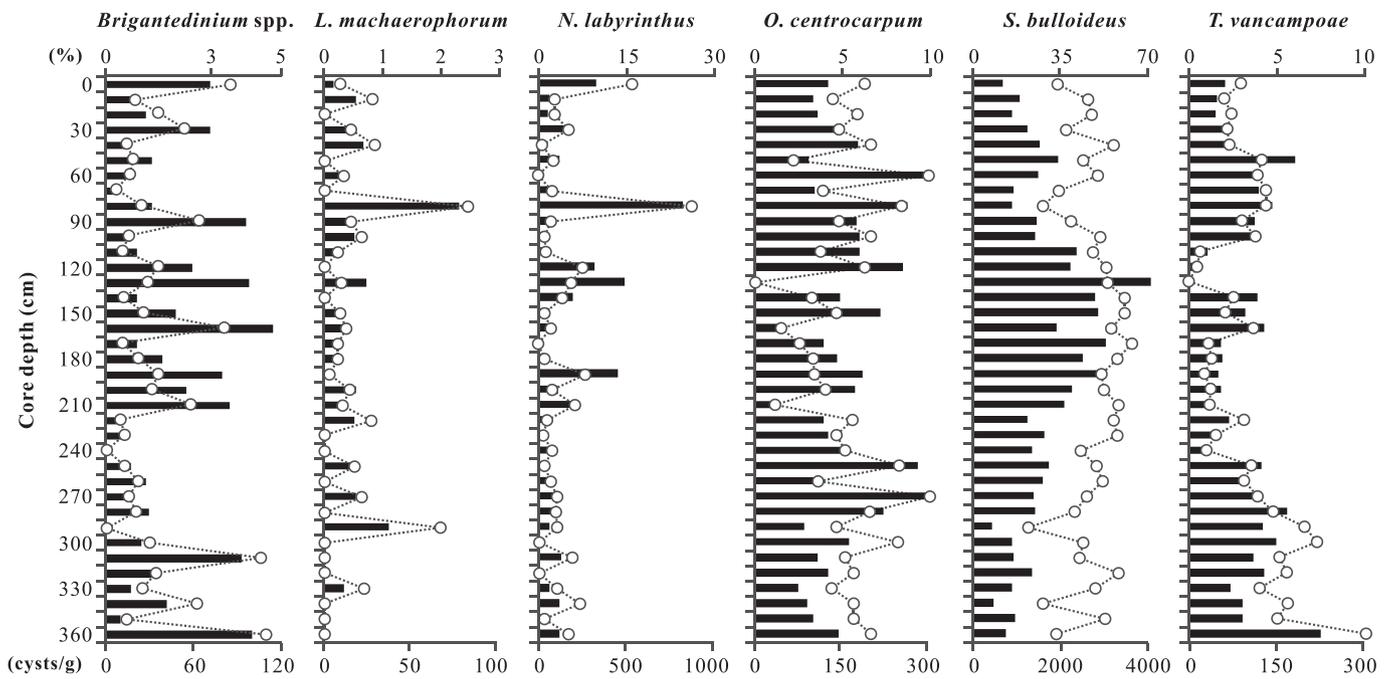


Fig. 4. Relative abundances (%; open circle) and concentrations (cysts/g of dry sediment, black bar) of major dinoflagellate cyst species from piston core 03–10.

around 123° E (St. A3 and C3 in this study, see Figs. 1 and 6). It has been suggested that phytoplankton growth in the northern ECS is limited by silicate availability farther offshore (Zhang et al., 2007). In fact, such a pronounced decrease in SPM concentrations across the shelf zone

corresponds to a decreasing pattern of protoperidinioid relative abundance as a function of longitude (Fig. 6). The nitrogen budget, however, is difficult to calculate relative to silicate due to complex nitrogen cycling activities, including nitrogen fixation by certain phytoplankton

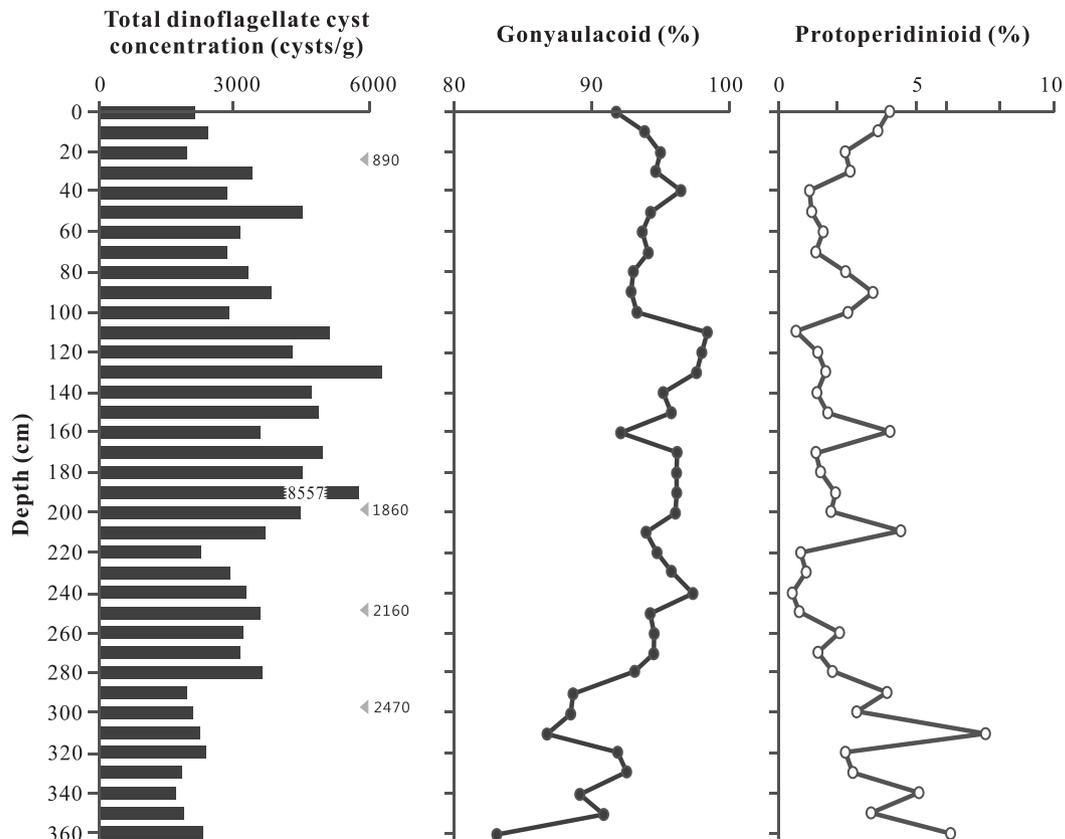
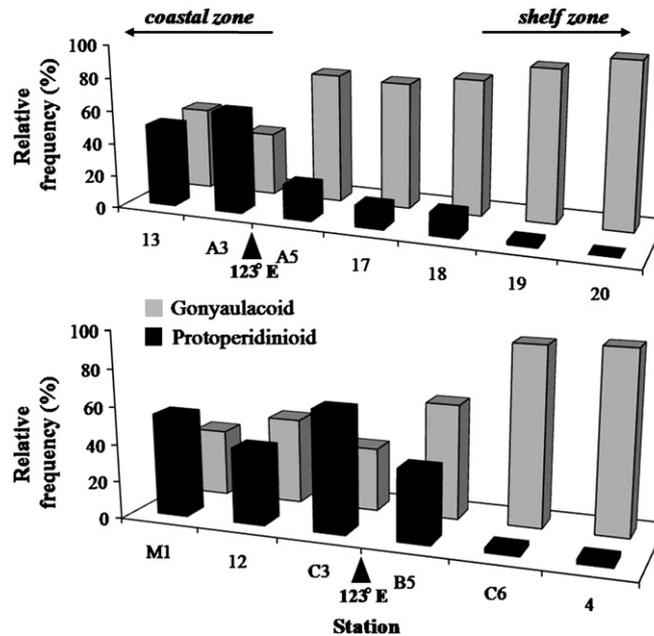


Fig. 5. Down-core variations of total dinoflagellate cyst concentrations and relative abundances (%) of the gonyaulacoid and protoperidinioid groups in core 03–10. Each triangle represents an AMS  $^{14}\text{C}$  age (years B.P.).



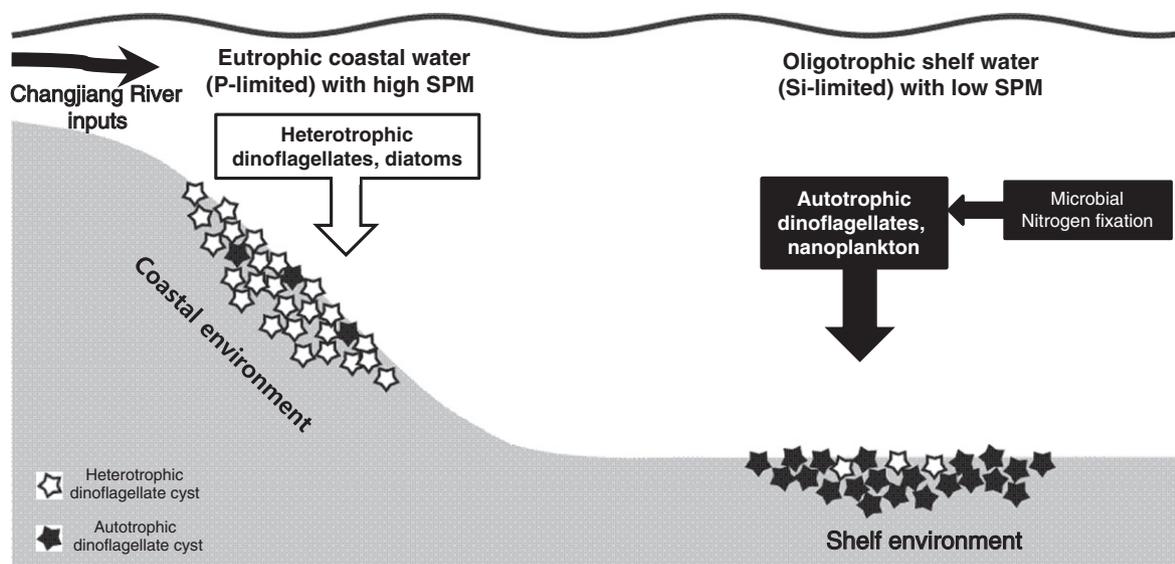
**Fig. 6.** Variations in relative abundance (%) of protoperidinioid and gonyaulacoid cyst groups identified from the surface sediment samples along the northern shelf of East China Sea. Note that relative abundances of the gonyaulacoid group in the surface sediments gradually increase toward the shelf, while those of the protoperidinioid group clearly show the opposite trend. Triangle indicates a sharply decreasing boundary of SPM concentration on the northern shelf of the East China Sea.

species (e.g., cyanobacteria) (Zhang et al., 2007). Such biological fixation can continually supply nitrogen into the sea in the form of compounds that can be utilized as nutrients for primary production (Hattori and Wada, 1974; Mahaffey et al., 2005; Capone and Knapp, 2007). Saino and Hattori (1980) suggested that nitrogen fixation could be an important source of nitrogen in the Kuroshio-influenced areas that show very low nitrate concentrations. As observed in the Changjiang Estuary and the ECS (Zhang et al., 2007), an increase in the particulate organic carbon (POC)/particulate nitrogen (PN) ratio in an offshore direction may be the result of consistent remineralization of nitrogen relative to carbon in the water column. In this study, a shift from high biogenic silica (BSi)/POC ratios in the coastal waters to low BSi/POC ratios in the open shelf area, with a corresponding decrease in diatom biomass, has been recognized. Therefore, it is entirely possible that although nutrient conditions are generally poor in terms of nitrogen and silicate in the offshore areas of the northern ECS (e.g., Zhang et al., 2007), autotrophic dinoflagellates (i.e., the gonyaulacoid group) or nannoplankton can still bloom because of biological nitrogen fixation (Fig. 7). In conclusion, the supply of nitrogen and silicate from the Changjiang discharge remained relatively low in the outer shelf of the northern ECS due to the influence of the oligotrophic Kuroshio Current (Guo, 1991). However, nitrogen could have been constantly supplied by nitrogen fixation, resulting in a selective advantage for the autotrophic (gonyaulacoid) dinoflagellates, while the growth of diatoms and heterotrophic (protoperidinioid) dinoflagellates may have been limited by the availability of silicate in the water column. Further studies are needed to improve our understanding of the key biogeochemical and depositional processes as well as other sea-surface environmental factors (e.g. temperature and salinity) that control dinoflagellate cyst records in the northern ECS. Notably, it has been reported that the recent construction of the Three Gorges Dam in the upper reaches of the Changjiang may result in a reduction in the supply of silicate and SPM to the shelf, changing the dominant phytoplankton species composition from diatoms (siliceous) to flagellates (non-siliceous) off the river mouth and the ECS (Kim et al., 2006b; Li et al., 2007; Chai et al., 2009). We speculate that in the future this change will yield more severe variations in the nutrient concentrations, ratios and potential nutrient limitation of phytoplankton assemblages in the ECS shelf.

Taken as a whole, the gonyaulacoid dinoflagellate cysts are suggested to be a potentially useful proxy indicator of marine productivity in the shelf environment of low nutrient concentration levels, especially of silicate. This implies that the vertical variations of dinoflagellate cyst concentrations (i.e. the gonyaulacoid group) in core 03–10 can be indicative of changes in marine productivity over the northern ECS shelf during the Holocene period. Previous studies have reported that the postglacial increase of marine productivity over the northern ECS shelf appears to be punctuated, particularly between ca. 2000 and 3000 years B.P. (An et al., 2000, 2006; Kang et al., 2010; Kim et al., 2010). There are considerably lower dinoflagellate cyst concentrations in core 03–10 until ca. 2000 yr B.P., followed by a marked increase (Fig. 5). We speculate that the lower concentration of dinoflagellate cysts during this period (2000–3000 years B.P.) indicates a deterioration of nutrient availability in the northern ECS shelf environment, probably linked to reduced sea surface temperatures and sea-surface salinity as a result of a weakened influence of the warm Kuroshio Current waters over the northern ECS (Ijiri et al., 2005; Xiang et al., 2007; Lim et al., 2011). Further investigations on additional sediment cores from this area and therefore, more precise correlation between signals of the late Holocene climatic changes are required for improving our paleoclimatic interpretation.

## 5. Conclusions

The northern ECS shelf sediments showed a prominent disparity in species compositions of dinoflagellate cysts between coastal sediments around the mouth of the Changjiang (dominated by protoperidinioid species) and offshore sediments (dominated by gonyaulacoid species). The predominance of gonyaulacoid cysts over protoperidinioid cysts in the shelf region suggests that the growth of diatoms and diatom-feeding heterotrophic dinoflagellates (i.e., the protoperidinioid group) may have become limited by the availability of silicate in the water. In contrast, autotrophic dinoflagellates (i.e., the gonyaulacoid group) not reliant on silicate availability in the water would still have been able to bloom because of a continual supply of nitrogen through microbial nitrogen fixation. Spatial distributions of dinoflagellate cysts along the cross-shelf



**Fig. 7.** Schematic diagram of dinoflagellate cyst productions on the northern shelf of the East China Sea in relation to river inputs and nutrient conditions. As the Changjiang River water flows eastward onto the shelf, SPM concentration rapidly decreases. The growth of siliceous phytoplankton and diatom-feeding heterotrophic dinoflagellates becomes limited in the shelf region due to the lack of silicate in the water. Autotrophic dinoflagellates that are not relying on silica availability in the water take advantage due to a continual supply of nitrogen through microbial nitrogen fixation.

section have been successfully matched to nutrients and SPM data, supporting this hypothesis. This study suggests that gonyaulacoid dinoflagellate cysts are potentially useful tools for reconstructing paleoproductivity in shelf environments with low nutrient levels.

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