Change in zooplankton community in Onagawa Bay, northeastern Japan after the Tohoku Earthquake and tsunami in 2011 off the Pacific coast of Japan

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Abstract: Change in abundance and composition of the zooplankton community was studied at the innermost part of Onagawa Bay, northeastern Japan, before and after the Tohoku Earthquake and tsunami of 2011. Abundance of zooplankton groups did not drastically decrease just after the tsunami except for cladocerans and the larvae of benthic organisms. The decrease of the former may have been caused by their resting eggs being swept away by the tsunami or buried in the sediment just before their spring increase, while that of the latter by a population decline of their adults. The number of cladoceran species decreased from 7 to 5, with increasing dominance of *Podon leuckarti* after the tsunami. The percentage of the genera *Acartia* and *Oithona*, combined, was 73% of all copepod genera before the tsunami and increased to 85% after the tsunami. Zooplankton abundance increased with the increase of chlorophyll concentration from 2013, two years after the tsunami. The basic structure of the breakwater broken by the tsunami was reconstructed by the end of 2014 with a shallower sill depth, and the water exchange between the inside and outside of the breakwater became restricted. As a result, dissolved oxygen concentration decreased not only on the bottom but also in the water column and the species diversity of copepods decreased at the innermost station. Long-term monitoring should be continued.

Key words: Onagawa Bay, Tohoku Earthquake, tsunami, zooplankton

Introduction

Onagawa Bay is located in the southern Sanriku area, facing the Pacific Ocean, with a length of about 7 km and a width of 2–3 km. Aquaculture of oysters, scallops and coho salmon had been widespread in the bay. The Tohoku Earthquake and tsunami that occurred on March 11, 2011 caused devastating damage to the Sanriku coastal area, including Onagawa Bay. The inundation height was more than 14 m and the maximum run-up height exceeded 30 m in Onagawa Bay (Mori et al. 2012). The breakwater at the inner part of the bay was broken by the tsunami. Aquaculture facilities were greatly damaged and aquaculture production in Onagawa plummeted in 2011 to less than 2% of the previous year (Onagawa Town 2020). The tsunami altered sedimentary features (Seike et al. 2016, Yokoyama et al. 2018) and affected the benthic community (Kaneko et al. 2018, Sato-Okoshi 2018). Kaneko et al. (2018), based on a comprehensive survey in the whole bay, showed that the mud content increased in the whole bay and accompanied homogenization of COD (chemical oxygen demand) and heavy metals such as Cu took place after the tsunami. Recently, the mud content and concentration of chemicals such as N-hexane extract show a decreasing tendency. However, in the innermost part of the bay, several years after the tsunami, COD and heavy metal contents of bottom sediments are increased. Therefore, recovery from the disaster and new environmental concerns from reconstruction work are taking place at the same time. The abundance and species number of macrobenthos greatly decreased after the tsunami, and the community was dominated by opportunistic species indicative of eutrophic environments (Kaneko et al. 2018, Sato-Okoshi 2018). The macrobenthos community had recovered to the pre-tsunami condition in the central bay in 2014, but the abundance
is still low and the community is unstable in the innermost part of the bay.

On the contrary, plankton communities seemed to be less affected than benthos by the tsunami, and recovered to their pre-tsunami condition. Tachibana et al. (2017) suggested that there was no serious effect of the tsunami on the phytoplankton community in Otsuchi Bay on the central Sanriku coast, because the species composition in May 2011, 2 months after the tsunami, was similar to that observed in May 2012 and 2013. A similar conclusion was drawn by Nishitani et al. (2012) on phytoplankton composition for Kesennuma Bay and Moune Bay by sampling from 2 months after the tsunami for 18 months. Seasonal change in four phytoplankton groups did not differ 12 months after the tsunami from the pre-tsunami period in Sendai Bay (Taniuchi et al. 2017), the largest bay in the Sanriku area. Seasonal succession of the diatom community is reported not to have been seriously affected by the tsunami in the bay (Watanabe et al. 2017). The exceptional case is the significant increase in cyst abundance of *Alexandrium* spp. in the surface layer of the sediments after the tsunami in Sendai Bay (Kamiyama et al. 2014) and Funka Bay, Hokkaido (Natsuike et al. 2014). They suggested that either re-suspension and vertical transport of *Alexandrium* cysts from the deep layers of the sediments or a new production of cysts had occurred.

Nishibe et al. (2016) compared zooplankton abundance and composition before and after the tsunami in Otsuchi Bay. They suggested that there were no significant and lasting influences of the tsunami on the holozooplankton taxa, but planktonic larvae of bivalves, gastropods, and polychaetes showed reduced abundance, possibly reflecting the damage due to the tsunami on their benthic populations.

The basic structure of the broken breakwater in Onagawa Bay was reconstructed by the end of 2014. After that, water exchange between the inner part and outer part of the bay became restricted and oxygen depletion in the bottom layer appeared (Kaneko et al. 2018, Sato-Okoshi 2018). The aim of this paper is to clarify the change in zooplankton community before and after the tsunami at the innermost station of the bay, where we had been collecting basic data on environmental parameters and zooplankton composition before the earthquake and tsunami, in order to understand the effects of the tsunami. We also report the change in zooplankton composition that occurred several years after the tsunami under oxygen-reduced environmental conditions caused by the reconstruction of the breakwater.

**Materials and Methods**

Zooplankton samplings were conducted between October 2000 and February 2011, but monthly from July 2011 to March 2017 at the innermost station of Onagawa Bay. Exact dates varied between different taxonomic groups. In 2011, field surveys could not be conducted from March to June because of the tactical problems caused by the Tohoku Earthquake and tsunami. The location of the sampling station was 38°26.14’N, 141°27.83’E (St. O1) from October 2000 to February 2012, and 38°26.30’N, 141°27.70’E (St. 1) from March 2012 onward (Fig. 1). These stations were 340-m apart, but were treated during analysis of the results as the same station. Zooplankton samples were collected by vertical tows from near the bottom to the surface with a Norpac net (45 cm mouth diameter, Motoda (1957)).
Table 1. Approximate duration of available data on the abundance of 7 taxonomic groups (copepods, appendicularians, cladocerans, chaetognaths, hydromedusae, cirriped larvae and polychaete larvae), cladoceran species, copepod genus and species composition of all adult plankton. There were no data on polychaete larvae from January 2011 to February 2012.

| Year | Copepods | Cladocerans | Appendicularian | Polychaete larvae | Cirriped larvae | Hydromedusae | Polychaete larvae |
|------|-----------|-------------|----------------|------------------|----------------|--------------|-----------------|
| 2000 |            |             |                |                  |                |              |                 |
| 2001 |            |             |                |                  |                |              |                 |
| 2002 |            |             |                |                  |                |              |                 |
| 2003 |            |             |                |                  |                |              |                 |
| 2004 |            |             |                |                  |                |              |                 |
| 2005 |            |             |                |                  |                |              |                 |
| 2006 |            |             |                |                  |                |              |                 |
| 2007 |            |             |                |                  |                |              |                 |
| 2008 |            |             |                |                  |                |              |                 |
| 2009 |            |             |                |                  |                |              |                 |
| 2010 |            |             |                |                  |                |              |                 |
| 2011 |            |             |                |                  |                |              |                 |
| 2012 |            |             |                |                  |                |              |                 |
| 2013 |            |             |                |                  |                |              |                 |
| 2014 |            |             |                |                  |                |              |                 |
| 2015 |            |             |                |                  |                |              |                 |
| 2016 |            |             |                |                  |                |              |                 |
| 2017 |            |             |                |                  |                |              |                 |

The mesh size of the net was 0.11 mm or 0.1 mm from October 2000 to February 2012, but 0.1 mm from March 2012 and thereafter. The volume of water filtered was estimated from the reading of a flowmeter (Rigosha) attached to the mouth of the net.

Water temperature and salinity were measured with a CTD (MSTD PK-200, Alec Electronics, or RINKO-profiler, ASTD102, JFE Advantec Co., Ltd.) from the surface to the bottom layer. Dissolved oxygen concentration was measured with a RINKO-profiler. Water samples for chlorophyll a determination were collected with a Van Dorn sampler at 5 m intervals from the surface to the bottom. A 200-mL water sample was filtered through a Whatman GF/F filter. The filters were extracted in 90% acetone from October 2000 to April 2012 and in N,N-dimethylformamide from May 2012 to March 2017, and chlorophyll a concentration was measured with a fluorometer (10-AU, Turner Designs) according to Holm-Hansen et al. (1965). No calibration was made for the above-mentioned extraction methods, because there was no significant difference between the two methods applied to the same water samples collected almost monthly from February 2012 to September 2013 using Matlab R2019b (paired-sample t-test, n=15, p=0.3158).

In the laboratory, zooplankton were sorted into 7 taxonomic groups (copepods, cladocerans, appendicularians, cirriped larvae, chaetognaths, hydromedusae, and polychaete larvae) and enumerated. Copepods include their nauplii, copepodites and adults. Abundances of these 7 taxonomic groups were available from October 2000 to October 2001, from October 2005 to November 2009 except November 2006, from January to February 2011, and from July 2011 to March 2017 (Table 1). We did not count polychaete larvae from January 2011 to February 2012. Of these taxa, cladocerans were sorted into species from October 2000 to October 2001, from November 2002 to January 2005 except November 2003, and from May 2012 to March 2017. Copepods were sorted into genus from October 2005 to October 2008 except November 2006, and from March 2012 to March 2017. Species level data on copepods are available from March 2012 to March 2017. From March 2012, all adult zooplankton were sorted into species.

The Shannon-Wiener index ($H'$; Shannon 1948) was calculated for a monthly comparison of the species diversity of adult copepods.

Results

Environmental conditions

The water temperature at the surface layer was highest in July-September, being 21.0–24.9°C, and lowest in February-March, being 4.2–7.8°C (Fig. 2A, B). Temperatures were homogenous throughout the water column from October to February. Salinities lower than 32 were observed from spring to fall in the surface 6 m (Fig. 2A, B). These oceanographic features are common to both before and after the earthquake and tsunami. Chlorophyll a concentration in the water column is shown in Fig. 2A, B. Average chlorophyll a concentration in the water column in 2012 showed peaks in February and April, being 8–10 μg L⁻¹, but after that lower values (2 μg L⁻¹ or less) were observed from June to December that year. The seasonal maximum concentration increased from 2013 to 2015, with the maximum value of more than 18 μg L⁻¹ attained in March 2015. The highest concentration, 45.6 μg L⁻¹, was observed at 15 m depth in March 2015. There were spring and fall blooms and a summer increase in chlorophyll concentration in Onagawa Bay. The spring bloom occurred in January–April, the fall bloom in September or October, and the summer increase occurred in July–August. Chlorophyll a concentration was high throughout the water column during the spring blooms but high concentrations were restricted to the upper half of the water column during the summer increase and fall blooms. There was a small summer increase in 2011 but no summer increase or fall bloom in 2012, though from 2014 a conspicuous fall bloom occurred again.

Dissolved oxygen concentration showed a decreasing trend in the water column with values less than 5 mg L⁻¹...
Zooplankton community

Copepods were the most abundant taxon among the 7 zooplankton groups investigated in the present study, occupying 82.6% (42.7–98.9%) of all zooplankton. They were followed by appendicularians (6.9%), cirriped larvae (4.0%), and cladocerans (2.7%) throughout the whole study period (Fig. 4).

Copepod abundances were generally higher in warm seasons, with the highest value of about 46,000 ind. m$^{-3}$ occurring before the tsunami. The abundance was not very low several months after the tsunami, but significantly increased from 2013, with more than 156,000 ind. m$^{-3}$ in 2014 and 2016. The abundance was also high even in the winter of 2016. Change in genus and species composition will be introduced forthwith.

Appendicularian abundances were generally high, about 2,000 ind. m$^{-3}$, in warm seasons before the tsunami, and were not particularly low in the summer just after the tsunami. The abundance became higher after that, with the highest value of 17,723 ind. m$^{-3}$ observed in April 2014. In 2016, the abundance was also high in winter as well as in the warm seasons.

Cladocerans were generally abundant from spring to summer with the maximum abundance of about 2,760 ind. m$^{-3}$ recorded in June 2007, before the tsunami, but the abundance was quite low, 367 ind. m$^{-3}$ in the summer just after the tsunami. Their abundance increased from 2014 onward, with the maximum value of 13,600 ind. m$^{-3}$ observed in February 2016. Change in species composition of cladocerans will be introduced forthwith.

Chaetognaths were generally abundant in summer and their abundance was especially high in the summer just after the tsunami, with the highest value of slightly over 2,000 ind. m$^{-3}$ observed in August 2011. Relatively higher values of 500 ind. m$^{-3}$ were maintained in the warm seasons of 2012–2014 but returned to the lower values of the pre-earthquake period after that.

Hydromedusae were abundant from late winter to fall but the abundance was low in 2008, 2009 and 2011. Their

Fig. 2A. Time series of vertical profile of water temperature (°C, a), salinity (b) and chlorophyll $a$ concentration ($\mu$g L$^{-1}$, c) at St. 1 in Onagawa Bay from October 2000 to February 2011, just before the 2011 earthquake and tsunami off the Pacific coast of Tohoku.
abundances increased from 2012 with the highest value of about 1,700 ind. m$^{-3}$ observed in March 2017.

Cirriped larvae occurred all year round but tended to be abundant in warm seasons. The abundance was not particularly low just after the tsunami but became higher in 2014–2016, with the highest value of about 35,600 ind. m$^{-3}$ observed in May 2015, which was 25 times higher than the mean value of the pre-tsunami period.

Fig. 2B. Same as Fig. 2A but for July 2011 to March 2017.

Fig. 3. Time series of vertical profiles of dissolved oxygen concentration (mg L$^{-1}$) in the water column at St. 1 in Onagawa Bay from May 2012 to July 2017.
Polychaete larvae occurred all year round and tended to be abundant in winter and spring-summer. We did not count their abundance from January 2011 to February 2012 but the seasonal maxima became a little higher than those before the tsunami after 2013, except for the highest value of 7,764 ind. m$^{-3}$ recorded in January 2007.

**Cladocerans**

Seven species of cladocerans appeared at St. 1 during the study period: *Evadne nordmanni* Lovén, 1836, *Evadne spinifera* P.E. Müller, 1867, *Evadne tergestina* Claus, 1877, *Penilia avirostris* Dana, 1852, *Podon leuckarti* (G.O. Sars, 1862), *Podon polyphemoides* (Leuckart, 1859), and *Podon schmackeri* Poppe, 1889 (Fig. 5). Before the tsunami, *P. leuckarti* dominated in spring, *E. nordmanni* in summer and *P. polyphemoides* in summer-fall. *Penilia avirostris* and *E. tergestina* appeared in summer and fall and *E. spinifera* occurred in the fall. Overall, *P. leuckarti* and *P. polyphemoides* were dominant, each comprising about 36% of total cladocerans, followed by *E. nordmanni* making up 27%. On the other hand, after the tsunami, *E. nordmanni* abundance was quite low until 2015, and the dominant species were *P. leuckarti* in spring, *P. polyphemoides* and *E. tergestina* in summer and fall in 2012 and 2013. Abundance of cladocerans increased from 2014 onward, which is attributable to the increase of *P. leuckarti* and *E. nordmanni*. The dominance of the former species was conspicuous, comprising more than 70% of total cladoceran abundance after the tsunami. *E. spinifera* and *P. schmackeri* which occurred in low abundances before the tsunami, did not appear after the tsunami. *P. avirostris*, which appeared before the tsunami and also in August of 2012 and 2013 after the tsunami, did not appear thereafter.

**Copepods**

Copepod genus composition during 2005–2008 (before the tsunami) and 2012–2017 (after the tsunami) is shown in Fig. 6. In the spring of 2012, one year after the tsunami, copepod genus composition did not differ from that before the tsunami, except that *Microsetella* did not appear from March to July (Fig. 6). The genera *Acartia* and *Oithona* were the dominant copepods in Onagawa Bay. The abundance of the genus *Acartia* was less than 6,700 ind. m$^{-3}$ in 2005–2008 and was at a similar level in 2012 and 2013, 1 and 2 years after the tsunami, but increased from 2014 with a maximum value of 63,600 ind. m$^{-3}$ in February 2016. The abundance of the genus *Oithona* was less than 3,500 ind. m$^{-3}$ in 2005–2008, but increased a little earlier than *Acartia* after the tsunami, namely from 2013, with a maximum value of 20,000 ind. m$^{-3}$ in February 2016. *Paracalanus*, *Microsetella*, *Euterpinia*, *Corycaeus* and *Oncaea* became more abundant after the tsunami than before. Among them, *Paracalanus* and *Corycaeus* exhibited peak abundances in 2016, while *Euterpinia* and *Oncaea* peak
Fig. 5. Time series of abundance of cladoceran species at St. 1 in Onagawa Bay before (a) and after the earthquake and tsunami (b).

Fig. 6. Time series of abundance (a) and composition (b) of copepod genera at St. 1 in Onagawa Bay from October 2005 to March 2017.
abundance was in 2012 and decreased thereafter. Microsetella has remained at higher abundances since 2013. The percentage of the total number of copepods that was comprised by the genera Acartia and Oithona combined was 73%, followed by the genus Pseudocalanus (13%) before the tsunami, and this increased to 85% with less than 4% of individuals belonging to any other genus after the tsunami.

Seasonal succession of copepod genera before the tsunami was as follows: Pseudocalanus increased in spring when the Oyashio Current entered into the bay, and Oithona also increased in spring. Acartia and Microsetella increased in summer, and Paracalanus increased in summer-fall. This seasonal succession was essentially the same after the tsunami, but some genera showed extended periods of high abundance: Acartia from late winter to summer, Oithona almost all year round, and Microsetella in summer and winter.

After March 2012, species identifications of adult copepods were determined. Four species of Acartia appeared at St. 1, A. hudsonica Pinhey, 1926, A. longiremis Liljeborg, 1853, A. omorii Bradford, 1976 and A. steueri Smirnov, 1936 (Fig. 7). Acartia omorii was the most dominant species and occupied 77.5% of the total number of copepods of the genus Acartia during the investigation period, followed by A. hudsonica (17.1%), A. steueri (4.5%) and A. longiremis (0.7%). Acartia longiremis occurred only in May and June 2014. Seven species of the genus Oithona appeared: O. atlantica Farran, 1908, O. attenuata Farran, 1913, O. davisiae Ferrari F.D. & Orsi, 1984, O. nana Giesbrecht, 1893, O. plumifera Baird, 1843, O. similis Claus, 1866 and O. simplex Farran, 1913 (Fig. 8). Among these species, O. davisiae and O. similis were the two dominant species, comprising 54.6% and 41.7%, respectively of all Oithona individuals during the investigation period, followed by O. atlantica (2.0%), O. nana (0.9%), and O. simplex (0.7%). Oithona davisiae was especially abundant, 12,800 ind. m$^{-3}$, in the early spring of 2016. In 2012–2013, O. similis dominated the Oithona species, but from the fall of 2014, O. davisiae outnumbered O. similis and the latter species decreased thereafter. At the other stations in the central and outer part of the bay (Sts. 6 and 8), however, O. similis dominated (not shown). Seasonally, O. similis was abundant in spring, while O. davisiae was abundant in summer and fall. Exceptionally, the latter species exhibited high abundances from the fall of 2015 to the winter of 2016, with the highest value observed in February 2016.

Seasonal succession of copepods after the tsunami can
be summarized as follows. In spring, *Pseudocalanus newmani* Frost, 1989 increased. In spring and summer of 2012, when copepod abundance was low, *Oithona similis* and *Acartia omorii* dominated adult copepods. *O. similis* dominated in the following years, but was replaced by *Oithona davisae* in 2016 which began to increase from the fall of 2014. In summer, *A. omorii*, *O. similis*, *Paracalanus parvus* s.l. (Claus, 1863) and *Microsetella norvegica* (Boeck, 1865) dominated. *Acartia hudsonica* was abundant only in late spring to summer of 2015. In the fall, *A. omorii*, *O. davisae*, *Euterpinia acutifrons* (Dana, 1847) and *P. parvus* s.l. were dominant. In winter, *A. omorii*, *O. similis*, *O. davisae* and *M. norvegica* were dominant. Overall, after the tsunami, *O. davisae* was very important at this station because it comprised 25.4% of adult copepods, followed by *A. omorii* (21.3%) and *O. similis* (19.4%).

At stations in the central and outer part of the bay (Sts. 3, 6, and 8) in summer, *Oncaea scottodicarloi* Heron & Bradford-Grieve, 1995 was abundant in 2013–2015 and *Oncaea media* Giesbrecht, 1891 was abundant in 2015 and 2016, with the former species remaining abundant in fall and even winter in some years.

Species diversity of copepods, $H'$, was low one year after the tsunami, but increased from 2012 to 2014 (Fig. 9). Very low values, however, were found in the spring from 2015.

**Discussion**

Seasonal change in temperature and salinity at the innermost station in Onagawa Bay was essentially the same before and after the tsunami. However, 2015 was an exceptional year in that the Oyashio Current water stayed for an extended period from February to May at St. 1. The highest chlorophyll *a* concentration in the present study, 45.6 µg L$^{-1}$, was also observed in March that year. High nutrient concentration (dissolved inorganic nitrogen concentration at the surface was 9.2 µM in March) and boreal diatoms such as *Thalassiosira nordenskioeldii* Cleve, *Chaetoceros debilis* Cleve, and *Chaetoceros socialis* Laud er brought in by the Oyashio Current have induced such high chlorophyll *a* concentrations (Tohoku Ecosystem-Associated Marine Sciences project, unpublished data). Zoop lankton also occurred at high abundances in May 2015 (Fig. 4), mainly due to large numbers of copepods (75%) and cirriped larvae (23%). Most of these copepods were composed of nauplii (60%), genus *Acartia* (20%, mostly copepodites) and genus *Pseudocalanus* (7%, mostly copepodites). Therefore, the contribution of the genus *Pseudocalanus*, which is a typical cold water species, was not large.

Usually, there are spring and fall blooms and a summer chlorophyll increase in Onagawa Bay. The spring bloom consists of microplankton, while the summer increase and fall bloom consists of pico- and nanoplan kton (Abe et al. 2011). The fall bloom was not remarkable in 2011 and both a summer increase and fall bloom were not observed in 2012, the year the tsunami hit and the next year. However, both the summer increase and fall bloom appeared again from 2013. Nutrient concentrations in summer and fall have increased in accordance with increased human activities, such as aquaculture, after the tsunami around the area, but a detailed discussion of this will be published elsewhere.

Four months after the earthquake and tsunami we were able to resume our field survey from July 2011 and at that time the abundances of the major zooplankton groups were not particularly low, except for cladocerans, which were quite low from July 2011 to March 2012 (Fig. 4). Hydromedusa abundance was quite low in 2011, but similar levels had been observed in 2009. On the other hand, chaetognaths were very abundant in the summer of 2011, with a maximum value of over 2,000 ind. m$^{-3}$ in August 2011. This is about 7 times higher than the maximum value observed before the tsunami, and the seasonal maximum in 2012–2014, about 500 ind. m$^{-3}$, was a little higher than before the tsunami, but decreased thereafter (Fig. 4). This increase in chaetognath abundance in 2011 and the relatively higher abundance in 2012–2014 suggests the influence of the broken breakwater enabling their transport into the innermost part of the bay. However, most of the taxonomic groups increased in abundance after 2013, except
for chaetognaths and polychaetes. The peaks in abundance of groups that increased their populations were found between 2014 and 2016. On the other hand, Nishibe et al. (2016) reported that the abundance of the planktonic larvae of benthic invertebrates was very low in May 2011, 2 months after the tsunami, compared with the following 2 years in Otsuchi Bay. In the present study, there are no data on the abundance of polychaete larvae from January 2011 to February 2012. However, the fact that benthothis abundance was greatly reduced and the composition drastically changed just after the tsunami (Abe et al. 2014, Kaneko et al. 2018, Sato-Okoshi 2018) suggests that the planktonic larvae of polychaetes may have been greatly reduced just after the tsunami.

Average total abundance of the 7 taxonomic groups from March to October, during which zooplankton were generally abundant, after the tsunami was plotted along with average chlorophyll $a$ concentration in the water column for the same period (Fig. 10). Average chlorophyll $a$ concentration was quite low in 2012, but increased from 2013 onward. Zooplankton abundance increased with increasing chlorophyll $a$ concentration from 2012 to 2014, but not for the high chlorophyll $a$ concentration periods thereafter. In 2015, Oyashio water stayed at St.1 for a longer time than in a usual year and the chlorophyll $a$ concentration was very high in spring, but not particularly high in summer. That may be why zooplankton abundance was low for the high chlorophyll $a$ concentration in 2015. Alternatively, environmental conditions could have turned detrimental for zooplankton. This temporal change in chlorophyll $a$ concentration can explain the lower abundances of most of the zooplankton groups in 2012 and their increase from 2013 onwards. Aquaculture production in Onagawa dropped to a very small amount in the year of the tsunami (68 million yen), less than 2% of the previous year (3.8 billion yen), and recovered to half the amount of pre-tsunami levels in 2012, before finally reaching a similar level in 2014 and thereafter (Onagawa Town 2020). Coho salmon aquaculture, which is a type of aquaculture where food is actively supplied, comprised 66–78% of the total aquacultural production in Onagawa. Therefore, nutrients dissolved from remaining food and feces may have increased with the re-development of aquaculture.

Cladocerans increased from spring to summer in Onagawa Bay. Marine cladoceran populations are recruited totally or primarily from resting eggs (Egloff et al. 1997). Cladocerans are able to rapidly increase their numbers when environmental conditions are favorable because they can reproduce offspring by parthenogenesis. The abundance of cladocerans was quite low in the summer of 2011, just after the tsunami. The tsunami after the earthquake may have swept away the resting eggs of cladocerans in the sediments in March 2011, just before their seasonal increase. Komazawa & Endo (2002) investigated the hatching rate of resting eggs of three cladoceran species (Eudanoe nordmanni, Podon polyphemoides and Podon leuckarti) collected from Onagawa Bay during 40 days of incubation. They found that resting eggs were either evenly distributed in the 4 depth layers of 2 cm each down to 8 cm but hatching rate was higher in the top 4 cm, and in the case of P. leuckarti hatching did not occur in the layer below 4 cm. Seike et al. (2016) investigated the sedimentary features of the central part of Onagawa Bay after the tsunami and reported that the seafloor sediments consisted of two lithological layers. The surface 8 cm was composed of muddy sediments deposited by normal depositional processes and/or the weakening tsunami current. On the other hand, the lower part of the sediment consisted of tsunami-induced deposits, namely, laminated sandy sediments generated by the strong currents associated with the 2011 tsunami. Likewise, the bottom sediments collected near St. 1 of the present study in 2013 were composed of the upper 10 cm layer of muddy sediment and a lower sandy sediment layer (Kaneko personal communication). Therefore, the low abundance of cladocerans after the tsunami may have been caused by resting eggs being swept away by the strong tsunami current or buried deeper than 4 cm in the sediment.

In the seasonal cycle of cladocerans in Onagawa Bay, Podon leuckarti appeared first in winter and attained its highest abundance in spring (April–June), when water temperature ranges from 6 to 8°C (Figs. 2 and 5). The highest abundance of the species, about 14,000 ind. m$^{-3}$, was recorded in February 2016, when the bottom temperature was 7.7°C. After the tsunami, the increase of P. leuckarti was remarkable (Fig. 5). Acceleration of brood production has been reported for P. leuckarti, in which more than one brood of different ages may be found in the same brood chamber (Egloff et al. 1997).

The abundance of copepods was not very low several months after the tsunami but significantly increased from 2013 (Fig. 4). Genera that increased in abundance after 2013 included Acartia, Oithona, Paracalanus, Microsetella, and Corycaeus, while the genera Euterpina and Oncaea showed highest abundance in 2012. All of these genera are dominant copepods in Onagawa Bay as reported by.
Uye (1982a) (Fig. 6). Similar genus composition in summer was reported in the early 1950’s by Yamazi (1953). The fact that many genera increased in abundance from 2013 suggests that environmental conditions, such as food availability, for copepods improved. The genus *Pseudocalanus* remained at similar abundances before and after the tsunami. The dominant species of this genus is *Pseudocalanus newmani*, a cold water species that appears in Onagawa Bay only in spring (Fig. 6). This species may not be able to survive the warmer seasons, taking advantage of improved food conditions, which may be the reason why its abundance did not change before and after the tsunami. Yamada et al. (2012) suggested that *Pseudocalanus* spp. disappear when the water temperature rises above 15°C in Okkirai Bay, central Sanriku coast. The most abundant genera in Onagawa Bay, *Acartia* and *Oithona*, increased from 2012 to 2016, while *Euterpinia* and *Oncaea* decreased from 2012 to 2016.

Copepod genus composition was essentially the same before and after the tsunami, except that *Microsetella* did not appear from May to July 2012. This may be because *Microsetella* is not abundant in the innermost part of the bay and appears in deeper parts of the water column. *Microsetella norvegica* occurred mainly in the central and outer part of Onagawa Bay (Sts. 6 and 8, not shown). In Tokyo Bay, this species occurs also mainly in the central and outer areas (Itoh & Nishida 2015). The distributional depth of *M. norvegica* was found in the mid-deeper layer in Tokyo Bay by water bottle samplings (Anakubo & Murano 1991). In Onagawa Bay, harpacticoids, of which *M. norvegica* is the dominant species in the bay, proved to not be abundant, but appeared in spring and increased in August 2012, according to pump samplings at the innermost station. Its main distributional depth was in the bottom 5–6 m in spring-early summer (Abe 2013). Thus, this species was not collected by net sampling but collected by pump sampling. As the pumped water was filtered through 110μ mesh, mesh size was not important. For unknown reasons this species was not collected by net sampling.

Copepod abundance was generally higher in warm seasons before the tsunami. This tendency was essentially the same after the tsunami. In February 2016, copepod abundance was the second highest, following October 2014, which may be partly because the water temperature did not decrease below 7.6°C that month and the production rate of winter populations may have increased.

Four *Acartia* species (*Acartia hudsonica*, *Acartia longiremis*, *Acartia omorii* and *Acartia steueri*) were abundant in Onagawa Bay after the tsunami. Among them, *A. hudsonica*, *A. omorii* and *A. steueri* are known to produce resting eggs (Marcus 1996). The abundance of *Acartia* in 2012, one year after the tsunami, was almost the same as that before the tsunami. *A. omorii* dominated *Acartia* population in 2012 and thereafter. Uye (1982a) reported that *A. omorii* (as *A. clausi*) was the dominant copepod in Onagawa Bay, which is also applicable to the copepod community after the earthquake. Uye (1982b) investigated the population dynamics of *A. omorii* (as *A. clausi*) in Onagawa Bay and showed that this species is present all year round and produces offspring throughout the year. He pointed out that the facultative resting eggs produced by this species bring time-released hatching effects that are advantageous to extending its occupation in the habitat by opportunistic resurgence as well as in maintaining its constant presence by regulating the population density. The second most dominant *Acartia* species was *A. hudsonica* in Onagawa Bay after the tsunami. *A. hudsonica* has been reported to be more confined to the innermost part of Maizuru Bay, central Japan (Ueda 1987). Ueda showed that the seasonal abundance of these two species was very similar in Maizuru Bay. In Onagawa Bay, *A. omorii* occurred all year round, but *A. hudsonica* occurred only in spring. *A. steueri* tended to occur more abundantly in the inner-central part of Onagawa Bay than in the outer area (St. 8), where this species occurred only once in May 2013.

In the spring of 2012, one year after the tsunami, *A. hudsonica* did not appear and *A. steueri* was scarce at the innermost station. Both species were totally absent at other stations in Onagawa Bay (Sts. 3, 6, 8) in that spring. Judging from the seasonal occurrence of the adult population (Fig. 7), the resting eggs of the former species may have been swept away by the tsunami just before hatching, and those of the latter species just after production following the seasonal increase of the adult population. On the other hand, *A. omorii* should have existed as plankton when the tsunami hit, and maintained its population after that.

Nishibe et al. (2016) reported that *A. hudsonica* was more abundant than *A. omorii* in the inner part of Otsuchi Bay. In Onagawa Bay, *A. omorii* was dominant both before and after the tsunami. This difference may be partly because there are no big rivers in Onagawa Bay and the environment is not suitable for *A. hudsonica* to proliferate.

Nishibe et al. (2016) reported that *O. similis* dominated the *Oithona* species in Otsuchi Bay, while in the present study *O. davisi* dominated at the innermost station in Onagawa Bay from 2014. *O. similis*, however, dominated at the other stations in the central and outer part of Onagawa Bay. The distribution pattern of these two species in the present study is consistent with a previous report that *O. davisi* is much more abundant than *O. similis*, particularly in the inner part of inlets during summer and fall, and the latter species is distributed mainly in the outer part of inlets during winter and spring (Ueda 1991). Dominance of *O. davisi*, however, began from 2014 at the innermost station in Onagawa Bay, which suggests environmental conditions changed in favor of *O. davisi*. This species change coincided with the reconstruction of the basic structure of the breakwater and the shallowing of the sill depth from about 20 m before the tsunami to about 10 m during the reconstruction process. This may have reduced the water exchange between the inside and outside of the breakwater. Itoh & Nishida (2015) suggested that *O. davi-
saes populations increased with advanced eutrophication in Tokyo Bay. The effects of the destruction of the breakwater by the tsunami and the possibility that its reconstruction may have caused ecosystem change are of concern from the viewpoint of ecosystem health. For instance, Yamada et al. (2017) reported a decrease of ammonium and phosphate concentrations, and an increase in chlorophyll a concentrations caused by a decrease in the number of cultivated shellfish, as well as an increase in dissolved oxygen concentration at the bottom and a decrease in heterotrophic bacteria for Ofunato Bay, Sanriku area. The restoration work in Ofunato Bay was completed in March 2017, and its effect is of interest from the viewpoint of water quality and ecosystem health in the bay.

An oxygen depleted layer has been reported in the bottom sediment of the innermost part of Onagawa Bay after the tsunami (Kaneko et al. 2018, Sato-Okoshi 2018). Dissolved oxygen concentration has also decreased in the water column with values of less than 5 mg L\(^{-1}\) appearing in the lower layers since 2014 (lowest value of 1.79 in September 2016, Fig. 3). Such low values were not observed in the near-bottom layer at the station near St. 1 of the present study during the period from 2001 to 2010, when the lowest value of 6.2 mg L\(^{-1}\) was reported in July 2002 (Miyagi Prefecture, Tohoku Electric Power Company (2003–2012)). Species diversity of copepods was low one year after the tsunami, but increased from 2012 to 2014 (Fig. 9). Very low values, however, were found in the springs from 2015, which coincides with the reconstruction of the basic structure of the breakwater and shallowed sill depth. It is expected that aquaculture will be developed further in the future. Therefore, monitoring on water quality and plankton composition should be continued.

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