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Original article

Recovery of coastal fauna after the 2011 tsunami in Japan revealed by bimonthly underwater visual censuses conducted over six years

Reji Masuda [1,*], Makoto Hatakeyama [2], Mizuki Ogata [1], Katsuhide Yokoyama [3] and Masaru Tanaka [4]

[1] *Maizuru Fisheries Research Station of Kyoto University, Maizuru, Kyoto 625-0086, Japan*
[2] *NPO Mori-umi, Kesennuma, Miyagi 988-0582, Japan*
[3] *Tokyo Metropolitan University, Hachioji, Tokyo 192-0397, Japan*
[4] *Moune Institute for Forest-Sato-Sea Studies, Kesennuma, Miyagi 988-0582, Japan*
* Correspondence: reiji@kais.kyoto-u.ac.jp; Tel.: +81-773-62-9063

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Introduction

In March 2011, a massive tsunami with a maximum height of 40 m hit the Pacific coast of northeast Japan following an earthquake. A tsunami of this scale results in the extensive removal of shallow benthic fauna and causes extremely intense disturbance to the marine ecosystem [1]. Such a catastrophic event can, nevertheless, provide unique opportunities to observe the subsequent ecological succession.

Here, we report the findings from an underwater visual census of fish and macroinvertebrate assemblages, which began 2 months after the tsunami and continued for 6 years. The present paper updates the findings reported in a previously published paper that were based on data collected during the first 5 years after the tsunami [2].

Materials and methods

Underwater visual censuses were conducted every 2 months from May 2011 to March 2017 at four locations in and around Moune Bay, Kesennuma, Miyagi, Japan. Station (St.) 1 was located in the inner part of the bay where the impact of the tsunami was greatest, having had a run-up height of 15 m [3]. St. 2 was located along a shallow rocky shore where the impact of the tsunami was limited. St. 3 was located at the mouth of the bay, and St. 4 was situated outside the bay. At each station, we established ten 50-m transects, and all fish within a 1-m distance either side of each transect were recorded along with their size and abundance. Fish standard lengths were visually estimated. In addition, macroinvertebrates, including the moon jellyfish *Aurelia* sp., the sea cucumber *Apostichopus japonicus*, and the abalone *Haliotis discus hannai*, were also enumerated and measured for length.

Fish abundance, species richness, and total fish biomass, calculated by visually estimating the body length of each species, were compared both among stations and years after the tsunami. A two-way repeated-measures ANOVA followed by a Holm's pairwise test was applied to identify significant differences in water temperature, fish abundance, species richness, and fish biomass.

Temporal shifts in fish community structure were visually inspected by ordinating Bray–Curtis similarities with non-metric multidimensional scaling (nMDS). The biomass of each species at each station was combined for each year and 4th-root transformed for this analysis.

Results

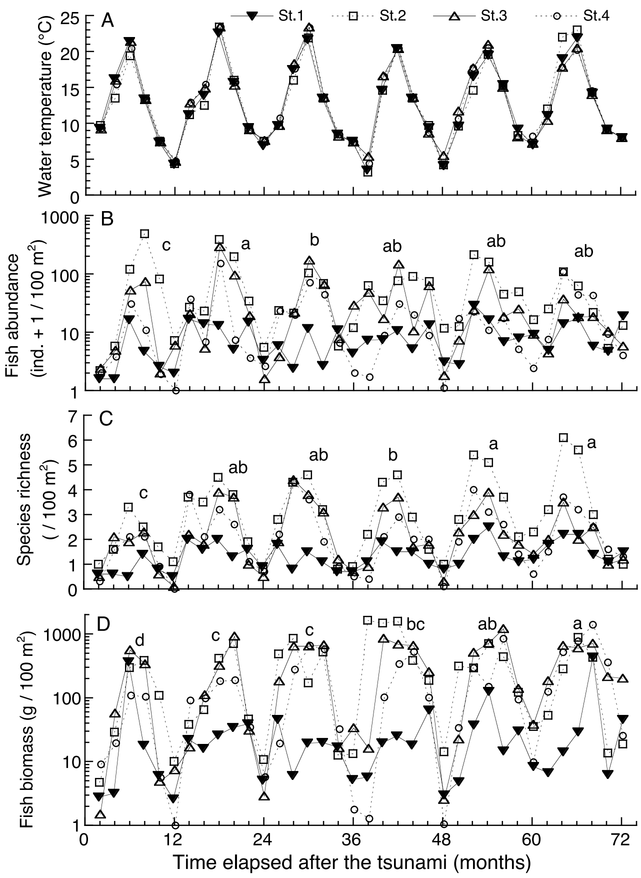

Fig. 1. (**A**) Sea bottom temperature, (**B**) fish abundance, (**C**) species richness, and (**D**) fish biomass of coastal fauna in and around Moune Bay during the first 6 years following the 2011 tsunami. Different letters indicate significant differences among years.

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Sea bottom temperature was highest in September, ranging from 19.4 to 23.7 °C, and lowest in March, ranging from 4.1 to 8.0 °C, with the exception of the fourth year, during which the lowest temperature recorded (3.2 °C) was in May (Fig. 1A). Both fish abundance and species richness exhibited seasonal changes. The total number of fish individuals was very low in May 2011 but rapidly increased during that year. Abundance was significantly lower in the first year than that in all other years, as was the species richness (Fig. 1B, C). Total fish biomass increased significantly over the course of the study (Fig. 1D). Fish abundance, species richness, and biomass were highest at St. 2 and lowest at St. 1.

Only a small number of fishes were found in May 2011, 2 months after the tsunami. The dominant species at that time was the sunrise sculpin *Pseudoblennius cottoides*, and most of the fishes observed were juveniles. Six months after the tsunami, the banded goby *Pterogobius elapoides* was dominant and highly abundant. In the second and third years, several tropical fishes were recorded; for example, the manybar goatfish *Parupeneus multifasciatus* and the bluestriped fangblenny *Plagiotremus thinorhynchos* were recorded in September 2012. Relatively large individuals started to be observed over the course of the study. In the fourth year or later, cold water-origin fishes such as the great sculpin *Myoxocephalus polycanthocephalus* and the starry flounder *Platichthys stellatus* were recorded. Larger individuals of the black rockfish *Sebastes cheni* were also recorded in the fourth year or later (Fig. 2).

The abundance of moon jellyfish was highest in the first 2 years, whereas that of sea cucumber continuously increased during the study period. Significantly more abalone were found in the fifth and sixth years compared to the first 4 years.

Fig. 2. A shoal of black rockfish observed at St. 2 in July 2014.

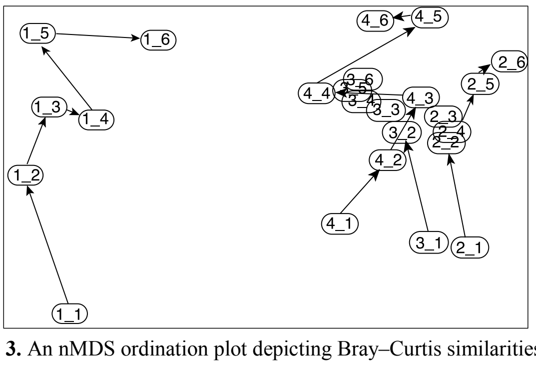

Fig. 3. An nMDS ordination plot depicting Bray–Curtis similarities of total fish biomass for each species observed in Moune Bay in the first 6 years post-tsunami. Each plot represents a station (St.) and year, e.g., 1_6 represents the data for St. 1 in the sixth year.

The nMDS analysis revealed three distinct clusters of fish assemblages (Fig. 3): In all 6 years, St. 1 formed one cluster; a second cluster was formed by the first year at St. 2, St. 3. and St. 4; and the third cluster was composed of the other time points and stations (i.e., the second year or later at St. 2–4).

Discussion

Typical temperate coastal fish assemblages in Japan show regular seasonal fluctuations both in abundance and species richness [4]. Fish assemblages in the present study sites had stabilized 2 years after the tsunami with respect to fish abundance and species richness. Fish biomass continued to increase during the course of the study due to the growth of long-lived fishes.

The findings of the present study support the prediction that small-bodied opportunistic species become dominant under highly disturbed conditions [5]. The banded goby, which does not survive more than 1 year (Masuda, unpublished data), was extremely abundant in the first year of the study. The lack of competitors or predators in the first year after the tsunami may have allowed the temporal expansion of the population of this species.

Sunrise sculpin was the dominant fish two months after the tsunami. The larvae of this species are common in the area offshore of Otsuchi Bay (ca. 50 km north of the present study site) from November to March, whereas juveniles can be captured by beach seine nets from April to August [6]. Therefore, the individuals observed in the present study were probably in the pelagic stage when the tsunami occurred.

Tropical fish species were recorded only in the second and third years after the tsunami. This is because the earliest colonizers after the heavy disturbance were from adjacent cold-temperate waters, whereas in the second year, tropical vagrants arrived to occupy the vacant niches. They were, however, subsequently expelled by competitors or predators in the fourth year or later.

Fish assemblages generally exhibit some annual fluctuation depending on oceanographic conditions. Thus, further observations are required to gain more insights into the succession process and resilience of coastal reef fauna in cold-temperate waters.

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