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Tsunami-induced changes in abalone and sea urchin populations in Otsuchi Bay, Japan

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Abstract — The effects of a tsunami on abalone (*Haliotis discus hannai*), and sea urchin (*Mesocentrotus nudus*) populations in Otsuchi Bay, Japan, are reported. Changes in density and size composition of the two species are compared at three locations along nine transects in the inner, middle and entrance parts of Otsuchi Bay. The intensity of tsunami impacts, and degree of recovery differed among locations and species. Tsunami impacts on the abalone were greatest in the inner part of the bay, where density remains almost 0 inds./m^2 even in 2015. However, clear changes in density and size composition of the abalone have not been confirmed in the middle and entrance parts of the bay until 2015. In the inner part of the bay, an increase in urchin density is attributed to continuous successful recruitment following the tsunami, and this phenomenon was considered as a factor for shrinkage of algal communities and the abalone population in the inner part.

Key words: abalone, *Haliotis discus hannai*, rocky shore ecosystem, monitoring survey, mega-earthquake, *Mesocentrotus nudus*, tsunami disturbance

Introduction

Coastal marine areas comprise various ecosystems that sustain high biodiversity and biological productivity. At the same time, coastal areas are continuously exposed to the variety of natural and artificial disturbances that can occur over a wide range of time scales. Disturbance can induce positive and/or negative influences on inhabiting organisms in various processes. Monitoring surveys on population dynamics offer fundamental information for detecting and evaluating the organisms' responses to such disturbances.

On 11 March 2011, a 9.0 MW mega earthquake occurred off the Pacific Coast of northeastern Honshu Island, Japan. The epicenter was located at about 130 km east-southeast of the Oshika Peninsula (38°06.2′N, 142°51.6′E) at a depth of 24 km (Japan Meteorological Agency 2011). This earthquake, hereafter referred to as the Great East Japan Earthquake, was the most powerful on record for Japan, with tsunamis generated by it impacting about 2000 km of the Japanese Pacific Coast.

In addition to events associated with huge earthquakes such as coastal uplift (Castilla et al. 2010), tsunamis can severely impact shallow marine ecosystems, damaging benthic organisms by sweeping away them and by destroying or altering habitat. Such impacts have huge potential to devastate coastal benthic communities. Previous researches on tsunami disturbance of coastal marine ecosystems is limited to a few mega-earthquakes, such as the 2004 Indian Ocean earthquake (Kumaraguru et al. 2005, Whanpetch et al. 2010) and the 2010 Chilean earthquake (Hernandez-Miranda et al. 2014, Jaramillo et al. 2012), as huge tsunamis are very rare events.

As the effects by the tsunami reached the wide area and variety of benthic animals in the Sanriku Coast, clarification of the effects requires different areas and species along it to be examined. Previous researches have demonstrated tsunami impact and recovery processes to differ between benthic species (Seike et al. 2013, Watanabe et al. 2014). However, there has been limited information on populations of benthic organisms before earthquakes and tsunamis in devastated areas, precluding the full nature and extent of tsunami impacts from being ascertained. Additionally, effects of tsunamis on important fishery resources, especially species occurring on rocky shores, have not been described circumstantially in previous disasters.

Spatial variation in impact and recovery following a tsunami have been reported for various scales in devastated areas (Hayasaka et al. 2014, Kawamura et al. 2014, Watanabe et al. 2014), though little is known of variation in tsunami effects at smaller scales, such as within a bay.

In Otsuchi Bay (Iwate Prefecture, Sanriku Coast), monitoring survey for the abundance of the abalone (*Haliotis discus hannai*) and the sea urchin (*Mesocentrotus nudus*) has been carried out in the western and southern regions since 1994 (present study), and near the mouth of the bay since 2009 (Kawamura et al. 2014). Both the abalone and sea urchin are economically important as fishery resources, and are ecologically important, being common and conspicuous grazers in the food web of the rocky shore ecosystem on the Sanriku Coast (Won et al., 2011, 2013).

The monitoring survey in this study can be separated into three periods. The first period of the monitoring was between 1994 and 2003, conducted by the Fisheries Cooperative Association of East Kamaishi (FCAEK) and a research diving company Fukuda Marine Project (FMP). The second period was from 2007 to 2012, conducted by FCAEK alone. The third period was from 2013 to present, carried out by FCAEK, FMP and International Coastal Research Center (ICRC), Atmosphere and Ocean Research Institute, University of Tokyo. Although methodology differed among these periods, transect lines are common to all.

Herein we report and discuss changes in the abundances of the abalone (*H. discus hannai*) and the sea urchin (*M. nudus*) that occur over a 20-year period, before and after the mega earthquake.

Materials and Methods

Monitoring survey was performed in Otsuchi Bay, Sanriku Coast, about 160 km northwest of the epicenter. Otsuchi Bay is narrow, approximately 8 km length in the east-west direction, and 3.5 km wide at its entrance (Fig. 1).

The abalone (*H. discus hannai*) and the sea urchin (*M. nudus*) abundance was monitored along 9 fixed transect lines set in western and southern coast of Otsuchi Bay. For monitoring purposes, we separated the bay into three areas: inner (I), middle (M) and entrance (E) part of the bay (Fig. 1). Three fixed transect lines were established in each part. Lines I1, I2 and I3 were located on the western or southern coast in the inner part of the bay. Lines M1–3 and E1–3 were placed on southern coast in the middle and entrance part of the bay, respectively. These lines were established in abalone fishing grounds; we do not document the exact location of these lines, to prevent poaching (a request made by the local Fisheries Cooperative Associations). The start position of each transect was fixed, and a rope of 50 or 100 m (marked at intervals of 10 m) was then laid by boat along the sea floor, in a fixed orientation offshore.

Annual surveys were almost always conducted in October (before the start of the abalone harvest season) from 1994 to 2015, except for 2004–2006. Line I2 was not surveyed between 1998 and 2003, Line E2 was not surveyed in 2000, and Line M3 was not surveyed in 2013. Lines I1 and E1 were surveyed in late August of 2013.

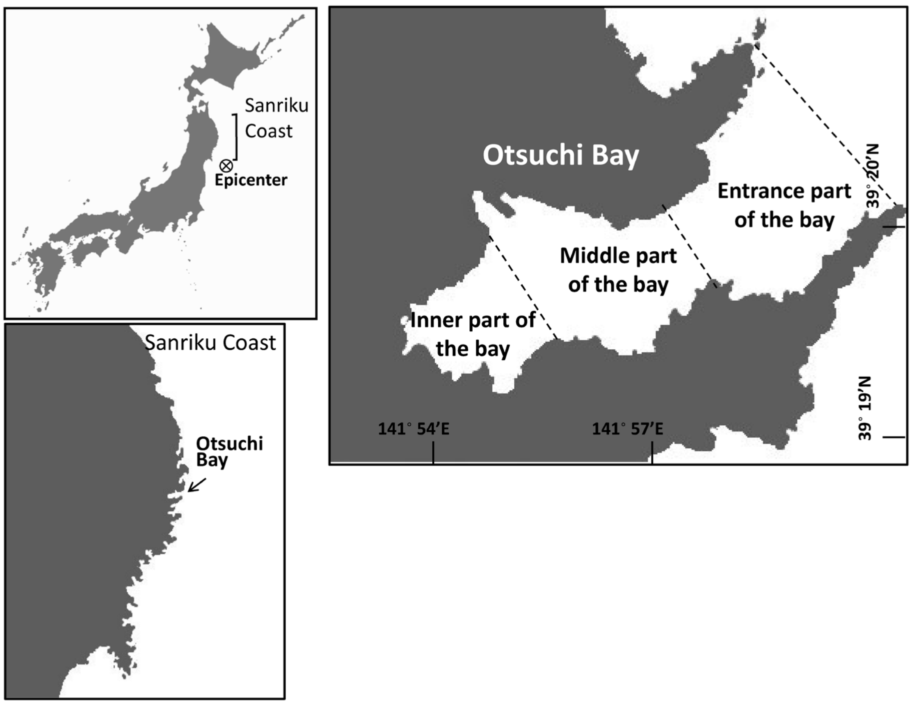

Fig. 1. Location of the study site Otsuchi Bay, the three parts inside the bay and the epicenter of the Great East Japan Earthquake.

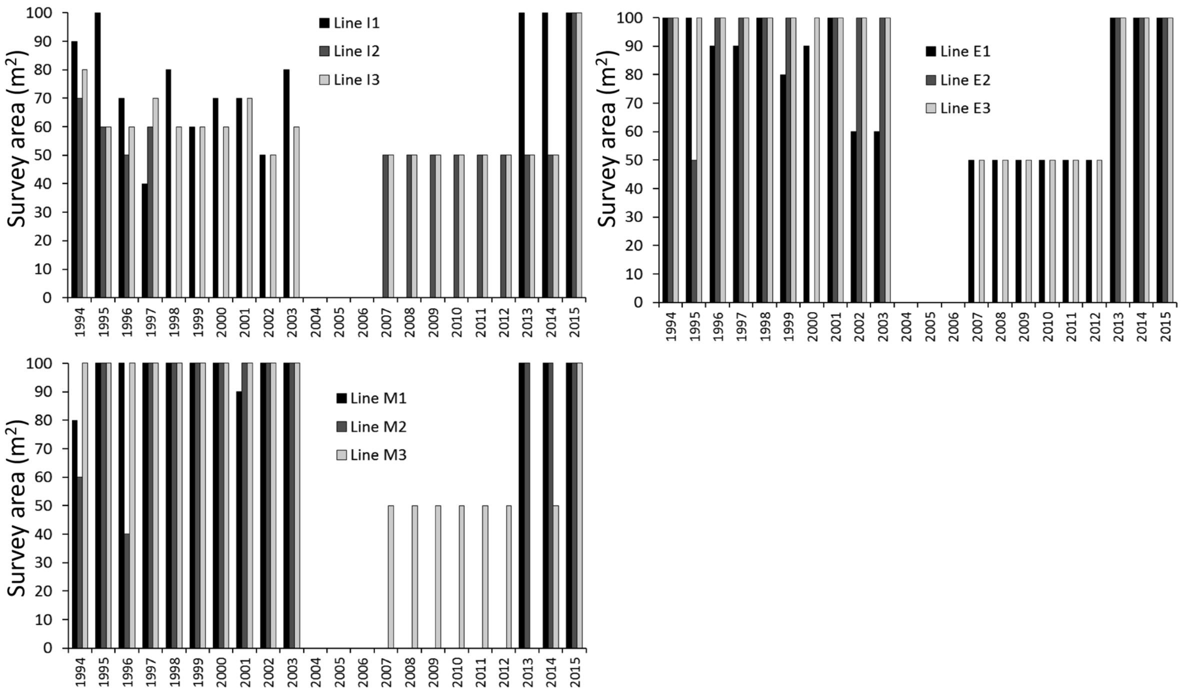

Fig. 2. Survey areas along three survey lines in the inner (Lines I1–3), middle (Lines M1–3) and entrance part (Lines E1–3) of the bay in each year.

In the transect survey, numbers of the abalone occurring inside 1-m-wide belt, 0.5 m either side of 100 m-length transect line were recorded by a diver on SCUBA at 10 m intervals. However, as most abalone occurred in the first 50 m (see Results) of the transects, 50-m-length transects were used in surveys in the second survey period (2007–2012) and for Lines I2 and I3 in 2013 and 2014. Analysis of variation in abalone density along survey lines uses only those data for the first 50 m of transect lines, even when surveys extended to 100 m from shore. When seabed depth reached 20 m along a transect, surveys were halted. As survey lines were set on rugged reef, the distance from the start point to the end point over 20 m depth sometimes varied, even though the survey lines were set in the fixed direction. As surveys could be conducted to 40 m from shorelines along Line I1 in 1997 and Line M2 in 1996, abalone densities for the two lines have been calculated from data for 40 m^2 of survey area. The survey area of each line is shown in Fig. 2.

In the field, the shell length (SL) of the abalone was categorized into one of three size classes: ≥90 mm, 50 to <90 mm, and <50 mm. However, only two size classes (≥ and <90 mm SL) were determined along all lines between 2007 and 2012, Lines I2 and I3 in 2013 and 2014, and Line M3 in 2014.

During the first and third survey periods, sea urchin densities were determined along all lines, except for Lines M3, I2 and I3 in 2013 and 2014. In the same way as for the abalone, numbers of the sea urchin within the area of 1 m wide along the transect line were recorded at 10 m intervals by divers on SCUBA. Test diameter (TD) of each urchin was classed into one of three size classes: ≥60 mm, 40 to <60 mm, and <40 mm.

In parallel with the counting of the abalone and the sea urchin, the cover degrees by a large brown alga *Saccharina japonica* var. *religiosa* and other algal species except for encrusting algae like crustose coralline algae were surveyed. The algal cover degrees of *S. japonica* var. *religiosa* and other seaweeds in the survey areas of 1 m width were measured by 10%, based on diver's visual observation, at the interval of 10 m along the survey lines. Recording the algal cover degrees was conducted in the all fixed lines from 1994 to 2003 (the first survey period), and in Lines E1–3, M1–2 and I1 from 2013 to 2015 (the third survey period), although not in the second survey period and in the other survey lines on the third survey period.

In addition, water depth was also recorded at intervals of 10 m of the line, using a dive computer (Suunto Oy, Finland). At intervals of 10 m, the major types of bottom materials (bedrock, stone, boulder, cobble, sand and mud) were recorded by the diver's observation.

Data analysis

As abalone were surveyed to 50 m from shore during the second and part of the third survey periods, the number and size composition of abalone, algal cover and average water depth were compared between the survey areas of 0–50 m (nearshore area) and >50 m (offshore area) using data from the 9 survey lines with survey areas of more than 60 m^2 in the first and third survey periods (Line I1: 1994–1996, 1998–2001, 2003 and 2013–2015; Line I2: 1994, 1995, 1997, 2001 and 2015; Line I3: 1994–2001, 2003 and 2015; Lines M1, M3, E1 and E3: 1994–2001 and 2013–2015; Line M2: 1994, 1995, 1997–2003 and 2013–2015; Line E2: 1995–1999, 2001–2003 and 2013–2015). In comparison between near- and offshore areas, the algal cover degrees in nearshore areas were given as averages in five values at 0, 10, 20, 30, 40 and 50 m of each survey line and those in offshore areas were averages in the available number of values at 10 m intervals in the survey areas of >50 m along the survey lines. Data of the algal cover degrees along Lines I1 and E1 in 2013 were not used for analyses, as surveys along these two lines in 2013 were conducted not in October but in August, and macroalgal abundance, especially that of *S. japonica* var. *religiosa*, fluctuates seasonally (Funano 1983).

Results

Comparison between near- and offshore areas

The percentage of the abalones in the nearshore (0–50 m) and offshore (>50 m) areas along transects of more than 60 m^2 during the first and third survey periods is depicted in Fig. 3. Almost all individuals were recorded from the nearshore area along the three survey lines in the inner part of the bay (92.0–99.1%). Along the three survey lines in the entrance part of the bay, the percentages of the abalone from the nearshore area were lower than those in the middle and inner part of the bay, however 66.9–74.5% of the total number of abalone were found from the nearshore area. The majority (80.9%) of the abalone along all lines occurred in the nearshore area.

Size composition of abalone differed between the near- and offshore areas (Pearson's chi-square test, $p<0.01$). The frequency of abalone ≥90 mm SL was greater in the offshore area than in the nearshore area (Fig. 4). Although Fig. 4 shows the frequency in the total counted abalone in the nearshore and offshore areas along all lines, the similar tendency for higher frequency of individuals ≥90 mm SL in the offshore area was found on each survey line.

Along all transects, average of the algal cover degree was higher in the nearshore than offshore areas, with the difference in the algal cover degree of *S. japonica* var. *religiosa* more pronounced than other seaweeds (Fig. 5a, b).

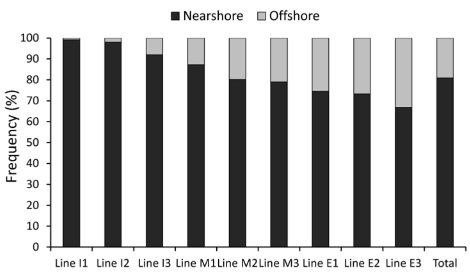

Fig. 3. Frequencies of the abalones *Haliotis discus hannai* in nearshore and offshore areas along transects, and frequencies of those in the total of all transects.

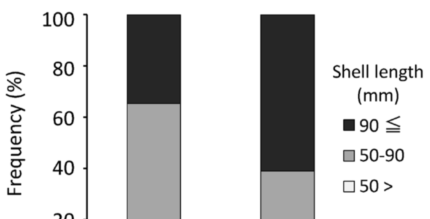

Fig. 4. Size-class compositions of the abalone in nearshore and offshore areas along transects.

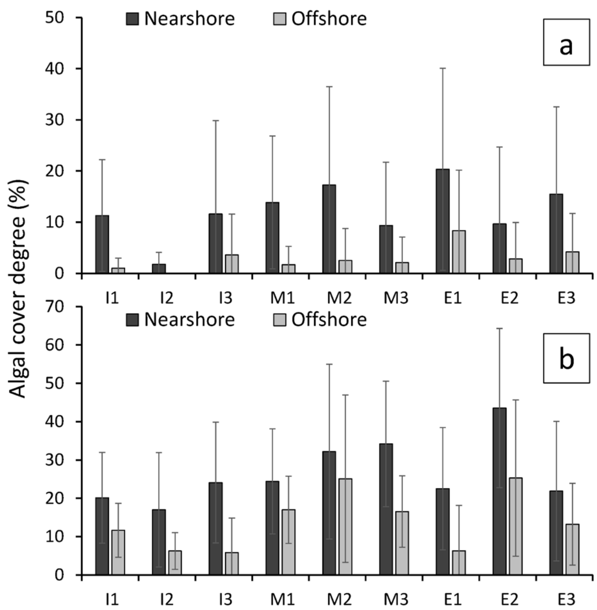

Fig. 5. Algal cover degrees by the kelp *Saccharina japonica* (a) and other seaweeds (b) in nearshore and offshore areas along transects. Bars show standard deviation of the mean.

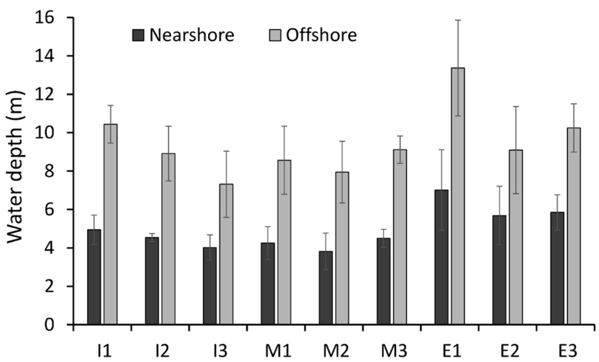

Fig. 6. Water depth in nearshore and offshore areas along transects. Bars show standard deviation of the mean.

We attribute variation in average water depth along any given transect between years to slight deviation in the position of survey line, and to the state of the tidal cycle during sampling periods. The average water depth was greater in the offshore areas than in the nearshore areas (Fig. 6).

As landscape features of the nearshore areas, kelp beds of *S. japonica* var. *religiosa* occurred primarily. Algal beds of *Sargassum* species (*S. yezoense* and *S. confusum*) and turfs of red algae (mainly *Gelidium elegans*, *Symphyocladia latiuscula* and *Mazzaella japonica*) were found mainly in the nearshore areas. Stones and cobbles covered by crustose coralline algae (CCA) were characterized the offshore areas, along with turfing *Dilophus okamurae* and articulated coralline algae and/or patches of *Neoholmesia japonica* and *Agarum clathratum*.

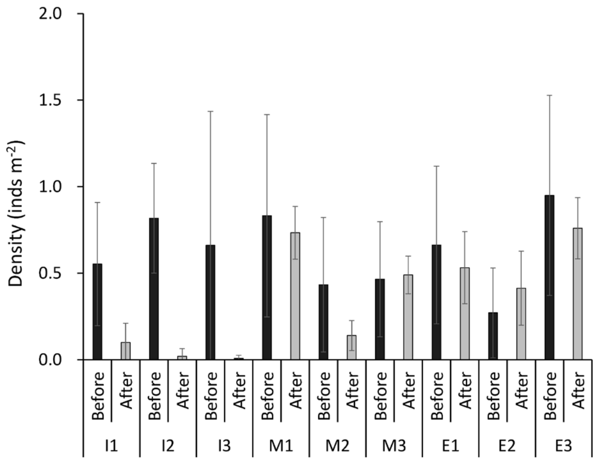

Fig. 7. Pre- and post-tsunami densities of the abalone *Haliotis discus hannai* in nearshore areas along transects. Bars show standard deviation of the mean.

Abalone density and size composition

Pre- and post-tsunami data on average abalone density in the nearshore areas (40–50 m^2) were compared for each survey line (Fig. 7). The average densities did not show distinct changes between before and after the tsunami along all the three lines in the entrance part of the bay (E1–E3) and Lines M1 and M3 in the middle part of the bay. However, considerable reductions in post-tsunami abalone density are apparent along Line M2 and all three lines in the inner part of the bay (I1–I3), although variations in abalone density before the event were relatively large.

Temporal changes in density and size-class composition of abalone along each line are shown in Fig. 8. Along Lines E1 and M3, densities drastically decreased from October 2010 to October 2011 and gradually recovered to levels comparable to pre-tsunami densities in 2015. Direct effects of the tsunami cannot be identified along lines E2 and M1 as no data are available for those years around 2011, though abalone average density from 2013 to 2015 was greater than that in 1994–2003 on Line E2 and almost the same as before the tsunami on Line M1 (Fig. 7). Post-tsunami abalone density along Line E3 gradually reduced, although the direct reduc-

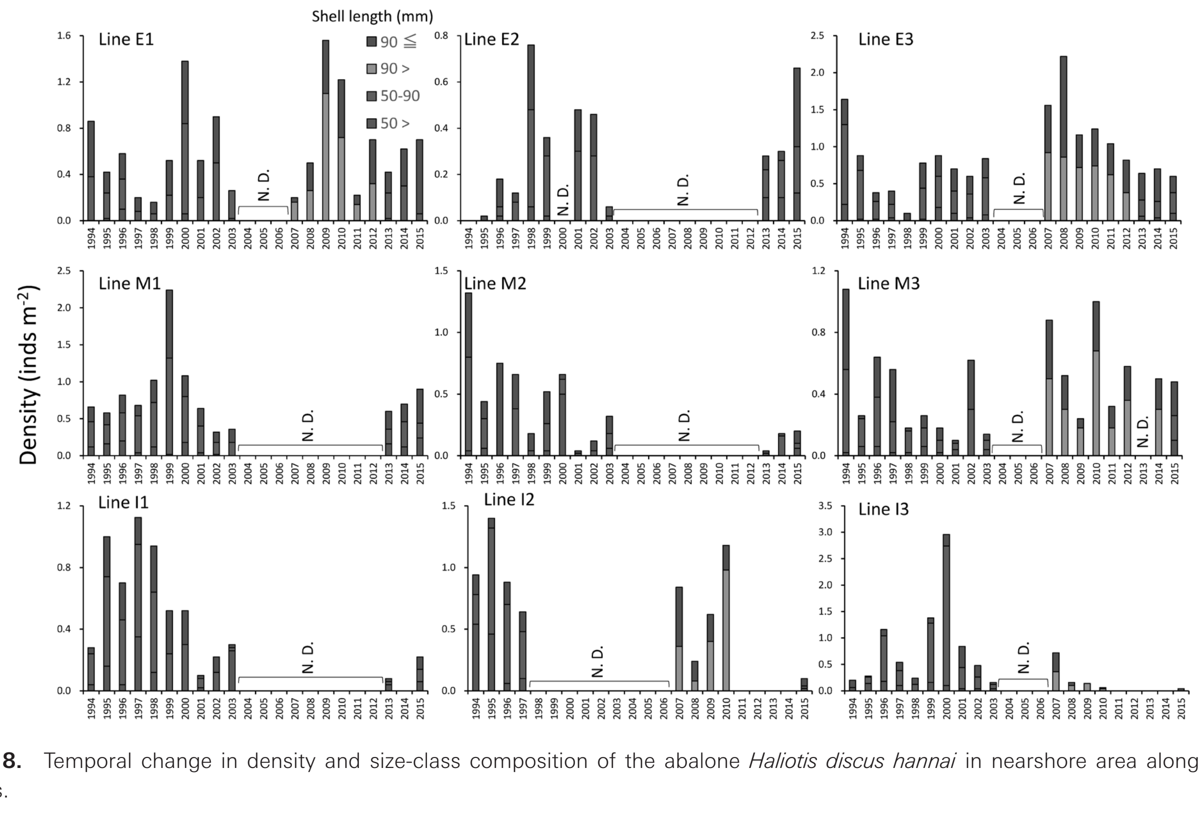

Fig. 8. Temporal change in density and size-class composition of the abalone *Haliotis discus hannai* in nearshore area along transects.

tion attributable to the tsunami was small. Direct effects by the tsunami on abalone density along Lines M2 and I1 cannot be determined due to a lack of data for these transects around 2011, though densities from 2013 to 2015 are only marginally lower than those that preceded the tsunami. Abalone density along Line I2 plummeted to 0 inds./m^2 following the tsunami, and has remained low to 2015. Tsunami-attributable reduction in abalone density along Line I3 is unclear, as the density was previously low in the four years preceding 2011 (Fig. 8).

The frequency of abalone ≥90 mm SL gradually increased from 2011, reaching 91.4% on Line E1. No clear changes in the size-class structure of abalone were apparent along any other survey lines.

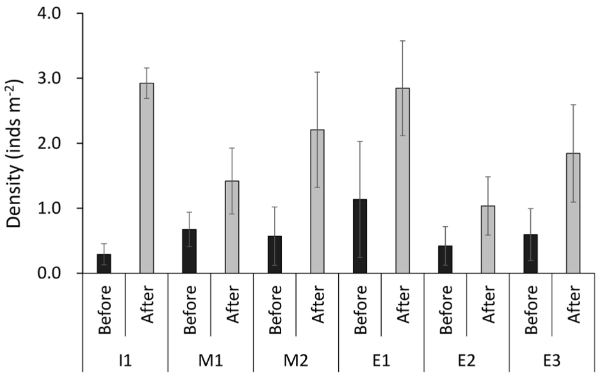

Fig. 9. Pre- and post-tsunami densities of the sea urchin *Mesocentrotus nudus* along transects. Bars show standard deviation of the mean.

Sea urchin density and size-class composition

Sea urchin densities from 1994–2003 and 2013–2015 were compared along all transect lines, with the exception of Lines M2, I2 and I3, as sea urchins were not counted in 2013 and 2014 (Fig. 9). Along all survey lines average post-tsunami densities were greater than pre-tsunami densities.

Along the three survey lines in the entrance part of the bay (E1–E3), post-tsunami densities of the sea urchin increased, though the increases were moderate, and the size compositions that ≥60 mm size class was dominated did not change between before and after the event (Fig. 10). Along the lines in the middle and inner part of the bay (M1–M3 and I1–I3), the increases in sea urchin density were large with notable increases in the frequency of <40 mm TD size class, especially along Lines M2 and I1.

Algal cover degree of the kelp and other seaweeds

Changes in the average cover degree of the kelp *S. japonica* var. *religiosa* and other seaweeds along each transect line are shown in Fig. 11. Annual variation in pre-tsunami (1998 to 2003) cover degrees of the kelp and other seaweeds was considerable. Tendencies in the temporal change of algal cover degrees were similar along the survey lines before the tsunami, being generally low in 2000 and high in 2001.

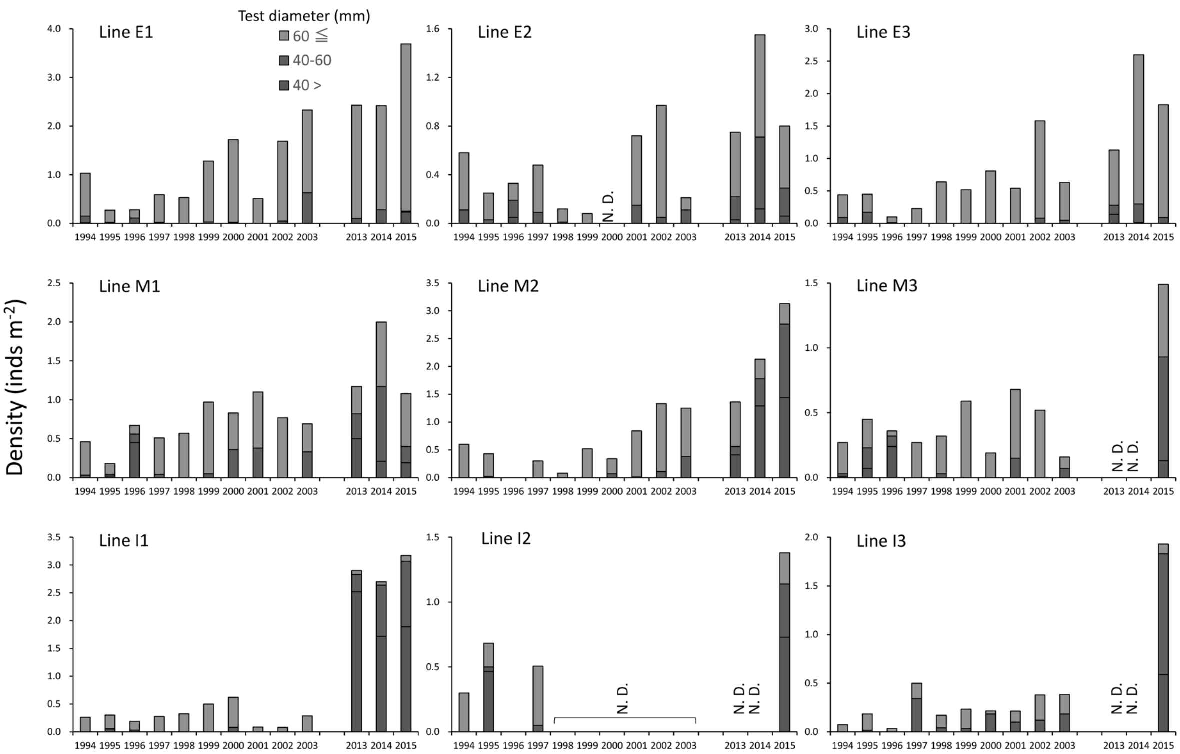

Fig. 10. Temporal change in density and size-class composition of the sea urchin *Mesocentrotus nudus* in nearshore area along transects.

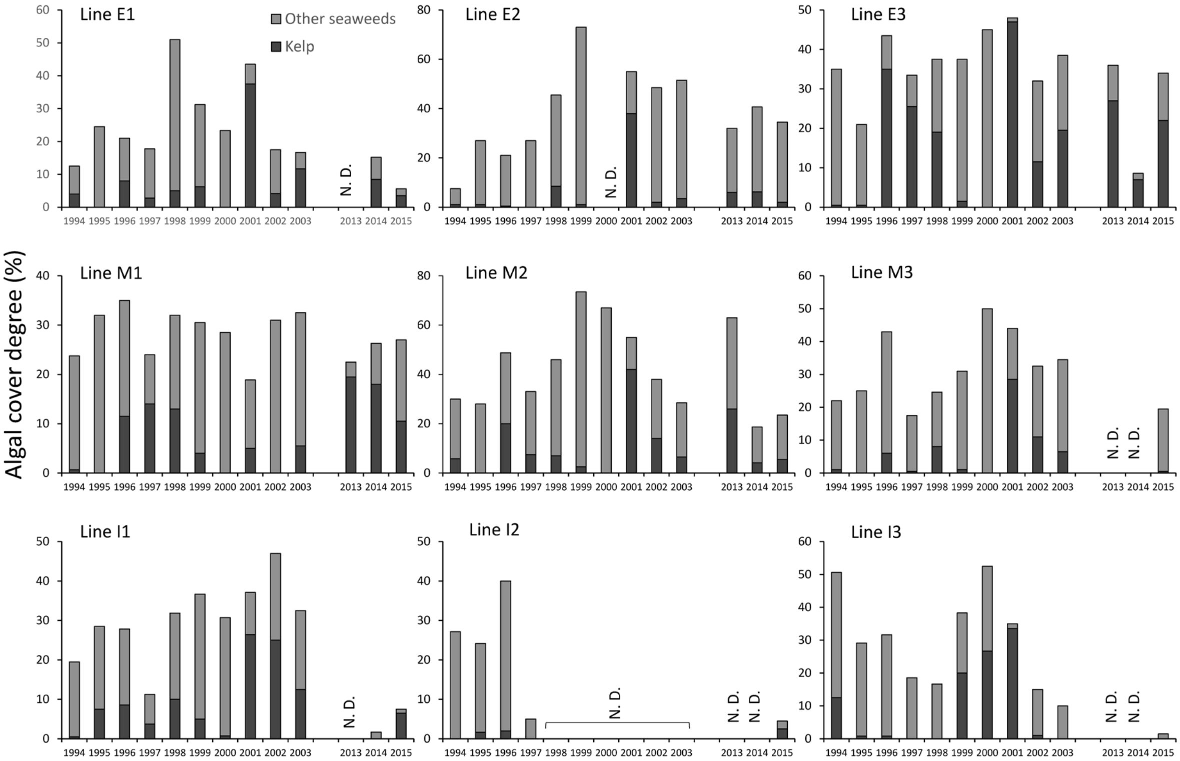

Fig. 11. Temporal change in algal cover degree by the kelp *Saccharina japonica* and other seaweeds along transects.

Ranges in total cover degree of the kelp and other seaweeds did not differ appreciably among the survey lines from 1998 to 2003.

Along Lines E1–3, the cover degrees of the kelp after the tsunami were at a similar level to the average cover degrees before the event (Lines E1–3: 7.9, 6.2 and 16.0%, respectively) (Fig. 11), whereas the cover degrees of other seaweeds decreased along Lines E1 and E3 compared with the average values before the event (Lines E1 and E3: 18.0 and 21.2%, respectively). In the middle part of the bay, the temporal change in the cover degree of the kelp was variable among the survey lines. While cover degree of the kelp after the event increased along Line M1, it did not change appreciably along Line M2, and it decreased along Line M3, compared with pre-tsunami average values (Lines M1–3: 5.4, 10.5 and 6.3%, respectively). In contrast, post-tsunami cover degree of other seaweeds was lower than average pre-tsunami values along Lines M1–3 (23.5, 34.3 and 26.2%, respectively). Along all the three lines in the inner part of the bay, the cover degrees of other seaweeds generally lower than average pre-tsunami values (Lines I1–3: 30.3, 24.1 and 29.8%, respectively). In the inner part of the bay, the decreases in the total algal cover after the tsunami were conspicuous, with reductions attributed mainly to lower cover degrees of other seaweeds.

Discussion

Abalone density and algal cover degree in nearshore (0–50 m) and offshore (>50 m) areas were compared. Using all survey data over all survey periods, 80.9% of all abalone occurred in nearshore areas.

In Otsuchi Bay, main habitats for the adult and large juvenile abalone are *S. japonica* var. *religiosa* kelp forest, whereas small juvenile abalone inhabits deeper areas characterized by crustose coralline algae (CCA areas). Abalone densities were much higher in the nearshore areas with kelp forests than in the offshore areas, where reefs and stones were typically covered by CCA, as our survey design was selected for data on adults and relatively large juveniles of abalone.

The percentages of the abalone counted in the offshore areas along the survey lines differed among locations, being low along lines in the inner part of the bay and higher along transects in the entrance part of the bay. A positive correlation was found (Pearson's correlation coefficient, $r=0.62$, $p=0.076$; Fig. 12) between the percentage of abalone and average cover degree of *Saccharina* kelp in the offshore areas along each survey line. Average cover degree of *S. japonica* var. *religiosa* in the offshore areas along the three survey lines in each part of the bay was highest in the entrance part, intermediate in the middle part and least in the inner part of the bay (5.11, 2.09 and 1.53%, respectively). This difference

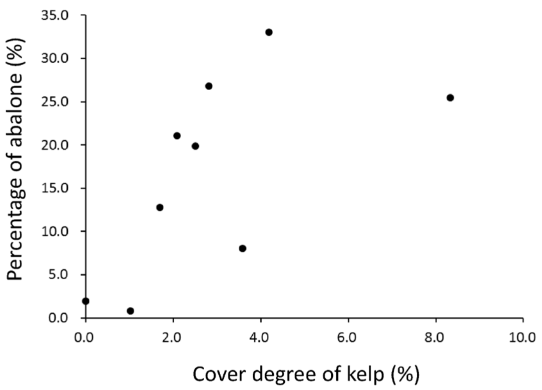

Fig. 12. Relationship between the average values in algal cover degree of the kelp *Saccharina japonica* in offshore areas and percentage of the abalone *Haliotis discus hannai* counted in offshore areas along nine survey lines during whole survey period.

in the distribution and abundance of the kelp beds, main habitats for the adult and large juvenile abalone, in the offshore areas is considered as one of the major factors for the difference of the percentages of the abalone counted in the offshore area among the locations inside the bay.

The size-class compositions of the abalone were different between the nearshore and offshore areas along the survey lines. While juvenile abalone occured in deeper CCA areas, the relative percentages of 50 to ≤90 mm, and <50 mm SL size classes were lower in the offshore areas than in the nearshore areas. As the juveniles of around 20 mm SL starts moving from CCA areas as their main habitats to kelp beds in shallower areas as main habitats for the adults and large juveniles (Takami et al. 2012), the difference in the size composition is thought to occur after the ontogenetic change in habitat. The lower percentage of individuals ≥90 mm SL may reflect higher fishing pressure in shallower areas, as transects were set in the abalone fishing grounds and 90 mm SL is the minimum size allowed for fishing.

Temporal changes in abalone population

Temporal changes in the density of the abalone along the survey lines seemed to be different among the locations inside the bay. For those lines for which we have data in 2010 and 2011 (Lines E1, E3, M3, I2 and I3), abalone density decreased from 2010 to 2011 along all transect lines. This decrease was a likely consequence of the tsunami, the effects of which seem to have been larger in the inner part than in the middle and entrance part of the bay. Post-tsunami abalone densities along the three survey lines in the inner part remained very low, with no abalone found on Lines I2 and I3 until 2014 and on Line I1 in 2014. While the reduction in the density by the tsunami was especially large in Line I2, an apparent decrease in density due to other factors had already commenced on Line I3 before the tsunami.

In the entrance and middle parts of the bay, the reductions in abalone density were moderate and the densities tended to recover after the event. In another monitoring survey in Otsuchi Bay, abalone did not significantly decrease in density following the tsunami at Nagane, on the northern coast of the entrance part of the bay (Kawamura et al. 2014), which is similar to the result of the monitoring survey in the entrance and middle part of the bay in the present study.

Differences in impact by the tsunami and response of abalone populations to the disturabances throughout the bay indicate that the impact of the tsunami differed among locations even inside the Otsuchi Bay, and that the impact was greater in the inner part of the bay. This is most likely because of the shape of Otsuchi Bay, and the pathway of the tsunami, entering it from the east and surging forward almost parallel to the bay's north and south coasts. In the inner part of the bay, the tsunami is thought to hit at right angle to the western coast of the bay, and it caused the largest impacts inside Otsuchi Bay.

In the inner part of the bay, cover degrees of the large brown alga *S. japonica* var. *religiosa* and other seaweeds remain much lower than in the middle and entrance parts. This severe reduction in algal coverage is likely to be a consequence of increase in the density of the sea urchin, of which high grazing pressure reduced the juvenile sporophytes of brown algae (Muraoka 2008). As large brown algae are important for abalone as habitat and food, it is considered that the reduction in the community of *S. japonica* var. *religiosa* is one of the main factors suppressing the abalone density to very low level in the inner part of the bay. In addition, the increased bulldozing effects on newly-settled juvenile abalone by the sea urchin (McShane 1991) may negatively affect abalone populations in the inner part of the bay.

At Nagane in the entrance part of Otsuchi Bay, Kawamura et al. (2014) reported that juvenile abalone <40 mm SL appeared to be more seriously affected by the tsunami than adults. The weaker adhesion to the substratum of juvenile abalone and weaker protection by their main habitat CCA area without algal canopy moderating physical disturbances was thought to render the tsunami impacts stronger than those on large juvenile and adult abalone within kelp communities. Abalone of 2009 and 2010 year classes severely damaged by the tsunami in March 2011 appear to have grown to 70–100 mm SL by October 2015, which is estimated by the reported age-SL relation in the abalone from the fields in the Iwate Prefecture (Hirose 1974). However, changes in the size-class structure by large disappearances of 2009–2010 year classes yet to be observed in the entrance part of the bay until 2015, in the present survey. This inconsistency may be explained by the improved survival of the juveniles after the tsunami. Sea urchin species are considered as a strong competitor for foods and shelters (Andrew and Underwood 1992, Strain et al. 2013), and are also as potential predator for abalone species (McShane 1991, Won et al. 2013). Large reductions in abundance of the sea urchin *M. nudus* by the tsunami were reported by previous research conducted in the Ohtsuchi Bay (Kawamura et al 2014) and at another site on the Sanriku Coast (Takami et al. 2013). In addition, small gastropods such as *Homalopoma amussitatum*, which compete with juvenile abalone for food (Takami et al. 2001, Kawamura et al. 2004), are also likely to have been severely disturbed by the tsunami, and disappeared from the CCA areas as their adhesive strength to the substratum was also weak. Although abundances of the sea urchin and gastropods recovered after the tsunami, such a large reductions in populations of competitors and potential predators might have enabled an increase in survival of juvenile abalone, alleviating any tsunami impacts on 2009 and 2010 year classes.

Water temperature within the bay during winter and early spring of 2014 and 2015 were particularly low by an extension of the cold Oyashio current. The residence of the cold seawater from the Oyashio current fatally affects the survival of young-of-the-year abalone (Takami et al. 2008). Although the negative influence on 2013 and 2014 year classes was not obvious in the present research of which the major target was adult and large juvenile abalone, severe reductions in the abalone population may occur in the future by increased mortality of those year classes in Otsuchi Bay.

Temporal changes in sea urchin populations

The lack of data on sea urchin densities from 2004 to 2012 precludes determination of the effects of the tsunami on sea urchin populations. However, the clear reduction by the tsunami and the following rapid recovery in the density of the sea urchin were confirmed at Nagane in the entrance part of the bay (Kawamura et al. 2014). Similar to small juveniles of the abalone, weaker adhesion to substrata and weaker protection by CCA areas without algal canopy are thought to be related to the larger impacts on the sea urchin density than those on adult and large juvenile abalone (Takami et al. 2013, Kawamura et al. 2014). As post-tsunami abalone densities decreased at all locations inside Otsuchi Bay, sea urchin densities are also likely to have severely decreased throughout the bay.

In the entrance part of the bay, the size composition in the observed sea urchins, which was mainly composed of the individuals ≥60 mm TD, did not change clearly, and post-tsunami increase in density has been small. The situation after the tsunami could be explained by coming back to the survey zones of the sea urchins washed away by the tsunami to deeper sea bottom, as reported at Nagane in Otsuchi Bay by the previous study (Kawamura et al. 2014).

In contrast to sea urchin populations at the entrance part of the bay, the size-class structure of populations changed considerably after the tsunami and the densities of the sea urchin became higher than those before the event in the inner part of the bay. The change in size-class composition and increase in density were caused by the sharp rise of urchins <40 mm TD, although no individual of that size class had been observed along Lines I1–3 during 10 years of surveys preceding the tsunami. It indicates that successful recruitment of the sea urchin had continued during several years after the tsunami in 2011. From the result of the observation on bottom materials, fine sediments (sands and muds) that once covered subtidal bedrock in deeper offshore areas throughout the inner part of the bay prior to the tsunami appears to have been was washed away by the tsunami. Freshly exposed habitat is now sparsely covered by thin CCA and numerous sea urchins <40 mm TD on bedrocks were confirmed in the third survey period (Fig. 13). As CCA induce settlement of the larval sea urchin *M. nudus* and CCA areas are main habitats for them (Sano et al. 2001), the expansion of the CCA areas to deeper zones habitat appears to have facilitated recruitment of the sea urchin in the inner part of the bay.

Variations in tsunami impact and recovery process

This study clearly showed that tsunami impacts on and recovery of abalone and sea urchin populations differed

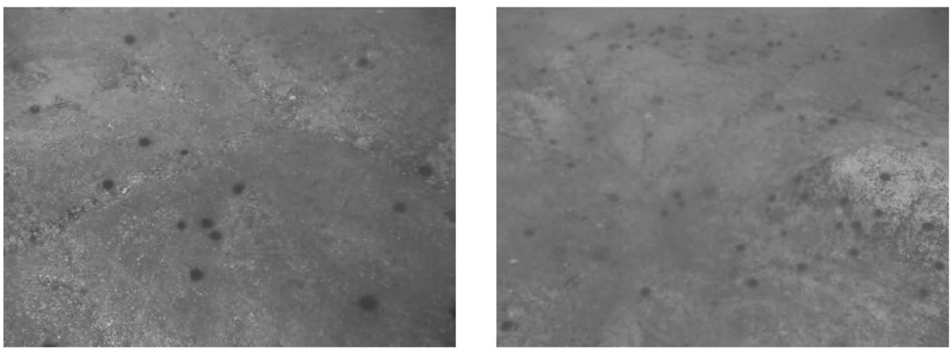

Fig. 13. Typical offshore seabed along transect I1, inner Otsuchi Bay (October 2014). The veneer of sand and mud has been swept away by the tsunami, with numerous recently recruited juvenile urchin (*Mesocentrotus nudus*), the small black spheres on crustose coralline algae.

among the locations inside a bay. The physical disturbance of the tsunami directly influenced abalone and sea urchin densities, with the secondarily altered physical and biological environment then continuing to impact populations in different ways among locations inside Otsuchi Bay. Distance from the quake epicenter and the shape of bays were considered major factors contributing to differences in tsunami-induced impacts on benthic organisms along the Sanriku Coast (Kawamura et al. 2014). Our results reveal differences in tsunami-induced impacts on coastal benthic communities at the even smaller spatial scales of within a bay.

Tsunami impacts and recovery differed in the two species, the abalone and sea urchin. These differences might reflect differences in species ecological characteristics, such as the habitat use and adhesive strength to substrata. Although various coastal benthic animals have been affected by the tsunami along the Sanriku Coast, data describing differences in impact and recovery are limited. It is important to examine ecological characteristics of each species so that the reasons for apparent variations in tsunami effects and mechanisms of recovery can be better understood.

In this research, the long-term changes in abalone and sea urchin populations before and after a major tsunami were described by utilizing data from the continuous monitoring survey. These surveys were originally performed for abalone stock management purposes, in established fishing grounds. Accordingly, fishing pressure might influence the temporal changes in density and size-class composition of the abalone. However, the clear reduction in abalone density and increase in small-sized urchin density throughout the inner part of the bay are considered to be attributable largely to tsunami disturbance. Continued monitoring of abalone and urchin populations will provide further insights into recovery and management of these resources, facilitating sustainable fisheries in the future.

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