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Assessment and future prediction of climate change impacts on the macroalgal bed ecosystem and cultivation in the Seto Inland Sea

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Abstract: Macroalgal bed ecosystems are an important platform for coastal biological production and fisheries. After the late 1990s, rapid decline or disappearance of macroalgal beds, generally called *Iso-yake*, has been spreading along the coast of western Japan where there is an influence of warm ocean currents. This phenomenon has been occurring with an increasing trend in water temperature in recent decades and is considered to be an impact of the climate change.

The Seto Inland Sea is the largest semi-enclosed sea area in Japan, and macroalgal beds in the area are still intact with no prominent sign of *Iso-yake*. However, water temperature in the Seto Inland Sea has also been increasing for a few decades, and according to climate change scenarios, negative impacts to macroalgal beds and their ecological functions are possible in the future in the area. Against this background of concern, we conducted research on the assessment and future prediction of climate change impacts on the macroalgal bed ecosystem in the Seto Inland Sea and associated sea areas. The research consisted of 1) field monitoring of macroalgal beds and associated spatio-temporal variation in water temperature, including along the coast of Kyushu (Nagasaki) where loss or changes of macroalgal beds has created a large social problem; 2) experiments on physiology and behavior of key species in macroalgal bed ecosystems (macroalgae and herbivorous fish) with respect to temperature and other conditions to understand the mechanisms of the ecosystem shift; 3) construction of an original physical model to reproduce past temperatures in the environment and predict future ones in the applicable ocean areas; and 4) interpreting the impact of future water temperature conditions predicted by the model on macroalgal beds. In addition, impacts on macroalgal cultivation, which is an important industry in the Seto Inland Sea, were also assessed. In this paper, some of the main results and conclusions are introduced.

Key words: macroalgal bed, macroalgal cultivation, climate change, Seto Inland Sea

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Introduction

Macroalgal bed ecosystems offer various ecosystem services, which substantially contribute to human welfare. Among the services provided by the macroalgal beds, their contributions as nursery grounds, habitats and actual fishery grounds of commercially important fishes and shellfishes are significantly important in Japan.

However, rapid disappearance of macroalgal beds and subsequent desertification of the seafloor, which is a phenomenon generally called '*Iso-yake*', has been spreading along the Japanese coast (Fisheries Agency, 2007). In particular, along the coast of western Japan (that is, central Honshu, Shikoku and Kyushu coastal areas facing the Pacific Ocean and East China Sea), where the warm currents *Kuroshio* and *Tsushima-danryu* flow offshore, nearly 20 % of the macroalgal beds have already been lost since the early 1990s when a nationwide research of macroalgal bed distribution was conducted (Akimoto and Matsumura, 2010). Most of the lost beds were constituted by warm-temperate kelp, mainly macroalgae belonging to the genus *Ecklonia*, and macroalgae belonging to Family Sargassaceae, which were the most important foundation species along temperate rocky shores in Japan. As a result, production of fisheries resources that rely on these beds (such as abalones) has been decreasing tremendously in those regions (Serisawa *et al*., 2004).

Increasing coastal water temperatures over several recent decades and an increase in browsing of herbivorous animals (fishes and invertebrates like sea urchins) on macroalgae associated with the temperature rise are considered direct factors in the *Iso-yake* occurrence (Fisheries Agency, 2007). In addition, in some areas in western Japan, sub-tropical macroalgae and corals expand their distribution as the 'original' macroalgal beds decline (Tanaka *et al*., 2012). Ocean area along Kuroshio is one of the hot-spots showing a much larger increase in surface seawater temperature than the global mean, and temperate coastal ecosystems in the 'hot-spots', which also includes the Australian coasts, eastern coastal area of South America, etc., have been suffering from `tropicalization' (Vergés *et al*., 2014).

The Seto Inland Sea is the largest semi-enclosed sea area in Japan, situated between western Honshu and Shikoku Islands and connected with the Pacific Ocean via the Bungo and Kii Channels. In contrast with the drastic change in the macroalgal beds along the Shikoku and Kyushyu areas being affected by the warm currents, macroalgal beds in the Seto Inland Sea have remained productive and still contribute to the coastal fisheries, which are important industries in this region (Yoshida *et al*., 2011). This is attributable to the special environmental characteristics of the Seto Inland Sea, which experiences little direct effects of the Kuroshio and maintains lower water temperature conditions than those of the Pacific coastal regions.

However, water temperature in the Seto Inland Sea is also showing an increasing trend (+0.11 ~ 0.33 ℃/ 10 y at surface, National Research Institute of Fisheries and Environment of Inland Sea, 2015). If it continues to increase according to the present scenarios of climate change, macroalgal beds in the Seto Inland Sea are also feared to be greatly diminished and fisheries relying on these macroalgal beds will be seriously damaged (Yoshida, 2018).

In addition to the importance of fisheries, macroalgal cultivation, such as for *nori* (laver, *Pyropia* spp.) and *wakame* (sea mustard, *Undaria pinnatifida*), is also an important industry in the Seto Inland Sea. Macroalgal cultivation occupies over 20 % of the total production value (131 billion yens in 2012) of fisheries and aquaculture of the Seto Inland Sea. However, increases in water temperature can also have a great impact on the cultivation because these macroalgae are so sensitive to higher temperature conditions.

United against these future fears, we joined the research project by Ministry of Agriculture, Forestry and Fisheries named "Technology development for circulatory food production systems responsive to climate change" (2013-2017) and conducted research on predicting climate change impacts on macroalgal bed ecosystems and cultivation in the Seto Inland Sea and its connecting waters. The research consisted of 1) field monitoring of macroalgal beds and associated spatio-temporal variation in water temperature, including along the coast of Kyushu (Nagasaki) where loss or changes of macroalgal beds has created a large social problem; 2) experiments on physiology and behavior of key species in macroalgal bed ecosystems (macroalgae and herbivorous fish) with respect to temperature and other conditions to understand the mechanisms of the ecosystem shift; 3) construction of an original physical model to reproduce past temperatures in the environment and predict future ones in the applicable ocean areas; 4) interpreting the impact of future water temperature conditions predicted by the model on macroalgal beds; and 5) macroalgal cultivation. In this paper, we introduce the outline of our research and show some of the main results and conclusions.

Outline of the research

Field monitoring and surveys of macroalgal beds along spatio-temporal environmental gradients in western Japan

To find any specific relationship between change of macroalgal beds and the environment, including water temperature conditions, we have been conducting field monitoring and surveys in two areas in western Japan.

One area is along the coast of Nagasaki Prefecture (north-western Kyushu) where *Iso-yake* has been a serious social problem since the late 1990s. The monitoring was begun in 1998 when drastic changes in macroalgal beds were first observed. Beds of a warm temperate kelp *Ecklonia kurome* were greatly damaged by browsing of herbivorous fish, such as *Siganus fuscescens*, *Calotomus japonicus* and *Kyphosus bigibbus*, along the coast of Nomo-Zaki, Nagasaki Peninsula. Extremely high summer water temperatures seriously damaged the kelp in 2004 and 2008, and in combination with heavy browsing, kelp beds completely disappeared in Nomo-Zaki until 2013. Sargassaceous plants, the other major member of rocky macroalgal beds, seemed to be more tolerant to high temperature than the kelp, but heavy browsing concentrated on *Sargassum* after the kelp disappearance. The number of *Sargassum* species in the beds has gradually decreased, and *S. macrocarpum* became the dominant species until 2011. However, this species also disappeared due to browsing and the effects of a typhoon soon after kelp had disappeared. After those large brown algae disappeared, only small undergrowth macroalgae, such as *Colpomenia sinuosa* and *Padina* spp., constituted the macroalgal beds. Similar situations were observed in many places in Nagasaki Prefecture, but expansion of corals and tropical *Sargassum* species were observed in some places after kelp and temperate *Sargassum* beds disappeared (Kiyomoto *et al*., 2018).

The other area of the survey was the western Seto Inland Sea and Bungo Channel, which connects the western Seto Inland Sea and Pacific Ocean. We set many survey stations along a geographical north to south transect from Hiroshima Bay in the Seto Inland Sea to southern Uwa Sea, which is an eastern part of the Bungo Channel, and conducted surveys on the macroalgal bed vegetation in 2013-14. Within this relatively small geographical area (ca. < 200 km in distance), there is a large surface water temperature gradient, especially during winter, in which the annual minimum temperature drops below 10 ℃ in Hiroshima Bay but never drops below 15 ℃ in the southern Uwa Sea (Yoshida *et al*., 2011). We found clear shifts in macroalgal vegetation along the temperature gradient in beds 1) composed of kelp + *Sargassum*, 2) composed of only *Sargassum*, 3) with no large brown algae but small undergrowth algae, and 4) with tropical *Sargassum* and some corals in the *Iso-yake* landscape (barren seafloor with crustose coralline algae) (Shimabukuro *et al*., 2018). Interestingly, this geographical shift in the vegetation was analogous to the temporal shift in vegetation observed in Nagasaki after the late 1990s.

These results indicated that there were discrete steps in the vegetative changes as macroalgal beds declined or turned into an *Iso-yake* situation, and water temperature increase was a strong driving factor of the change. The field monitoring and surveys also indicated that warm-temperate kelp was the most vulnerable to increasing seawater temperature.

In-house experiments on the effects of water temperature rise on key organisms in macroalgal bed ecosystems

Physiological vulnerability of kelp and *Sargassum* to high temperature conditions and behavioral characteristics of rabbit fish (*Siganus fuscescens*), which is one the major herbivorous fish, was examined by indoor experiments in our research (Murase and Noda, 2018). The experiments were also aimed at finding some threshold temperature conditions relating to the macroalgal bed ecosystem changes caused by physiological limits or the effects of browsing behavior.

High-temperature tolerance in *Ecklonia kurome*, which is a main kelp species in the Seto Inland Sea and Kyushu, was tested. Young sporophytes of *E. kurome* exhibited slight growth under 28 ℃, but under 29 ℃, the growth rate was negative and they were dead within 9 days of culture. It was reported that upper temperature limits for survival of the kelp *Ecklonia bicyclis*, one of the main temperate kelps in Japan, was also 29 ℃, so it is difficult for kelp beds in western Japan to be persistent when summer water temperatures exceed 29 ℃ for a relatively long period, a situation that has recently come to occur frequently. Sargassaceous plants are more tolerant to high temperature conditions, and upper limits of temperature for survival of main temperate species such as *S. patens* and *S. macrocarpum* are about 30-31 ℃. We also found that photosynthetic activity of *S. macrocarpum* never declined under 30 ℃, whereas that of *E. kurome* declined soon after being transferred to the experimental condition of 30 ℃.

Rabbitfish showed a preference of macroalgal species for browsing, but both kelp and Sargassaceous plants could be grazed by rabbitfish. However, the ability of grazed plants to regenerate was larger for Sargassaceous plants than kelps because some species of *Sargassum* are able to regenerate the basal part (holdfast or stem) of the plant (Yatsuya *et al*., 2012).

Rabbitfish grazed more under higher temperature. They grazed little under 20 ℃, and browsing almost stopped at 15 ℃. Browsing behavior was affected not only by temperature, but also the size of its school. More macroalgal tissue was grazed by an individual fish as the size of the school of the fish grew, although actual intake by the fish was getting smaller. That means a large amount of macroalgal tissue was wasted without being assimilated by fish and more grazed tissues were scattered on the seafloor when the school of the fish was large.

These results described recent drastic changes in macroalgal beds. Extremely high summer water temperature can cause large-scale decline of kelp beds. Though some kelp or *Sargassum* beds get over the catastrophic event, browsing of herbivorous fish concentrates on the remaining beds, which means the size of fish school attacking each bed becomes larger. The loss of macroalgae by browsing accelerates and the beds disappear rapidly. And, if damage is so large as to restrain macroalgal reproduction, the change proceeds irreversibly.

Construction of a physical model for numerical-simulation of the temperature environment in the Seto Inland Sea and *Kuroshio* coastal area – Reproduction of past temperature history and collation with current macroalgal bed distribution

To understand how current macroalgal bed distributions were determined by water temperature conditions and how they will change according to future climate change, we constructed an original *Kuroshio* - Seto Inland Sea hydrodynamic model in our project. The objective of the model is to reproduce and understand past interannual variations in water temperature, salinity and currents in the Seto Inland Sea and Kuroshio region, as well as to develop a tool for future prediction of these physical conditions in response to climate change.

The main characteristic of the model was a high resolution 1 km grid because macroalgal beds distributes very locally as a narrow belt along the coast, in general, and outputs of the model should exhibit the physical conditions corresponding to the distribution. Also, parameters corresponding to the effects of tide and river discharge were incorporated in the model as well as general ocean model parameters like heat fluxes and wind stress, etc., because these parameters can substantially affect the physical conditions of coastal areas, especially those in the Seto Inland Sea.

On the other hand, we illustrated current macroalgal bed distribution in the Seto Inland Sea and Kuroshio coastal region in western Japan on a GIS map. Nationwide research on macroalgal bed distribution in Japan was conducted in the early 1990s under the initiative of the Ministry of the Environment, but after that, no research on a nationwide scale has been conducted. However, loss of macroalgal beds due to spreading of *Iso-yake* has become prominent in various places since the late 1990's, and many local governments (prefectures) troubled with *Iso-yake* expansion have conducted their own original research on the status of macroalgal beds in their local areas (Akimoto and Matsumura, 2010). We referred to their reports for constructing the map of the current distribution from late 1990's to 2014. For some areas, we used the results of our field surveys described above (for Uwa Sea area of Ehime Prefecture) and the results of interviews.

Comparisons of macroalgal bed distribution in early 1990's and current distributions on the map indicated great losses of temperate macroalgal beds of kelp and *Sargassum* in areas directly exposed to the Pacific Ocean (e.g., Kochi and Miyazaki Prefecture). Along the coast of the Bungo and Kii Channels (Oita, Ehime and Tokushima Prefectures), the southern boundary of kelp bed distribution has shifted northward a few tens of kilometers during these approximately 20 years.

The current macroalgal bed distribution was overlayed with the outputs of surface water temperature (SST) conditions reproduced by the *Kuroshio*-Seto Inland Sea Physical Model (Shimabukuro *et al*., 2018), and it was determined what kind of SST outputs best fitted and most explained the macroalgal bed distribution. One clear result was shown in the distribution of kelp beds. The current distribution of kelp beds in the Seto Inland Sea and Bungo Channel was clearly within the area where the total days of SST < 15 ℃ (daily mean) was over 70 days / year (mean of 1993 - 2014). Under 15 ℃, activities of herbivorous fish almost stop even though kelp maintains its high productivity under that temperature condition (Yatsuya *et al*., 2014). Therefore, a duration of 70 days without herbivory is considered to be needed for persistent establishment of kelp beds.

Prediction of future water temperature conditions and macroalgal bed distributions in the Seto Inland Sea

Using the *Kuroshio* - Seto Inland Sea hydrodynamic model we constructed the future water temperature environment and macroalgal bed distributions reflecting that environment for the relevant sea areas. The prediction was based on the scenarios RCP 2.6 and RCP 8.5 in IPCC AR 5. The boundary condition of the outer region of the corresponding area of the model referred to the output of the atmospheric ocean coupled model MIROC 5 corresponding to AR 5 (by National Research Institute of Fisheries Science). Predictions were made for the decades of the 2050s and 2090s, respectively.

Under both RCP scenarios, surface water temperature increase is larger in the Seto Inland Sea area than in the coastal area facing the Pacific Ocean and in Bungo and Kii Channels. Also, water temperature increase from the current (2010s) was larger in winter than in summer in the Seto Inland Sea. In summary, under the RCP 8.5, a scenario of comparatively high greenhouse gas emissions, water temperature increases + 2 ~ 4 ℃ in the 2050s (mean of the 10 years, the same hereafter) and + 4 ~ 6 ℃ in the 2090s compared to the current temperatures both in winter and summer, though the degree of temperature increase is quite different locally among sea areas. Under RCP 2.6, in which measures against greenhouse gas emissions are the most effective, water temperature increases + 1 ~ 3 ℃ in the 2050s from current levels but its rise thereafter was predicted to be little up to the 2090s.

According to the prediction of future water temperature environment, the distribution of kelp beds in the Seto Inland Sea was also predicted (Shimabukuro *et al*., 2018). Two criteria were used for the prediction, including a warm condition criterion and a cool condition, which regulates the kelp distribution. For the cool condition criterion, kelp beds can be maintained at the places where the total days of SST < 15 ℃ (daily mean) is over 70 days / year, which was mentioned in the former section. For the warm condition criterion, kelp beds cannot be maintained when ambient daily mean SST reaches 29 ℃ over 6 consecutive days. This was the survival limit of the kelp *Ecklonia kurome* determined in the indoor experiment.

Applying these criteria on the predicted SST output of the model, future kelp bed distribution in the Seto Inland Sea was predicted. Kelp beds will remain only in Iyo-Nada and Aki-Nada sea areas in the 2050s and will completely disappear in the Seto Inland Sea by the 2090s under the RCP 8.5 scenario. On the contrary, under the RCP 2.6 scenario, in which future temperature rise will be moderate, most of the current kelp beds were predicted to remain into the 2090s.

Effect of climate change on macroalgal cultivation

As mentioned in Introduction, macroalgal cultivation, such as for *nori* (laver) and *wakame* (sea mustard), is an important regional industry in the Seto Inland Sea, but water temperature is extremely important as it is for natural macroalgal beds. "Seedlings" of *nori* and *wakame* are cultured in artificial tanks on land during the summer as a minute generation of conchocelis (*nori*) or gametophytes (*wakame*). As ambient water temperature decreases in autumn, juvenile thalli of *nori* or *wakame* begin to be cultured in the cultivation field. Ambient water temperature of 23 ℃ is recommended at the start of the culture, but the water temperature in autumn has been increasing in the last several decades in the Seto Inland Sea. As a result, suitable seasonal timing for the start of cultivation has been delayed by 10 to 20 days since the 1980s.

Recently, production in *wakame* cultivation has been affected by the changes in water temperature (Tanada, 2016), though production of *nori* cultivation has been more affected by nutrient depletion, which is also a recent serious problem in the Seto Inland Sea (Abo *et al*., 2015). In *wakame* cultivation, seedlings are produced in an ambient condition in outdoor tanks, so its production is easily affected by abnormal weather (e.g., extremely high air temperature in summer). In addition, many producers tend to begin cultivation in autumn according to the old-fashioned cultivation schedule without waiting for the appropriate water temperature drops. All of these events lead to significant loss of seedlings due to physiological damage or herbivory under high temperature conditions. As a result, in the Naruto district, where the largest production area of *wakame* exists, shortages and quality deterioration of seedlings have been causing sharp declines in recent production, which is now less than 40 % of the peak in early 1990s (Tanada, 2016).

Further, the seasonal duration in which both *nori* and *wakame* can be produced was predicted to be shortened in the future. In 2090s, the seasonal timing at which ambient seawater temperature drops below 23 ℃ will be delayed by about 4 weeks and 5.5 weeks from the current under the RCP 2.6 and 8.5 scenarios, respectively. Under these conditions, cultivation has to be begun in mid-winter (January) and cultivation will be impossible in the current first half of the production season. The duration in which water temperature drops below 15 ℃ is also predicted to be shortened, and thus, cultured *nori* and *wakame* will be exposed to more heavy herbivory of fish.

Conclusions and future prospect for adaptations

We predict temperate macroalgal beds composed of kelp in the Seto Inland Sea will disappear by the end of this century under the RCP 8.5 scenario in which an extreme water temperature increase was predicted by the model simulation. As most of the beds were predicted to remain under the RCP 2.6 scenario, it will be a great value for the coastal ecosystem and fisheries or human lives relying on these ecosystems to make maximum efforts to reduce greenhouse gas emissions. In addition, macroalgal beds in some areas were more likely to remain than those in other areas, possibly due to physical characteristics, such as tidal currents or upwellings, specific to these areas. These areas should be preferentially subject to conservation of macroalgal beds. Combined with existing *Iso-yake* countermeasures protecting macroalgal beds from browsing pressures by herbivorous animals, productivity and ecological functions of these macroalgal beds will be preserved effectively.

As these macroalgae are originally cold-water species, it will become more difficult to cultivate *nori* and *wakame* with increasing seawater temperatures. For immediate measures, breeding of varieties tolerant to higher water temperatures and their application will be effective, but they are still in the early stage of development. In the *wakame* cultivation industry, seedling production is still performed in its traditional and extensive way by the *wakame* farmers. Artificial seedling technology has proved to be effective for a stable mass supply of seedlings, avoiding the influence of weather conditions (Tanada *et al*., 2015). Practical spreading of this technology among the farmers will be important for maintaining *wakame* production. However, when future water temperature increases exceed the adaptable range of this macroalgal cultivation, introduction of new cultured macroalgae, which are tolerant to warmer condition and with high economic values, will be needed. *Hijiki* (*Sargassum fusiforme*) and *tosaka-nori*

(*Meristotheca papulose*) are candidates, and there are an increasing number of producers who have started cultivating them. Even in macroalgal cultivation, it will be necessary to develop countermeasures against browsing of herbivorous animals, similar to macroalgal bed conservation countermeasures.

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Authors surveyed characteristics of five *Sargassum* forests along the geograohical temperature gradients from the western Seto Inland Sea to the Bungo Channel area. Luxuriant forests with many temperate *Sargassum* species and a kelp (*Ecklonia kurome*) were observed at the two stations in the Seto Inland Sea (Hiroshima Bay and Iyo-nada sea). Analogous flora and luxuriance was also observed in the northern part (the Sata-Misaki Pen.) and central part (the coast of Uwajima-City) of the Bungo-Channel though increase of coralline algae and sea urchins which symbolizes ‘marine desert’ (*Iso-yake*) was also observed. At the southern part (the coast of Ainan-cho), sub-tropical *Sargassum* and corals appeared and replaced the temperate *Sargassum* and *Ecklonia*. Relationship of the shift of *Sargassum* forests observed and the notable gradient in coastal water temperature along the two sea areas was discussed.

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Along the coast of Kochi Prefecture, southwestern Japan, macroalgal bed of temperate kelp (*Ecklonia cava*) has been tremendously decreasing and it has serious impact on abalone fishery. In addition, the authors clarified by field surveys that temperate *Sargassum* species which are also important constitutes of macroalgal beds have been replaced by tropical species, *S. ilicifolium*. Behind these events, the coastal water temperature has been increasing since the 1970s at the rate of 0.3 ℃/decade in the annual mean. In addition to the trend, the authors considered that those events became prominent in 1998 when the largest ENSO occurred and extremely high water temperature observed in the year accelerated the change.

(3) Tanada N., 2016: Development of a practical method for mass seedling production using free-living gametophytes and a new cultivar tolerant to warm waters for early harvesting of *Undaria pinnatifida* (Harvey) Suringar. *Aquabiology*, **225**, 464-471. (in Japanese with English abstract)

The production of *wakame*, *Undaria pinnatifida* in cultivation in Tokushima, which is one of the largest producing area in Japan, has been decreasing seriously after the 1990s. The decrease is supposed to be due to water temperature increase, especially during autumn when seedlings of *Wakame* are started to be cultured in the sea, because the seedlings are sensitive to high temperature conditions at that stage. Authors developed new techniques in mass seedling production and its control, and it can enable to make new cultivars of *Wakame* which can have tolerance to high temperatures.