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Temporal change of eelgrass *Zostera marina* bed in Matsukawa-ura Lagoon, Fukushima Prefecture

Akira MATSUMOTO[1)]*, Kaoru NARITA[1)], Tsuneo FUJITA[1)],
Tatsuma SATO[2)], Ikuo MATSUMOTO[2)] and Toshihiro WADA[3)]

Abstract: This study estimated the area of eelgrass beds in Matsukawa-ura Lagoon and investigated spatiotemporal changes of the area using satellite images obtained after the 2011 off the Pacific coast of Tohoku Earthquake. Furthermore, we examined the spatial distribution of mud contents in the lagoon after the earthquake. In April 2012, the eelgrass beds were observed in small area (0.013 km^2) of the northern part of the lagoon. Almost all eelgrass was physically removed by devastating tsunami waves. In September 2014, the bed area had increased sharply to approximately 0.39 km^2. The spatial distribution also expanded from the northern to the central lagoon. In November 2015, the rate of increase was only approximately 10% compared with the previous year. No remarkable change was found in the spatial distribution. The mud content was 0–79%, the eelgrass bed was observed in the area where the mud contents were less than 30%. The eelgrass bed area in 2015 was roughly twice that in 2010. Eelgrass beds had expanded to the upper edge of the waterway after the earthquake. The subtidal zone, which is suitable for eelgrass growth, expanded because of ground subsidence.

Keywords : *Matsukawa-ura Lagoon, Zostera marina, Tsunami, Subsidence*

1. Introduction

Matsukawa-ura Lagoon, a shallow brackish lagoon located in northeastern Fukushima prefecture, communicates with the Pacific Ocean at the northern entrance of the lagoon (Fig. 1). Matsukawa-ura Lagoon has a 23-km circumference and surface area of 5.9 km^2. Before the 2011 off the Pacific coast of Tohoku Earthquake (hereinafter, *the earthquake*), approximately 70% of the surface area (5.9 km^2) was dry at low tide, forming a tidal flat (GEOSPATIAL INFORMATION AUTHORITY OF JAPAN, 2011). Actually, Matsukawa-ura Lagoon is a major fishing ground for Manila clams (SATO *et al*., 2007). During 1910–1970, artificial seeding of the edible red alga *Porphyra tenera*, made the area a major fishery that supplied other "nori" seaweed production areas throughout Japan (IWASAKI and MATSUDAIRA, 1954). Because of environmental changes occurring from 1971 spurred by waterway dredging

1) Fukushima Prefectural Fisheries Experimental Station Soma Branch, Soma, Fukushima 976–0022, Japan
2) Fukushima Prefectural Inland Water Fisheries Experimental Station, Inawashiro, Fukushima 969–3283, Japan
3) Institute of Environmental Radioactivity, Fukushima University, Fukushima 960–1296, Japan
*Corresponding author:
E-mail: mattun_s15@yahoo.co.jp

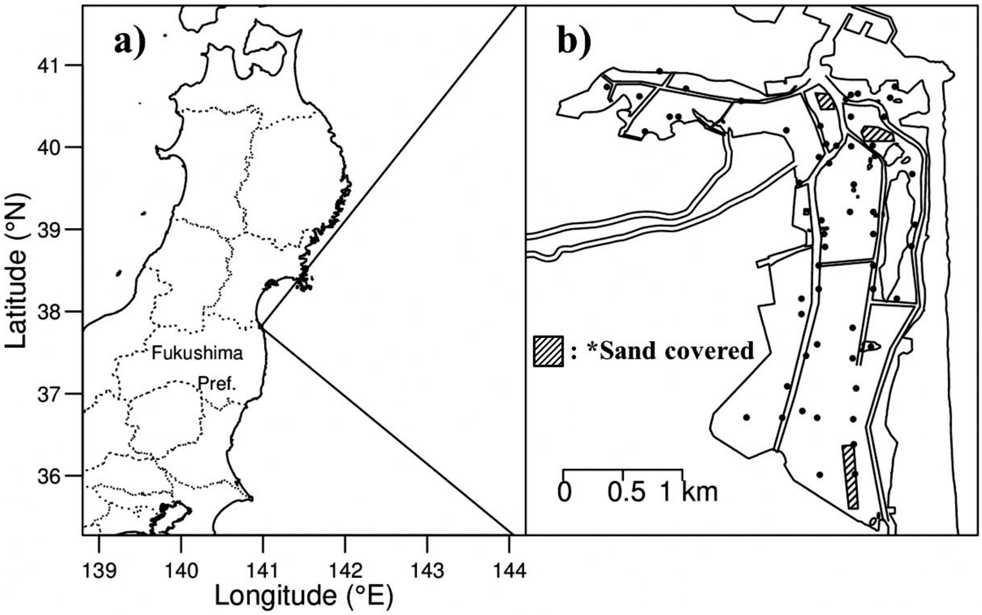

Fig. 1 Map of the study area in Matsukawa-ura Lagoon, Fukushima Prefecture: a) Map of Tohoku, Japan; and b) Map of Matsukawa-ura Lagoon, Fukushima Prefecture and 60 stations of sediment sampling. *Sand-covered during 2012–2013.

operations from the entrance to the inside of the lagoon (YANAI and OWADA, 1976), Matsukawa-ura fishery changed from artificial seeding of *Porphyra tenera* to *Monostroma nitidum* culture (ONO *et al.*, 1972). In the northeastern part of the lagoon, the eelgrass bed was formed before the earthquake (GEOSPATIAL INFORMATION AUTHORITY OF JAPAN, 2011). The eelgrass *Zostera marina* stretches its rhizomes and roots to the sandy bottom. The leaf length reaches 1 m or more. These rhizomes or roots of the eelgrass have sometimes disturbed the Manila clam fishery. Therefore, the excess eelgrass near the fishing ground was sometimes thinned out by fisherman before the earthquake. Nevertheless, the eelgrass bed generally plays important ecological roles by attaching diatoms as a primary producer to their leaves (DUFFY *et al.*, 2015). It is widely known to be a nursery ground for various juvenile fish including commercial fish species (e.g., KIKUCHI and PERES, 1977). In addition, in recent years, growth-inhibiting bacteria have been found from eelgrass possessing strong activity against the toxic dinoflagellate *Alexandrium tamarense* and red tide raphidophytes *Chattonella antiqua* and *Heterosigma akashiwo* (ONISHI *et al.*, 2014; IMAI *et al.*, 2016). The earthquake's consequent tsunami temporarily removed many eelgrass beds from Miyako Bay, Iwate Prefecture and Matsushima Bay, Miyagi Prefecture, not only Matsukawa-ura Lagoon (SAKAMAKI and NISHIMURA, 2014; SAKAMAKI *et al.*, 2016; OKADA and FURUKAWA, 2013; SASA *et al.*, 2012; KOMATSU *et al.*, 2015). After the tsunami, recovery trends were observed for some eelgrass beds (SASAKI *et al.*, 2016; MURAOKA *et al.*, 2016). As in these eelgrass beds, the recovery trend was also apparent in the Matsukawa-ura Lagoon. In fact, the recovery reportedly interfered with the Matsukawa-ura fishery. Considering the fishery and ecosystem comprehensively, the eelgrass bed in Matsukawa-ura Lagoon might exert a particularly useful function. Nevertheless, no report describes a study showing the spatial distribution of eelgrass beds in the lagoon after the tsunami. Examination of the spatiotemporal changes of eelgrass beds after the tsunami must therefore be conducted. As described herein, we estimated the eelgrass bed area and examined spatiotemporal changes of the lagoon area using Google Earth satellite images obtained after the earthquake. Furthermore, we investigated factors determining the distribution of eelgrass beds in the lagoon.

2. Materials and methods

Estimation of area of eelgrass beds using satellite imagery

For this study, we used Google Earth satellite images showing Matsukawa-ura Lagoon taken in April 2012, September 2014, and November 2015. We used Google Earth Pro (Ver. 7.1.5.1557) to identify eelgrass *Zostera marina* based on the color tone of the imagery. Matsukawa-ura Lagoon was shallow (approximately 1.5 m) enough that the edge of eelgrass bed (black) could be distinguished from sandy bottom (light brown) as well as Waquoit Bay, Massachusetts (SHORT and BURDICK, 1996). The outer edge of the identified eelgrass was traced to ascertain its exact latitude and longitude. Each eelgrass area was estimated to 0.1 m^2 based on the latitude and longitude using R statistical software (Ver. 3.3.2, R DEVELOPMENT CORE TEAM, 2016) and a geosphere software package (ver 1.5–5, HIJMANS, 2016). The areas (km^2) of all eelgrass beds were found every year. In addition, we examined the temporal change of the spatial distribution of the eelgrass bed. Furthermore, we estimated the area of eelgrass bed before the earthquake using GIS data obtained from the acoustic and aircraft surveys conducted in 2010 (GEOSPATIAL INFORMATION AUTHORITY OF JAPAN, 2011). Thereby, we were able to compare eelgrass areas before and after the earthquake.

Sediment sampling and determination of mud content

Using an Ekman-Birge sampler, we collected surface sediment samples (approximately 3 cm) from 60 sites around Matsukawa-ura Lagoon in July every year from 2012 through 2015 (Fig. 1b). The particle-size distribution of sediments was measured using laser diffraction/scattering particle-size analyzers (SALD–3100; Shimadzu Corp.). The mud content was calculated from the percentage of the particle size less than 0.063 mm in the particle-size distribution. The spatial distribution of mud contents was examined using spline interpolation using statistical software R (Ver. 3.3.2, R DEVELOPMENT CORE TEAM, 2016) and the akima package (ver 0.6–2, AKIMA and GEBHARDT, 2016). The relation between the spatial distribution of mud content and that of eelgrass was investigated. Furthermore, we compared the spatial distribution of mud contents in our sediment samples after the earthquake and that of distribution surveyed in 2010 (GEOSPATIAL INFORMATION AUTHORITY OF JAPAN, 2011).

3. Results and discussion

Spatiotemporal distribution of eelgrass bed and mud contents

In April 2012, the eelgrass bed was found in the northern part of the Matsukawa-ura Lagoon. Its area was as small as 0.013 km^2 (Fig. 2a). Approximately two years later in September 2014, the area had increased sharply by approximately 30 times (0.39 km^2). The spatial distribution also expanded from the northern part to the center of the lagoon (Fig. 2b). In November 2015,

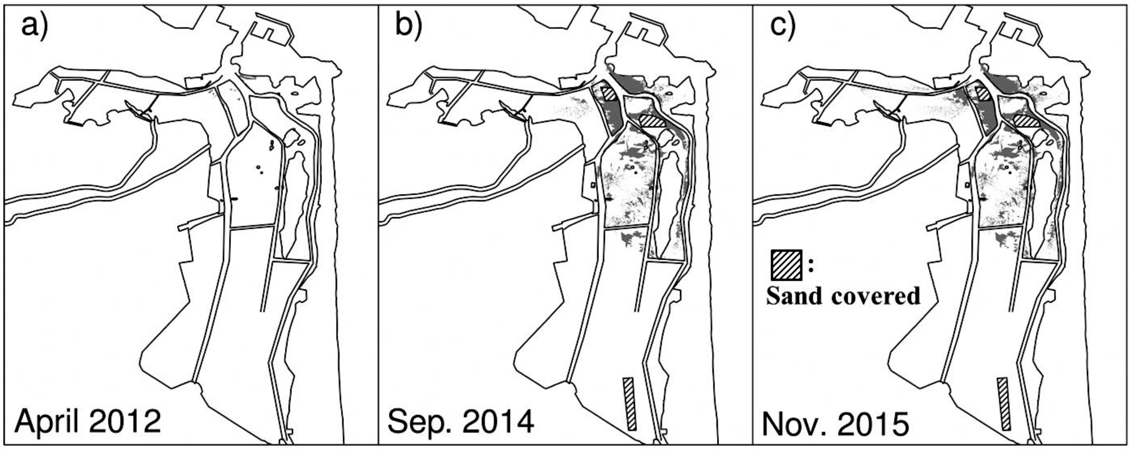

Fig. 2 Spatiotemporal change of eelgrass bed (km^2) in Matsukawa-ura Lagoon during 2012–2015: a) April 2012, b) Sep. 2014, and c) Nov. 2015.

the increase of the area was only approximately 10% compared with that of the previous year. No remarkable change was found in the spatial distribution (Fig. 2c). In the lagoon as well as other coastal areas (personal communication), the leaf length and shoot density of eelgrass were highest in summer and lowest in winter. Moreover, other types of seaweed grow in winter. Therefore, to minimize underestimation and overestimation, we specifically examined September and November (2014 and 2015, respectively) in this study, when the eelgrass grew and when no other algae were observed. The eelgrass bed area before the earthquake was estimated as approximately 0.22 km^2 from the survey conducted by Geospatial Information Authority of Japan in 2010. The area after the earthquake (in 2012) was estimated as approximately 0.013 km^2, which was remarkably lower than the area before the earthquake. The devastating tsunami following the earthquake destroyed the sandbar facing the Pacific Ocean in the eastern part of the lagoon (NISHI *et al.*, 2012). From the eelgrass area in April 2012, almost all eelgrass beds had been physically removed by the devastating tsunami. Some effects such as construction activity might have been used to restore the sandbar. In other coastal areas, it had been reported that much of the eelgrass beds had been removed from the bottom by tsunami wave action (WHANPETCH *et al.*, 2010; MURAOKA *et al.*, 2016; NAKAOKA *et al.*, 2017). Although it was suggested that almost all the eelgrass plants in Matsukawa-ura Lagoon had been removed from the bottom by the tsunami, a few eelgrass plants had remained in the northern part of the lagoon in 2012 (Fig. 2a). The little remaining eelgrass was also observed visually in another study (ABE *et al.*, 2017). In that study, the area of eelgrass bed reportedly expanded to roughly twice its area of 2010 during the subsequent three years. In addition, the northern and central part of the lagoon into which the eelgrass bed had expanded are major fishing grounds for Manila clams (SATO *et al.*, 2007). Therefore, some concern arose that the rhizomes or roots of the eelgrass might disturb the Manila clam fishery. However, ABE *et al.* (2017) reported that the little remaining eelgrass might serve as refuges for the clams because of their function as a natural barrier resist-

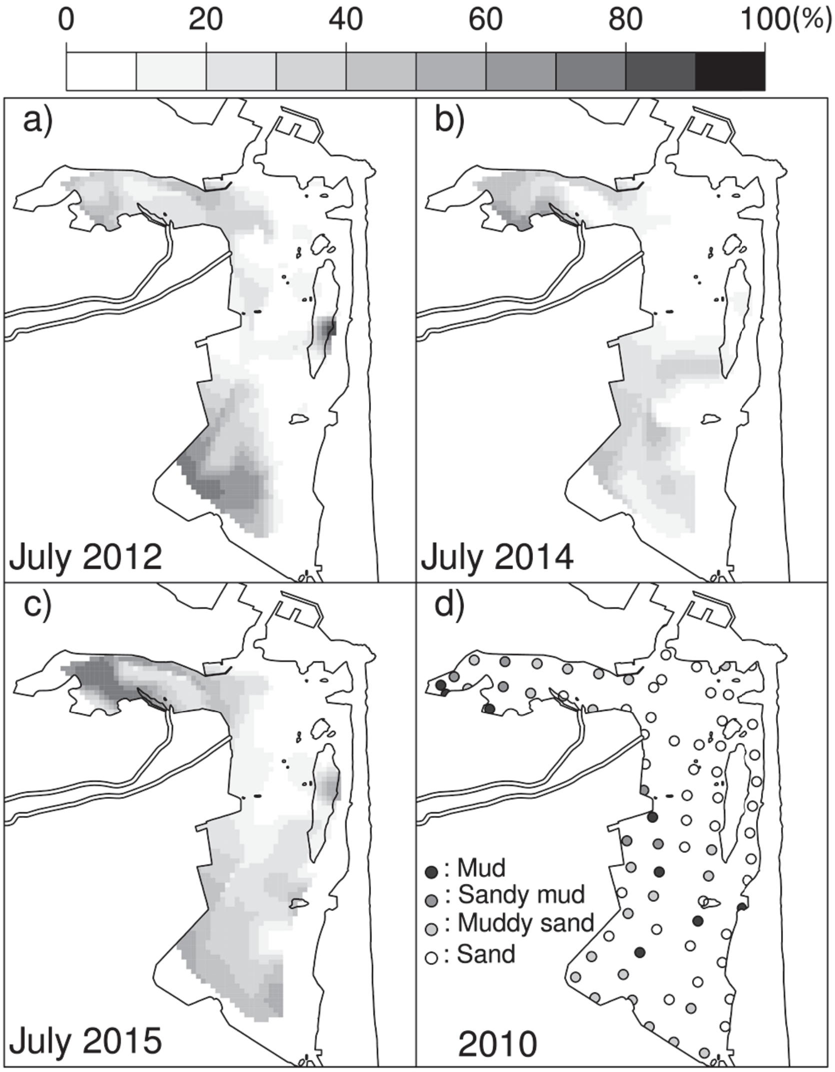

Fig. 3 Temporal change of spatial distribution of mud content (%) in Matsukawa-ura Lagoon during 2012–2015 and sediment distribution in 2010: a) July 2012, b) July 2014, c) July 2015, and d) 2010.

ing the tsunami waves. Therefore, the possibility exists that the eelgrass was beneficial for the recovery of clams and the entire ecosystem in the lagoon after the tsunami. Although eelgrass beds in other prefectures that had reportedly disappeared because of the tsunami had also started to recover (MURAOKA *et al*., 2016), no report of any other study describes eelgrass beds that had increased beyond the pre-tsunami area.

The spatial distribution and the temporal change of mud contents are depicted in Fig. 3. In July 2012, the mud content was low (0–17.1%) in the northern and the central parts of the lagoon. However, the mud contents were high (76.4%) in the southern area of the lagoon (Fig. 3a). During 2014–2015, the spatial distribution of high mud contents was shifted from the south to the west of the lagoon (Figs. 3b, 3c). In 2015, maximum mud contents (79.0%) were observed in the western part of the lagoon (Fig. 3c). Low mud contents (less than 30%) were observed in the central part of the lagoon in all years. Comparison showed that the spatial distribution of high and low mud contents in the south and west of the lagoon in 2012 differed from that in 2010 (Figs. 3a and 3d, GEOSPATIAL INFORMATION AUTHORITY OF JAPAN, 2011). Nevertheless, no clear difference was apparent between the spatial distribution, which was high in the western lagoon in 2015 and that in 2010 (Figs. 3c and 3d, GEOSPATIAL INFORMATION AUTHORITY OF JAPAN, 2011): The high and low mud contents observed in the southern and western areas of the lagoon in 2012 might be attributable to the tsunami. After the tsunami, the supply of particles of different particle sizes from Koizumi-gawa River, Udagawa River, and Ume-kawa River (ARITA *et al*., 2014) suggest that the spatial distribution of mud contents might have returned to the state that prevailed in 2010, before the tsunami.

Factors controlling the eelgrass bed distribution

Comparison between the eelgrass bed distribution in 2015 (Fig. 2c) and that of mud contents the same year (Fig. 3c) shows that the eelgrass bed was observed in the northern and central parts of the lagoon, where the mud contents were less than 30%. Four important factors control eelgrass growth (Table 1). Generally, previous reports demonstrate that mud contents of less than 30% are suitable for eelgrass bed formation (Table 1, FISHERIES AGENCY OF JAPAN and MARINO-FORUM 21, 2007). Therefore, the current distribution of the eelgrass bed in the lagoon was apparently also regulated by mud contents in our study. As described in the previous section, although the spatial distribution of mud contents had reverted to that in 2010 (Fig. 3d), the eelgrass bed area had expanded to roughly twice that of 2010 in the following three years (Figs. 2, 4). In other words, the spatial distribution of the eelgrass bed before the earthquake would be regulated by some factor different from the mud contents. The change in the spatial distribution of eelgrass bed after the earthquake is portrayed in Fig. 4. Apparently, the eelgrass bed after the earthquake had expanded to shallow areas such as the upper edge of waterway which dried out at low tide before the earthquake, with no expansion to the center of the waterway (Figs. 4b and 4d). YANAI and OWADA (1976) observed bottom water velocity with consideration of the waterway topography. Reportedly, the water velocity increased from the shallow area (upper edge) to the deepest area (center) of the waterway (Fig. 4a), where it exceeded 0.6 m/s (YANAI and OWADA, 1976). Generally, earlier reports describe that water velocity of less than 0.6 m/s is suitable for eelgrass bed formation (Table 1, MORITA and TAKESHITA, 2003). Accordingly, the center of the waterway was thought to be unsuitable for the eelgrass bed formation. Although the water velocity in upper edge of the waterway is slow (YANAI and OWADA, 1976), the eelgrass bed formation might be inhibited because of drying at low tide in these shallow areas (intertidal zone) before the earthquake (Fig. 4c,

Table 1. Eelgrass growth conditions*

Environmental condition	Threshold value
(1) Mud content	less than 30%
(2) Water velocity	less than 0.6 m/s.
(3) Shields parameter	less than 0.2
(4) Depth	1–2 m (not dried out)

(*MORITA and TAKESHITA, 2003; FISHERIES AGENCY OF JAPAN and MARINO-FORUM 21, 2007)

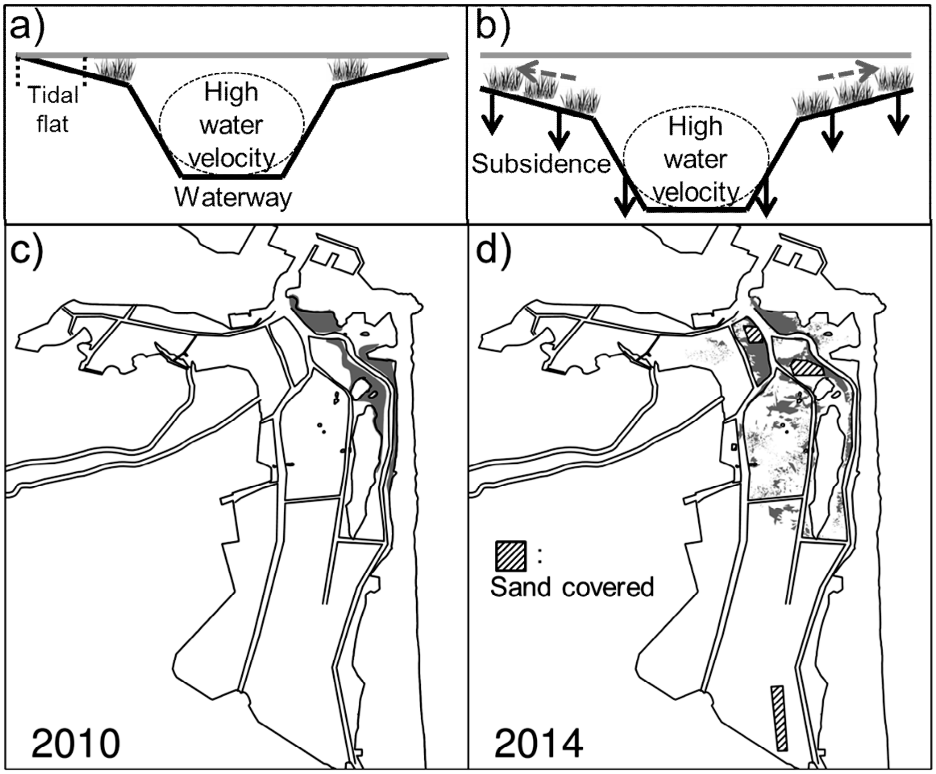

Fig. 4 Schematic diagram of the change in the spatial distribution of eelgrass bed (areas filled in gray) caused by land subsidence after the earthquake in Matsukawa-ura Lagoon: a) vertical and c) horizontal distributions of eelgrass before the earthquake (2010); b) vertical and d) horizontal distributions of eelgrass after land subsidence caused by the earthquake.

Table 1, Geospatial Information Authority of Japan, 2011). However, the eelgrass bed expanded to these shallow areas after the earthquake (Fig. 4d). Change from intertidal to subtidal zone because of subsidence in these shallow areas might be regarded as a main factor of the eelgrass bed expansion in the lagoon. Ground subsidence on the Oshika Peninsula in Miyagi Prefecture and Ofunato Bay in Iwate Prefecture were reported to be approximately 100 cm and 75 cm respectively; with other remarkable results also on the Sanriku coast (Geospatial Information Authority of Japan, 2017). In addition, subsidence of approximately 30 cm was reported in Soma City, Fukushima Prefecture (Geospatial Information Authority of Japan, 2017), where the lagoon depth also became several tens of centimeters deeper in 2011 (Hidaka *et al.*, 2012). However, dredging operations were conducted during 2012–2013 in the waterway, where sand had been deposited by the tsunami. The dredged sand covered an area that had been part of the clam fishery ground before the tsunami (Fig. 1b). These areas dried out at low tide after the sand coverage, and eelgrass did not grow (Figs. 2b, 2c). As explained above, the relief of growth inhibition with the increase of water depth because of subsidence might have contributed to the rapid eelgrass bed expansion in the shallow area which sand had not covered.

4. Implications for the future eelgrass bed distribution

Much of the eelgrass bed in the Andaman Sea coast of Thailand was affected heavily by the tsunami following the earthquake in 2004 (WHANPETCH *et al.*, 2010). In Mangoku-ura Bay, located approximately 80 km north-northeast of Matsukawa-ura Lagoon, although the eelgrass bed was not heavily affected by the tsunami following the 2011 off the Pacific coast of Tohoku Earthquake, the eelgrass bed decreased in later years (MURAOKA *et al.*, 2016; NAKAOKA *et al.*, 2017; SHOJI and MORIMOTO, 2016). As negative effects of approximately 0.8 m of subsidence and low water transparency, the decrease mentioned above might derive from the low light penetration (NAKAOKA *et al.*, 2017; SHOJI and MORIMOTO, 2016). In contrast to other coastal areas including Mangoku-ura Bay, the eelgrass bed expansion observed in our study was thought to be the result of the positive effect of the increase in water depth associated with the subsidence. However, the subsided ground has been returning gradually around the lagoon as well as in other coastal areas of Sanriku (GEOSPATIAL INFORMATION AUTHORITY OF JAPAN, 2017). In the future, if the ground and water depth in the lagoon were to return to their levels before the earthquake, then the growth inhibition of eelgrass attributable to the drying would occur again (Table 1–4). In other words, the area of eelgrass bed and the distribution would be reduced to the pre-earthquake scale. Given the fact that the eelgrass bed had not increased substantially during 2014–2015 (Fig. 2) and the fact that the spatial distribution of mud content had returned to that in 2010 (Fig. 3), the eelgrass bed in the lagoon would not expand further in the future.

In the coastal ecosystem, eelgrass is a fundamentally important species that provides important ecosystem services. However, coastal development and climate change cause the global loss of eelgrass beds; protection and management approaches are necessary to protect them from further losses (WAYCOTT *et al.*, 2009). Although eelgrass restoration programs have been launched in many countries (ORTH *et al.*, 2006), restoration success with recovery of nursery function of eelgrass is less than 30% (VAN KATWIJK *et al.*, 2015). Results of the present study show that the expansion of upper edge of subtidal zone might be crucially important for eelgrass bed expansion in the lagoon, although we did not clarify the recovery of the above nursery function of eelgrass beds in this study. In addition, current eelgrass beds in the lagoon are likely to decrease in the future. Accordingly, it is necessary to monitor the eelgrass beds and their growth conditions in Matsukawa-ura Lagoon continuously.

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