

## Advantages of small-sized macroalgae in seaweed bed restoration in Kyushu, western Japan

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**Abstract:** Seaweed beds composed of large-sized macroalgae (i.e., *Sargassum* spp. and *Ecklonia* spp.) have been declining along the coast of western Japan, especially in Kyushu. Excessive feeding by herbivorous fish is likely responsible for the loss of macroalgal beds, but we have not yet developed effective techniques to remove these fish. Recent research started in Kyushu have focused on the advantages and roles of small-sized macroalgae in the restoration of seaweed beds because small-sized macroalgae may be less vulnerable to herbivory than large-sized macroalgae and may have value as food and habitat for fishery benthos such as purple sea urchin (*Heliocidaris crassispina*). This study discusses the results of recent research on the benefits of small-sized macroalgae in seaweed bed restoration in Kyushu and highlights: (1) the low vulnerability of small-sized macroalgae to feeding by herbivorous fish, (2) the functionality of small-sized macroalgae as food for *H. crassispina*, and (3) the results of field restoration trials of small-sized macroalgae in sites with high feeding pressure from herbivorous fish. (1) The vulnerability of small-sized macroalgae to feeding by brown chub (*Kyphosus bigibbus*), Japanese parrotfish (*Calotomus japonicus*), and mottled spinefoot (*Siganus fuscescens*) were examined in tank experiments. Small-sized macroalgae were found to be less vulnerable than large-sized macroalgae to feeding by all fish species examined. Additionally, vulnerability to feeding was found to vary among species of small-sized macroalgae; red algae such as *Gelidium elegans* and *Dichotomaria falcata* tended to be the least susceptible. (2) Tank experiments also revealed that various small-sized macroalgae were useful as food for *H. crassispina*, although the gonad index values (GI) of the sea urchin fed any of the small-sized macroalgae were lower than that fed large-sized macroalgae. In addition, GI of the sea urchin fed red algae (*G. elegans* or *Palisada intermedia*) was higher than those fed the other species of small-sized macroalgae. (3) Attempts to restore small-sized macroalgae were conducted at two sites (Nagasaki and Kagoshima) in Kyushu and succeeded in increasing small-sized macroalgae such as Gelidiales and Rhodomelaceae by removing sea urchins. However, large-sized macroalgae such as *Sargassum* spp. did not increase at either site. Furthermore, GI of *H. crassispina* which left unremoved or moved to the removal area increased in the restored seaweed bed at Kagoshima. These studies suggest that various small-sized macroalgae have lower susceptibility to consumption by herbivorous fish and serve as food resources for *H. crassispina*. Therefore, the use of small-sized macroalgal species could be an effective means of seaweed bed restoration, thereby increasing fishery resources such as *H. crassispina* in waters with high feeding pressure from herbivorous fish.

**Key words:** herbivorous fish, *Heliocidaris crassispina*, isoyake, Kyushu

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## Introduction

Recently, seaweed beds composed of large-sized macroalgae such as *Ecklonia* spp. and *Sargassum* spp. have been rapidly declining along the coast of western Japan, especially in Kyushu (Kadota *et al.* 2023; Kiyomoto *et al.* 2021; Tanaka *et al.* 2012; Yoshimura *et al.* 2009). It has been suggested that environmental changes such as rise in water temperatures have disturbed the balance between animal herbivory and seaweed production, and are causing the decline in seaweed beds (Fisheries Agency 2021). Therefore, removal of herbivorous animals and/or transplantations of mature seaweed individuals that supply large amounts of diaspores such as zoospores, are adopted to restore seaweed beds in Japan. So far, restoration of large-sized macroalgae using these methods has been successful at several sites (Agatsuma *et al.* 1997; Ishikawa *et al.* 2017; Fisheries Agency 2021; Taino and Hosogi 2011; Yotsui and Maesako 1993). However, such attempts to restore seaweed beds have failed at some sites, and these failures are attributable to feeding by herbivorous fish, which are more vagile than sea urchins. On the other hand, efficient methods for removing herbivorous fish have not been established yet.

For the reasons described above, small-sized macroalgae have attracted more attention in seaweed bed restoration in Kyushu (Miyazaki Prefecture 2014; Yoshimura *et al.* 2015). Small-sized macroalgae refer to all seaweeds except for large-sized macroalgae such as *Ecklonia* spp. and *Sargassum* spp., and include various species of brown, green, and red algae (Fujita *et al.* 2010). Among these, small-sized upright macroalgae other than coralline algae, such as *Dictyota* spp. and *Gelidium* spp., are expected to be the target species for restoration. Two advantages of using small-sized macroalgae have been suggested (Miyazaki Prefecture 2014; Yoshimura *et al.* 2015). First, they may be less vulnerable to predation by herbivorous fish than large-sized macroalgae. Second, despite their size, small-sized macroalgae may offer provision of food and habitat for fishery organisms. Therefore, it is expected that small-sized macroalgae can be propagated by removing sea urchins without removing herbivorous fish, thereby improving fishery resource conditions. However, it is not known whether small-sized macroalgae have lower vulnerability to feeding by herbivorous fish than large-sized macroalgae, and the effects of small-sized macroalgae as food and habitat are known only for a limited number of fishery resources in Kyushu. Furthermore, field trials of seaweed bed restoration targeting small-sized macroalgae have rarely been conducted.

Recently, studies on small-sized macroalgae for seaweed

bed restoration have been conducted in Kyushu, where the ecological impact of herbivorous fish is expected to be particularly strong. This paper discusses recent studies on the benefits of small-sized macroalgae for seaweed bed restoration and highlights the following three points: (1) the lower vulnerability of small-sized macroalgae to feeding by herbivorous fish, (2) the functionality of small-sized macroalgae as food for purple sea urchin (*Heliocidaris crassispina*), and (3) the results of field restoration trials of small-sized macroalgae in two sites with high feeding pressure from herbivorous fish. The functionality of small-sized macroalgae had been reported by Yoshimura *et al.* (2015), who suggested that small-sized macroalgae provided an important habitat for juvenile spiny lobster (*Panulirus japonicus*) and food for abalones (*Haliotis* spp.) and turban shell (*Turbo sazae*). In this paper, we describe the benefits of small-sized macroalgae for *H. crassispina*, which have been studied following the Yoshimura's (2015) study.

### Lower vulnerability of small-sized macroalgae to feeding by herbivorous fish

Mottled spinefoot (*Siganus fuscescens*), Japanese parrotfish (*Calotomus japonicus*), and various kyphosids including brown chub (*Kyphosus bigibbus*) are known to be typical browsers of seaweeds in western Japan (Vergés *et al.* 2014). To evaluate the vulnerability of small- and large-sized macroalgae to feeding by these three fish, tank experiments were conducted (Table 1). In these experiments, large-sized macroalgae and small-sized macroalgae were simultaneously offered to the herbivorous fish and the reduction in each alga was monitored over time. In the experiment with *K. bigibbus* (mean total length, 43.0 cm), one large-sized (*Sargassum alternato-pinnatum*) and six small-sized macroalgae (brown algae: *Padina arborescens*, *Dictyopteris undulata*, and *Dictyopteris prolifera*; red algae: *Gelidium elegans* and *Dichotomaria falcata*; green algae: *Codium intricatum*) were evaluated (Kadota *et al.* 2022). The results showed that *S. alternato-pinnatum* was the most vulnerable to feeding by *K. bigibbus*, followed by *P. arborescens*. In contrast, the other seaweeds were not so vulnerable to feeding by *K. bigibbus*. Analysis of stomach contents of wild *K. bigibbus* also showed that large-sized macroalgae such as *Sargassum* spp. and *Undaria pinnatifida* made up a significant portion of the stomach contents from spring to early summer when both large-sized and small-sized macroalgae are abundant (Yatsuya *et al.* 2015).

In the experiment with *C. japonicus* (mean total length, 36.8 cm), one large-sized (*Sargassum fusiforme*) and five small-sized macroalgae (brown algae: *P. arborescens* and *D. undulata*; red algae: *Palisade papillosa* and *G. elegans*; green algae: *Codium fragile*) were evaluated (Noda and Kadota 2024). The results showed that *S. fusiforme* was the most vulnerable to feeding by *C. japonicus*, followed by *P. arborescens*, *D. undulata* and *P. papillosa* were slightly damaged, while *G. elegans* and *C. fragile* suffered little damage.

Two tank experiments were conducted to evaluate the vulnerability to feeding by *S. fuscescens*. In the first experiment, the feeding selectivity of three size classes of *S. fuscescens* (mean total length, 8.7, 20.6 and 30.0 cm) was evaluated by providing *S. fusiforme* as the large-sized macroalga and *P. arborescens* or *Ishige okamurae* (brown algae) as the small-sized macroalga (Kiriyama *et al.* 2005). The results showed that *S. fuscescens* tended to prefer *S. fusiforme* to either of the small-sized macroalgae in all size classes. The second experiment was conducted on *S. fuscescens* with an average total length of 28.1 cm, using the same method as for *K. bigibbus* (Kadota *et al.* 2022). The results showed that *S. alternato-pinnatum*, *P. arborescens* and *C. intricatum* were the most vulnerable to feeding by *S. fuscescens*. Unlike the results from the other herbivorous fish, small-sized macroalgae were eventually damaged after the large-sized macroalga was lost. However, *G. elegans* was less vulnerable to the herbivory and *D. falcata* suffered little damage.

The results of a series of vulnerability experiments suggest that large-sized macroalgae are more vulnerable to feeding by all herbivorous fish examined, and that various small-sized macroalgae are less susceptible to feeding by herbivorous fish, although these experiments tested a limited number of seaweed species. Among small-sized macroalgae, brown algae such as *P. arborescens* tended to be more vulnerable to feeding, while red algae such as *G. elegans* and *D. falcata* tended to be less vulnerable. This suggests that red algae such as *G. elegans* will be promising small-sized macroalgae for seaweed bed restoration in Kyushu. However, a previous tank experiment showed that *G. elegans* and *D. falcata* were more vulnerable than brown algae to feeding by scalpel sawtail (*Prionurus scalprum*; Kadota *et al.* 2022). Although *P. scalprum* is not considered to have as great an impact on seaweed as the three species mentioned above (Fisheries Agency 2021), these red algae should be carefully considered as candidates for restoration of seaweed beds in the area with a large *P. scalprum* population.

### The functionality of small-sized macroalgae as food for *H. crassispina*

*Heliocidaris crassispina* is an important fishery resource in Kyushu. The individuals in seaweed beds with abundant food can be used as a fishery resource, while those in barren sites do not develop gonads and cannot be used for fishery resource. Two tank experiments were conducted to evaluate the food values of small-sized macroalgae for *H. crassispina* (Table 2). Shao *et al.* (unpublished data) offered *H. crassispina* caught in barren sites salted *U. pinnatifida* as a large-sized macroalga and *D. undulata* and *G. elegans* as small-sized macroalgae for 2 months. The results showed that the gonad index values (GI) of *H. crassispina* fed the small-sized macroalgae were higher than that of the unfed group. When comparing the two small-sized macroalgae, *G. elegans* had a better food value than *D. undulata*. However, GIs of *H. crassispina* fed the small-sized macroalgae did not increase as much as that fed the large-sized macroalga.

Another experiment was conducted by Takada (2016) to evaluate the food values of different small-sized macroalgae. In this experiment, eight small-sized macroalgae (brown algae: *Colpomenia sinuosa*, *D. undulata*, *D. prolifera*, *Dictyota spinulosa* and *P. arborescens*; red algae: *G. elegans* and *Palisada intermedia*; green algae: *C. fragile*) were offered to *H. crassispina* and GIs were compared with *H. crassispina* that were fed salted *Saccharina japonica*. The results showed that these small-sized macroalgae had some food values for *H. crassispina*, but not as much as the large-sized macroalga. Additionally, the red algae had the highest food values among the small-sized macroalgae examined and GIs of the urchins fed the red algae reached about 80% of that fed the large-sized macroalga.

Furthermore, GI of *H. crassispina* was investigated in seaweed beds composed of small-sized macroalgae and the outside of the beds (areas with relatively few small-sized macroalgae) at two depths (2 and 7 m) in Nagasaki (Kadota *et al.* 2022). GI in the seaweed beds was higher than that in the outside areas at both depths. As a result, the time period when GI became over 6% (the lower limit to have commercial value) was longer in the seaweed beds than in the outside areas. When comparing the shallow seaweed bed composed of mainly red algae with the deep seaweed bed mainly composed of brown algae, GI was higher in the shallow seaweed bed than in the deep seaweed bed. However, GI peaked at 8.9% in the shallow seaweed bed in Nagasaki (Kadota *et al.* 2022), while GI peaked at 11.8% in the seaweed bed composed of *Sargassum*

Table 1 Vulnerability of large-sized macroalgae and small-sized macroalgae to feeding by herbivorous fish

Species	Relative vulnerability					References
	1 (high)	2	3	4	5 (low)	
<i>Kyphosus bigibbus</i>	<b>Sargassum alternato-pinnatum</b> (B)	<i>Padina arborescens</i> (B)	<i>Codium intricatum</i> (G)* <i>Dictyopteris undulata</i> (B)* <i>Dictyopteris prolifera</i> (B)* <i>Dichotomaria falcata</i> (R)* <i>Gelidium elegans</i> (R)*			Kadota <i>et al.</i> (2022)
<i>Calotomus japonicus</i>	<b>Sargassum fusiforme</b> (B)	<i>Padina arborescens</i> (B)	<i>Dictyopteris undulata</i> (B)	<i>Palisada perforate</i> (R)	<i>Codium fragile</i> (G)* <i>Gelidium elegans</i> (R)*	Noda and Kadota (2024)
<i>Siganus fuscescens</i>	<b>Sargassum fusiforme</b> (B)	<i>Padina arborescens</i> (B)				Kiryama <i>et al.</i> (2005)
	<b>Sargassum fusiforme</b> (B)	<i>Ishige okamurae</i> (B)				Kiryama <i>et al.</i> (2005)
	<i>Codium intricatum</i> (G)	<i>Dictyopteris prolifera</i> (B)	<i>Dictyopteris undulata</i> (B)	<i>Gelidium elegans</i> (R)	<i>Dichotomaria falcata</i> (R)*	Kadota <i>et al.</i> (2022)
	<b>Sargassum alternato-pinnatum</b> (B)					
	<i>Padina arborescens</i> (B)					

Bold text, large-sized macroalgae; regular text, small-sized macroalgae

G, green algae; B, brown algae; R, red algae

An asterisk indicates the seaweeds that were particularly resistant to feeding damage (decrease rate of 20% or less).

Table 2 The effect of large-sized macroalgae and small-sized macroalgae on gonad index of *Heliocidaris crassispina*

Species	Gonad index				References
	1 (high)	2	3	4 (low)	
<b>Salted <i>Undaria pinnatifida</i></b> (B)	<i>Gelidium elegans</i> (R)	<i>Dictyopteris undulata</i> (B)		Non-feeding	Shao <i>et al.</i> (unpublished)
<b>Salted <i>Saccharina japonica</i></b> (B)	<i>Palisada intermedia</i> (R)	<i>Codium fragile</i> (G)			Takada (2016)
	<i>Gelidium elegans</i> (R)	<i>Padina arborescens</i> (B)			
		<i>Dicyyota spinulosa</i> (B)			
		<i>Dictyopteris undulata</i> (B)			
		<i>Dictyopteris prolifera</i> (B)			
		<i>Colpomenia sinuosa</i> (B)			

Bold text, large-sized macroalgae; regular text, small-sized macroalgae

G, green algae; B, brown algae; R, red algae

spp. in Kyoto (Yatsuya and Nakahara 2004). Therefore, GI would be higher in the seaweed beds composed of small-sized macroalgae than that in the barren sites, but not as high as GI in the seaweed beds composed of large-sized macroalgae.

The results of tank experiments and field surveys suggest that small-sized macroalgae are food resources for *H. crassispina*, although their food values are lower than large-sized macroalgae. In particular, red algae such as *G. elegans* had the highest food value among the small-sized macroalgae examined. Therefore, red algae could be promising candidates among small-sized macroalgae for the restoration of seaweed beds as food resources for *H. crassispina* in Kyushu.

#### Field trials of restoration of small-sized macroalgae in sites with high feeding pressure from herbivorous fish

Field experiments to restore small-sized macroalgae were conducted on two reefs in Nagasaki Prefecture and Kagoshima Prefecture, Kyushu (Igari *et al.* 2022; Kadota *et al.* 2022). At both sites, sea urchins (mainly *H. crassispina* in Nagasaki and *Echinometra mathaei* and *Echinostrephus aciculatus* in Kagoshima) were initially removed, and seaweeds were subsequently monitored. The results showed that coverage of small-sized macroalgae increased in the experimental areas compared with the control areas where sea urchins were not removed by the following spring. The small-sized macroalgae that increased were mainly red algae such as Gelidiales and Rhodomelaceae. However, large-sized macroalgae such as *Sargassum* spp. hardly increased at both sites. Change in GI of *H. crassispina* left removed or moving to the experimental area was also monitored in the Kagoshima site after the removal (Igari *et al.* 2022). The GI in the experimental area was higher than that in the control area and the GI only in the experimental area exceeded 6% in the following spring.

#### Conclusions and future research directions

Barren sites have persisted where herbivory of sea urchins and herbivorous fish are high. In such reefs, sea urchins have small gonads and are therefore not suitable for commercial catch. However, studies conducted in Kyushu suggest that the removal of sea urchins once from the areas could change such a situation via the following process. First, because small-sized macroalgae are less vulnerable to predation by herbivorous fish, small-sized macroalgae increase. Then, the propagated small-sized macroalgae serve as valuable food resources for *H. crassispina* left unremoved or moving to the removal areas,

and lead to the increase in the GI, which becomes a good fishery resource. Once sea urchins become fishery resources, periodic harvesting of them would help maintain low sea urchin densities. Previous studies have shown that small-sized macroalgae provide an important habitat for juvenile spiny lobster and food for abalones and turban shell (Yoshimura *et al.* 2015). Other fishery resources are also expected to increase along with *H. crassispina* in the favorable cycle described above. Thus, we consider the use of small-sized macroalgal species to be an effective means of restoration of seaweed beds that have experienced high feeding pressure from herbivorous fish, and to thereby increase fishery resources such as *H. crassispina* in Kyushu.

Red algae, especially *G. elegans*, are thought to be promising candidates of small-sized macroalgae for seaweed bed restoration in Kyushu. *Gelidium elegans* is less vulnerable to feeding by herbivorous fish and a good food resource for *H. crassispina* (Kadota *et al.* 2022; Noda and Kadota 2024; Takada 2016). In addition, *Gelidium* and species of related genera create a better habitat for juvenile spiny lobster (Yoshimura *et al.* 2015). They have also been utilized as the major sources for commercial extraction of agar, making them important fishery resources. The characteristics of *G. elegans* could efficiently increase the fisheries resources in the areas with high feeding pressure from herbivorous fish. Furthermore, the maximum critical temperature for the growth of *G. elegans* is reported to be higher than those for many large-sized macroalgae (Baba 2010; Baba 2021; Komazawa 2017; Murase 2022). This characteristic could be another advantage in seaweed bed restoration by allowing adaptation to climate change. However, crops of *Gelidium* (mainly *G. elegans*) have been declining on the coast of Hachijo-jima Island, off the southern coast of Kanto, central Japan (Komazawa 2017), possibly due to the decreased nutrient concentrations in the water. Small-sized macroalgae encompass a diverse range of species, but only a limited number of them have been evaluated for their advantages in the resistance to herbivorous fish, food value for fishery resources, and other biological characteristics. Further studies are needed to evaluate more diverse small-sized macroalgae from a broader perspective, including environmental factors such as water temperature and nutrients on their growth.

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