

Nutrient status of Otsuchi Bay (northeastern Japan) following the 2011 off the Pacific coast of Tohoku Earthquake

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Abstract On 11 March 2011, the Sanriku coast of Japan was struck by a massive tsunami associated with the 2011 off the Pacific coast of Tohoku Earthquake. The tsunami caused large disturbances in bottom sediments and severe destruction of human-made structures, natural landscapes and infrastructures such as sewage treatment systems and aquaculture facilities. A serious and continuing concern is a fundamental alteration of the nutrient regime in the impacted regions, which may exert a profound influence on the processes of ecosystem recovery and fishery reconstruction. We investigated the nutrient status of the water column of Otsuchi Bay, a small embayment that was heavily damaged by the tsunami. Our data collected between May 2011 and July 2014 revealed some prominent features in nutrient parameters that were potentially linked to effects of the tsunami. These features include (1) high turbidity and high concentrations of nitrite and silicic acid until September 2011, (2) the spread of seawater characterized by high phosphate concentration and low total inorganic nitrogen (ammonium + nitrate + nitrite) to phosphate (TIN/P) ratio during the mixing period between November 2011 and January 2012, and (3) an increase in the TIN/P ratio during the mixing period of subsequent years to become higher than it was before the earthquake. These data not only provide evidence of the alteration and subsequent recovery of the nutrient status of Otsuchi Bay after the earthquake but also suggest a possible tsunami-induced alteration in nutrient stoichiometry which appeared to last until at least the beginning of 2014.

Keywords The 2011 off the Pacific coast of Tohoku Earthquake · Tsunami · Otsuchi Bay · Nutrients · Turbidity

1 Introduction

On 11 March 2011, the eastern coast of Japan was struck by a massive tsunami associated with the 2011 off the Pacific coast of Tohoku Earthquake, which had a moment magnitude of 9.0 (Mori et al. 2011; Satake et al. 2013; Tajima et al. 2013). The tsunami caused serious and extensive damage to the coastal society and natural environment (Kazama and Noda 2012; Suppasri et al. 2012). Although the extent and nature of the damage differed greatly between localities, depending on their societal, environmental, and geographical settings, some general features characterize the modes of tsunami-induced disturbances on the Sanriku coast of the Iwate and Miyagi prefectures. These features include large disturbances (massive resuspension, mixing, and transport) of bottom sediments (references in Goto et al. 2014), severe destruction of human-made physical structures (e.g., banks, piers, and water gates) and natural coastal landscapes (mudflats, sandy beaches, saltmarsh) (Ogasawara et al. 2012; Okayasu et al. 2013; Tappin et al. 2012; Udo et al. 2012), enormous discharges of land-derived debris (soil, wood, houses, cars) to the coastal sea (Arii et al. 2014; Ministry of the Environment of Japan 2014), and disruption of infrastructures such as sewage treatment systems and aquaculture facilities (Okuda and Ohashi 2012; Qi et al. 2014). One serious and ongoing concern arising from the damage is the alteration of the nutrient status of the impacted marine environments. Here, the term “nutrient status” refers to the concentrations, chemical compositions, and stoichiometry of major nutrients, including nitrogen, phosphorus, and silica, with consideration of their variability in time and space. It

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is known that even slight or moderate changes in the nutrient status of the water column can affect: phytoplankton productivity, the basis of marine food webs (Cloern et al. 2014; Hecky and Kilham 1988; Rabalais et al. 1996); the growth of seaweeds, including those that are important as aquaculture products (Coelho et al. 2000; Harrison and Hurd 2001); and the occurrence of harmful algae, which can damage oysters and other shellfish (Anderson et al. 2002; Heisler et al. 2008). Therefore, tsunami-induced changes to the nutrient status of coastal marine environments, if any, may exert profound and prolonged influences on the ongoing processes of ecosystem recovery and fishery reconstruction in the impacted regions.

This study was conducted as part of the post-tsunami ecosystem monitoring program supported by the Tohoku Ecosystem-Associated Marine Sciences (TEAMS) research program (<http://www.i-teams.jp/e/>). Our objective was to assess the nutrient status of Otsuchi Bay subsequent to the 2011 earthquake. Otsuchi Bay is a semi-enclosed bay opening to the western North Pacific. Its length and width are approximately 7 and 2–4 km, respectively. Three rivers, the Otsuchi, Kozuchi, and Unosumai, with a total water discharge of 3–35 m³ s⁻¹ (Anbo et al. 2005), flow into the bay. The residential areas of Otsuchi town and the Unosumai area of Kamaishi city, in which about 22,000 people lived before the earthquake, are distributed along the coastal zone of the bay and the watersheds of the rivers. The coastal community and the societal and industrial (especially fishery-related) infrastructures of these areas were severely damaged by the tsunami, which reached a maximum height in Otsuchi Bay of 15.1 m (Iwate Prefecture 2013). In Otsuchi town, the number of tsunami victims reached 1600. In the inundated area, approximately 6.68 km², about 5600 buildings collapsed (Yanagawa and Sakai 2014). The amount of rubble in Otsuchi town and the Unosumai area of Kamaishi city was 612 ktons, and

235 ktons of tsunami deposits were left on the inundated area (Kamaishi city 2011; Otsuchi town 2014). The sewage treatment plant of Otsuchi town located near the river mouth of the Kozuchi River went out of operation due to the tsunami. As an emergency response, primary effluent was released into the Kozuchi River from the end of March 2011 until the restoration of normal operation of the plant on 31 July 2012 (Ministry of Land, Infrastructure, Transport and Tourism of Japan 2011; Iwate prefecture 2014).

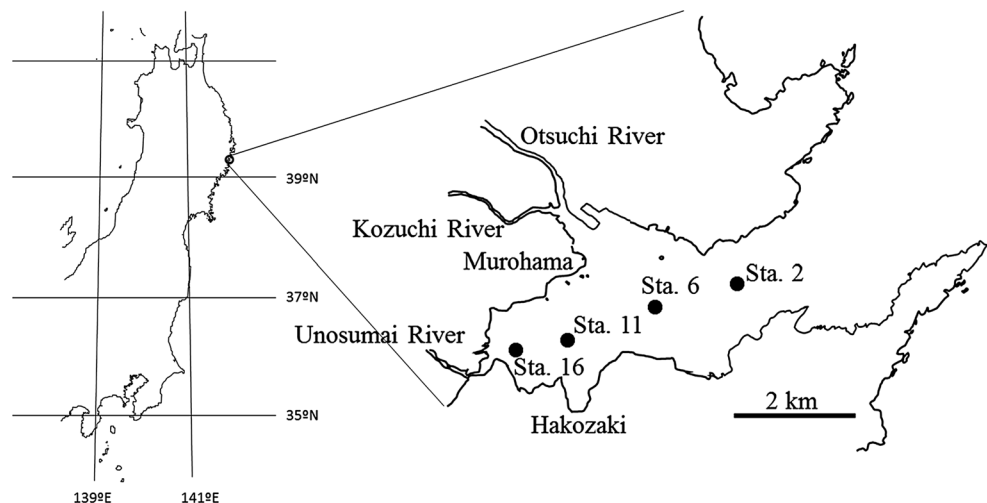
Physical parameters as well as concentrations of inorganic nutrients and chlorophyll *a* were monitored for more than 3 years, from May 2011 to July 2014. The Ocean Research Institute (a predecessor of the Atmosphere and Ocean Research Institute) of the University of Tokyo established a field station at Otsuchi town in 1973 called the Coastal Marine Research Center, which was reformed as the International Coastal Research Center (ICRC) in 2003. Since the establishment of this center, researchers have used the facility to examine the nutrient and other ecological properties of Otsuchi Bay. In this study, we took advantage of this research to compare our data with those collected before the earthquake (Fukuda et al. 2007, and unpublished; Hattori 1976, 1977a, b, 1978a, b; Hattori et al. 1974).

2 Materials and methods

2.1 Study site and sample collection

Water samples were collected from four stations (2, 6, 11, and 16) along a transect from the center of Otsuchi Bay to the mouth of the Unosumai River (Fig. 1). Stations 2, 6, 11, and 16 were located near the center of Otsuchi Bay (39°20′36″N, 141°56′47″E; water depth: 46 m), at the point intersection of the transect and the extension line from the

Fig. 1 Locations of sampling stations in Otsuchi Bay, Japan



joint mouth of the Otsuchi and Kozuchi rivers (39°20′29″N, 141°55′49″E; water depth: 39 m), in the vicinity of the area between the communities of Murohama and Hakozaki (39°20′11″N, 141°54′47″E; water depth: 20 m), and at the mouth of the Unosumai River (39°20′00″N, 141°54′6″E; water depth: 10 m), respectively. Samples were collected every 2 months from 27 May 2011 to 4 March 2014. Depth profiles of temperature, salinity and turbidity were determined by conductivity–temperature–depth (CTD) sensors (ACL2180-TPM; Alec Electronics, Japan: May to July 2011; ASTD687; JFE Advantech, Japan: September 2011 to March 2014; ASTD102; JFE Advantech, Japan: May to July 2014). The turbidity data were only collected from 27 May 2011 to 28 November 2012 because the turbidity sensor had below-acceptable performance after 30 January 2013. Secchi depth was used to estimate the bottom of the euphotic layer (Secchi depth \times 2; Holmes 1970). The mixed-layer depth was determined based on a 0.125 unit σ_T criterion from that of the surface water (Levitus 1982). A 12-L Niskin sampler was used to collect seawater samples at predetermined depths (primarily at 4- to 26-m intervals), with the exception that only surface water samples were collected at Stations 6, 11, and 16 on 27 May 2011. To determine inorganic nutrient [nitrate (NO_3^-), nitrite (NO_2^-), ammonium (HN_4^+), phosphate (PO_4^{3-}) and silicic acid ($\text{Si}(\text{OH})_4$)] concentrations, seawater samples were contained in 10-ml acrylic resin tubes and stored at -20°C until analysis. To determine the concentration of chlorophyll *a* (hereafter Chl. *a*), subsamples of seawater were filtered through GF/F filters (Whatman International) and the filters were stored at -20°C until analysis.

2.2 Determination of concentrations of inorganic nutrients and chlorophyll *a*

Concentrations of NO_3^- , NO_2^- , HN_4^+ , PO_4^{3-} , and $\text{Si}(\text{OH})_4$ were determined calorimetrically using an auto-analyzer (AACS II or AACS III; Bran+Luebbe, Germany) according to Armstrong et al. (1967). Before the analysis of $\text{Si}(\text{OH})_4$, frozen samples were stored in the dark at room temperature for ~48 h (Gordon et al. 1993). We used unfiltered seawater samples for the nutrient analysis according to the protocol of WOCE (Gordon et al. 1993). Note that, although inorganic nutrients in unfiltered sample waters are considered to be mostly soluble in oceanic waters (WOCE; Gordon et al. 1993), they can also include those associated with particles (e.g., by absorption), especially in high turbidity waters. In this paper, the sum of NO_3^- , NO_2^- and NH_4^+ concentration is referred to as total inorganic nitrogen (TIN) concentration because high-turbidity water was included in the samples (see “Results”). The detection limits, defined as three times the standard deviation of repeated measurements of the blank, were 0.05, 0.02, 0.1, 0.02, and $0.3\ \mu\text{M}$ for NO_3^- , NO_2^- , HN_4^+ , PO_4^{3-} , and $\text{Si}(\text{OH})_4$,

respectively. Chl. *a* concentrations were determined by fluorometry (Fluorometer 10-AU; Turner Designs, USA), using the acidification method (Holme-Hansen et al. 1965) after extraction with N, N-dimethyl formamide (Suzuki and Ishimaru 1990).

2.3 Statistical analysis

Differences in the variables among different periods were tested by Kruskal–Wallis one-way ANOVA on ranks test and then by the post hoc Dunn’s method because the normality test (Shapiro–Wilks) for variables failed ($p < 0.05$). To analyze the relationships between variables, the reduced major axis was used to define the line of best fit (Quinn and Keough 2002). The statistical analyses were performed using SigmaPlot 12.5 (Hulinks, USA). The regression line was calculated using Excel 2013 (Microsoft, USA).

2.4 Nutrient data collected before the tsunami

The nutrient status of the Otsuchi Bay before the earthquake was examined using data reported in the literature. These data consisted of those collected by Dr. Akihiko Hattori between 1973 and 1977 (hereafter, B1 data; Hattori 1976, 1977a, b, 1978a, b; Hattori et al. 1974) and those obtained by the first author of the present paper and his colleagues between 1996 and 2008 (hereafter, B2 data; Fukuda et al. 2007, and unpublished). The B1 data included the nutrient concentration data [NO_3^- , NO_2^- , HN_4^+ , PO_4^{3-} , and $\text{Si}(\text{OH})_4$] mainly collected at the bay center near Stations 2, 6 and 11 of this study. These data were collected

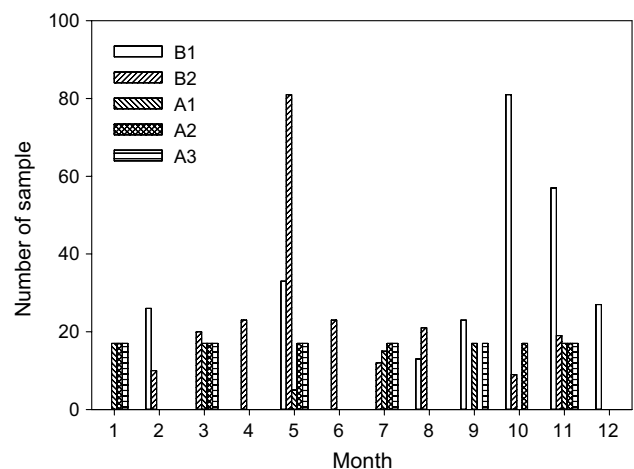


Fig. 2 Frequency distribution of the number of data before and after 2011 off the Pacific coast of Tohoku Earthquake by month of survey. Data before May 2011 were obtained from the literature (see Sect. 2). The data collected before the earthquake were separated into two groups (B1 1973–1977 and B2 1996–2008), while those collected after the earthquake were divided into three groups (A1 May 2011–March 2012; A2 May 2012–March 2013; and A3 May 2013–March 2014)

in different months (Fig. 2). Nutrient concentrations were determined colorimetrically [using the cadmium column-diazotization method for NO_3^- , the diazotization method for NO_2^- , the phenol-indophenol method for ammonium, the molybdate method for PO_4^{3-} and the molybdate method for $\text{Si}(\text{OH})_4$] for samples with or without filtration through grass fiber filters (GF/C). The B2 data consisted of those collected mainly at the bay center near Stations 2 and 11 of this study. These data were collected through all seasons, although the data were most intensively collected in May (Fig. 2). Nutrient concentrations were determined for NO_3^- , NO_2^- , HN_4^+ , PO_4^{3-} using an autoanalyzer, according to the method described in the present paper. Note that the B2 data lack the data of $\text{Si}(\text{OH})_4$ concentration.

To facilitate the comparison of the nutrient status between before and after the earthquake, we separated the seasonal data into three periods: stratified period (May–September), mixing period (October–January) and Oyashio intrusion period (February–April).

3 Results

In this section, the temporal changes in physical and nutrient parameters at different depths are described for Station 2 (near the center of the bay) as a representative example, unless otherwise noted.

3.1 Water temperature, salinity, euphotic layer depth, and turbidity

During the observation period, the surface water temperature began to increase at the end of March and then reached the annual maximum value of about 22 °C in September (Fig. 3). Subsequently, the water temperature decreased toward the annual minimum value of around 5 °C in March. In the summer period, from May to September, while water stratification was developed in the upper layer of the water column, the salinity of the lower layer of the water column became greater than 33.7 (except during 2012), indicating intrusion of Tsugaru current saline water into the bay (Hanawa and Mitsudera 1987). In this period, the salinity of the surface water decreased remarkably near the center of the bay (station 2), suggesting high river discharge. Between October and February, the mixed-layer depth deepened except between October 2013 and February 2014 (Table 1). During this high-mixing period, the entire water column filled with the highly saline water, except in autumn of 2013. Between February and April, Otsuchi Bay was filled with cold (<7 °C) low-salinity (<33.7) water transported by the Oyashio Current (Hanawa and Mitsudera 1987). The euphotic layer depth varied in the range of 2.5–16.0 m (Table 1).

High turbidity following the earthquake lasted until at least September 2011 (Fig. 3d). Between May and July 2011, turbidity was greater than 0.25 ppm (kaolin turbidity) throughout the water column. At this time, high turbidity exceeding 1 ppm was distributed in the surface and the near-bottom layers (Fig. 4a, b). In September 2011, the high turbidity zone was in the lower part of the water column (Fig. 4c). High turbidity in the subsurface layer was also observed in March 2012 (Figs. 3d, 4f). Aside from 2011, high turbidity near the bottom was also observed between May and November 2012 (Fig. 3d).

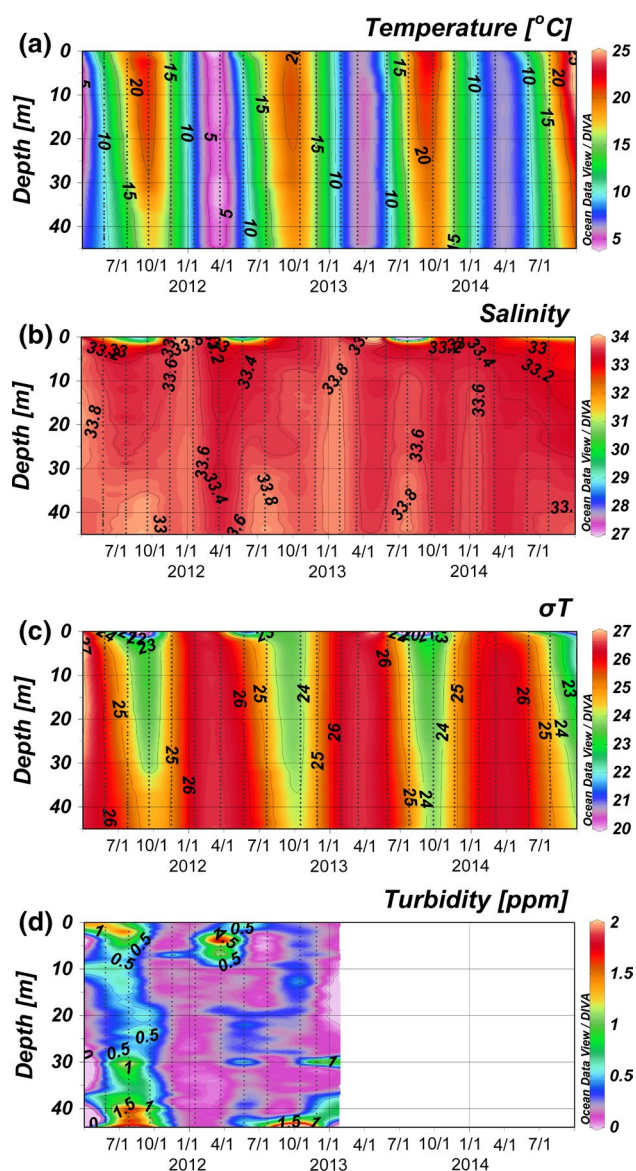


Fig. 3 Temporal variations in **a** water temperature, **b** salinity, **c** density (in σ_T units), and **d** turbidity at station 2 in Otsuchi Bay from 27 May 2011 to 23 July 2014. The turbidity data had below-acceptable performance after 19 November 2011

Table 1 Summary of the degree of transparency and the mixed-layer depth at four sampling stations in Otsuchi Bay by date of the survey

Date of survey	Transparency (m)				Mixed layer depth (m) ^a			
	Station 2	Station 6	Station 11	Station 12	Station 2	Station 6	Station 11	Station 12
27 May 2011 ^b	10.1 (20.2)	7.1 (14.2)	6.3 (12.6)	6.1 (Bottom)	<5	<5	<5	<5
27 July 2011	9.5 (19.0)	9.0 (18.0)	8.0 (16.0)	3.0 (6.0)	<5	<5	<5	<5
20 September 2011	11.0 (22.0)	12.0 (24.0)	8.5 (17.0)	9.0 (Bottom)	<5	<5	<5	<5
17 November 2011	11.5 (23.0)	10.0 (20.0)	7.5 (15.0)	10.0 (Bottom)	19.3	18.5	Bottom	<5
16 January 2012	12.0 (24.0)	11.0 (22.0)	11.5 (Bottom)	10.0 (Bottom)	21.9	<5	5.7	<5
22 March 2012	4.0 (8.0)	7.0 (14.0)	5.0 (10.0)	2.5 (5.0)	<5	<5	<5	<5
22 May 2012	9.0 (18.0)	7.0 (14.0)	5.0 (10.0)	5.0 (10.0)	<5	<5	<5	<5
22 July 2012	9.0 (18.0)	9.0 (18.0)	9.5 (19.0)	3.0 (6.0)	<5	<5	<5	<5
16 October 2012	9.0 (18.0)	9.0 (18.0)	8.0 (16.0)	5.5 (Bottom)	8.2	<5	<5	<5
28 November 2012	12.5 (23.0)	10.0 (20.0)	10.5 (Bottom)	>10 (Bottom)	9.7	<5	<5	<5
30 January 2013	10.2 (20.4)	7.8 (15.6)	6.5 (13.0)	3.8 (7.6)	13.5	<5	9.4	<5
12 March 2013	13.0 (26.0)	15.0 (30.0)	14.5 (Bottom)	>10 (Bottom)	12.3	10.7	<5	<5
28 May 2013	6.5 (13.0)	6.7 (13.4)	5.5 (11.0)	5.0 (10.0)	<5	<5	<5	<5
23 July 2013	5.5 (11.0)	4.0 (8.0)	3.6 (7.2)	3.0 (6.0)	<5	<5	<5	<5
25 September 2013	8.5 (17.0)	8.0 (16.0)	7.5 (15.0)	6.0 (Bottom)	<5	<5	<5	<5
19 November 2013	8.5 (17.0)	8.0 (16.0)	6.8 (13.6)	4.0 (8.0)	<5	<5	<5	<5
20 January 2014	16.0 (32.0)	16.0 (32.0)	14.5 (Bottom)	>10 (Bottom)	<5	<5	<5	<5
4 March 2014	6.5 (13.0)	7.5 (15.0)	6.0 (12.0)	7.9 (Bottom)	<5	<5	<5	<5
28 May 2014	10.5 (21.0)	7.5 (15.0)	8.0 (16.0)	5.0 (10.0)	<5	<5	<5	<5
23 July 2014 ^c	7.0 (14.0)	–	–	2.5 (5.0)	<5	<5	<5	<5

Numbers in parentheses indicate the euphotic layer depth estimated from the degree of transparency (see Sect. 2)

^a The mixed layer depth was based on a 0.125 unit σ_T criterion (Levitus 1982)

^b Water sample was collected from only 1 m depth at Stations 6, 11 and 16

^c Water sample was collected from Stations 2 and 16

3.2 Temporal changes in inorganic nutrients and chlorophyll *a* concentrations after the earthquake

NO_3^- was depleted in the surface water in summer, during which stratification developed (Fig. 5a). NO_3^- concentration began to increase with the increase in water mixing depth and then reached its annual maximum in March, when Oyashio water intruded into Otsuchi Bay. In March 2012, the NO_3^- concentration reached >10 μM , a value greater than those of the similar period in 2013 and 2014. However, no remarkable feature of NO_3^- concentration was observed in the high-turbidity period between May and September 2011.

Except for 2011, NO_2^- was lower than 0.3 μM throughout the water column, except during the high-mixing period between November and January (Fig. 5b). In 2011, however, the NO_2^- concentration was greater than 0.3 μM in the high-turbidity water that existed between May and September. In this period, the maximum NO_2^- concentration in the water column occurred near the bottom (Fig. 5b). The

NO_2^- concentration in the bottom water in 2011 at Station 2 decreased from 1.33 μM in May to 0.38 μM in September, but then increased to 0.83 μM in November. Figure 6a shows the temporal variation in the nitrite-to-nitrate ($\text{NO}_2^-/\text{NO}_3^-$) ratio. The $\text{NO}_2^-/\text{NO}_3^-$ ratio was high between May and September of 2011. Notably, in May 2011, the $\text{NO}_2^-/\text{NO}_3^-$ ratio exceeded 1 throughout the water column, whereas in July and September of 2011, the $\text{NO}_2^-/\text{NO}_3^-$ ratio was high (>1) only within the euphotic layer.

Seasonal fluctuations in HN_4^+ concentration showed a different pattern from those of NO_3^- and NO_2^- (Fig. 5). HN_4^+ concentration increased throughout the water column in March, and it remained at a relatively higher concentration in the near-bottom layer than in the surface layer in the stratified period between May and September. In 2011, however, the HN_4^+ concentration in the near-bottom layer between May and September was lower than that in corresponding periods of 2012, 2013, and 2014. Additionally, a notable subsurface maximum in HN_4^+ concentration was observed at Stations 2 and 6 (data not shown) in September 2011 (Fig. 5c).

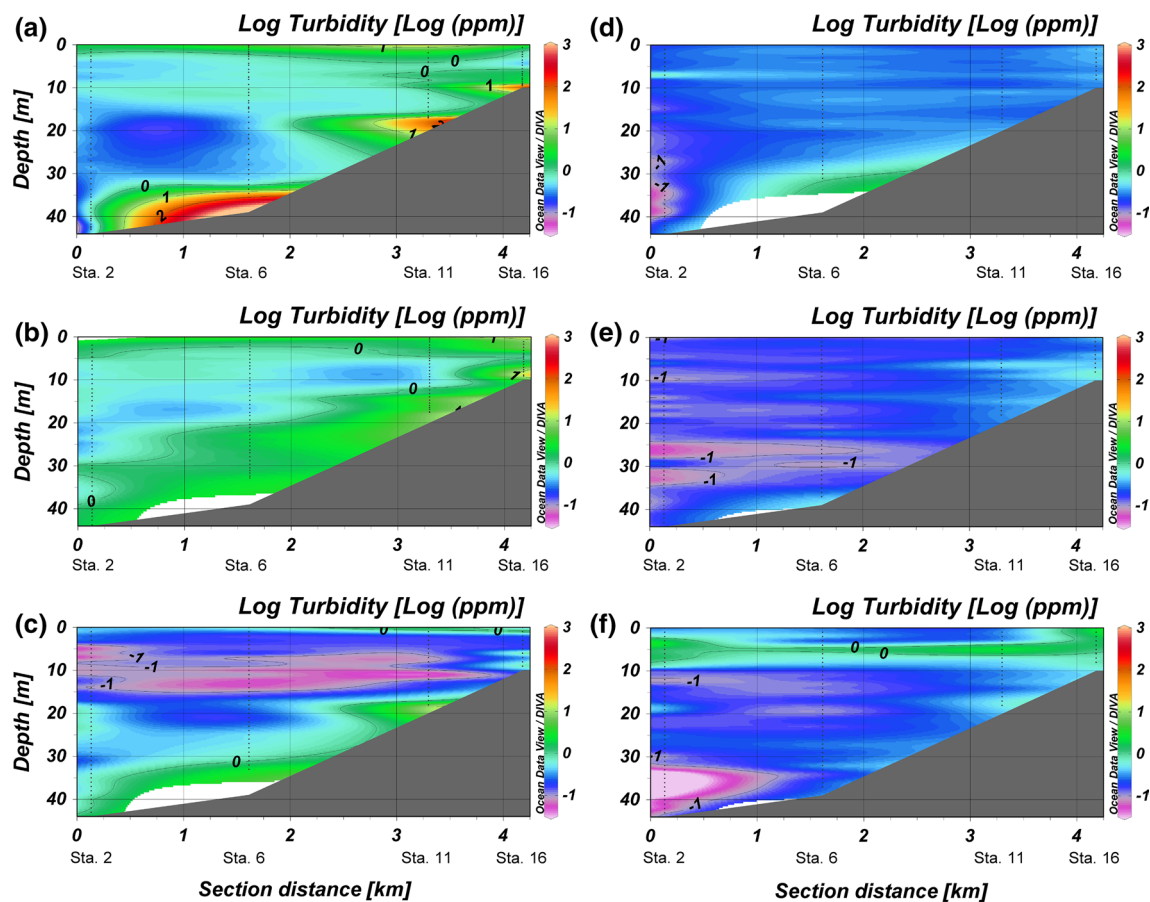


Fig. 4 Spatial distribution of turbidity (in logarithmic scale) on **a** 22 May, **b** 27 July, **c** 20 September, and **d** 17 November 2011, and **e** 16 January and **f** 22 March 2012

PO_4^{3-} in the upper part of the water column was almost depleted during the stratified period, and then increased throughout the water column in the mixing period (Fig. 5). Although this general pattern was common between the 3 years, PO_4^{3-} concentrations between September 2011 and March 2012 were notably higher than those in the corresponding period after 2 years. High- PO_4^{3-} water ($>0.5 \mu\text{M}$) first appeared in the near-bottom layer at Station 2 in September 2011 (Fig. 7a–e). Subsequently, PO_4^{3-} concentration increased in the aphotic layer in November and then spread throughout the entire bay during the high-mixing period between January and March, except that the concentration was low in the euphotic zone in March when spring phytoplankton bloom was likely initiated, as indicated by high Chl. *a* concentration at the depth of 10 m (Fig. 5f). From November 2011, the concentration of TIN also began to increase from the lower part of the water column and then reached its peak in March 2012 (Fig. 7j).

The TIN/P ratio displayed large variability in time and space (Figs. 6b, 7k–o). The mean TIN/P in the bay was notably low in November 2011 [5.8 ± 0.6 ($n = 17$)] and January 2012 [6.9 ± 0.3 ($n = 17$)]. In March 2012, TIN/P

in the aphotic layer became greater than 10. The TIN/P ratio in the mixing period in the next winter was close to the Redfield ratio (16) [means of November 2012 and January 2013 were 15.2 ± 1.5 ($n = 17$) and 13.6 ± 1.8 ($n = 17$), respectively], which was followed by the higher TIN/P ratio in January 2014 (23.8 ± 5.0 ; $n = 17$) (Fig. 6b).

The pattern of seasonal fluctuation in $\text{Si}(\text{OH})_4$ concentration was generally characterized by high and low concentrations during the mixing and stratified period, respectively (Fig. 5). In September 2011, however, higher $\text{Si}(\text{OH})_4$ concentration compared with those in the corresponding period of 2012 and 2013 was observed. The distribution of $\text{Si}(\text{OH})_4$ in September 2011 was complex and differed from the distributions of the other nutrients (Fig. 8), being characterized by the presence of the subsurface maximum around the bottom of the euphotic layer at Stations 2, 6, and 11 (Fig. 8). The $\text{Si}(\text{OH})_4$ concentration in March 2012 tended to be higher than those in March 2013 and 2014, a trend similar to that of NO_3^- and PO_4^{3-} concentrations (Fig. 5). The $\text{Si}(\text{OH})_4$ -to-TIN ratio (Si/TIN) in March 2012 was relatively high (15.9 ± 3.5 ; $n = 17$), compared to the corresponding ratio during the mixing period

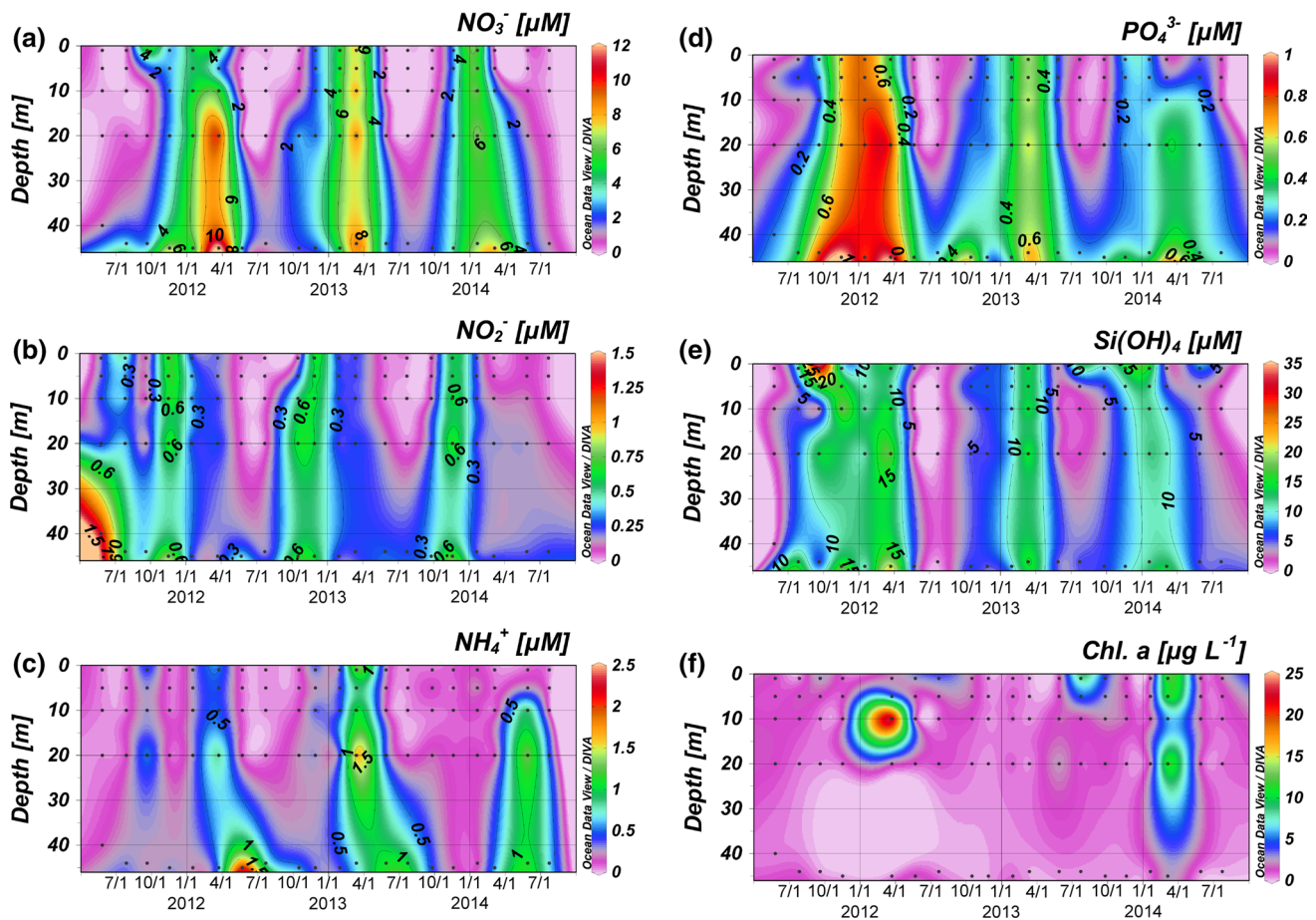


Fig. 5 Temporal variation in concentrations of **a** NO_3^- , **b** NO_2^- , **c** NH_4^+ , **d** PO_4^{3-} , **e** Si(OH)_4 , and **f** Chl. *a* at Station 2 in Otsuchi Bay from 27 May 2011 to 23 July 2014

in the winters of 2012 and 2013 [7.8 ± 1.9 ($n = 34$) and 12.0 ± 3.4 ($n = 34$), respectively] (Fig. 6c).

Chl. *a* concentration in the euphotic layer varied in the range of $0.09\text{--}39.3 \mu\text{g L}^{-1}$ during the investigation period, with the highest value at the depth of 5 or 10 m in March 2012. We identified no notable feature or trend that might be related to the tsunami impact (Fig. 5f).

3.3 The nutrient concentrations before and after the earthquake

Mean concentrations of inorganic nutrients calculated for stratified, mixing and Oyashio intrusion periods were compared with the B1 data (1973–1977), the B2 data (1996–2008), and the data collected during three successive years following the earthquake (A1 data: May 2011–March 2012; A2 data: May 2012–March 2013; A3 data: May 2013–March 2014) (Fig. 9). This comparison revealed several notable features: (1) during the stratified period of the year immediately after the earthquake (A1), median NO_2^- concentrations were more than twofold and

significantly ($p < 0.05$) higher than the mean values found for the corresponding period in B1 and B2, (2) irrespective of the period, median Si(OH)_4 concentrations in A1 were significantly ($p < 0.05$) higher than the corresponding values found in B1, and (3) the median PO_4^{3-} concentration in the mixing period of A1 was more than twofold and significantly ($p < 0.05$) higher than those in the corresponding period in B1 and B2 as well as in A2 and A3. TIN did not display marked difference in concentration between before and after the earthquake, except that the median TIN concentration determined during the mixing period of A2 was higher than those in B1 and B2.

3.4 TIN/P ratio before and after the earthquake

The temporal changes in the phosphorus to nitrogen nutrient stoichiometry were examined by plotting the concentrations of TIN (y-variable) and PO_4^{3-} (x-variable) in two-dimensional space for the individual datasets collected before (B1, B2) and after (A1, A2, A3) the earthquake (Fig. 10). In each of these graphs, a reference line is given

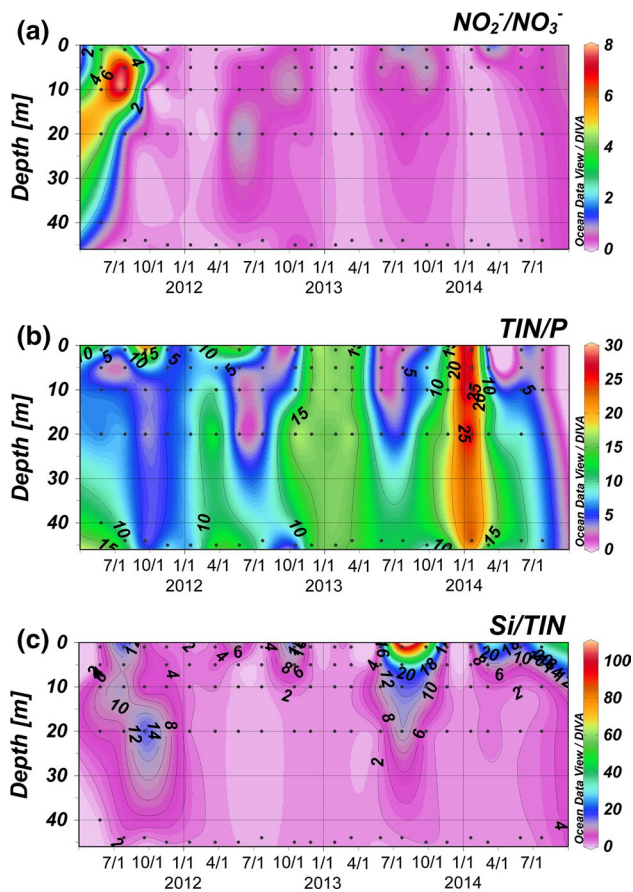


Fig. 6 Temporal variations in **a** $\text{NO}_2^-/\text{NO}_3^-$ ratio, **b** TIN/P ratio, and **c** Si/TIN ratio at Station 2 in Otsuchi Bay from 27 May 2011 to 23 July 2014

to indicate the Redfield ratio ($\text{N}:\text{P} = 16$). In B1, the plots scattered broadly, displaying a large and nonsystematic deviation from the Redfield ratio. The correlation between TIN and PO_4^{3-} was insignificant ($p > 0.05$). In contrast, in B2, there was a positive correlation between TIN and PO_4^{3-} ($R = 0.851$, $n = 207$, $p < 0.001$), with the slope of the regression being 13.0 (Table 2). During the year immediately after the earthquake (A1), the correlation between TIN and PO_4^{3-} was weaker than that in B2 and there was a notable deviation toward low TIN/P ratios, especially during the mixing period. Reflecting this deviation, the slope of the regression that related TIN to PO_4^{3-} was gentle (10.0) (Table 2). During subsequent years (A2 and A3), the deviation in TIN/P ratio from the Redfield ratio was moderated, as indicated by the increased slopes of the TIN to PO_4^{3-} regression, which were 15.9 and 17.1 for A2 and A3, respectively (Table 2). During the mixing period, there was a notable deviation toward high TIN/P ratios: 18.3 ± 6.8 ($n = 34$) for A3 (Fig. 6b). The steep slope of the regression that related TIN to PO_4^{3-} for A3 was resulted from this deviation (Fig. 10).

4 Discussion

Based on the physical dimensions of the bay (length 7 km; width 2–4 km) and moderate residual current (ca. 3–5 cm s^{-1} ; Otake et al. 2009), it is inferred that the water residence time within the bay is on the order of a week, or less than a month. Despite the coarse resolution (2-month interval) of our sampling relative to the water residence time, we identified some notable features in the nutrient status of the bay following the 2011 earthquake and tsunami event. These features include (1) high turbidity, (2) high NO_2^- (up to 1.33 μM) and $\text{Si}(\text{OH})_4$ (up to 32.5 μM) until September 2011, (3) the spread of high-phosphate water and notably low TIN/P ratio (mean 6) during the mixing period between November 2011 and January 2012, and (4) an increase in TIN/P, which approached or exceeded the Redfield ratio ($\text{N}:\text{P} = 16$), during the mixing periods of the subsequent years. The identification of these features is based on the evaluation of the time-series nutrient data collected over a 3.5-year period following the earthquake event, and the comparison of the nutrient data collected after the earthquake with those collected before the earthquake, the latter being discontinuous and largely different from the former in nature, especially in regard to spatiotemporal resolutions. Given these inherent limitations in our approach, any inference on a possible connection between the earthquake and the nutrient status of Otsuchi Bay should be made with extreme caution. Any “anomalous” features found in the year (or years) following the earthquake might not be truly associated with the earthquake and tsunami, but would rather be a reflection of natural variability caused by other forces. Keeping these limitations in mind, the details are discussed in the following subsections.

4.1 High turbidity until September 2011

In May and July 2011, high-turbidity water was distributed in the surface layer and a lower part of the water column (Figs. 3, 4). In the following September, the depth of the high-turbidity zone extended down to the deeper part of the bay. Nishi et al. (2013) estimated the distribution pattern of the maximum velocity of the massive tsunami and the bottom shear stress in Otsuchi Bay from numerical simulation, and then evaluated the tendency for erosion using the Shields number (bottom shear stress divided by the submerged density and the diameter of sediment) as an indicator. They pointed out that the seafloor of the inner part of Otsuchi Bay could be easily eroded by the tsunami current and that resuspended sediments would tend to be transported by it. Changes in the chemical composition of the sediment surface in Otsuchi Bay after the earthquake are

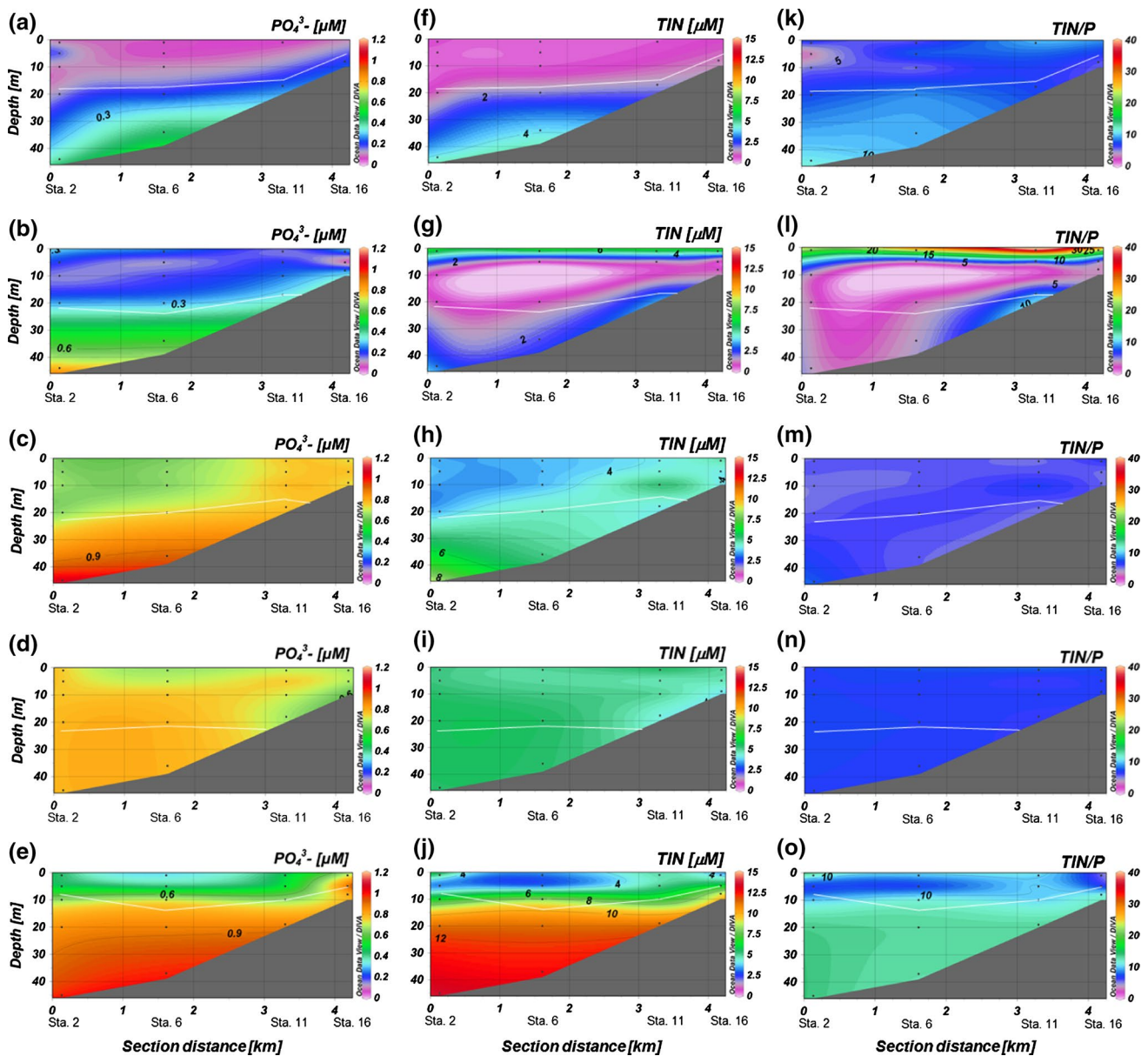


Fig. 7 Spatial distribution of **a–e** PO_4^{3-} , **e–j** TIN, and **k–o** TIN/P ratio along the transect from Station 2 to Station 16 on **a, k** 27 July 2011, **b, g, i** 20 September 2011, **c, h, m** 17 November 2011, **d, i, n**

16 January 2012, and **e, j, o** 22 March 2012. *White solid lines* show the bottom of the euphotic layer

in agreement with the behavior of the sediment under the tsunami current (Naiki et al. 2015). Other data also suggest that massive amounts of sediments were introduced into Otsuchi Bay due to the tsunami. Okayasu et al. (2013) estimated that about one-third of the sediments from the sand-bar located at the river mouth of the Unosumi River were deposited on the inundated area along the river. Although it is not completely clear what mechanism caused the high-turbidity condition to last more than 6 months, the fact that high turbidity was found not only near the bottom but also in the surface layer and in the inner part of the bay suggests

that riverine input of tsunami deposits on land contributed to the maintenance of the high-turbidity condition for a prolonged period. In addition, atmospheric deposition of dust might have also contributed to the increase in turbidity, although this assertion requires further investigation.

4.2 Unusual nutrient status during the high-turbidity period

During the high-turbidity period, the concentration of NO_2^- was remarkably high (up to $1.33 \mu\text{M}$) relative to

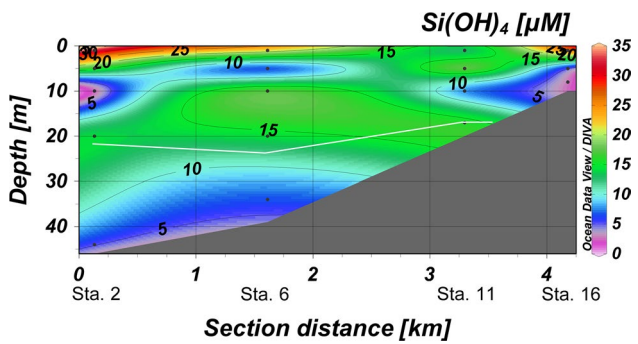


Fig. 8 Spatial distribution of Si(OH)_4 along the transect from Station 2 to Station 16 on 20 September 2011. White solid lines show the bottom of the euphotic layer

those in the corresponding periods of 2012 and 2013. Such high NO_2^- concentration has rarely been observed in Otsuchi Bay before the earthquake (Fukuda et al. 2007, and unpublished; Hattori 1976, 1977a, b, 1978a, b; Hattori et al. 1974). An unusual feature in the high NO_2^- concentration was high $\text{NO}_2^-/\text{NO}_3^-$ ratio (2–6) throughout the water column in July and September 2011. Generally, in oxic water columns of coastal marine environments, NO_2^- concentration is low ($<0.5 \mu\text{M}$; Kamykowski and Zentara 1991). This is because in oxic seawater columns, NO_2^- is primarily produced as an intermediate product of nitrification (oxidation of NH_4^+ to NO_3^-), during which the accumulation of NO_2^- is generally known to be small (i.e., the oxidation of NH_4^+ to NO_2^- , rather than the oxidation of NO_2^- to

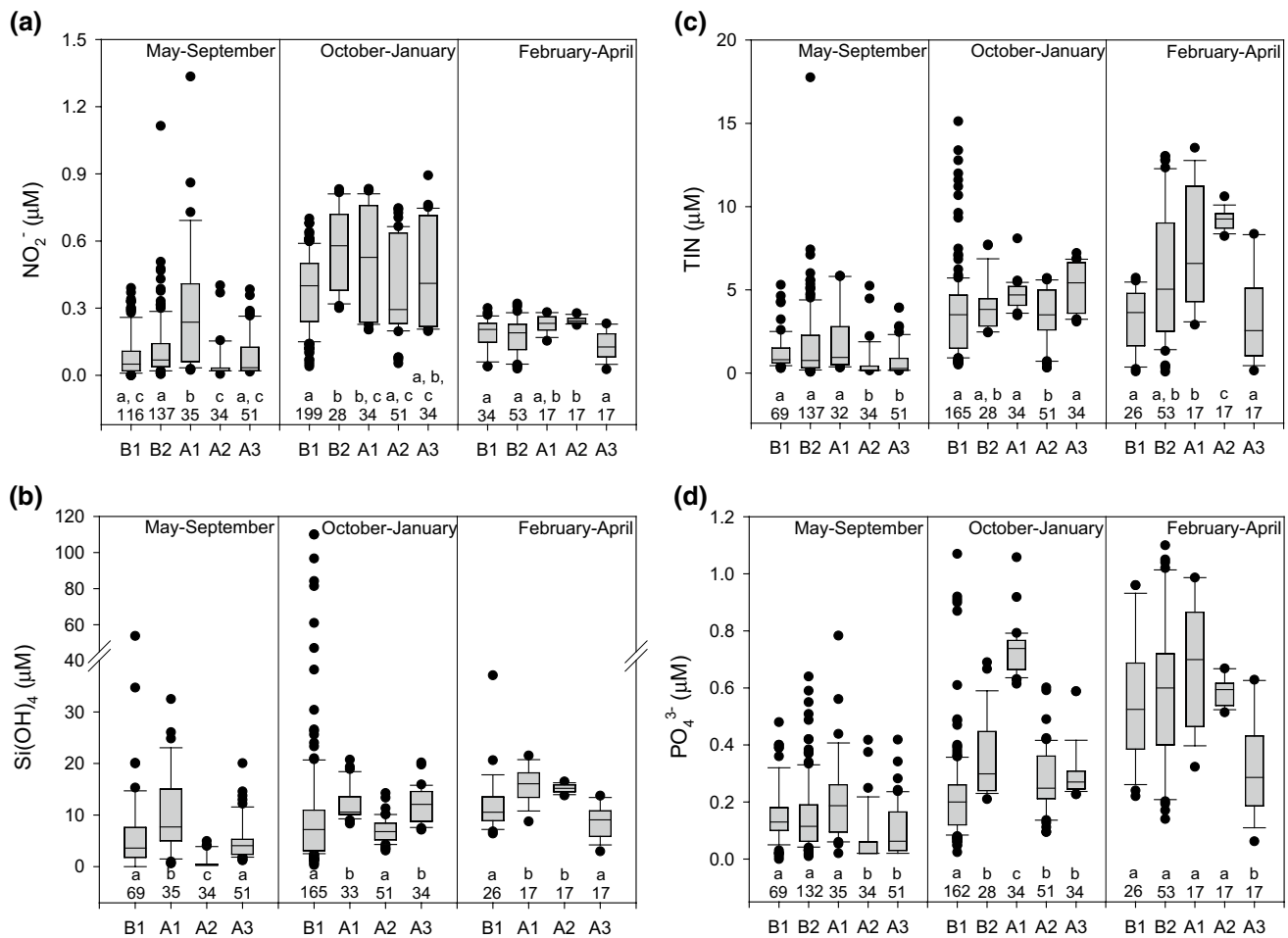


Fig. 9 Box plots of concentrations of **a** NO_2^- , **b** Si(OH)_4 , **c** TIN, and **d** PO_4^{3-} obtained from two different periods before the earthquake (B1 1973–1977 and B2 1996–2008), and three different periods following the earthquake (A1 May 2011–March 2012; A2 May 2012–March 2013; and A3 May 2013–March 2014). Data were grouped according to: stratified period: May–September; high mixing period: November–January; Oyashio intrusion period: February–April. The

bottom and top of the box indicate 25th and 75th percentiles, respectively, and the line inside the box indicates the median. Error bars 10th and 90th percentiles. Closed circle outlier. The letters below the boxes indicate group categorized by difference in mean values based on Kruskal–Wallis one-way ANOVA on ranks with post hoc Dunn's method with a significance level of $p < 0.05$. The numbers below the boxes indicate the number of data points

Fig. 10 Relationship between TIN and PO_4^{3-} for the data collected before (*B1* 1973–1977 and *B2* 1996–2008) and after (*A1* May 2011–March 2012; *A2* May 2012–March 2013; and *A3* May 2013–March 2014) the earthquake for stratified period (*closed circles*), high mixing period (*open circles*), and Oyashio intrusion period (*closed inverted triangles*). The linear regression line and the Redfield ratio are indicated by the *solid* and *dashed* lines, respectively

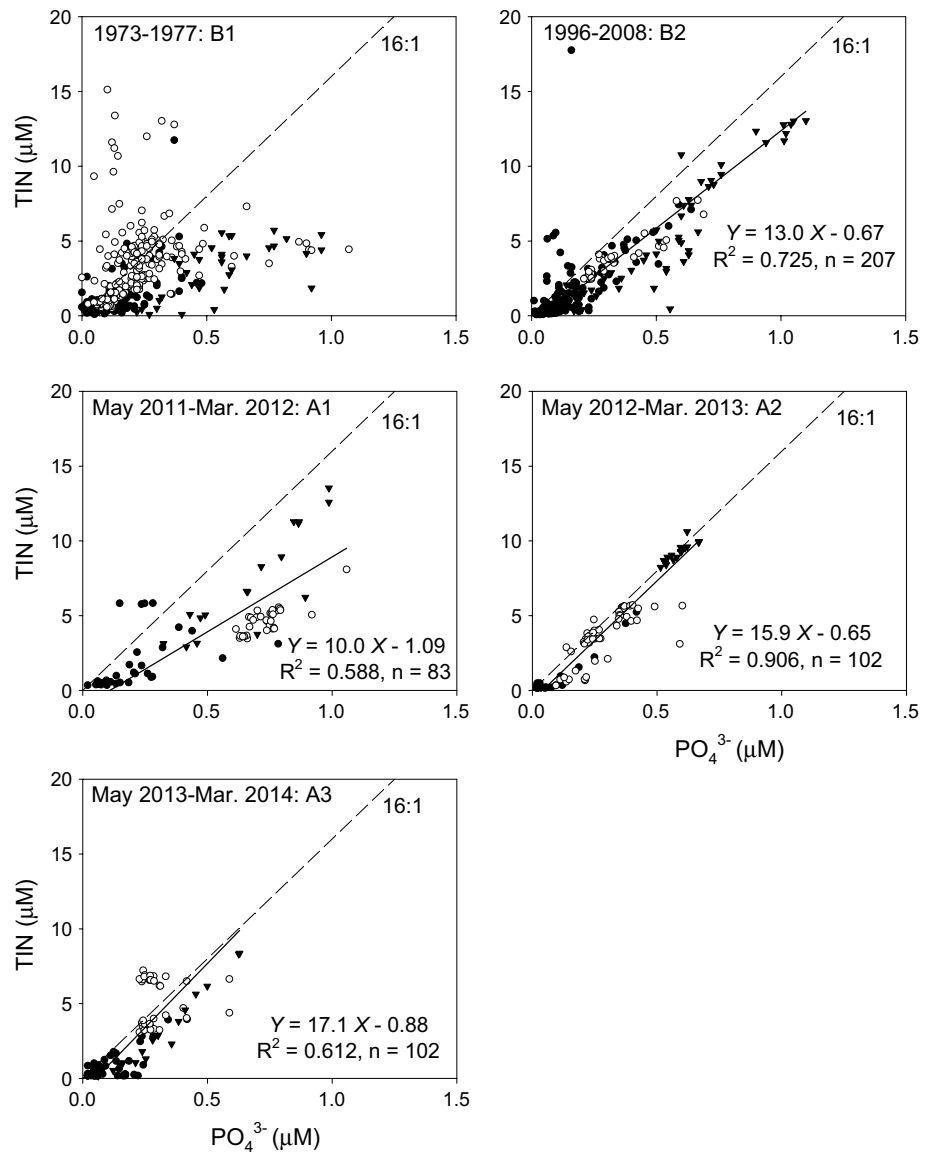


Table 2 Summary of regression analysis between total inorganic nitrogen (sum of nitrate, nitrite and ammonium: TIN) and phosphate

Period	Slope (95 % CI)	Intercept (95 % CI)	R^2	n	p	References
Before the Tsunami						
1996-2008	13.0 (12.1–14.0)	−0.67 (−1.02 to −0.32)	0.725	207	<0.001	Fukuda et al. (2007) Fukuda et al., unpublished.
After the Tsunami						
May 2011–March 2012	10.0 (8.6–11.4)	−1.09 (−1.93 to −0.24)	0.588	83	<0.001	This study
May 2012–March 2013	15.9 (15.0–16.9)	−0.65 (−0.97 to −0.33)	0.906	102	<0.001	This study
May 2013–March 2014	17.1 (15.0–19.2)	−0.88 (−1.42 to −0.35)	0.612	102	<0.001	This study

(PO_4^{3-}) in Otsuchi Bay. The regression lines were estimated by reduced major axis method (see Sect. 2)

NO_3^- , usually represents a rate limiting step of nitrification; Lomas and Lipschultz 2006; Ward 2002). However, under hypoxic conditions, the nitrification may result in the accumulation of NO_2^- , as observed in wastewater

treatment plants (Jianlong and Ning 2004; Ruiza et al. 2003). Also, under anoxic conditions, the prominent accumulation of NO_2^- may occur as a consequence of release during dissimilatory reduction of NO_3^- (Knowles 1982;

Philips et al. 2002). Our data showing the maximum NO_2^- concentration in the near-bottom layer in May and July might be a reflection of the NO_2^- release from hypoxic or anoxic sediments to the overlying water. However, this scenario would not completely explain the relatively high NO_2^- concentration and high $\text{NO}_2^-/\text{NO}_3^-$ ratio even in the surface mixed layer. The transport of NO_2^- released from the sediment to the surface layer would be strongly impeded by the presence of a pycnocline between May and September. This raises the possibility that a large quantity of nitrite was discharged into the bay via inflowing surface and ground waters. Frozen fish products, which were stored in refrigerated warehouses, were released to the surrounding area by the tsunami, and the rotting materials covered the landside of the bay (Kasai and Kobayashi 2012; Tabaru et al. 2012). It is likely that massive putrefaction of fish and other organic material following the tsunami deposit resulted in the creation of reduced environments around the bay, which was promoted by microbial activity enhanced due to warmer temperatures in May and July. In support of this hypothesis, Sugihara et al. (in preparation) detected a high Mn concentration in part of a shell of *Mytilus galloprovincialis*, which accumulated after the earthquake, collected from intertidal zone of Otsuchi Bay in September 2011, suggesting that a reduced environment in which Mn could exist in dissolved form appeared around the bay.

During the later part of the high-turbidity period, the concentration of Si(OH)_4 increased throughout the water column until May 2012. The range of the concentration of Si(OH)_4 in the high-turbidity period in 2011 was significantly higher than those observed in the stratified periods of 2012 and 2013 and that reported previously in 1973–1977 (B1). In contrast to the concentration of Si(OH)_4 in the high-turbidity period, the ranges of the concentrations of TIN and PO_4^{3-} did not differ largely from those before the earthquake. This decoupling among the distributions of Si(OH)_4 , TIN, and PO_4^{3-} , and the distribution of turbidity in the bay suggests that a high amount of Si(OH)_4 was introduced in association with the riverine input of sediments.

4.3 Possibility of high PO_4^{3-} loading from the sediment during the mixing period in 2011

During the mixing period between October 2011 and January 2012, PO_4^{3-} concentration was high relative to those found in the corresponding period of the subsequent years (2012–2013, 2013–2014) and those reported for the period before the earthquake (1973–1977, 1996–2008). The increase in PO_4^{3-} concentration began from the near-bottom layer in the center of the bay in September, and water with a low TIN/P ratio, which was much lower than the Redfield ratio, then spread to whole of the water column in

the mixing period. This could be explained by the spread of high PO_4^{3-} and low DIN/P water formed near the bottom to the whole bay due to upwelling induced by eastward wind at the inner part of Otsuchi Bay which may cause three-dimensional mixing to transport sediment-contact water to the surface (Furuya et al. 1993; Otobe et al. 2009; Shikama 1990). High PO_4^{3-} and low TIN/P water was formed near the bottom, presumably because of the release of PO_4^{3-} from anoxic sediment (Howarth 1988) accompanied by depletion of TIN due to denitrification (Burgin and Hamilton 2007; Howarth 1988). This might be related to the tsunami-induced loading of sediments and debris to the bottom of the bay.

4.4 The nutrient status following 2012 and 2013

The low TIN/P ratio in the mixing period of 2011 was moderated by intrusion of Oyashio water in March 2012, following which the TIN/P ratio in the mixing periods of 2012 and 2013 became higher than those in 1996–2008, approaching the Redfield N/P ratio of 16. Generally, in the offshore region of the Sanriku region, the TIN/P ratio in subsurface water is typically around 13–14 (Fukuda et al., unpublished data; Kasai et al. 1997; Whitney 2011). Therefore, Otsuchi Bay waters during the mixing and Oyashio intrusion periods in 2012–2013 and 2013–2014 were generally more enriched in N and depleted in P relative to the “source” seawater that intrudes into the bay in winter. In contrast, before the earthquake (B2; 1996–2008), the TIN/P ratio was close to the value of the “source” water during the mixing and Oyashio intrusion period. Possible mechanisms can be hypothesized to explain the increase in TIN/P following the second year after the earthquake: (1) an increase in TIN/P ratio of organic and inorganic materials discharged into the bay from land; (2) a decrease in denitrification in the sediment; (3) increased nitrogen fixation; and (4) alteration in nitrogen to phosphorus stoichiometry of biotic communities in and/or around the bay. Future studies should examine these possibilities in greater detail via the continuation of monitoring and a thorough evaluation of nutrient cycling mechanisms in the bay.

4.5 Concluding remarks

During our observation period, temporal changes in nutrient status following the earthquake were detected. Representative physical disturbances caused by the tsunami on the coastal ecosystem include physical erosion and reconstruction of the seafloor. In Otsuchi Bay, distinctive accumulations of NO_2^- , Si(OH)_4 , and PO_4^{3-} occurred or began before the diminishment of high turbidity. Such physical erosion and reconstruction of the seafloor may have been one of the key processes controlling the nutrient status following

the tsunami, although other factors (e.g., nutrient discharge from disturbed lands surrounding the bay) may have also contributed to the alteration in the nutrient status. The role of the reconstructed seafloor in the nutrient dynamics remains unclear. In addition to the possible alteration in the nutrient status during the subsequent year of the earthquake (2011–2012), our results also suggested that the change in the nutrient status continued until at least the beginning of 2014. In the investigated region, large-scale public works to restore infrastructure, reconstruction of fisheries including the rebuilding of aquaculture facilities, and other related changes in human activity will continue for at least several years. Continuation of the monitoring of the nutrient status is necessary to provide a scientific basis for the sustainable use of the ecosystem services provided by Otsuchi Bay.

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