Impacts of the 2011 tsunami on tidal flat ecosystems: future perspectives for conservation of macrozoobenthic biodiversity

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Abstract We report on the impacts of the 2011 tsunami disaster on tidal flat ecosystems along the northeastern Japanese coast. Habitat structure was drastically modified by the tsunami, seismic subsidence, and/or liquefaction, resulting in intensive changes of associated biota. Although the biotic community has gradually recovered over the past 5 years, ongoing restoration projects are emergent threats for coastal ecosystems. Surveys revealed that several tidal flats in semi-enclosed bays are distinguished as key habitats for endangered macrozoobenthos, such as Cerithioidea gastropods and the marsh crab *Chasmagnathus convexus*. We also found that an estuarine system (the Samegawa River) in southern Fukushima Prefecture maintained a high diversity of endangered macrozoobenthos even after the tsunami. These key areas should be preserved as habitats for source populations in the meta-population network, for future conservation of biodiversity in tidal flats.

Keywords: Tidal flat, Earthquake, Tsunami, Endangered species, Macrozoobenthos, Conservation

Introduction

The Pacific coast of northeastern Japan was struck by a huge tsunami generated by the M 9.0 Great East Japan Earthquake on 11 March 2011 (Okada et al. 2011). The earthquake and tsunami intensively disturbed tidal flats, salt marshes, and sandy shores in the area (Kanaya et al. in press). Drastic changes in the community composition of macrozoobenthos have been reported from tidal flats across large spatial scales. For example, Miura et al. (2012) noted a sharp reduction of the dominant gastropod *Batillaria attramentaria* on five tidal flats in Sendai Bay. Urabe et al. (2013) also reported a taxon-specific reduction in species diversity of macrozoobenthos on tidal flats.

Biotic communities in the affected areas have been recovering gradually over the past 5 years. However, anthropogenic disturbances associated with ongoing restoration projects (e.g., reconstruction of huge sea walls) have become a potential threat for biotic communities (Okoshi 2015; Kanaya et al. in press). In this study, we classified the types of habitat alterations caused by the 2011 disaster. We also assessed the tsunami impacts on five endangered macrozoobenthic taxa in Sendai Bay. Finally, we discuss the potential threats of ongoing restoration projects on tidal flats in Japan.

Methodology

On 11 March 2011, an M 9.0 megathrust earthquake occurred in the western Pacific (38.322°N, 142.369°E), centered about 130 km east of Sendai City, Miyagi Prefecture. Huge tsunami up to 20 m high hit broad areas of the eastern Japanese coast (Okada et al. 2011). Seismic subsidence occurred intensively near the epicenter, with surfaces shifting up to 90 cm near the Oshika Peninsula (Kanaya et al. in press).

First, we summarized the types of disturbance associated with the earthquake, tsunami, and restoration projects based on the findings of Kanaya et al. (in press). Second, population sizes of four endangered Cerithioidea gastropods, *Batillaria multiformis* (NT in Miyagi Prefectural Red List), *B. zonalis* (CR+EN), *Cerithidea moerchii* (VU), and *Cerithideopsilla djadjariensis* (VU), and the marsh crab *Chasmagnathus convexus* (CR+EN) were surveyed at the Tsuya River, Samegawa River, and 25 sites in Sendai Bay (see Figs. 1 and 2). At each site, a 30-minute field observation was conducted on a tidal flat by two or more researchers to assess the population sizes; these surveys were performed from one to several times at each site during 2011–2015. A pre-tsunami survey was conducted at each site from 2001 to 2010. The population size was classified into five categories: abundant, few (2–10 individuals), one (only 1 individual), extirpated (present pre-tsunami but absent post-tsunami), and absent (both pre- and post-tsunami). Finally, a detailed census focusing on all macrozoobenthos taxa was conducted in August 2014 and August 2015 at four sites in the estuary of the Samegawa River. Surveys at each site combined a 30-minute field observation plus a sampling using a 1-mm mesh sieve and a 15 cm φ × 20 cm deep core.

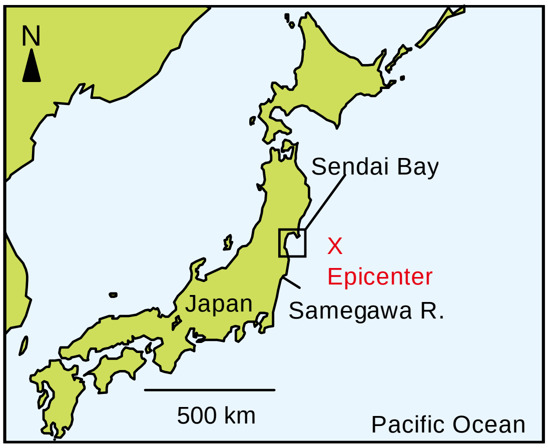

Fig. 1 Map of the Sendai Bay and Samegawa River.

Table 1. Classification of habitat alterations induced by the 2011 disaster in intertidal habitats along the eastern Japanese coast. Modified from Kanaya et al. (in press).

Causes	Impacts
Tsunami	Sediment scouring caused submergence of tidal flats
	Sediment deposition led to the creation of new tidal flats
	Vegetation loss in marshes, sand dunes, and coastal forests
	Destruction of coastal structures
Seismic subsidence	Submergence of existing tidal flats
	Creation of new tidal flats
Liquefaction	Sand/mud boiling led to changes in sediment type
	Lateral flow led to both submergence of existing tidal flats and creation of new tidal flats
	Destruction of coastal structures
Restoration projects	Reclamation and excavation led to coastal habitat destruction
	Seawall construction led to coastal habitat destruction
	Mitigation of tidal flat damage

Results and Discussion

Disturbance of tidalflats after the 2011 earthquake

The disaster-linked changes in Japanese tidal flats are summarized into four major categories (Table 1). First, the tsunami induced scouring, sediment deposition, vegetation losses, and destruction of coastal structures. For example, the tsunami washed away marsh plants and sand dune vegetation in Gamo Lagoon (Kanaya et al. in press). Tsunami currents also deposited a huge amount of drifting sea sand on coastal areas in Sendai Bay (Szczuciński et al. 2012). Intense physical disturbance induced extirpation of macrozoobenthos on tidal flats (Miura et al. 2012; Urabe et al. 2013). Second, seismic subsidence induced the elimination and/or creation of tidal flats. In Mangoku-ura Inlet, most of the tidal flat became subtidal and a part of the land behind the shore became intertidal (Okoshi 2015). Third, liquefaction caused mud boiling, lateral flow, and destruction of coastal structures. Okoshi (2015) described the mud/sand boiling in inner Tokyo Bay. In some cases, liquefaction induced a massive lateral flow, resulting in submergence of the intertidal zone (Kanaya et al. in press). Finally, restoration projects has become potential threats for biodiversity on the tidalflats in the area (see below).

Changes in population size of endangered macrozoobenthos

Intensive physical disturbances and changes in habitat structure drastically modified the associated biota. Figure 2 shows the changes in population sizes of the five endangered taxa. The marsh-associated species *C. moerchii* was extirpated at four of seven sites and maintained the pre-tsunami population size at only two sites in inner Matsushima Bay. *C. djadjariensis* was extirpated at three of six sites, and it occurred abundantly only in Mangoku-ura Inlet and inner Matsushima Bay. Before the tsunami disaster, *B. multiformis* had occurred abundantly at most of the studied sites (20 of 27 sites), but except for populations in Mangoku-ura and inner Matsushima Bay most of these populations were extirpated. *B. zonalis* had been found only at Hatsutsu-ura. Fortunately, the population was maintained after the tsunami, and three additional populations were newly discovered in Matsushima Bay. It was possible that new recruitment of *B. zonalis* occurred in the 3 habitats after the tsunami. The marsh-associated crab *C. convexus* was nearly extirpated, whereas two new populations were found in the Tsuya River and Samegawa River.

These findings indicate that tidal flats in the sheltered bay areas where the tsunami was distinctively attenuated, namely inner Matsushima Bay and Mangoku-ura Inlet, are important sources of planktonic larvae of the endangered taxa for other disturbed habitats. Such key tidal flats should be conserved for future restoration of endangered macrozoobenthos in Sendai Bay.

Endangered species in Samegawa River

During the 2014 and 2015 survey, we found 30 endangered taxa in the Samegawa River estuary (Table 2). Stenohaline marine taxa such as the bivalves *Acharax japonica*, *Macoma praetexta*, *Moerella jedoensis*, *Nitidotellina hokkaidoensis*, and *Soletellina boeddinghausi* and echiuran and sipunculan worms occurred at a seawater-dominated lagoon on the northern side of the river mouth. Marsh-associated and/or polyhaline brackish taxa such as assiminid gastropods, the bivalve *Corbicula japonica*, the polychaetes *Tylorrhynchus osawai* and *Notomastus* sp., and the crabs *C. convexus*, *Chiromantes haematocheir*, *Deiratonotus cristatus*, and *Sestrostoma toriumii* occurred at marshes and tidal flats in the freshwater-affected estuary.

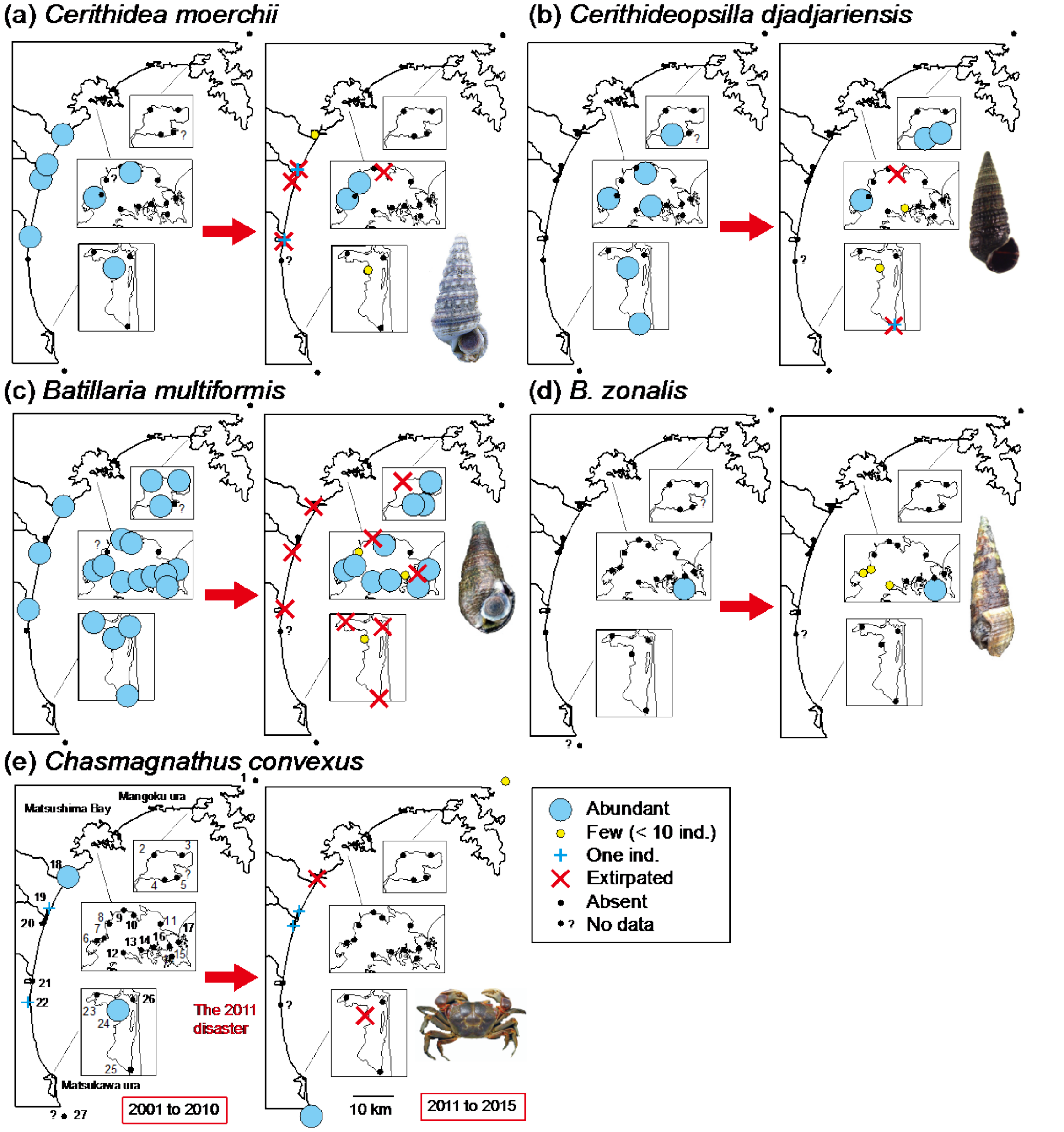

Fig. 2 Tsunami-induced changes in population sizes of the 5 endangered taxa in Tsuya River (38.766 N, 141.513 E), Samegawa River, and 25 tidalflats in Sendai Bay. [1] Tsuya R., [2] Sawada, [3] Urashuku, [4] Ohama, [5] Inodoshi, [6] Hitsuga ura, [7] Sokanzan, [8] Fukuura Is., [9] Nishinohama, [10] Zenigami, [11] Tona, [12] Katsura Is., [13] Nono Is., [14] Sabusawa Is., [15] Hatsutsu ura, [16] Otakamori, [17] Katsugiga ura, [18] Gamo, [19] Ido ura. [20] Hiro ura, [21] Torinoumi, [22] Ushibashi, [23] Obamahara, [24] Uda R., [25] Isobe, [26] Uno o, [27] Samegawa R

Table 2. List of endangered macrozoobenthos recorded in the Samegawa River estuary during the 2014-2015 survey

Taxa	Red list category MP [a]	MOE [b]	JAB [c]
Anthozoa			
Edwardsiidae sp.			DD
Synandwakia hozawai	NT		NT
Gastropoda			
Nozeba ziczac	CR+EN	NT	NT
Retusa insignis	NT		
Assiminea aff. *parasitologica*	NT	NT	NT
Angustassiminea castanea		NT	NT
An. yoshidayukioi	VU	NT	NT
Bivalvia			
Acharax japonica		VU	VU
Arthritica reikoae		DD	DD
Macoma contabulata		NT	NT
Ma. incongrua	NT		
Ma. praetexta		NT	NT
Moerella jedoensis		NT	NT
Mo. rutila	NT	NT	NT
Nitidotellina hokkaidoensis	NT	NT	NT
Soletellina boeddinghausi		CR+EN	CR+EN
Corbicula japonica		NT	NT
Nipponomysella subtruncata		NT	NT
Mya arenaria oonogai	NT	NT	NT
Solen strictus	NT		
Polychaeta			
Tylorrhynchus osawai	NT		NT
Chaetopterus cautus	NT		VU
Notomastus sp.	NT		NT
Echiura			
Arhynchite cf. *arhynchite*			DD
Sipuncula			
Sipunculus nudus			NT
Siphonosoma cumanense	NT		NT
Decapoda			
Chasmagnathus convexus	CR+EN		NT
Chiromantes haematocheir	NT		LP
Deiratonotus cristatus	NT		VU
Sestrostoma toriumii	VU		NT

[a] Miyagi Prefecture (http://www.pref.miyagi.jp/uploaded/attachment/207586.pdf), [b] Ministry of the Environment (https://www.env.go.jp/press/files/jp/20555.pdf, https://www.env.go.jp/press/files/jp/20556.pdf), [c] Japanese Association of Benthology (http://benthos-society.jp/red_list_benthos_20150623.pdf). Red list category: CR+EN, critically endangered or endangered; VU, vulnerable; NT, near threatened; DD, data deficient; LP, threatened local population.

Some of the endangered taxa rarely occurred at other tidal flats in northeastern Japan (Ministry of the Environment 2015; authors' unpubl. data), and the population size of *C. convexus* in the Samegawa River estuary was the largest among those in Fukushima and Miyagi prefectures (Fig. 2e). Since the ocean current flows northward (i.e., toward Sendai Bay; Higashi et al. 2015), macrozoobenthos in Samegawa River would be a significant source of planktonic larvae for the meta-population network in Sendai Bay

Impacts of restoration works on coastal biodiversity

Anthropogenic disturbances associated with ongoing restoration projects are now of increasing concern (Okoshi 2015; Kanaya et al. in press). We found that the tidal flat and marshes in the Samegawa River were damaged by construction of huge sea walls (Fig. 3a). Reed marsh habitat for *C. convexus* was intensively disturbed by the reconstruction of a floodgate (Fig. 3b). In the Tsuya River, habitat of *C. convexus* is also threatened by ongoing sea-wall construction (authors' pers. obs.). Along the Sendai Bay coast, huge sea walls (7.2 to 16 m high; Fig. 3c) are now being constructed at a broad spatial scale, leading to loss of the natural coastline in the area. Reclamation projects have also damaged the habitats of intertidal macrozoobenthos such as *B. multiformis* (Kanaya et al. in press). In Matsukawa-ura, construction of a flood wall devastated the local population of batillarid gastropods on the landward edges of the tidal flats. In this case, however, compensative creation of the tidal flat was done after the bank revetment (Fig. 3d), which may allow for future recolonization of macrozoobenthos after a certain period of time.

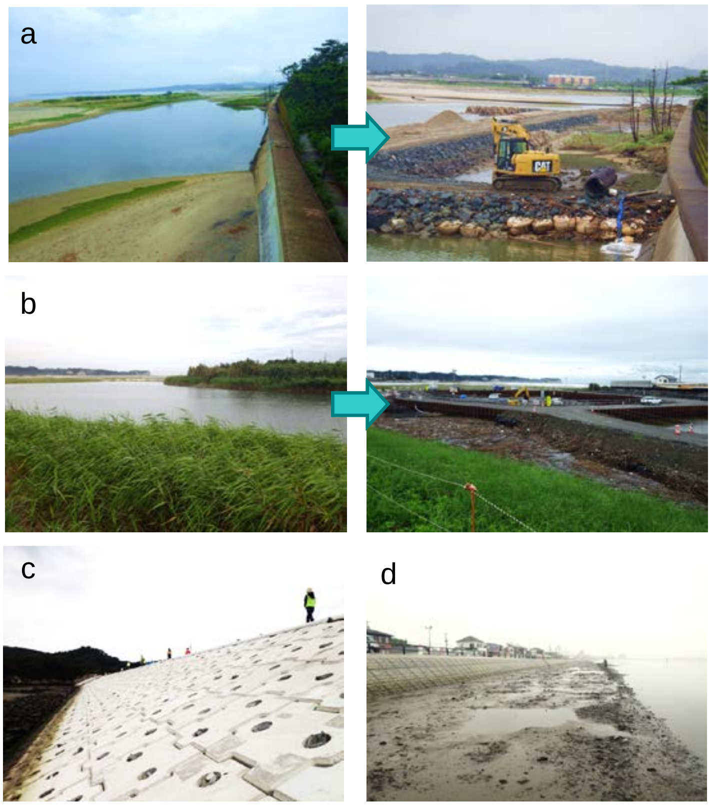

Fig. 3 Disturbance caused by restoration projects after the 2011 tsunami: (a) construction of sea wall on the tidal flat in the Samegawa River, (b) destruction of reed marsh by construction

of a floodgate in the Samegawa River, (c) huge sea wall (height; +6.4 m T.P.) in Hatsutsu ura, and (d) mitigation of tidal flat damage after construction of the bank revetment in Obamahara, Matsukawa ura .

Conclusions

Our surveys revealed disaster- and restoration-induced changes in tidal flat habitats along the northeastern Japanese coast. Endangered macrozoobenthos were extirpated at many tidal flats along Sendai Bay, but populations still remained in Matsushima Bay, Mangoku-ura Inlet, and at several other sites. These remnant populations are important source populations for future restoration of biodiversity. At present, ongoing restoration projects are becoming a threat to the coastal biotic community. Appropriate assessment and adaptive management are required for future restoration of coastal biodiversity in the tsunami-disturbed areas.

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