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The 2011 Tohoku Tsunami, Marine Ecosystem Dynamics, and the Re-establishment of Coastal Aquaculture Facilities in Onagawa Bay, Japan

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Abstract

For many towns and villages along the Pacific coast of northern Japan, also locally known as the "Sanriku Coast", fishing and aquaculture had been the primary industries. However, the 2011 Great East Japan Earthquake and tsunami devastated these communities, destroying most of fishing vessels, and severely damaged fishery related infrastructure including entire aquaculture installations. Reconstruction of coastal aquaculture facilities was therefore a pressing issue for many of the tsunami-affected areas. However, recent studies report, to a varying degree, negative effects of marine aquaculture operations on the surrounding environment. There are mainly two methods that are widely used for aquaculture operations along the Sanriku Coast. One is hanging culture using a long-line system to cultivate shellfish and edible ascidians. The other method is fish cages for farming finfish. In connection with aquaculture operations, benthic communities are often used as indicators of environmental health and trends in coastal marine ecosystems. This study thus reviews the general impacts of both fin and shellfish mariculture operations on the surrounding environment and considers the implications of the rehabilitation of coastal aquaculture facilities in Onagawa Bay for marine ecosystem dynamics following the 2011 Tohoku earthquake and tsunami with particular reference to the dynamics of benthic macrofaunal communities.

Introduction

On 11 March 2011, the Great East Japan Earthquake and subsequent tsunami severely damaged extensive areas of the Pacific coast of the Tohoku region in northern Japan. This region is locally known as the "Sanriku Coast", and offshore of the coast is lying the intersection of major warm and cold ocean currents, providing some of the most productive fishing grounds on earth. Many towns and villages in the Sanriku region are therefore renowned for its commercial fishing and aquaculture industry. Major ports, such as Onagawa, are locally famous for a variety of wild-caught and farmed seafood including flatfish, Pacific cod, salmon, shellfish and cultured ascidians. In Onagawa Bay alone, there used to be over 1200 long-lines for culturing scallops, oysters and edible ascidians as well as around 120 fish cages for farming salmonids. However, the 2011 earthquake and tsunami destroyed the entire aquaculture installations in the embayment. Rebuilding coastal aquaculture was therefore a pressing issue for many of the tsunami-affected coastal communities for the potential positive social and economic effects.

Recent studies, however, often demonstrate, to a varying degree, negative effects of marine aquaculture operations on the environment through changes in the physical, chemical and biological attributes of sediments below and the water column around aquaculture facilities (e.g., Tovar *et al*., 2000; Borja *et al*., 2009; Forchino *et al*., 2011; Sarà *et al*., 2011; Farmaki *et al*., 2014; Tomassetti *et al*., 2016). After the 2011 Tohoku disaster, both fin and shellfish aquaculture facilities have been steadily re-established in Onagawa Bay, mainly along low-energy coastal waters where organic material may readily accumulate, and questions regarding the potential effect of such rebuilding activities on coastal ecosystems have arisen.

This study first reviews change in the spatial coverage of fin and shellfish aquaculture facilities following the 2011 Tohoku earthquake and tsunami in Onagawa Bay. This is followed by a brief account of the general impacts of fin and shellfish aquaculture operations on the surrounding environment. Benthic communities have long been used as indicators of environmental health and trends in coastal marine ecosystems (Borja *et al*., 2009; Forchino *et al*., 2011; Tomassetti *et al*., 2016). Simple schematic representation is thus constructed to summarise the impacts of changes in multiple environmental factors on the recovery of coastal ecosystem based on a case study of benthic macrofaunal community dynamics in Onagawa Bay. This paper provides the implications of the rehabilitation of coastal aquaculture facilities for marine ecosystem dynamics following the 2011 Tohoku earthquake and tsunami with particular reference to the dynamics of benthic macrofaunal communities in Onagawa Bay.

Spatio-temporal change in fin and shellfish aquaculture facilities in Onagawa Bay

There are mainly two methods that are commonly used for aquaculture operations in Onagawa Bay. One is hanging culture using a long-line system in which cultured organisms such as oysters, scallops and edible ascidians are suspended on vertical ropes, typically down to around 15 to 20 m in depth below buoys floating on the surface. The other method is floating fish cages for farming salmonids, usually made of mesh framed with steel and/or plastic and with floating modules fixed along the cage boundaries.

Prior to the 2011 disaster, there were 1217 long-lines and 119 fish cages for aquaculture operations in Onagawa Bay. After the complete removal of the aquaculture facilities by the disaster, 135 long-lines and 56 fish cages were re-constructed by February 2012 (nearly a year later), which accounted for the recovery of 11.1% and 47.1%, respectively (Fujii *et al*., 2019). In March 2017, the number of the respective aquaculture facilities were recovered by 60.0% (730 long-lines) and 58.8% (70 fish cages), which corresponded to the total surface areas of 0.115 km^2 and 0.016 km^2, respectively (Fujii *et al*., 2019). This also reveals that the spatial extent of shellfish/ascidian culture covers 87.5% of the total area used for aquaculture operations, in comparison with finfish farms (12.5%), in Onagawa Bay.

Environmental impacts of finfish aquaculture

In coastal aquaculture, finfish farming normally requires a significant amount of feed and nutrients input into the ocean. This can change pelagic-benthic energy fluxes. Overfeeding often leads to excessive flux of organic matter onto the seafloor, potentially altering local sediment characteristics and benthic community composition (Crawford *et al*., 2003). Chemicals and excess nutrients from formulated feeds as well as feces associated with bio-deposition can therefore not only enrich sediments but even disturb and/or smother benthic communities dwelling below the associated farming facilities (Borja *et al*., 2009; Forchino *et al*., 2011; Tomassetti *et al*., 2016).

Recent studies also suggest that bio-deposits produced from finfish mariculture can disperse and spread through the water column and thereby affect benthic communities at a much broader spatial scale than the immediate vicinity of aquaculture facilities (up to several kilometres) (Borja *et al*., 2009; Yokoyama, 2010; Sarà *et al*., 2011).

Although the spatial extent of finfish farms is significantly smaller than that of shellfish culture in Onagawa Bay, the degree of environmental impact exerted by finfish farming is likely to depend primarily on environmental conditions such as: hydrography; average current speed; depth under farm facilities; distance to farm; sediment granulometry, as well as anthropogenic/operational factors such as: the size of the farm; the cultured species; years of production; annual production; type of feed; culture methods (Wu, 1995; Borja *et al*., 2009; Yokoyama, 2010; Forchino *et al*., 2011; Sarà *et al*., 2011; Tomassetti *et al*., 2016).

Environmental impacts of shellfish/ascidian aquaculture

Environmental effects of shellfish and ascidian aquaculture on seafloor may be somewhat different from those associated with finfish culture in cages (Weise *et al*., 2009). Cultured shellfish and ascidians feed entirely on naturally occurring phytoplankton in the water column. Consumed organic material and nutrients then return to the environment as feces or undigested waste, which falls onto the seafloor and may become important food source for benthic deposit feeders (Shumway *et al*., 2003; McKindsey *et al*., 2006). Shellfish/ascidian culture is generally considered to have less environmental impacts than finfish aquaculture because cultured organisms do not require any input of external feed or fertilizers and are grown at comparatively lower intensity (Shumway *et al*., 2003; McKindsey *et al*., 2006; Weise *et al*., 2009).

However, overstocking of these cultured organisms may deplete phytoplankton locally and affect the seafloor environment directly through their feeding activities (Crawford *et al*., 2003). Further, abrupt change in cultivation intensity may lead to an unbalanced ecosystem (Shumway *et al*., 2003). For example, in Ofunato Bay located on the Sanriku Coast, significant increase in phytoplankton biomass, which was followed by significant decrease in nutrients, was considered to be caused by the massive reduction in the number of shellfish mariculture rafts following the 2011 Tohoku earthquake and tsunami (Yamada *et al*., 2017).

Re-establishment of coastal aquaculture and ecosystem response in Onagawa Bay

Fujii *et al.* (2019) examined spatio-temporal dynamics of benthic macrofaunal communities in relation to changes in multiple environmental factors with particular reference to the rehabilitation process of coastal aquaculture facilities in Onagawa Bay, following the 2011 Tohoku earthquake and tsunami. They showed well-defined increases in macrofaunal abundance, biomass, and species diversity during the study period between 2012 and 2018 (Fujii *et al*., 2019). Comparison with the pre-tsunami data (2008-2011) also confirmed that the benthic macrofaunal community largely recovered over the duration of this period (Fujii *et al*., 2019). These community changes correlated significantly with a combination of both natural and anthropogenic factors, namely: (1) proximity to the nearest aquaculture facilities; (2) wind fetch length (exposure); (3) sediment grain size; (4) the total area of the aquaculture facilities (Fujii *et al*., 2019). These findings suggest: (a) the physical presence of aquaculture facilities has significant positive effects on benthic macrofaunal populations; (b) wind fetch length, as an indicator of exposure, significantly affects benthic macrofaunal communities; (c) changes in sediment granulometry significantly influence the dynamics

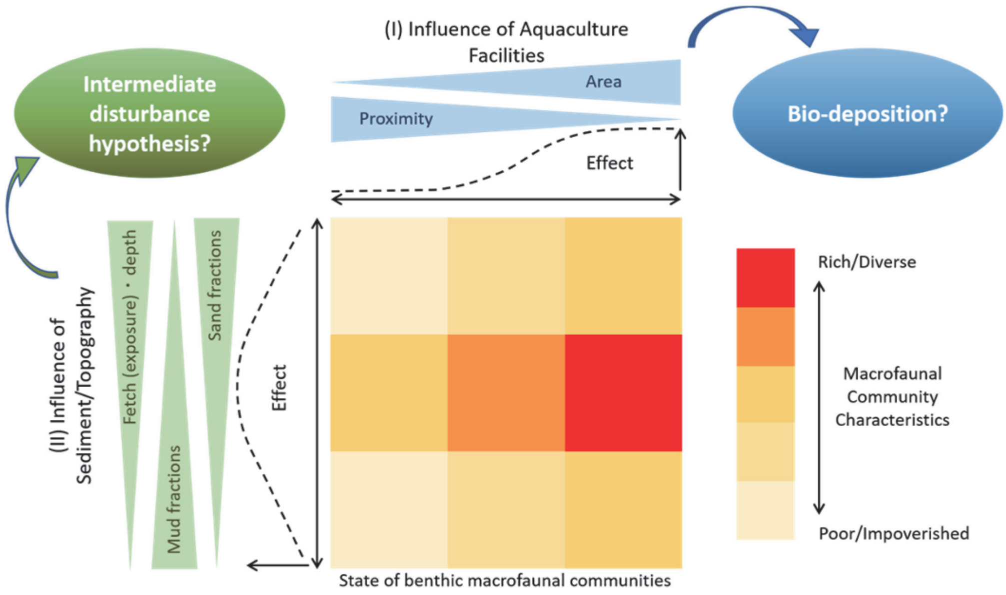

Fig. 1. Schematic representation of relations between benthic macrofaunal communities and key environmental variables illustrating their likely effects and possible mechanisms: (I) along a gradient of aquaculture facilities; (II) along a gradient of sediment/topography.

of macrofaunal community structure; (d) increasing extent of aquaculture facilities has significant positive effects on benthic macrofaunal populations (**Fig. 1**).

Before the 2011 disaster, the sand fractions were significantly higher at some locations in Onagawa Bay. However, the disaster brought anomalous deposition of mud across the whole bay following vigorous erosion and deposition of fine-grained sediments associated with a strong tsunami-induced current (Seike *et al*., 2016). Abrupt increase in fine-grained sediment could adversely affect benthic community through smothering and clogging feeding structures of suspension-feeders (Thrush *et al*., 2004). Spills of toxic chemicals (e.g., heavy oil) may also have exacerbated impacts on subtidal benthic communities immediately after the 2011 tsunami (Abe *et al*., 2015). However, the combination of local hydrodynamic processes and the flux of organic matter (bio-deposit) generated by the re-establishment of aquaculture operations in Onagawa Bay may have counteracted such negative impacts and thereby positively influenced the dynamics of benthic macrofaunal populations and fuelled benthic recovery (Fujii *et al*., 2019).

Conclusion

In Onagawa Bay, coastal aquaculture operations may well have played a significant role in shaping the occurrence and distribution patterns of benthic macrofauna and thereby influencing recovery of benthic community at an ecosystem-scale following even a catastrophic natural disaster such as the 2011 Tohoku earthquake and tsunami in Japan. To better understand the mechanisms of such marine ecosystem dynamics, there is a need for future research on how distribution of aquaculture operations relates to the physical, chemical and biological attributes of the surrounding water and sediments below and how other environmental parameters such as coastal topography and/or hydrodynamic processes interrelate benthic-pelagic dependencies across Onagawa Bay.

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