Anthropogenic nitrogen is changing the East China and Yellow seas from being N deficient to being P deficient

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Abstract
Addition of the increased anthropogenic nitrogen (NOx and NH4) emitted from northeast Asian countries to the Yellow and East China seas and coastal waters around Korea has resulted in an unparalleled increase in the nitrate (N) concentration relative to the phosphate (P) and silicate (Si) concentrations in the upper ocean. We found that for the Yellow Sea the increase in N over P was largely explained by increased atmospheric nitrogen deposition, whereas for the northern East China Sea, downstream of the Changjiang River plume, the trend in N increase relative to P was more associated with a change in the combined input of nutrients from atmospheric deposition and riverine discharges. In contrast, the dynamics of the N to P relationship in the southern East China Sea was largely controlled by a change in the intrusion intensity of the Kuroshio Current, which has a low N : P ratio. The disproportionate and persistent input of nutrients to the marine waters of this region over the past four decades has transformed extensive areas from being N deficient to being P deficient, and has concurrently decreased the concentration of Si relative to N. In coastal waters around Korea in particular, these shifts in the nutrient regime have been accompanied by a change from diatom-dominated to dinoflagellate-dominated blooms. Given the complexity of coastal ecosystems, the associations between changes in nutrient regimes and biological changes need to be investigated in other coastal areas receiving increasing loads of anthropogenic nitrogen.

On a millennium time scale, N and P inventories in the global ocean tend to converge to a nearly constant ratio of 16 (Anderson and Sarmiento 1994; Gruber and Sarmiento 1997) because of the restorative nature of ocean biogeochemical processes (Tyrrell 1999). In the contemporary global ocean, where the condition of N deficiency is widespread, N2-fixing microorganisms bring N into the near-equilibrium with respect to P. As N deficiency is alleviated by N2 fixers, the rate of denitrification (resulting in a loss of N) in low oxygenated or anoxic environments tends to increase as a result of increased respiration of organic matter (Gruber 2004). By comparison, P input from weathering and P burial in sediments approximately balance the ocean P budget (Delaney 1998). A conceptual model that describes the impact of biological feedback on ocean N and P inventories shows that the ocean N inventory cannot exceed the product of the ocean P inventory and the mean N : P ratio of phyttoplankton (16/1), but approaches that value because of the slow growth rate of N2 fixers or denitrifiers (Tyrrell 1999).

The slight N deficiency in the global ocean is being rapidly perturbed by the much greater input of anthropogenic nitrogen (NOx and NH4, where NOx refers to NO and NO2 and NH4 refers to NH3 and NH4+) relative to P. The northeast Asian countries (China, Japan, and Korea) have become the largest source of

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The composition of bloom-forming phytoplankton species. Significant correlation of this increase with the rate of anthropogenic nitrogen deposition (Kim et al. 2011a, 2014a). Moreover, another major nutrient input into the northeast Asian marginal seas is via the Changjiang River discharge, which has also increased over time (Dai et al. 2011; Liu et al. 2018).

This input of anthropogenic nitrogen could increase the phytoplankton biomass in Asian marginal seas that have been N deficient (Kim et al. 2014b). Such an increase in the production of planktonic organic matter could exacerbate hypoxia by increased oxidation of the resulting organic matter (Wang et al. 2016). Moreover, the disproportionate increase in N relative to both P and Si may trigger a change in the phytoplankton community structure (Tilman et al. 1982; Vallina et al. 2014a). The immediate and long-term consequences of anthropogenic nitrogen input are becoming evident, but their magnitude and direction remain largely unknown.

In this study, we assessed whether the study area (East China Sea, Yellow Sea, and coastal waters around Korea) is shifting from N deficiency towards P deficiency as a result of anthropogenic nitrogen input, using observational data spanning nearly four decades (1980–2016). We also assessed whether the changeover in the nutrient regime is associated with the change in the bloom-forming phytoplankton group in the coastal waters of Korea. Data on bloom-causative species have been obtained from the analysis of a total of 1470 phytoplankton bloom events that occurred in the coastal waters around Korea over the period of 1981–2008. This study presents observational evidence supporting the direct influence of anthropogenic nitrogen on a large scale shift in nutrient regime from N deficiency to P deficiency, and hence on the composition of bloom-forming phytoplankton species.

**Methods**

**Nutrient data**

We used a total of 102,500 sets of nutrient data (nitrate; N, phosphate; P, and silicate; Si) that cover much of the East China Sea, the Yellow Sea and the coastal waters of Korea collected over a period of 36 years. The datasets used in our analysis are archived at three repositories: the Korea Ocean Data Center (http://www.nifs.go.kr/kodic/index.kodc); the Japan Ocean Data Center (https://www.jodc.go.jp/jodcweb/index.html); and the World Ocean Database 2018 (https://www.nodc.noaa.gov/OC5/WOD/pr_wod.html). Prior to data analysis, we evaluated the consistency of various sources of data to eliminate systematic errors caused by the differences in analytical methods and analysts. The detailed procedure for the quality control of data is described in Supplementary text S1. The seasonal coverage of the datasets is discussed in text S2. Nutrient concentration data below analytical detection limits (0.1 μM for N and Si, 0.01 μM for P) (Zhang et al. 2001) were not included in our analysis. The present study is a significant extension of the previous work of Kim et al. (2011a) (1) by expanding the study area southward to 25°N (approximately 24,400 datasets were newly added); (2) by including more recent data collected after 2010 (12,300 datasets); and (3) by including 9800 additional datasets archived at World Ocean Database that were not used in the previous study.

The abundance of N over P in seawater was calculated as $N' = [N] - R_{N/P} \times [P]$, where $[N]$ and $[P]$ are mean concentrations of N and P at a given depth range for each sampling location, and $R_{N/P}$ is the Redfield ratio of 16 (Anderson and Sarmiento 1994). A negative $N'$ value indicates the concentration of seawater N being lower than that predicted based on the concentration of P multiplied by 16, whereas a positive $N'$ value indicates the opposite condition. The $[N]$ term did not include dissolved organic nitrogen (DON), because the DON concentration did not change discernably even in the productive study area, particularly downstream of the Changjiang River (Kwon et al. 2018). The near conservative behavior of DON just like salinity means little utilization of DON by phytoplankton. Nonetheless, we cannot completely rule out the possibility of the involvement of DON in biological activity, because no experimental data regarding the utilization of DON by phytoplankton are available for our study area. Seawater NH$_4^+$ was not included in our analysis because no relevant data are available for our study area. However, were such data available it would be unlikely to change our conclusions significantly, because the concentration of NH$_4^+$ in our study area is an order of magnitude lower than that of N (Shin et al. 2003).

Variations in the $N'$ value reflect the net result of changes in external N input (via N$_2$ fixation, riverine input, and atmospheric deposition) and N removal (denitrification). As our analysis focused on surface nutrient data, it was reasonable to assume that the effect of denitrification on the seawater N concentration was minimal. N$_2$ fixation activity could also have contributed to an increase in $N'$, but the rate of N$_2$ fixation in our study area was found to be too small to discernably increase the seawater $N'$ (Kim et al. 2011a; Zhang et al. 2012). As a result, the temporal variations in the $N'$ value in the study area are likely to reflect the change in the input of anthropogenic nitrogen. In a similar way to that for $N'$, the concentration of Si relative to N was calculated using the formula $Si' = [Si] - R_{Si/N} \times [N]$, where $R_{Si/N}$ is the elemental ratio (1.12) of silicon to nitrogen in low latitude marine diatoms (Brzezinski 1985). The nutrient deficiency, indicated by $N'$ or $Si'$, was defined as the stoichiometric deficit of one element relative to another (Moore et al. 2013).

The nutrient concentrations for the majority of the total N data > 1 μM N and 85% of the total P data > 0.06 μM P) used in our analysis exceeded the limiting
levels; this indicates that our study area was not nutrient limited. Therefore, the use of N* or Si* was a reasonable indicator of nutrient deficiency in our study area.

**Determination of three regional domains**

To assess the temporal trends of N* in the study area, we applied empirical orthogonal function analysis to nutrient concentration data to identify unique spatial and temporal patterns (modes) in the data (text S3). This analysis revealed that the study area can be divided into three subregions, each showing a distinct trend in N* over time. The boundaries of three subregions are dynamic and coincide approximately with the boundaries of major currents. In particular, subregion B broadly corresponds to the area under the direct influence of freshwater discharge from the Changjiang River (text S4).

**Nutrient inputs via atmospheric deposition and river discharge**

The deposition of atmospheric nitrogen to the study area was determined from measurements made at Jeju and Kangwha (parts of the Acid Deposition Monitoring Network in East Asia and data available at https://www.eanet.asia/), and also at Anmyeondo (operated by the Korea Meteorological Administration). At Anmyeondo located on the west coast of Korea (36.53°N, 126.32°E), only wet nitrogen deposition was measured. Therefore, for the estimation of dry nitrogen deposition, we used measurements made at Kangwha (37.71°N, 126.27°E), north of Anmyeondo. Wet nitrogen deposition at monthly or yearly intervals was calculated as the product of total precipitation and the weighted mean concentration of NO₃⁻, NH₄⁺, and NO₂⁻ from the Changjiang River were derived from the studies of Dai et al. (2011) and Liu et al. (2018). As Liu et al. (2018) reported only on total nitrogen (TN) and total phosphorus (TP) loads, we estimated the riverine DIN load by multiplying TN by the DIN/TN ratio (0.5) (Yan et al. 2001), and the DIP load by multiplying TP by the DIP/TP ratio (0.14) (Yang et al. 2008). The proportion of the Changjiang River freshwater transported to the northern East China Sea was estimated to be 37% of the total Changjiang River discharge (Moon et al. 2012).

**Bloom forming phytoplankton**

In the early 1980s, the National Institute of Fisheries Science of Korea established a network of 130 observatories that monitor phytoplankton bloom events in the coastal regions of Korea (within 30 km of the coastline). The activities for monitoring phytoplankton bloom events have been performed at weekly intervals from 1981 to the present. The occurrence of a phytoplankton bloom was identified primarily by a change in the seawater color, and this water was sampled. Seawater samples were immediately preserved with Lugol’s solution and later examined for phytoplankton species identification and cell enumeration using an optical microscope. The phytoplankton species in the colored bloom water sampled may not contain all bloom-forming species occurring in waters around Korea. However, the similarity between the major bloom-forming phytoplankton species in our study and those detected in several other studies conducted in Korean coastal waters (Moon and Choi 2003) justifies our sampling strategy in bloom identification. The same protocols for bloom identification, sample collection, species identification, and cell enumeration have been applied consistently throughout the entire observational period and the resulting data are archived at http://www.nifs.go.kr/red/news_2.red.

A total of 1470 bloom events were observed in the coastal waters of Korea over the 28-year period from 1981 to 2008. Since 2009, the bloom survey was centered on harmful algal species; consequently, bloom data from 2009 onwards were not included in our analysis. Approximately 98% of the total bloom events occurred between March and October, with 68% of the total bloom outbreaks occurring between July and September (Fig. S1). In the 1980s, bloom surveys were primarily concentrated in Jinhae bay (128.4°–128.9°E, 34.7°–35.2°N), while in the subsequent period bloom data were obtained from both Jinhae bay and other coastal waters around Korea. Analysis of the seasonal and spatial coverage of the bloom data is described in text S5. We assessed the contribution of each phytoplankton group to the annual total bloom events by calculating the % proportion of the bloom events caused by a given group. Among eighth groups of phytoplankton identified, diatoms and dinoflagellates were the major bloom-
forming groups accounting for $80 \pm 8\%$ of the blooms observed over the study period.

**Results**

The nutrient regime changeover

Negative $N^*$ values ($N$ deficient condition) prevailed throughout surface waters (less than 20 m depth) of the Yellow Sea, the East China Sea, and the coastal waters of Korea during the 1980s (Fig. 1a). In the 1990s $N^*$ values remained predominantly negative, but the degree of $N$ deficiency reduced (Fig. 1b). The notable feature in this period was that positive $N^*$ values ($P$ deficient condition) began to emerge in the vicinity of the Changjiang estuary, and with time towards the 2000s the area having positive $N^*$ values progressively expanded beyond the estuary (Fig. 1c). The ocean region being transformed from $N$ deficiency to $P$ deficiency expanded mostly in a northeast direction to the northern part of the East China Sea (approximately agree with the summertime pathway of the Changjiang Diluted Water; text S4), eastwards to the coastal waters south and east of Korea, and also to the coastal areas southwest of the Changjiang estuary. During the transition period from the 2000s to the 2010s, the $P$ deficient area expanded in the northern part of the East China Sea, and also became evident in the Yellow Sea. In contrast, the degree of $P$ deficiency in the coastal waters east of Korea reduced, and eventually changed to a neutral condition ($N^*$ close to zero) (Fig. 1d).

The surface $N^*$ values generally increased in all three subregions showing slightly different trends (Fig. 2). In subregions A and B an increase in $N^*$ reversed to a trend of decrease in the mid-2010s and mid-2000s, respectively. For subregion C (the central and southern East China Sea), the increase in $N^*$ was considerably small relative to subregions A and B. However, $N$ deficiency has gradually narrowed over time.

**Discussion**

Factors affecting seawater $N^*$ dynamics

Over the past 36 years the rate of increase in $N^*$ in subregions A, B, and C differed among various time periods. To estimate the contribution of varying sources of nutrients to the seawater $N^*$ trends, for subregions A and B we compared anomalies of the seawater $N^*$ inventory with those of airborne and river-borne nutrient fluxes, and for subregion C we compared changes in $N^*$ with the change in nutrient flux from the intrusion of the Kuroshio Current into that region.

The $N^*$ inventory for the Yellow Sea (the red shaded area in the inset of Fig. 3a) was significantly correlated ($p$-value $< 0.05$) with the deposition of atmospheric nitrogen measured at the west coast of Korea (Figs. 3a, S2a). Both parameters increased until the early 2010s and then declined thereafter (Fig. 2a). The increase in atmospheric nitrogen deposition here was at least partially associated with the increasing emission of NO$_x$ from China (from 12.2 Tg in 2000 to 26.1 Tg in 2010) (Zhao et al. 2013). The emissions of NH$_3$ from China increased from 5.9 to 11.1 Tg over the period of 1980–1996, remained unchanged until 2005, and then declined slightly to 9.7 Tg in 2012 (Kang et al. 2016). The NO$_x$ emissions from China were predominantly from the provinces located along the Yellow Sea coast (for example, Beijing, Tianjin, Shandong, Jiangsu, Shanghai, and Zhejiang) and consequently, have probably affected the Yellow Sea $N$ concentration (thereby $N^*$ as well) through the addition of nitrogen pollutants transported via prevailing westerly winds (Luo et al. 2014). Some pollutant nitrogen may also be added to the Yellow Sea, via the Huanghe River (discharging into the Bohai Sea) and the Changjiang
River (discharging into the East China Sea). These contributions were not included in the Yellow Sea nutrient analysis because these rivers do not directly discharge into the Yellow Sea. However, the change in the Yellow Sea N inventory being greater than that in atmospheric nitrogen deposition to the same basin indicates that the riverine DIN load may be an equally important contributor to nutrient dynamics in the Yellow Sea (Fig. S3). Two Korean rivers (the Han and the Geum rivers) discharge directly into the Yellow Sea; the impact of the nutrient flux from those two rivers on the Yellow Sea N concentration (thereby N') was reported to be minor (Kim et al. 2013).

Changes in the N' inventory in the northern East China Sea (the red shaded area in the inset of Fig. 3b) also showed a significant correlation (p-value < 0.001) with changes in the nutrient flux from anthropogenic sources (riverine N' flux and atmospheric nitrogen deposition combined) (Figs. 3b, S2b). The N' flux from the Changjiang River and the seawater N' in the northern East China Sea both increased from the late 1980s to the 2000s, and declined thereafter (Fig. 2b). The increase in nutrient load from the Changjiang River was closely associated with the population growth in its watershed and the increased use of nitrogenous fertilizers (Dai et al. 2011). The atmospheric nitrogen deposition flux was only 26% of the N' flux from the Changjiang River. Therefore, river-borne nutrient input is a major factor determining the seawater N' dynamics in the northern East China Sea.

The dynamics of seawater N' in subregion C was found to be more controlled by the change in the intrusion of the Kuroshio Current having a low N : P ratio (13.7 : 1) than by the change in anthropogenic nitrogen input (Zhang et al. 2007a). A recent study has reported that, with the exception of years
after 2002, there has been a decline in intrusion into subregion C by the Kuroshio Current (Wu et al. 2017). This has led to a greater decrease in the input of P relative to N in subregion C, and resulted in an increase in N*. The gradual increase in N* in subregion C is broadly consistent with a decrease in the intrusion of the Kuroshio Current.

Anthropogenic nitrogen deposition vs. precipitation

Wet nitrogen deposition accounts for > 70% of total atmospheric nitrogen deposition added to the Yellow Sea (Zhang et al. 2007b), and is determined by the amount of precipitation and the concentration of NO\textsubscript{3}\textsuperscript{−} and NH\textsubscript{4}\textsuperscript{+} in precipitation. At the Anmyeondo and Jeju sites (located on the Korean side of the Yellow Sea and the northern East China Sea, respectively), the amount of wet nitrogen deposition was positively correlated with that of precipitation (Fig. 4). At Anmyeondo, 75 ± 11% of annual precipitation and 67 ± 11% of annual wet nitrogen deposition occurred during summer and fall. Rainfall at Jeju was approximately even among seasons; 66 ± 11% of annual precipitation and 56 ± 15% of annual wet nitrogen deposition occurred during summer and fall. Because of high anthropogenic emissions and the northerly monsoon in winter, the NO\textsubscript{3}\textsuperscript{−} and NH\textsubscript{4}\textsuperscript{+} concentration in rainwater is higher in winter than in summer (Zhang et al. 2011). The correlation between the rainwater NO\textsubscript{3}\textsuperscript{−} and NH\textsubscript{4}\textsuperscript{+} concentration and wet nitrogen deposition was weak.

Modeling studies have projected a future increase in summertime precipitation over the extended areas of East Asia, which will probably increase wet nitrogen deposition and phytoplankton biomass in the marginal seas adjacent to the East Asian countries (Wang et al. 2018). Therefore, future variabilities in precipitation and emissions of anthropogenic nitrogen could primarily dictate whether the study area is subject to excess N relative to P or Si.

Ecological implications of nutrient regime changeover (a case study in Korean coastal waters)

Complex interactions of physical (temperature, turbulence, and stratification), chemical (nutrients), and biological (grazing, food web, allelopathy, and mixotrophy) factors determine which phytoplankton groups dominate in blooms in the marine environment. Any change in one or more of these factors over an extended period could induce a change in bloom-forming phytoplankton species. However, data concerning all relevant factors that influence the dominance of particular phytoplankton groups in blooms are unavailable for most ocean environments. Therefore, for this section we only explored the association between a change in the bloom-forming phytoplankton group (from diatoms to dinoflagellates) in coastal waters of Korea and changes in ocean nutrients and temperature. These two factors have previously been shown to play a role in phytoplankton composition change (Marinov et al. 2010), and are also able to be tested because over 30 years of data concerning these factors are available. As data concerning other physical and biological factors are not available for Korean coastal waters, we could only assess their possible roles using several lines of circumstantial evidence.
In the ocean environment, phytoplankton species have a wide range of competitive abilities, depending on their capacities of nutrient transport, accumulation, and utilization (Flynn 2002). Their diverse responses to nutrient supply can lead to changes in the phytoplankton community structure (Lagus et al. 2004), and the competitive exclusion among phytoplankton groups tends to exert stronger control than that among within-group members (Vallina et al. 2014b). Among phytoplankton groups, diatoms and dinoflagellates are ubiquitous in global coastal waters, and their relative abundance has been identified as a good indicator of nutrient regime changeover (Egge 1998; Wasmund et al. 2017; Zhou et al. 2017). To further explore the link between the dominance of either diatoms or dinoflagellates in phytoplankton assemblages and changes in the regional nutrient regimes, we analyzed data on bloom-causing phytoplankton species in the coastal waters of Korea, and compared the involvement of diatoms and dinoflagellates in bloom events with seawater N* and Si* concentrations.

The % proportion of dinoflagellate blooms occurred per year in the coastal waters of Korea has increased over time from 1981 to 2008 (the pink bars and the pink line in Figs. 5, S4), and is consistent with the summer (July to September) trend of seawater N* in the same region from which bloom data were obtained (the yellow line in Fig. 5b). The % proportion of blooms dominated by diatoms per year has contrarily decreased during the same period (the blue bars and the blue line in Figs. 5, S4). The proportion of blooms caused by Skeletonema and Thalassiosira spp. decreased considerably and approached zero, whereas those caused by Chaetoceros spp. remained relatively constant (Fig. S4). Si is another limiting nutrient for diatoms (O汜cer and Ryther 1980). The concentration of Si relative to that of N in the study area has gradually decreased since the mid-1990s (the green line in Fig. 5b; text S6); this has probably been a major cause of the decrease in the frequency of diatom-dominated blooms. The broad agreement between the trends in the % proportions of diatom and dinoflagellate blooms and those of increasing N* and decreasing Si* in seawater is compelling evidence that the nutrient regime shifts have played a critical role in changing the dominant bloom species from diatoms to dinoflagellates in the Korean coastal waters.

Fig. 4. Correlation plots between precipitation (mm month\(^{-1}\)) or monthly mean concentration of NO\(_3^–\)+NH\(_4^+\) (\(\mu M\)) in rainwater and wet nitrogen deposition (mmol m\(^{-2}\) month\(^{-1}\)), measured at (a and b) Anmyeondo and (c and d) Jeju. The dashed lines indicate the least-square linear fits, and \(r\) refers to the correlation coefficient.
The change in nutrient regime may not be the only cause of the change in bloom-forming species from diatoms to dinoflagellates. The seawater temperature increase is another factor that could contribute to the change in bloom-forming species in the study area. During the period of 1968–2008, summertime surface temperature increased at a rate of 0.10°C decade⁻¹ (23.7 to 24.1°C) for the East Sea, 0.15°C decade⁻¹ (25.5 to 26.1°C) for the Yellow Sea and 0.38°C decade⁻¹ (25.5 to 27.1°C) for the coastal waters south of Korea (Seong et al. 2010). The temperature increase across the study area may favor dinoflagellates, as the optimal growth temperature for dinoflagellates (~26°C) was reported to be higher than that for diatoms (~24°C), in the East China Sea (Xiao et al. 2018). As a result, the increase in dinoflagellate bloom frequency was likely favored not only by the changeover in the nutrient regime but also by the increase in surface temperature in all coastal waters around Korea. We are not able to exclude the possibility of changes in stratification and turbulence as causes of change in the dominant bloom species from diatoms to dinoflagellates. As changes in turbulence and stratification are closely associated with the change in ocean temperature, the trend in ocean temperature may reasonably represent the trends in turbulence and stratification.

Our analysis did not explicitly evaluate how intrinsic biological factors (grazing, food web, allelopathy, mixotrophy) might cause changes in phytoplankton species composition. In our analysis we assumed that the impacts of those biological factors did not change throughout the study period, given the low likelihood that a particular biological process changed consistently over a decadal time scale. The lack of relevant biological data is a hindrance to the evaluation of the contributions of those factors to species composition change. Future
studies involving the long-term measurement of various biological factors will greatly contribute to the understanding of changes in the dominant bloom-causing phytoplankton groups in this region.

An increase in the frequency of dinoflagellate blooms and its association with a regional increase in the seawater N abundance are also supported by the findings of a range of studies, including local observations, incubation experiments and modeling studies in the East China Sea (e.g., Guo et al. 2014; Xiao et al. 2018). Moreover, anthropogenic change in the stoichiometry of nutrient loads has been reported to shift the dominance from diatoms to dinoflagellates in phytoplankton assemblages in the Yellow Sea, the South China Sea, and the North Sea (Cloern 2001; Glibert 2020). However, given the complexity of coastal ecosystems, future studies to distinguish the importance of anthropogenic nutrient inputs from the contribution of other factors are required to broaden our findings to other coastal areas.

The shift from diatoms to dinoflagellates as the major bloom-forming group has profound implications in regard to carbon export production in coastal and marginal seas. In terms of the efficiency of organic carbon export, organic matters associated with diatoms rapidly sink to the seafloor by aggregation and mass settlement, whereas dinoflagellate cells predominantly decompose in the water column (Guo et al. 2014). Both the decrease in the annual number of blooms and the increase in the proportion of dinoflagellate blooms in the coastal waters around Korea in recent years are expected to lower the efficiency of carbon export (Lee et al. 2011).

Conclusions

The present study has delineated a widespread shift from N deficiency to P deficiency in the East China and Yellow seas, and in much of the coastal waters surrounding Korea. The shift has occurred earlier in regions under the direct influence of the Changjiang River plume, and subsequently has propagated to other parts of the East China and Yellow seas and to the coastal waters of Korea (the change was observed at the Ieodo Ocean Research Station located in a midpoint between the Changjiang estuary and the coastal regions south of Korea). The extent of N deficiency in areas outside of the direct influence of the Changjiang River plume has consistently decreased over time. Moreover, in Korean coastal waters, the increase in P deficiency and the decrease in Si availability were found to be associated with an increase in the proportion of dinoflagellate-dominated blooms. To confirm whether the close association between nutrient regime shift and bloom-forming phytoplankton species change is generally applicable, extensive experimentation in other coastal areas will be needed.

If anthropogenic nitrogen emission continues to change in the direction of increasing supply of fixed forms of nitrogen, an understanding of the adaptations of phytoplankton to varying ocean nutrient systems (the composition of phytoplankton species, and more profoundly, the structure of the ecosystem) will become increasingly important.

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Conflict of Interest
None declared.

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