ISSN 2188-2037

www.scesap.org

Coastal Ecosystems

Impact of the tsunami caused by the Great East Japan Earthquake on seagrass beds and fish communities in Miyako Bay, Japan

Tsutomu Noda, Masami Hamaguchi, Yuichiro Fujinami, Daisuke Shimizu, Hideaki Aono, Yoshitomo Nagakura, Atsushi Fukuta, Hikaru Nakano, Yasuhiro Kamimura and Jun Shoji

Coastal Ecosystems, 2017, vol 4, 12-25

Regular Paper

Impact of the tsunami caused by the Great East Japan Earthquake on seagrass beds and fish communities in Miyako Bay, Japan

Tsutomu Noda[1], Masami Hamaguchi[2], Yuichiro Fujinami[3], Daisuke Shimizu[3], Hideaki Aono[4], Yoshitomo Nagakura[3], Atsushi Fukuta[5], Hikaru Nakano[5], Yasuhiro Kamimura[6] and Jun Shoji[5]

[1]Goto Laboratory, Seikai National Fisheries Research Institute, Japan Fisheries Research and Education Agency, 122-7 Nunoura, Tamanoura-machi, Goto, Nagasaki 853-0508, Japan

[2]National Research Institute of Fisheries and Environment of Inland Sea, Japan Fisheries Research and Education Agency, 2780 Maruishi, Hatsukaichi, Hiroshima 739-0452

[3]Miyako Laboratory, Tohoku National Fisheries Research Institute, Japan Fisheries Research and Education Agency, 4-9-1 Sakiyama, Miyako, Iwate 027-0097

[4]Seikai National Fisheries Research Institute, Japan Fisheries Research and Education Agency, 1551-8 Taira, Nagasaki 851-2213

[5]Takehara Fisheries Research Station, Hiroshima University, 5-8-1 Minato-machi, Takehara, Hiroshima 725-0024

[6]National Research Institute of Fisheries Science, Japan Fisheries Research and Education Agency, 2-12-4 Fukuura, Kanazawa, Yokohama, Kanagawa 236-8648

Corresponding author : Tsutomu Noda, e-mail: ttmnoda@affrc.go.jp

Abstract

The coastal areas of Miyako Bay on the Pacific coast of northeastern Japan were impacted by the devastating tsunami following the Great East Japan Earthquake on 11 March 2011. To evaluate the effects of the disturbance caused by the tsunami after the earthquake on seagrass *Zostera marina* beds and their associated fish community structures, seagrass vegetation, number of fish species, fish abundance and biomass were compared at two sites with different levels of disturbance in the Miyako Bay before (2010) and after the tsunami (2011 and 2012). Disappearance of seagrass vegetation at the innermost site of the bay in 2011 indicated a catastrophic disturbance on the seagrass vegetation by the tsunami. In contrast, a decrease in seagrass abundance at another site in a small inlet nearby was not as prominent as that noted at the innermost site. While the sevenspine goby *Gymnogobius heptacanthus*, a benthic invertebrate feeder, was dominant at both sites before the tsunami, the fish community became dominated by benthic carnivores after the tsunami. At the small inlet, abundances of the black edged sculpin *Gymnocanthus herzensteini* and the frog sculpin *Myoxocephalus stelleri* increased. On the other hand, the yellowfin goby *Acanthogobius flavimanus* and *M. stelleri* increased at the innermost site. The pattern of temporal change in fish community structure differed between the sites, possibly reflecting the differences in the level of Tsunami-induced disturbances in seagrass beds.

Keywords: tsunami impact, seagrass bed, fish community, Great East Japan Earthquake

Introduction

Seagrasses are important foundation species in coastal ecosystems (e.g. Dayton 1972), which serve a variety of ecological functions such as support for secondary production, refuge from predation and spawning substrates for fishes (Williams & Heck 2001). Moreover, seagrass beds increase the physical complexity of a habitat (Tokeshi & Arakaki 2012) and can provide a variety of microhabitats, affecting fish abundances and species richness (Horinouchi & Sano 1999; Horinouchi 2005; Walter & Haynes 2006; Hori *et al*. 2009). Therefore, seagrass beds support large numbers of fish species and individuals, including some commercially important ones (e.g. Kikuchi 1974; Adams 1976; Weinstein & Heck 1979; Beckley 1983; Pollard 1984; Sogard *et al*. 1989; Connolly 1994a, b; Edgar & Shaw 1995; Shoji *et al*. 2007).

The Miyako Bay is located in the middle of the Sanriku coast (Fig. 1), Pacific coast of northern Japan. Since the bay is composed of a variety of habitats such as seagrass beds, rocky and sandy shores, previous reports have shown that the Miyako Bay forms important habitats for various fishery resources (Yamashita *et al*. 1994; Okouchi *et al*. 1999, 2004; Chin 2009; Chin *et al*. 2010; Wada *et al*. 2010; Hamaguchi *et al*. 2011; Noda *et al*. 2013; Fukuta *et al*. 2017). However, there is still insufficient information on the ecological functions of seagrass beds in the Miyako Bay. Then, we started monitoring the seagrass beds of *Zostera marina* Linnaeus, 1753 and its associated fish communities in 2010 (Fukuta *et al*. 2017).

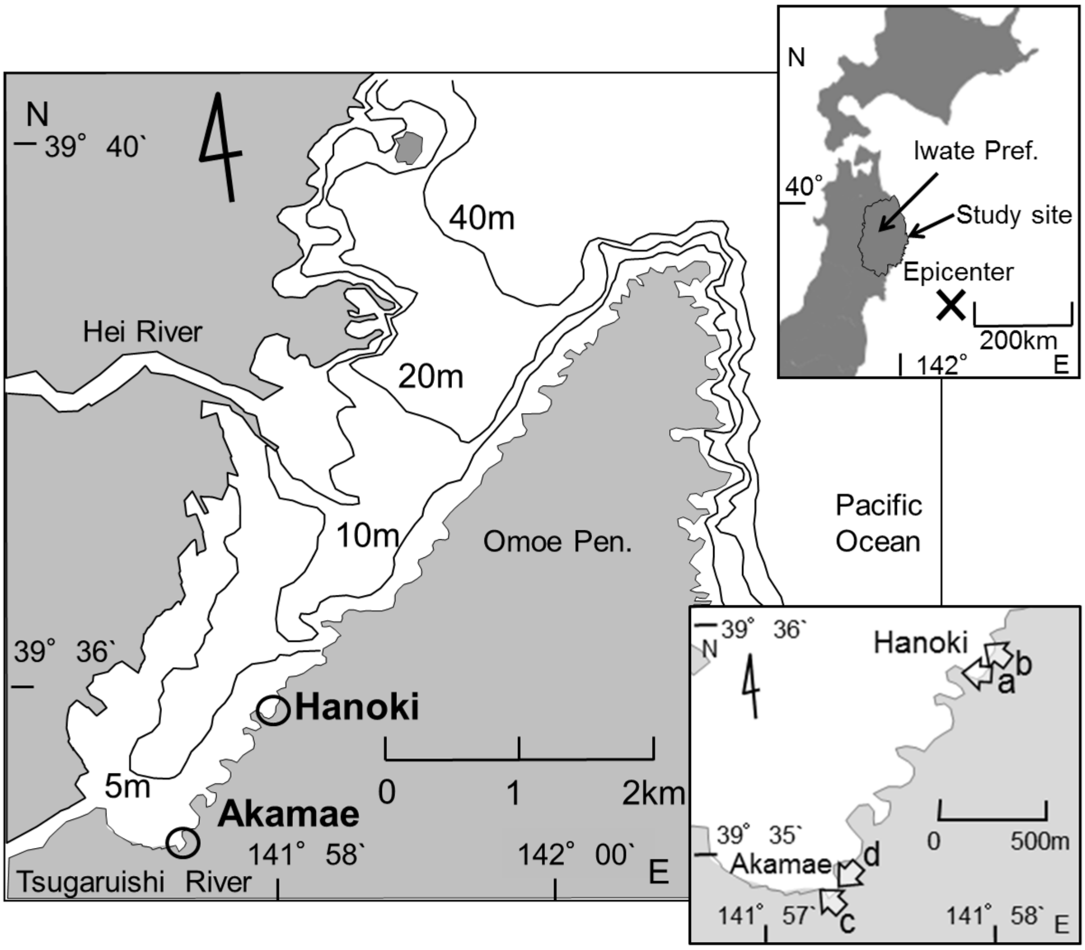

Fig. 1 Location of the sampling sites (Hanoki and Akamae: solid circles) in the Miyako Bay, the Pacific coast of northern Japan. The epicenter of the earthquake that caused the 2011 tsunami is indicated by a cross in the upper panel. The direction of the views of sampling sites (a-d) in Fig. 2 are indicated by arrows in the lower panel. Redrawn from Okouchi *et al*. (1999).

The coastal ecosystem of the Miyako Bay was impacted by the devastating tsunami following the Great East Japan Earthquake on 11 March 2011 (magnitude 9; the largest observed in Japan, N36° 06’ / E141° 16’). A tsunami of 10.4 m height and subsidence damage due to the earthquake of 0.33 m occurred at Tsugaruishi (N39° 35’ / E141° 57’), which is located near the inner area of the Miyako Bay. Since a catastrophic event rarely occurs at a large spatial scale under natural conditions, information regarding the extent to which such events affect natural ecosystems is limited (Nakaoka *et al*. 2006; Whanpetch *et al*. 2006, 2010; Hori *et al*. 2009; Tamaki & Muraoka 2011; Takami *et al*. 2013). Monitoring the succession processes and comparing habitat conditions between pre- and post-tsunami periods are essential in order to understand the mechanisms of high biological productivity of the coastal ecosystems and to attain sustainable use of fishery resources.

In the present study, the environmental conditions of seagrass beds and fish community structures at two sites with different levels of disturbance were compared using our monitoring data before (2010) and after (2011 and 2012) the tsunami. In addition, the effects of the tsunami on habitat conditions and fish community structures and their succession patterns were compared between the two sites with different magnitudes of tsunami impact.

Materials and Methods

Miyako Bay was near the epicenter of the mega-earthquake that occurred on 11 March 2011 (Fig. 1). It is a semi-enclosed bay and an estuary basin for both the Hei River and the Tsugaruishi River. Physical and biological surveys were conducted in seagrass beds at two sites, Hanoki and Akamae (Fig. 1, 2). Hanoki is in a small inlet and Akamae, 1 km south of Hanoki, is in the innermost part of the bay.

Fig. 2 Sampling sites at Hanoki (a: view towards west from the southeast shore , b: towards northwest from the east shore) and Akamae (c: towards northwest from the southeast shore, d: towards southwest from the northeast shore). The directions of views are shown by arrows in Fig. 1. [continued to next page]

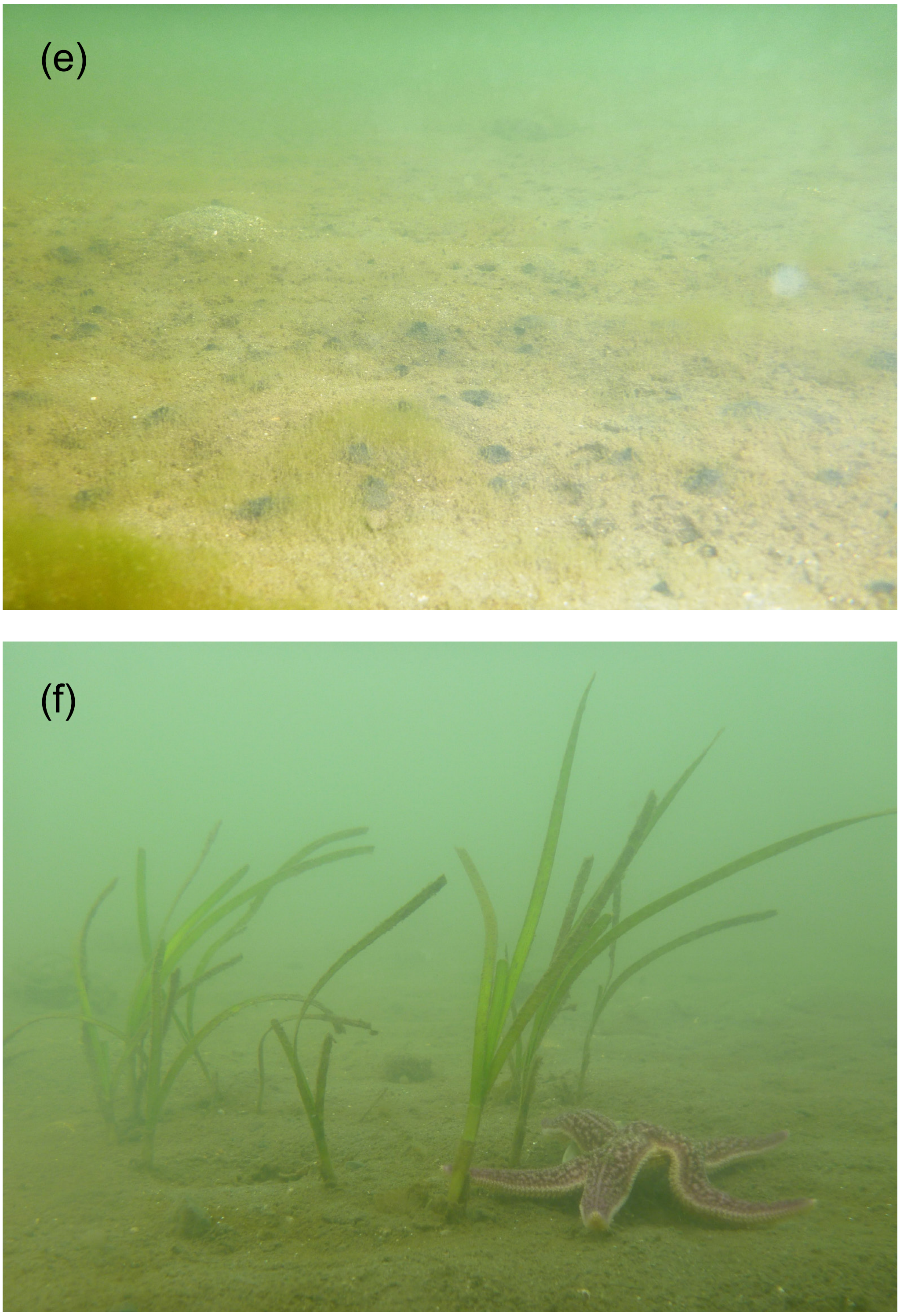

Fig. 2 continued. Underwater views at Akamae in (e) 2011 and (f) 2012. All photos by the authors.

Surveys of the seagrass vegetation and fish community were conducted on 5 June in 2010, 16 June in 2011, and 8 June 2012, at the time of maximum growth of seagrass in northern Japan (Miyazaki 2005; Ueda *et al*. 2006). Underwater observations by snorkelling or scuba diving were conducted to examine the seagrass vegetation before fish sampling at each site. Seagrass shoot density was measured with quadrats (0.5 m x 0.5 m) at 4 locations randomly selected within each site (Kamimura & Shoji 2009; Mohri *et al*. 2013; Fukuta *et al*. 2017). Leaf length of randomly-collected *Z. marina* (5–30 leafs) was measured using a ruler.

Fish were collected using a round seine net (Kamimura & Shoji 2009; Mohri *et al*. 2013; Fukuta *et al*. 2017) within seagrass beds of <1.5 m depth (= height of the seine net). Three sides of a square (10 m in side length) were surrounded using the net, with the other side facing the shore (around border of the seagrass bed). Each collection covered an area of 100 m^2 (10 m x 10 m) in a seagrass bed. Fish sampling was carried out 4 times on each sampling day at the two sites. Samplings were conducted during a tidal level of 50–130 cm from standard sea level in the day. Fish samples were preserved in 10% seawater formalin.

Water temperature and salinity were measured every month using a conductivity-temperature-depth (CTD) profiler (Compact-CTD act-HR or Rinko-profiler; JFE Advantech, Tokyo, Japan) closed to the bottom of a seagrass bed. The data between July 2010 and May 2011 were not available due to the loss of the CTD by the tsunami.

In the laboratory, fish were identified according to Nakabo (2002) and measured to the nearest 0.1g in wet weight (g). Mean number of fish species, fish abundance (number of fish individuals) and biomass (wet weight of fish) were described on the basis of area (100 m^2) covered by each fish sampling. The collected fishes during the samplings were divided into three groups according to habitat and feeding habit of each species (Kimura *et al*. 1982; Dotsu 1984; Noichi *et al*. 1993; Sawamura 1999; Kanou *et al*. 2004, 2005; Yagi *et al*. 2006; Hori *et al*. 2009; Sakurai *et al*. 2009), as follows: (1) pelagic species (P), (2) benthic invertebrate feeders (BI), and (3) benthic carnivores (BC) (Table 1, Fig. 3)

The data were grouped by site and year. Referring the result of non-normality test by the Shapiro-Wilk W-test, cases with $p < 0.05$ were subjected to Kruskal-Wallis test followed by the Tukey's test (for same numbers of samples) or the Scheffe's test (different numbers of samples) and those with $p > 0.05$ to one-way ANOVA followed by the Tukey's test with the SPSS (ver. 17, IBM, Armonk, New York, USA).

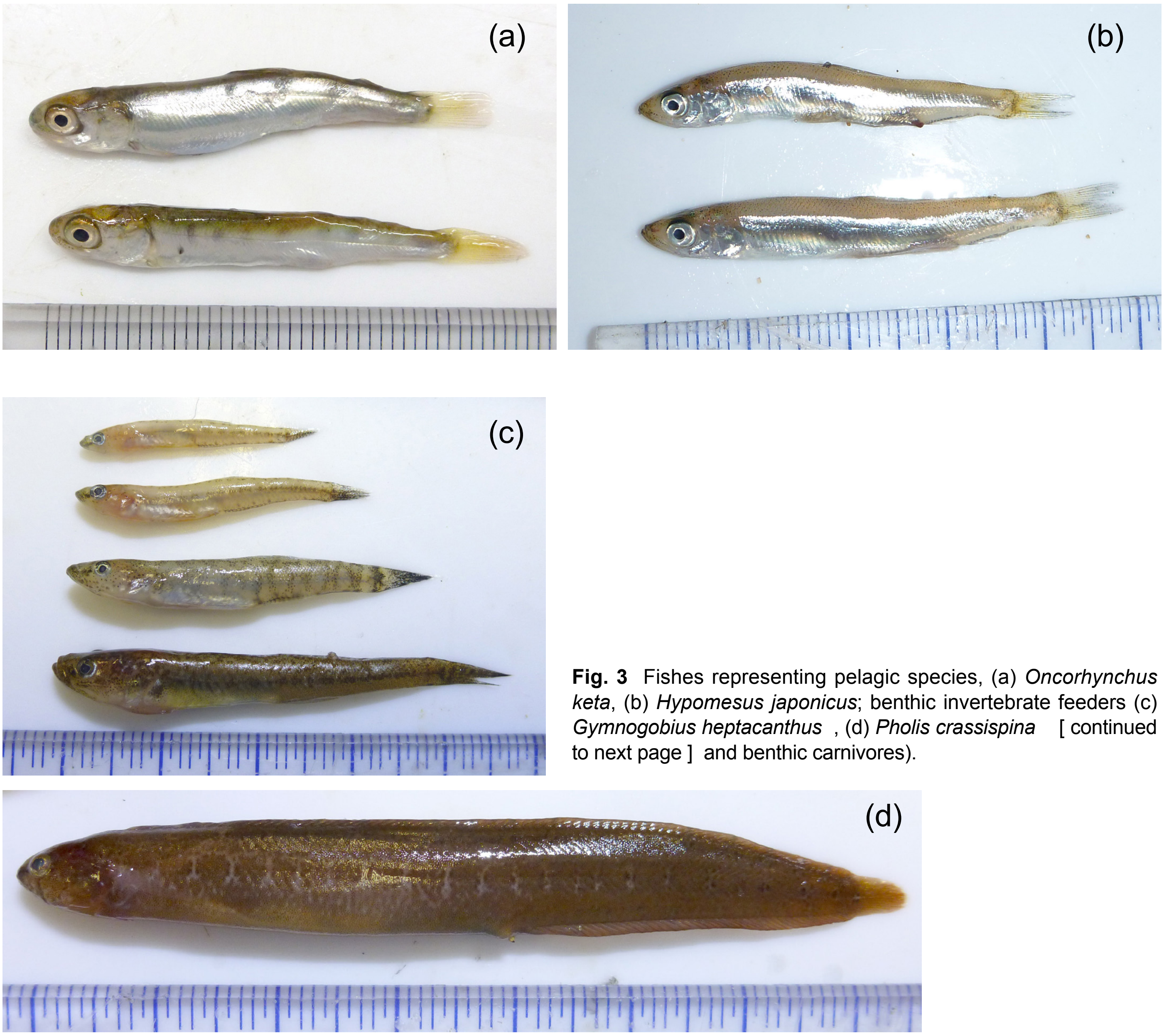

Fig. 3 Fishes representing pelagic species, (a) *Oncorhynchus keta*, (b) *Hypomesus japonicus*; benthic invertebrate feeders (c) *Gymnogobius heptacanthus* , (d) *Pholis crassispina* [continued to next page] and benthic carnivores).

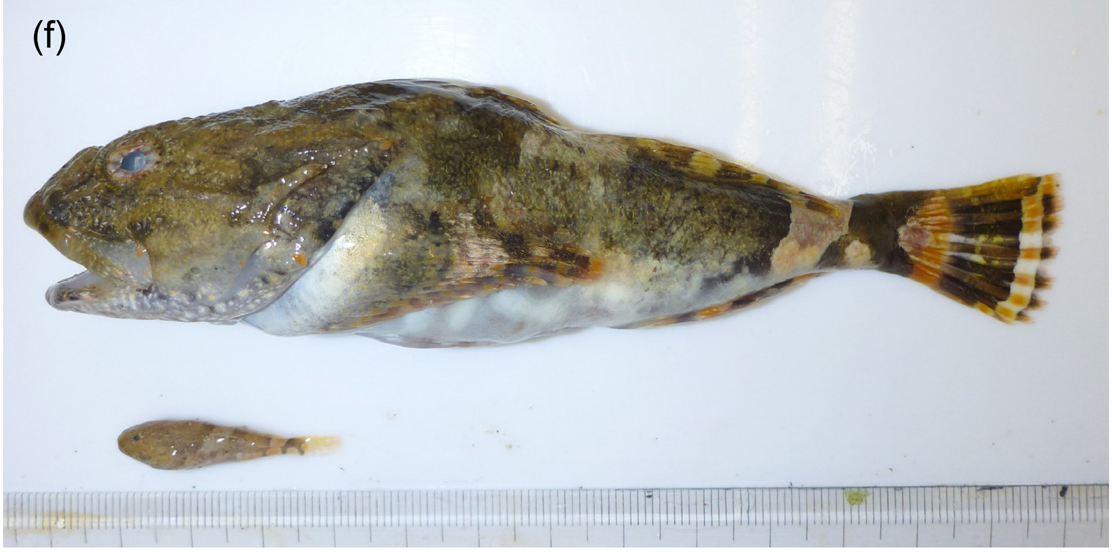

Fig. 3 continued. Fishes representing benthic carnivore species (e) *Acanthogobius flavimanus*, (f) *Myoxocephalus stelleri*.

Results

Environmental conditions and seagrass beds

Water temperature measured on the survey day was 16.0, 16.7, and 14.7°C at Hanoki and 15.3, 19.7, and 17.2°C at Akamae in 2010, 2011, and 2012, respectively (Fig. 4). Salinity during June at Akamae was relatively lower than that at Hanoki.

Seagrass shoot density (mean ± SE, number of shoots m^{-2}) at Hanoki was 32.0 ± 4.3 m^{-2}, 9.5 ± 8.8 m^{-2} and 31.5 ± 22.2 m^{-2} in 2010, 2011 and 2012, respectively (Fig. 2, 5). The effect of year was not significant (Kruskal-Wallis test followed by Tukey's test, $p > 0.05$). At Akamae, mean seagrass shoot density was 34.0 ± 4.2 m^{-2}, 0 m^{-2} and 6.0 ± 2.3 m^{-2} in 2010, 2011 and 2012, respectively. There was a significant difference in the shoot density in Akamae between 2010 and 2011 (Kruskal-Wallis test followed by Tukey's test, $p < 0.05$).

Leaf length of seagrass (mean ± SE, cm) at Hanoki was 51.5 ± 3.6 cm, 41.6 ± 1.4 cm and 33.8 ± 1.7 cm in 2010, 2011 and 2012, respectively. The length in 2012 was significantly shorter than in 2010 and 2011 (Kruskal-Wallis test followed by Scheffe's test, $p < 0.05$; Fig. 5). At Akamae, mean seagrass leaf length was 59.7 ± 4.8 cm and 38.0 ± 3.2 cm in 2010 and 2012, respectively. No data was available in 2011 due to the loss of the seagrass bed. There was a significant difference in leaf length at Akamae between 2010 and 2012 (Kruskal-Wallis test followed by Scheffe's test, $p < 0.05$).

Table 1. Abundance (mean number of individuals 100 m^{-2}) and biomass (mean wet weight, g 100 m^{-2}) of fishes collected at Hanoki and Akamae in the Miyako Bay from 2010 to 2012. Fish were grouped depending on their habitats and feeding habits as follows: P, pelagic species; BI, benthic invertebrate feeders; BC, benthic carnivores. Values to the left are for Hanoki and to the right for Akamae.

Species	Group	Hanoki / Akamae					
		------- No. of indiduals (100 m^{-2}) -------			------- Wet weight (g 100 m^{-2}) -------		
		2010	2011	2012	2010	2011	2012
Hypomesus nipponensis McAllister, 1963	P			/ 0.3			/ 0.1
Hypomesus japonicus (Brevoort, 1856)	P		/ 0.3	/ 0.5		/ 0.9	/ 1.6
Plecoglossus altivelis (Temminck and Schlegel, 1846)	BI		/ 1.8	/ 0.3		/ 3.1	/ 0.3
Oncorhynchus keta (Walbaum, 1792)	P	/ 1.8	1.0 / 3.8		/ 1.9	0.6 / 2.5	
Tribolodon brandti (Dybowski, 1872)	BI	0.5 /	/ 4.0	0.3 /	28.3 /	/ 31.5	15.4 /
Syngnathus schlegeli Kaup, 1856	BI	1.3 / 0.3	1.0 / 1.5	3.8 / 11.3	2.1 / 0.6	1.5 / 3.2	9.9 / 26.1
Sillago japonica Temminck and Schlegel, 1843	BI		0.3 /			1.4 /	
Scombrops gilberti (Jordan and Snyder, 1901)	BI			0.3 /			0.2 /
Ditrema spp.	BI	0.3 /			12.8 /		
Tridentiger trigonocephalus (Gill, 1858)	BC		0.3 / 0.3	/ 0.8		0.2 / 0.2	/ 2.4
Acentrogobius spp.	BC		/ 1.0	/ 0.5		/ 1.1	/ 1.4
Gymnogobius heptacanthus (Hilgendorf, 1879)	BI	214.8 / 4.0	14.5 / 1.5	26.5 / 10.3	176.6 / 4.0	6.2 / 0.7	22.5 / 9.0
Favonigobius gymnauchen (Bleeker, 1860)	BI		/ 0.3	3.0 / 5.8		/ 0.1	0.9 / 5.3
Acanthogobius flavimanus (Temminck and Schlegel, 1845)	BC	/ 0.3	0.8 / 6.8	0.3 / 6.3	/ 1.7	3.4 / 25.3	1.1 / 53.0
Ammodytes japonicus Duncker and Mohr, 1939	BI		1.8 /			1.7 /	
Opisthocentrus ocellatus (Tilesius, 1811)	BI	21.0 /		1.3 / 0.3	13.5 /		0.5 / 0.1
Opisthocentrus tenuis Bean and Bean, 1897	BI	45.0 /	1.0 / 0.8	3.3 / 0.5	34.7 /	0.4 / 0.4	2.0 / 0.3
Pholis nebulosa (Temminck and Schlegel, 1845)	BI	/ 2.5	/ 0.8	0.5 / 4.3	/ 10.5	/ 1.7	7.3 / 10.5
Pholis crassispina (Temminck and Schlegel, 1845)	BI	1.5 / 2.8	0.5 / 5.0	1.0 / 8.3	13.9 / 19.5	1.4 / 14.1	6.7 / 40.0
Hexagrammos otakii Jordan and Starks, 1895	BC	0.3 /	0.8 / 0.3	0.8 /	41.3 /	2.0 / 0.4	2.2 /
Hexagrammos agrammus (Temminck and Schlegel, 1844)	BC	0.3 /			35.0 /		
Pleurogrammus azonus (Jordan and Metz, 1913)	BI			0.3 /			0.2 /
Blepsias cirrhosus (Pallas, 1814)	BI	3.3 / 2.0	1.0 / 0.8	1.8 / 0.3	3.6 / 2.4	0.6 / 0.7	3.7 / 0.7
Hemitripterus villosus (Pallas, 1814)	BC		0.5 /	/ 1.3		6.0 /	/ 8.4
Pseudoblennius cottoides (Richardson, 1850)	BC	22.8 /	5.0 / 8.8	4.5 / 0.8	8.4 /	3.3 / 7.3	5.4 / 0.9
Myoxocephalus stelleri Tilesius, 1811	BC	0.8 / 3.3	0.8 / 2.0	22.5 / 40.8	5.2 / 3.9	0.6 / 3.7	41.5 / 59.6
Myoxocephalus brandti (Steindachner, 1867)	BC			0.3 /			0.2 /
Gymnocanthus herzensteini Jordan and Starks, 1904	BC			69.0 / 0.5			26.8 / 0.3
Ocynectes modestus Snyder, 1911	BC	/ 0.3			/ 0.3		
Pallasina barbata (Steindachner, 1876)	BI		0.3 /	/ 0.3		/ 0.1	/ 0.1
Liparis tanakai (Gilbert and Burke, 1912)	BC			/ 0.3			/ 11.0
Paralichthys olivaceus (Temminck and Schlegel, 1846)	BC	/ 0.3		/ 0.3	/ 5.1		/ 3.6
Pleuronectes yokohamae Günther, 1877	BC		0.3 / 0.8	2.3 / 0.8		0.1 / 0.3	14.7 / 0.1
Total		311.5 / 17.3	29.5 / 40.0	141.3 / 94.0	375.4 / 49.8	29.4 / 96.8	160.9 / 234.8
Total no. of species		12 / 10	16 / 18	18 / 22			

Fish abundance

A total of 1,929/605 fish belonging to 22/23 taxa of 15 and 15 families were collected from Hanoki and Akamae, respectively, during the surveys from 2010 to 2012 (Table 1). Numerically the six most dominant species at Hanoki were *Gymnogobius heptacanthus* ('sevenspine goby', 53.0 %), *Gymnocanthus herzensteini* ('black edged sculpin', 14.3 %), *Opisthocentrus tenuis* ('white nose prickleback', 10.2 %), *Pseudoblennius cottoides* ('sunrise sculpin': 6.7 %), *Myoxocephalus stelleri* ('frog sculpin', 5.0 %), and *Opisthocentrus ocellatus* ('prickleback', 4.6 %) (Table 1). At Akamae, the numerically six most dominant species were *M. stelleri* (30.4 %), *Pholis crassispina* ('mottled gunnel', 10.6 %), *G. heptacanthus* (10.4 %), *Acanthogobius flavimanus* ('yellowfin goby', 8.8 %), *Syngnathus schlegeli* ('seaweed pipefish', 8.6 %) and *P. cottoides* (6.3%).

The pattern of temporal change in the fish community structure differed between the two sampling sites (Fig. 5). There was no significant effect of year on number of fish species at Hanoki (one-way ANOVA followed by Tukey's test, $p > 0.05$), while the effect of year on the number of fish species was significant at Akamae between 2010 and 2012 (Kruskal-Wallis test, followed by Tukey's test, $p < 0.05$). At Hanoki, differences in the fish abundance and biomass between 2010 and 2011 were significant (one-way ANOVA followed by Tukey's test, $p < 0.05$), while these values were not significantly different at Akamae (Kruskal-Wallis test, followed by Tukey's test, $p > 0.05$). At both sites, fish abundance and biomass were not significantly different between 2010 and 2012 (one-way ANOVA followed by Tukey's test or Kruskal-Wallis test followed by Tukey's test, $p < 0.05$).

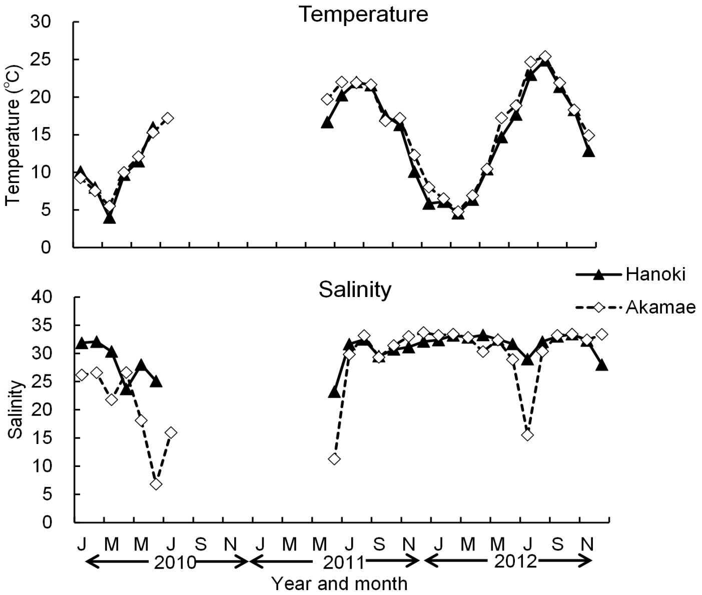

Fig. 4 Monthly changes in temperature and salinity at Hanoki and Akamae from 2010 to 2012. No data were available between July 2010 and May 2011 due to logger loss by the tsunami.

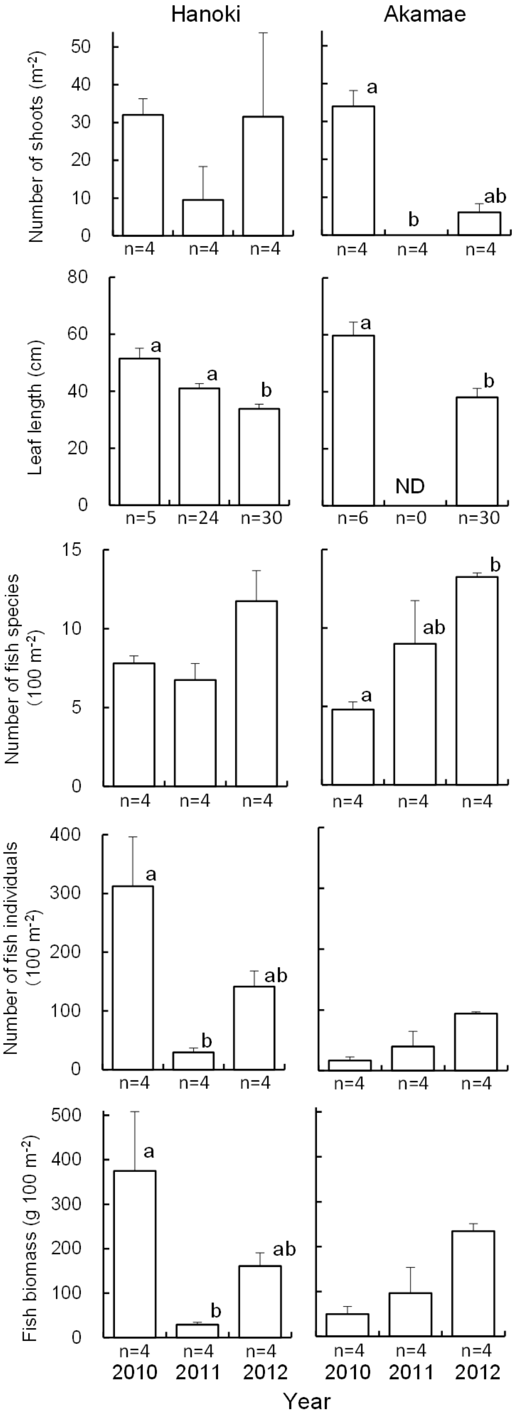

Fig. 5 Changes in mean seagrass shoot density, leaf length, number of fish species, mean fish abundance and biomass at Hanoki (left panels) and Akamae (right panels) from 2010 to 2012. Vertical bars show standard errors. ND indicates no data since no seagrass was observed at Akamae in 2011. Different letters show significant differences among years (Kruskal-Wallis test followed by Tukey's test or one-way ANOVA followed by Tukey's test. $p < 0.05$).

Fish community

The patterns of temporal change in the composition of dominant fish groups were similar at the two sampling sites (Fig. 6). At both sites, group BI was most dominant in terms of fish abundance and biomass in 2010 and group BC in 2012. Moreover, BI and BC had a greater number of fish species than group P. The number of group P species at Akamae was slightly higher than that at Hanoki, while amounting to less than 15% among total during the three years surveyed.

In contrast, temporal changes in the composition of dominant fish species differed between the two sampling sites (Table 1, Fig. 7). At Hanoki, group BI was dominated by *G. heptacanthus*, *O. tenuis* and *O. ocellatus* and BC by *P. cottoides* in 2010. There was a significant drop in the number of fish individuals of BI species at Hanoki in 2011 (Kruskal-Wallis test followed by Tukey's test, $p < 0.05$). Moreover, the number of fish individuals of BC species (*G. herzensteini* and *M. stelleri*) was significantly higher in 2012 (Kruskal-Wallis test followed by Tukey's test, $p < 0.05$: Fig. 7, lower two left panels).

At Akamae, BI was represented by *G. heptacanthus* and *P. crassispina*, and BC by *M. stelleri* in 2010 (Table 1, Fig. 7). However, *S. schlegeli* (BI), *P. cottoides* (BC) and *A. flavimanus* (BC) increased their numbers in 2011 (Kruskal-Wallis test followed by Tukey's test, $p < 0.05$). Moreover, individuals of *G. heptacanthus* (BI) and *M. stelleri* (BC) were significantly more abundant in 2012 (Kruskal-Wallis test followed by Tukey's test, $p < 0.05$). At both sites, *Oncorhynchus keta* (chum salmon) was most dominant in group P which was less abundant than BI and BC. In group P, there was no significant difference in the number of fish individuals between 2010 and 2012 (Kruskal-Wallis test followed by Tukey's test, $p > 0.05$).

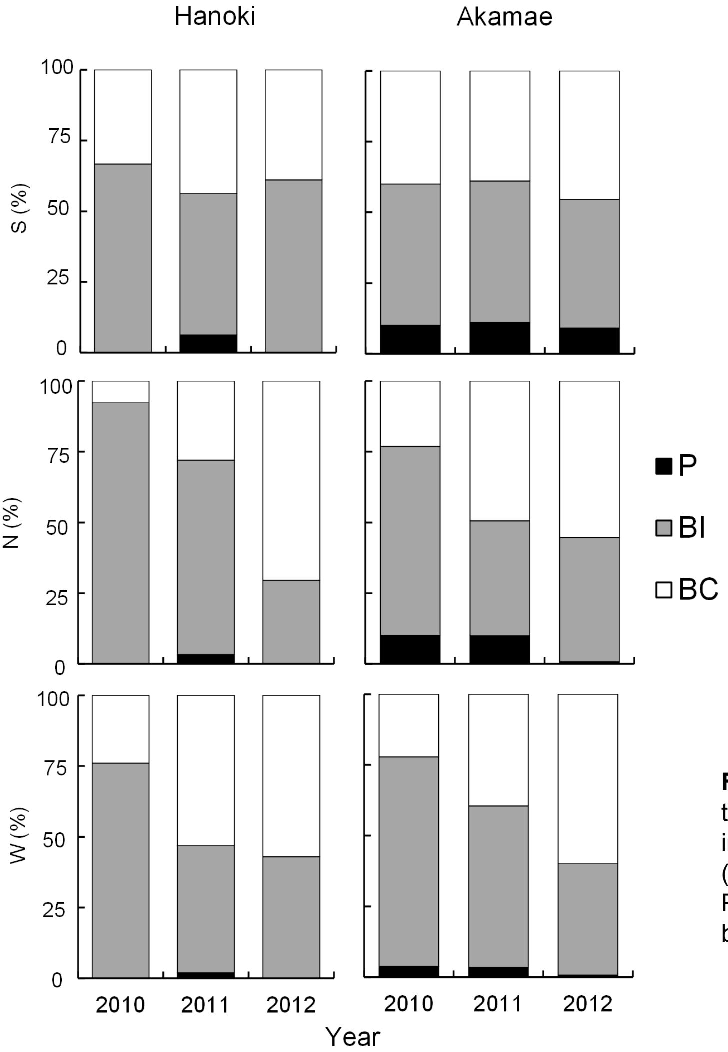

Fig. 6 Composition of fish assemblages in terms of the number of fish species (S, upper), number of fish individuals (N, middle) and biomass (W, lower) at Hanoki (left panels) and Akamae (right panels) in 2010–2012. P, pelagic species; BI, benthic invertebrate feeders; BC, benthic carnivores.

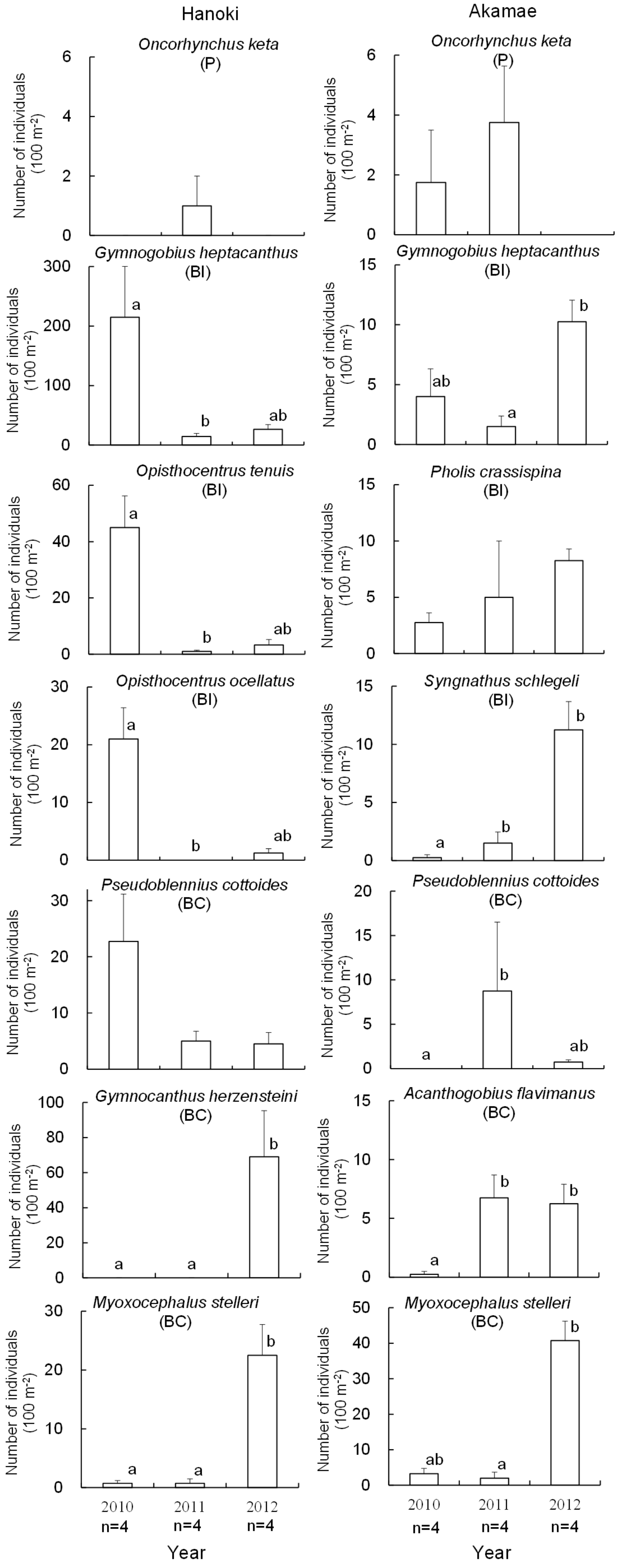

Fig. 7 Changes in the number of fish individuals of the seven dominant species at Hanoki (left panels) and Akamae (right panels) in 2010–2012. Vertical bars show standard errors. Different letters show significant differences among years (Kruskal-Wallis test followed by Tukey's test or one-way ANOVA followed by Tukey's test. $p < 0.05$).

Discussion

Hori *et al.* (2009) reported that the relationship between fish species diversity and the three-dimensional structure of seagrass bed in the Indian Ocean was affected by various magnitudes by the impact of the 26 December 2004 tsunami caused by the Sumatran earthquake. We analysed the effects of the tsunami on seagrass beds and fish communities in the Miyako Bay by conducting quantitative sampling from 2010 to 2012. The present study suggests that the effect of the tsunami was different between the two sites, with a more prominent effect of disturbance in the inner part of the bay (Akamae).

At Hanoki, the patterns of fluctuation of the mean fish abundance and biomass were similar to the fluctuations in seagrass shoot density. Some of BI species (e.g. *G. heptacanthus*, *O. tenuis* and *O. ocellatus*) that might depend on the seagrass habitat and were dominant in terms of abundance and biomass before the tsunami (2010) were replaced by group BC after the tsunami (especially in 2012, dominated by *G. herzensteini* and *M. stelleri*). In general, habitat complexity has been reported to influence fish community structures in seagrass beds (e.g. Heck & Crowder 1991; Orth 1992; Jenkins *et al.* 1998; Horinouchi & Sano 1999; Hovel & Fonseca 2005; Horinouchi 2005, 2007; Hori *et al*. 2009; Horinouchi *et al*. 2009; Warry *et al*. 2009). We suggest that temporal changes in the structure of the seagrass beds caused by the tsunami resulted in changes in the fish community at Hanoki.

At Akamae, on the other hand, the number of fish species, fish abundance and biomass increased from 2010 to 2011, even though the seagrass bed mostly disappeared after the tsunami. The increase in these values could be explained by the changes in fish community structure from seagrass-associated to other species corresponding to the drastic changes in their habitat. While *G. heptacanthus* numbers showed a somewhat similar pattern of change as seagrass shoot density, changes in the abundances of other fish species did not correspond with changes in seagrass shoot density. Fish species which inhabit seagrass beds (e.g. *G. heptacanthus*: BI and *M. stelleri*: BC) were dominant in 2010 and replaced by other species, especially *A. flavimanus* thereafter. Increase in abundance of BC species (*M. stelleri*) was commonly observed at both Akamae and Hanoki in 2012, although the fish community of the two sites were different before (2010) and after the tsunami (2011 and 2012). In fact, the most dominant species of group BC was *G. herzensteini* at Hanoki and *A. flavimanus* at Akamae in 2012.

* * *

Furthermore, the disturbance, including subsidence, caused by the tsunami and the earthquake could have changed the shape of river mouth and consequential direction of the Tsugaruishi River discharge. That might have caused large fluctuations in salinity at Akamae. In fact, salinity at Akamae in 2012 was higher than in 2010. Additionally, BI and BC species increased at Akamae in 2012 when seagrass recovered and fish biomass was greater than in 2010. Salinity has been suggested to be an environmental factor with a potential to affect seagrass-associated fish populations (Jones & West 2005; Yamada *et al*. 2007). Moreover, fish utilize even gaps or edges of seagrass patches (e.g. Fagan *et al*. 1999; Flynn & Ritz 1999; Ries *et al*. 2004; Connolly & Hindell 2006; Smith *et al*. 2008; Macreadie *et al*. 2010). The tsunami impact might have changed the environmental conditions including the characteristics of seagrass bed for the fish community.

Acknowledgments

We wish to thank Drs. T. Horii, D. Muraoka, N. Shirafuji, Y. Matsumoto, H. Okouchi, and H. Kinoshita for their valuable advice and guidance in the course of writing. We deeply appreciate the assistance of M. Fujise, T. Arauchi, S. Toda, M. Haga, T. Chiba, A. Kumagai, A. Sakai, T. Kikuchi, Y. Maekawa, T. Sasaki, S. Yamane, K. Yamane, K. Tanaka, R. Ito, Y. Kajiyama, and members of the Fish Stock Enhancement Conference around Miyako Bay for their help with the seine net survey and sorting of fish. We are also grateful to Prof. M. Tokeshi and two anonymous reviewers for their kind reviewing of the manuscript. The Fisheries Agency, the Ministry of Agriculture, Forestry and Fisheries of Japan funded a part of this study.

References

Adams S M (1976) Feeding ecology of eelgrass fish communities. Trans American Fisheries Society 105, 514 – 519.

Beckley L E (1983) The ichthyofauna associated with *Zostera capensis* Setchell in the Swartkops estuary, South Africa. South Africa Journal of Zoology 18, 15 – 24.

Chin B (2009) Study of seed production and stock enhancement technology of the black rockfish *Sebastes schlegelii* based on physiological and ecological characteristics. PhD thesis, Kyoto University, Kyoto, Japan.

Chin B, Nakagawa M, Tagawa M, Masuda R & Yamashita Y (2010) Ontogenetic changes of habitat selection and thyroid hormone levels in black rockfish (*Sebastes schlegelii*) reared in captivity. Ichthyological Research 57, 278 – 285.

Connolly R M (1994a) A comparison of fish community from seagrass and unvegetated area of a southern Australian estuary. Australian Journal of Marine and Freshwater Research 45, 1033 – 1044.

Connolly R M (1994b) Removal of seagrass canopy: effect on small fish and their prey. Journal of Experimental Marine Biology and Ecology 184, 99 – 110.

Connolly R M & Hindell J S (2006) Review of nekton patterns and ecological process in seagrass landscapes. Estuarine Coastal and Shelf Science 68, 433 – 444.

Dayton P K (1972) Toward an understanding community resilience and the potential effects of enrichment to the benthos at McMurdo Sound, Antarctica. In Parker B.C. (ed) Proceedings of the Colloquium on Conservation Problems in Antarctica. Kansas: Allen Press, pp. 81 – 95.

Dotsu Y (1984) The biology and induce spawning of the gobiid fish *Chaenogobius heptacanthus*. Bulletin of the Faculty of Fisheries, Nagasaki University 55, 9 – 18 (in Japanese).

Edgar G J & Shaw C (1995) The production and trophic ecology of shallow-water fish community in southern Australia I. Species richness, size-structure and production of fishes in Western Port Victoria. Journal of Experimental Marine Biology and Ecology 194, 53 – 81.

Fagan W E, Cantrell R S & Cosner C (1999) How habitat edges change species interactions. The American Naturalist 153, 165 – 182.

Flynn A J & Ritz D A (1999) Effect of habitat complexity and predatory style on the capture success of fish feeding on aggregated prey. Journal of Experimental Marine Biology and Ecology 79, 487 – 494.

Fukuta A, Kamimura Y, Hori M, Nakaoka M, Noda T, Yamashita Y, Otake T & Shoji J (2017) Offshore currents explain the discontinuity of a fish community in the seagrass bed along the Japanese archipelago. Fisheries Oceanography 26, 65 – 68.

Hamaguchi M, Fujinami Y & Yamashita Y (2011) Production of fishery resources in estuary areas. Ecosystem services of coastal waters – benefits of the sea and its sustainable use. Tokyo: Koseisya-koseikaku (in Japanese).

Heck K L J & Crowder L B (1991) Habitat structure and predater-prey interactions. In: Bell S.S., McCoy E., Mushinsky H. (eds) Habitat complexity: the physical arrangement of objects in space. New York: Chapman & Hall.

Hori M, Suzuki T, Monthum Y, Srisombat T, Tanaka Y, Nakaoka M & Mukai H (2009) High seagrass diversity and canopy-height increase associated fish diversity and abundance. Marine Biology 156, 1447 – 1458.

Horinouchi M (2005) A comparison of fish community from seagrass beds and the adjacent bare substrata in Lake Hamana, central Japan. Laguna 12, 69 – 72.

Horinouchi M (2007) Review of the effects of within-patch scale structural complexity on seagrass fishes. Journal of Experimental Marine Biology and Ecology 350, 111 – 129.

Horinouchi M & Sano M (1999) Effects of changes in seagrass shoot density and leaf height on abundances and distribution patterns of juveniles of three gobiid fishes in a *Zostera marina* bed. Marine Ecology Progress Series 183, 87 – 94.

Horinouchi M, Mizuno N, Jo Y, Fujita M, Sano M & Suzuki Y (2009) Seagrass habitat complexity does not always decrease foraging efficiencies of piscivorous fishes. Marine Ecology Progress Series 377, 43 – 49.

Hovel K A & Fonseca M S (2005) Influence of seagrass landscape structure on the juvenile blue crab habitat-survival function. Marine Ecology Progress Series 300, 179 – 191.

Jenkins G P, Keough M J & Hamer P A (1998) The contributions of habitat structure and larval supply to broad-scale recruitment variability in a temperate zone, seagrass-associated fish. Journal of Experimental Marine Biology and Ecology 226, 259 – 278.

Jones M V & West R J (2005) Spatial and temporal variability of seagrass fishes in intermittently closed and open coastal lakes in southeastern Australia. Estuarine and Coastal Shelf Science 64, 277 – 288.

Kamimura Y & Shoji J (2009) Seasonal changes in the fish assemblage in a mixed vegetation area of seagrass and macroalgae in the central Seto Inland Sea. Aquaculture Science 57, 233 – 241.

Kanou K, Sano M & Kohno H (2004) Food habits of fishes on unvegetated tidal mudflats in Tokyo Bay, central Japan. Fisheries Science 70, 978 – 987.

Kanou K, Sano M & Kohno H (2005) Ontogenetic diet shift, feeding rhythm and daily ration of juvenile yellowfin goby *Acanthogobius flavimanus* on tidal mudflat in the Tama river estuary, central Japan. Ichthyological Research 52, 319 – 324.

Kikuchi T (1974) Japanese contribution on consumer ecology in eelgrass (*Zostera marina* L.) bed, with special reference to trophic relationships and resources in fisheries. Aquaculture 4, 145 – 160.

Kimura K, Inoue S & Suzuki K (1982) Feeding habit of *Scombrops boops* (Pisces : Scombropidae) in Kumano-nada, central Japan. Bulletin of the Faculty of Fisheries, Mie University, 9, 191 – 199 (in Japanese).

Macreadie P I, Hindell J S, Keough M J, Jenkins G P & Connolly R M (2010) Resource distribution influences positive edge effects in a seagrass fish. Ecology 91, 2013 – 2021.

Miyazaki N (2005) Marine life off the Sanriku coast. Tokyo: Scientist Press (in Japanese).

Mohri K, Kamimura Y, Mizuno K, Kinoshita H, Toshito S & Shoji J (2013) Seasonal changes in the fish assemblage in a seagrass bed in the central Seto Inland Sea. Aquaculture Science 61, 215 – 220.

Nakabo T (2002) Fishes of Japan: with pictorial keys to the species. 2nd edition. Tokyo: Tokai University Press (in Japanese).

Nakaoka M, Tanaka Y, Mukai H, Suzuki T & Aryuthata C (2006) Tsunami impacts on biodiversity of seagrass communities in the Andaman Sea, Thailand: (1) Seagrass abundance and diversity. The Nagisa World Congress 8, 49 – 56.

Noda T, Nagakura Y, Ohta K & Aono H. (2013) Validation of transgenerational otolith marking using alizarin complexone for embryos in black rockfish *Sebastes schlegelii* ovaries. Aquaculture Science 61, 207 – 209.

Noichi T, Kusano M, Ueki D & Senta T (1993) Feeding habit of fishes eating settled larval and juvenile Japanese flounder (*Paralichthys olivaceus*) at Yanagihama beach, Nagasaki Prefecture. Bulletin of the Faculty of Fisheries, Nagasaki University 73, 1 – 6 (in Japanese).

Okouchi H, Kitada S, Tsuzaki T, Fukunaga T & Iwamoto A (1999) Number of returns and economic return rates of hatchery-released flounder *Paralichthys olivaceus* in Miyako Bay-evaluation by a fish market census. In: Howell B.R., Moksness E. and Svasand T. (eds) Stock enhancement and sea ranching. Oxford: Blackwell Science Publications, pp. 573 – 582.

Okouchi H, Kitada S, Iwamoto A & Fukunaga T (2004) Flounder stock enhancement in Miyako Bay, Japan. In: Bartley D.M. and Leber K.M. (eds) Marine ranching. Rome: FAO Fish Techology Papers 429, pp. 171 – 202.

Orth R J (1992) A perspective on plant-animal interactions in seagrasses: physical and biological determinants influencing plant and animal abundance. In: John D.M., Hawkins S.J. and Price J.H. (eds) Plant-animal interactions in the marine benthos. Oxford: Clarendon Press, pp. 147 – 164.

Pollard D A (1984) A review of ecological studies on seagrass fish communities, with particular reference to recent studies in Australia. Aquatic Botanica 18, 3 – 42.

Ries L, Fletcher R J, Battin J & Sisk T D (2004) Ecological responses to habitat edges: mechanisms, models, and variability explained. Annual Review of Ecology, Evolution, and Systematics 35, 491 – 522.

Sakurai I, Kaneta T, Nakamura T, Fukuda H & Kaneko T (2009) Food habits of fish communities in a *Sargassum confusum* bed off the coast of Ishikari, Hokkaido, Japan. Nippon Suisan Gakkaisi 75, 365 – 375 (in Japanese).

Sawamura M (1999) One-year comparison of stomach contents among demersal fishes off the coast of Usujiri, Hokkaido. Japanese Journal of Benthology 54, 14 – 23 (in Japanese).

Shoji J, Sakiyama K, Hori M, Yoshida G & Hamaguchi M (2007) Seagrass habitat reduces vulnerability of red sea bream *Pagrus major* juveniles to piscivorous fish predator. Fisheries Science 73, 1281 – 1285.

Smith T M, Hindell J S, Jenkins G P & Connolly R M (2008) Edge effects on fish associated with seagrass and sand patches. Marine Ecology Progress Series 359, 203 – 213.

Sogard S M (1989) Colonization of artificial seagrass by fishes and decapods crustaceans: importance of proximity to natural eelgrass. Journal of Experimental Marine Biology and Ecology 133, 15 – 37.

Tamaki H & Muraoka D (2011) Deterioration of tidal flat, *Zostera* and *Eisenia bicyclis* habitats by the Great East Japan Earthquake in Miyagi Prefecture. Journal of Japan Society on Water Environment 34, 400 – 404. (in Japanese).

Takami H, Won N & Kawamura T (2013) Impact of the 2011 mega-earthquake and tsunami on abalone *Haliotis discus hannai* and sea urchin *Strongylocentrotus nudus* populations at Oshika Peninsula, Miyagi, Japan. Fisheries Oceanography 22, 113 – 120.

Tokeshi M & Arakaki S (2012) Habitat complexity in aquatic systems: fractals and beyond. Hydrobiologia 685, 27 – 47.

Ueda S, Chikuchi Y & Kondo K (2006) Horizontal distribution and natural resource of seagrass in brackish Lake Obuchi, Aomori Prefecture, Japan. Japanese Journal of Limnology 67, 113-121 (in Japanese).

Wada T, Yamada T, Shimizu D, Aritaki M, Sudo H, Yamashita Y & Tanaka M (2010) Successful stocking of a depleted species, spotted halibut *Verasper variegatus* in Miyako Bay, Japan: evaluation from post-release surveys and landings. Marine Ecology Progress Series 407, 243 – 255.

Walter R P & Haynes J M (2006) Fish and coral community structure are related on shallow water patch reefs near San Salvador, Bahamas. Bulletin of Marine Science 79, 365 – 374.

Warry F Y, Hindell J S, Macreadie P I, Jenkins G P & Connolly R M (2009) Integrating edge effects into studies of habitat fragmentation: a test using meiofauna in seagrass. Oecologia 159, 883 – 892.

Weinstein M P & Heck Jr. K L (1979) Ichthyofauna of seagrass meadows along the Caribbean coast of Panama and in the Gulf of Mexico: comparison, structure and community ecology. Marine Biology 50, 97 – 107.

Whanpetch N, Nakaoka M, Mukai H, Suzuki T, Nojima S, Kawai T & Aryuthaka C (2006) Tsunami impacts on biodiversity of seagrass communities in the Andaman Sea, Thailand: (2) Abundance and diversity of benthic animals. The Nagisa World Congress 8, 57 – 66.

Whanpetch N, Nakaoka M, Mukai H, Suzuki T, Nojima S, Kawai T & Aryuthaka C (2010) Temporal changes in benthic communities of seagrass beds impacted by a tsunami in the Andaman Sea, Thailand. Estuarine, Coastal and Shelf Science 87, 246 – 252.

Williams S L & Heck K L J (2001) Seagrass community ecology. In Bertness M.D., Gaines S.D. and Hay M.E. (eds) Marine community ecology. Sunderland: Sinauer Associates.

Yagi Y, Bito C, Funakoshi T, Kinoshita I & Takahashi I (2006) Distribution and feeding habits of ayu *Plecoglossus altivelis altivelis* larvae in coastal water of Tosa Bay. Nippon Suisan Gakkaishi 72, 1057 – 1067 (in Japanese).

Yamada K, Hori M, Tanaka Y, Hasegawa N & Nakaoka M (2007) Temporal and special macrofaunal community changes along a salinity gradient in seagrass meadows of Akkeshi-ko estuary and Akkeshi Bay, northern Japan. Hydrobiologia 592, 345 – 358.

Yamashita Y, Nagahora S, Yamada H & Kitagawa D (1994) Effects of release size on survival and growth of Japanese flounder *Paralichthys olivaceus* in coastal waters off Iwate Prefecture, northeastern Japan. Marine Ecology Progres Series 105, 269 – 276.

Published: 1 October 2017

Editorial note: this paper is considered a valuable record of how the coastal system behaved before/after the tsunami/earthquake of 11 March 2011 in northern Japan.