RESEARCH NOTE
DESTRUCTION OF POPULATIONS OF BATILLARIA ATTRAMENTARIA (CAENOGASTROPODA: BATILLARIIDAE) BY TSUNAMI WAVES OF THE 2011 TOHOKU EARTHQUAKE

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Strong wave action often leads to a natural disturbance of coastal organisms (Sousa, 1984; Underwood & Jernakoff, 1984; Gaylord, 1999). Tsunamis associated with large earthquakes are an extreme form of this type of natural disturbance (Chavanich et al., 2005; Sri-Aroon et al., 2006; Nakaoka et al., 2007; Lomovasky et al., 2011), damaging coastal organisms and changing the community structure of coastal ecosystems (Kendall et al., 2006; Prathep & Tantiprapas, 2006; Sanpanich, Wells & Chitravong, 2006; Nakaoka et al., 2007; Yanagisawa et al., 2009; Whanpetch et al., 2010; Lomovasky et al., 2011).

On 11 March 2011, an undersea earthquake off the coast of the Tohoku district created tsunami waves that hit the Pacific coastline of northeastern Japan. Tsunamis increase in height as they approach the shore, particularly in confined bays and estuaries (Didenikova & Pelinovsky, 2011). Consequently, large tsunami waves were observed across several bays in the Tohoku district (Mori et al., 2011; Tsuji et al., 2011).

A tsunami such as this would be expected to lead to a significant disturbance of the benthic communities within these bays. Evaluating the impact of tsunamis is often difficult because of a lack of ecological data prior to the disturbance. However around 5 years before the tsunami, we conducted an ecological survey of the Asian mud snail, Batillaria attramentaria. This is the most abundant macro-invertebrate in the intertidal mudflats of northeastern Japan and a representative species in the mudflat community, interacting with many other coastal organisms, such as sea anemones, hermit crabs, eelgrass and other snails (Wonham, O’Connor & Harley, 2005). Batillaria attramentaria exhibits direct development and limited dispersal, and thus forms a relatively closed local population (Kojima et al., 2004).

A tsunami is expected to severely damage the snail populations. However, other factors such as sporadic bloom of harmful algae, infectious disease and human pollution may also cause a rapid decline of marine molluscs (Johnson, 1968; Bryan et al., 1986; Johannesson, Johannesson & Lundgren, 1995). Unfortunately, we do not have baseline data immediately before the tsunami, obscuring the factor damaging the snail population. However, it is still possible to evaluate the effect of the tsunami by comparing the sites exposed to the tsunami with those sheltered from the tsunami. In this study, we compared the ecology of B. attramentaria before and after the tsunami at exposed and sheltered sites, with the aim of evaluating the impact of the tsunami on this ecologically important mudflat species.

Between April 2005 and March 2006, we studied snail density at five mudflat sites on the Pacific coastline of northeastern Japan (Nagazuraura, Mangokuura, Katsuigigaura, Torinomi and Matsukawaura, see Fig. 1). Of these sampling sites, Nagazuraura, Katsuigigaura and Torinomi were substantially affected by the 2011 tsunami, with most houses and infrastructure being destroyed. On the other hand, the sampling sites at Mangokuura and Matsukawaura were not strongly affected by the tsunami. There was also some damage in these sites by the tsunami, but it was much less than the damage at the above three sites. We used the random quadrat method to estimate the density of snails, counting the number of B. attramentaria within more than 20 quadrats (15 cm x 25 cm) at each sampling site. Snails found within the quadrats were transported back to the laboratory, where shell length (from the outer margin of the aperture to the apex of the shell) was measured. We conducted this survey every month throughout the sampling period. In April 2012, a year after the tsunami, we repeated this study on B. attramentaria populations, using the same method as in the 2005–2006 survey. However, as snail density was extremely low after the tsunami, it was necessary to search a wider area surrounding the sampling sites in each bay.

We used a general linear-mixed model to compare (1) mean density and (2) mean shell size of B. attramentaria before and after the tsunami. Since we had repeatedly investigated the density and size of the snails during the period 2005–2006, the sampling period was treated as a random effect. All statistical analyses were performed using JMP v. 9.0 (SAS Institute, Carey, NC, USA).

Snail density changed significantly after the tsunami. The previously abundant snails in the mudflat had disappeared at three sampling sites. Although there is a possibility of reduction of the snails due to factors other than the tsunami, our study strongly suggests that the tsunami is the main factor causing the population declines of the snails since the damage of the snail population was clearly associated with the impact of the tsunami.
snails at these sites disappeared because they were covered by sands, are now covered by sand transported by the tsunami.

After the tsunami, the mudflats were covered by numerous snails, whereas we found no snails in quadrats at Nagazuraura (F$_{1,256.7} = 38.9$, $P < 0.001$), Katsugigaura ($F_{1,279.3} = 24.9$, $P < 0.001$) or Torinoumi ($F_{1,336.5} = 23.6$, $P < 0.001$, see Fig. 2) after the tsunami. These sites, which were formerly tidal mudflats, are now covered by sand transported by the tsunami. Snails at these sites disappeared because they were covered by sand or swept away by the tsunami. However, after our extensive search around the sampling site at Nagazuraura, we found c. 50 live snails along a newly formed channel, c. 100 m away from the sampling site. The mean shell size was significantly smaller after the tsunami (Fig. 3, $F_{1,257} = 89.3$, $P < 0.001$). All of the snails had a young and intact shell, suggesting that they had been newly recruited, perhaps from a nearby region. The B. attramentaria population at Torinoumi, which had been large before the tsunami, was also markedly reduced. After a few hours of searching, we finally found c. 50 snails on the remains of reed bed (only the roots of the reeds remained in the ground). Unlike Nagazuraura, snails found in the reed bed were larger than before the tsunami (Fig. 3, $F_{1,304} = 9.1$, $P < 0.003$). Perhaps the wave impact had been dampened by the presence of the reeds and there had been a selective loss of the smaller and lighter snails. There was little evidence of new recruitment at Torinoumi, possibly because a large proportion of surviving snails there (>80%, O. Miura, unpublished data) were castrated by infection of trematode parasites. Furthermore, new colonisation from other populations is less likely to occur there in the short term, since Torinoumi is relatively isolated geographically from other Batillaria populations and B. attramentaria has limited dispersal ability (Kojima et al., 2004).

The snail population had also disappeared from the sampling site in Katsugigaura. However, we found a relatively large population (c. 5,000 snails) in a closed-off section of the bay, c. 100 m from the sampling site. The mean shell size after the tsunami was similar to that before (Fig. 3, $F_{1,345} = 1.8$, $P = 0.18$), suggesting that both large and small snails survived the tsunami in this bay. Although the tsunami had removed all snails from the sampling site, some could have been trapped in this closed-off section of the bay, which was sheltered by an adjacent hill and was close to the endpoint of the tsunami.

The tsunami did not strongly affect the sampling sites at Mangokura and Matsukawaura as these bays are surrounded by hills and/or sand bars and have relatively small entrances. However, severe land subsidence (60–80 cm) associated with the earthquake changed the landscape of Mangokura (Geographical Survey Institute of Japan, 2011) and the former sampling site was not now exposed, even at low tide. We searched for snails in the sea and found that their density was c. 40 times smaller compared with before the tsunami (Fig. 2, $F_{1,313.5} = 63.0$, $P < 0.001$). The shell size distribution also changed, with mean shell size after the tsunami being significantly larger than before (Fig. 3, $F_{1,350.9} = 107.0$, $P < 0.001$). Ninety-seven per cent of the snails collected had a breakage of the shell aperture (Fig. 4), possibly due to attack by crab predators; this proportion is significantly higher than that before the tsunami (0.8%) (df = 1, $n = 254$, $\chi^2 = 304.6$, $P < 0.001$). This suggests that B. attramentaria had been subjected to subtidal predation, and that only the snails with a large, thick shell survived after the land subsidence.
In contrast, land subsidence was far less severe at Matsukawaura (20–30 cm) (Geographical Survey Institute of Japan, 2011). Snails from the sampling site at Matsukawaura had a similar density before and after the tsunami (Fig. 2, \( F_{1,42.4} = 0.6, P = 0.43 \)). Although the mean shell size was slightly increased after the tsunami (\( F_{1,2056} = 14.1, P < 0.001 \)), the difference was not remarkable, compared with that at the other sites where the tsunami hit (Fig. 3). These results suggest that the tsunami did not affect the snail population at the sampling site in Matsukawaura. However, mudflats close to the outer portion of the bay (c. 2.5 km from the sampling site) were washed away by the tsunami (15–20 m runup height, see Mori et al., 2011) and snail populations had disappeared there.

In addition to \( B. \) attramentaria, we looked for the closely related species, \( B. \) multiformis (Kojima et al., 2001), which live in the same mudflat habitat (Adachi & Wada, 1998). Although we frequently observed \( B. \) multiformis during the 2005–2006 survey (unfortunately, we did not record the snail density), we found no \( B. \) multiformis at or around the sampling sites in Nagazur aura, Katsugigaura and Torinoumi, suggesting local extinction of this species within the bays as a result of the tsunami. As with \( B. \) attramentaria, we found populations of \( B. \) multiformis at the sampling sites in Mangokuura and Matsukawaura, which were sheltered from the tsunami.

The \( B. \) attramentaria population was thus severely damaged by the tsunami, with the impact of the tsunami varying amongst the bays. This is paralleled by a study of the effects of the 2004 tsunami on littorinid snails in Thailand (Sampanich et al., 2006). Factors such as the direction and size of the tsunami, the shape of the bay and the presence of natural barriers (e.g. sand bars and windbreak forests) and artificial barriers (concrete blocks) may affect the impact of the tsunami on coastal environments. We found that the tsunami did not significantly damage the snail population in the inner part of Matsukawaura, suggesting that other coastal organisms may also have survived here. This bay may act as a key refuge for co-occurring area. (*Fenus*, 57: 115–120).

**REFERENCES**


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