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Floristic variation of beach vegetation caused by the 2011 Tohoku-oki tsunami in northern Tohoku, Japan

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ABSTRACT

The infrequency of tsunamis results in a lack of knowledge regarding the impact they have on ecosystems. Comparison of the floristic composition before and after tsunamis using permanent plots is an effective approach to estimate the ecological impacts of tsunamis in coastal environments. Here, we report the floristic changes in beach vegetation in northern Tohoku, Japan caused by the 2011 Tohoku-oki tsunami. Among the beaches studied, we observed differences in the vegetative characteristics of the beach flora, whereas similarities were found in vegetation response patterns, particularly for herbaceous vegetation. No significant interaction was found between the overall number of vascular plant species or the number of non-beach species and the tsunami disturbance; conversely, on beaches that experienced relatively small impacts, the number of typical/characteristic beach species, Pielou evenness index values, and Shannon-Wiener diversity index values were significantly lower after the tsunami. Following the tsunami, the herbaceous vegetation species composition on all of the beaches was characterized by a few non-beach species that are known to tolerate strong anthropogenic disturbances; in contrast, the damage to shrub vegetation was lower than that to herbaceous vegetation. Our findings are similar to what was observed following the 2004 Indian Ocean tsunami in Thailand, suggesting that the initial response patterns of beach vegetation to tsunamis are similar, regardless of the affected climatic zone and species composition. Long-term field monitoring is needed to elucidate post-tsunami recovery, vegetation succession, and the ecological impact of the increase of non-beach species.

1. Introduction

Rises in sea level associated with global climate change (Klein and Nicholls, 1998) may increase the frequency of massive natural disasters in coastal environments. Among potential coastal hazards, tsunamis have an especially striking impact on coastal areas experiencing rising sea levels. On 11 March 2011, a mega-quake that measured 9.0 on the Richter scale occurred off of the Pacific coast of Japan. Its epicenter was located 130 km east of Sendai, Miyagi Prefecture (Fig. 1). Unfortunately, the massive earthquake generated devastating tsunamis, including the 2011 Tohoku-oki tsunami, which resulted in massive destruction of human communities from the Kanto to Tohoku regions of eastern Japan. The maximum wave run-up of the 2011 Tohoku-oki tsunami was estimated to be as high as 41 m above sea level (Nöggerath et al., 2011). At least six other destructive tsunami-generating earthquakes above magnitude 8.0 have occurred in the Tohoku region: in 869, 1611, 1793, 1896, 1933, and 1968 (Fujii and Koketsu, 2008; Kanamori, 1977).

Although it is important to reconstruct social infrastructure rapidly after a catastrophe, restoration of local natural resources should carefully consider biodiversity and ecosystem functions (Sumi and Takemon, 2011). In October 2010, the Aichi Biodiversity Targets for biodiversity conservation and mitigation of the impacts of global environmental change were proposed at the 10th meeting of the Conference of the Parties to the Convention on Biological Diversity in Nagoya, Aichi Prefecture, Japan (http://www.cbd.int/sp/).

Although the importance of ecological risk assessment for natural coastal hazards is widely recognized (e.g., Clark, 1996; Gedan et al., 2011; Moksness et al., 2009), our knowledge of the

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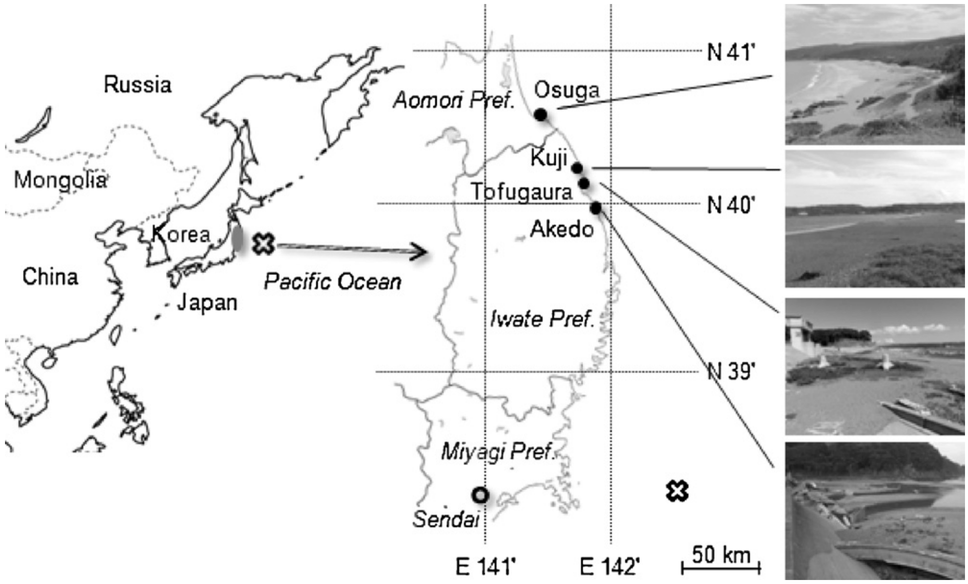

Fig. 1. Study beach locations and their appearance after the 2011 Tohoku-oki tsunami. The cross indicates the epicenter of the 2011 Tohoku earthquake. Detailed characteristics and degrees of impact of the tsunami on each study beach are shown in Table 1.

ecological impacts of tsunamis on coastal ecosystems (Dahdouh-Guebas and Koedam, 2006; Kaplan et al., 2009; Roemer et al., 2010), particularly from field-based data (Hayasaka et al., 2009, 2012a; Lomovasky et al., 2011), is lacking because of the infrequency of the occurrence of tsunamis. The floristic structure and species composition are the important bio-indicators for estimating the impact of disturbances on ecosystems. Here we report the floristic changes of beach vegetation caused by the 2011 Tohoku-oki tsunami with the aim of elucidating the natural resilience mechanisms of coastal ecosystems after a tsunami disturbance. Because we were studying beach vegetation in Tohoku region prior to the tsunami, we were able to monitor beach vegetation both before and after the tsunami.

2. Materials and methods

2.1. Study area

In August 2011, surveys of beach vegetation were conducted on four relatively flat, sandy beaches from northern Iwate to southern Aomori Prefecture (Fig. 1, Table 1). However, we were unable to survey beaches that disappeared due to ground sinking associated with the huge earthquake. At Osuga, there are no beach protection structures, such as revetments or wave-dissipating blocks, and this area therefore remains in a natural condition. Tofugaura and Akedo beaches, which were subjected to a wave height of more than 20 m, were severely damaged, including the fracturing and collapse of protective structures as a result of the tsunami (Table 1). Revetments at Kuji, which experienced a wave height of approximately 14 m, were not damaged by the tsunami.

The bioclimatic characteristics of the studied areas were determined by Kira's warmth index (WI; Kira, 1977). WI is calculated on the basis of meteorological records by applying the following formula:

$$\mathrm{WI} = \sum (t - 5)$$

where t is the mean monthly temperature above 5 °C. All of the study sites were within the cool-temperate bioclimatic zone, which is classified as having a WI of 45–85 °C; see Kira (1977) for the WI values of the other bioclimatic types. The climatic conditions of the study areas, based on meteorological data collected from 2000 to 2010 (http://www.data.jma.go.jp/obd/stats/etrn/index.php), were relatively similar, with mean annual temperatures of 9.5–10.4 °C, WI values of 72.3–81.3 °C, and mean annual rainfall of 1078–1494 mm.

2.2. Survey methods

The composition of the beach vegetation on each study beach was surveyed in the same plots using the same plot sizes studied by Hayasaka (unpublished data) in August 2003 in accordance with the methodology of Braun-Blanquet (1964) (field relevé; with separate sampling of the tree, shrub, and herbaceous layers in spatially homogeneous vegetation). The study plots were selected based on vegetation zones (i.e., herbaceous vegetation and shrub vegetation) from the shoreline to inland areas; however arboreal vegetation, such as *Pinus thunbergii* plantation, was excluded from the study. Plots were located using a GPS receiver. We surveyed additional plots if vegetation had colonized a site that contained no vegetation prior to the tsunami. Thus, one survey was conducted before the tsunami in August 2003 (approximately 8 years before the tsunami), and a second survey was conducted in August 2011, 5 months after the tsunami. The numbers of field relevés investigated at the four study beaches before and after the tsunami were 96 and 83, respectively, ranging in size from 1 m^2 (herbaceous vegetation) to 6 m^2 (shrub vegetation) (see Table 2 for the number of relevés for each study beach between the pre- and post-tsunami surveys). The numbers of relevés for herbaceous vegetation and shrub vegetation before the tsunami were 87 and 9, respectively, while the numbers after the tsunami were 74 and 9, respectively. The nomenclature used follows Ohashi et al. (2008). We distinguished non-beach species from beach species based on the primary habitat of each species taken from descriptions of the ranges of wild plants in Japan (Ohashi et al., 2008).

2.3. Data analysis

To test the interaction between the tsunami and the characteristics of beach flora on the studied beaches, we conducted a two-factor factorial ANOVA. Then, Welch's t-tests were used to