Predatory behavior of the sea stars *Asterias amurensis* and *Distolasterias nipon* on the Japanese scallop, *Mizuhopecten yessoensis*

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**Abstract:** Because sea stars are the primary predators of the Japanese scallop, *Mizuhopecten yessoensis*, they are being removed from scallop fishing grounds, despite the lack of information on their predatory impacts. We experimentally examined the predatory behavior of the sea stars *Asterias amurensis* and *Distolasterias nipon* on the Japanese scallop. In the first experiment, we hypothesized that sea stars respond to distant chemical cues from live scallops. However, the results showed that neither *A. amurensis* nor *D. nipon* responded to the chemical cues of live intact animals, though it is commonly known that they respond to the chemical cues of carrion. We also examined the effects of the relative sizes of the sea stars to the scallop on their predator-prey relationship. We altered the body size ratios of the Japanese scallop to *A. amurensis* in the summer and winter, and to *D. nipon* in the summer, and observed the scallops’ survival. In all experiments, logistic regression models were applied to changes in survival under different prey-to-predator size ratios, which were calculated by dividing the scallop size by the sea star size. Our results suggested that survival of the Japanese scallop rapidly increases with increasing body size. The ratios at which mortality was 50% provide an important parameter in estimating the predation risk from sea stars in scallop fishing grounds. Our study will contribute to the effective and responsible management of Japanese scallop mariculture.

**Key words:** Asteriidae, body size, Pectinidae, predator-prey interaction, sowing culture

**Introduction**

The largest scallop fisheries in the world (FAO 2018) are those that produce the Japanese scallop, *Mizuhopecten yessoensis* (Jay 1857). Their profit yields via export have also been the largest among all Japanese fisheries since 2012 (Ministry of Agriculture, Forestry, and Fisheries, Japan 2017). As over 50% of Japanese scallops are produced by mariculture along the Sea of Okhotsk coast of Hokkaido (Chiba 2016), its sustainability and effects on the ecosystem should be considered as an important component of the Code of Conduct for Responsible Fisheries (FAO 1995). Scallop mariculture is divided into two steps: the aquaculture of juveniles in suspended cages and the release of the juveniles to the wild. While the former step has been improved over time by technological advancements (Nishihama 1994, Kosaka 2016), much remains unknown about the latter step beyond basic population parameters such as growth, survival, and age structure in the wild (Goshima & Fujiwara 1994, Kurata 1996, Paturusi et al. 2000, Shinada 2006).

Understanding the process of mortality in the released scallops is the most important challenge in this mariculture. Predation is the primary cause of their mortality, and many local fishermen and researchers, based on their experiences, think that sea stars are the main predators influencing scallop populations. Large numbers of sea stars have consequently been removed from many scallop fishing grounds (Kosaka 2016) simply due to speculation regarding a negative correlation between the densities of the sea stars and scallops. However, no reports have yet quantified the effect of sea star predation in the wild. The removal of sea stars is thus based on uncertain information
about their predation. In scallop mariculture, simple predator-prey relationships at the species level should be carefully examined to efficiently manage a responsible fishery.

To discern the predation effect of sea stars on the survival of the Japanese scallop, it is necessary to know basic information about their predator-prey relationship. Although sea stars are certainly predators of the Japanese scallop, their predatory impacts may not always be serious in the wild. It is well known that sea stars respond to the chemical cues of food (Castilla & Crisp 1970, Zafiriou 1972, Sloan & Northway 1982, Valentinčič 1985, Drolet & Himmelman 2004), however, there have been no reports on how sea stars detect live scallops in the wild. In addition, body size is not a negligible factor when quantifying the predation impact of sea stars on the Japanese scallop. As the Japanese scallop grows larger than other sea star prey such as clams and mussels, the value of scallops as prey for sea stars may depend on their relative sizes. Indeed, size-dependent predation by sea stars is also known in other scallop species that grow to large sizes (Barbeau & Scheibling 1994, Barbeau et al. 1994, Arsenault & Himmelman 1996, Magnesen & Redmond 2012). The assumption that all sea stars can consume all scallops would oversimplify their actual relationship.

This study experimentally examines the feeding behavior of sea stars and how predation risk by sea stars on the Japanese scallop changes with their relative body size. As Asterias amurensis Lutken, 1871 and Distolasterias nipon (Döderlein, 1902) have been recognized as major scallop predators in the Sea of Okhotsk (Volkov et al. 1982, Silina 2008), our investigations focused on these two sea star species.

### Materials and Methods

Between two and four weeks before starting each experiment in this study, we collected Japanese scallops and A. amurensis and D. nipon individuals from the coast of the Sea of Okhotsk near Abashiri, Hokkaido, Japan by employing a bottom trawl and a cage trap, respectively. We measured the shell height (SH) of the scallops and the length between the mouth and the tip of one arm near the sieve plate (arm length, AL) of the sea stars. The scallops and sea stars were separately reared in aquariums (700 L) for which ambient seawater (approximately 10 L min⁻¹) was pumped up from Lake Notoro, one of the lagoons on the coast of the Sea of Okhotsk, at the Okhotsk Marine Research Center of Tokyo University of Agriculture. While food was not supplied to the sea stars for two to four weeks before the start of each experiment, the scallops could always feed on plankton in the pumped water.

To estimate how sea stars searched for live scallops in the wild, we examined the food detection ability of A. amurensis and D. nipon in the summer (from June 11 to July 29, 2015), whose mean water temperature was 17.4°C (between 13.2 and 20.4°C). We also examined the food detection ability of A. amurensis in the winter (from November 21, 2015 to January 14, 2016), whose mean water temperature was 2.5°C (between 0.0 and 6.0°C). We could not collect D. nipon during the winter, thus excluding it from the winter studies. In this experiment, we hypothesized that sea stars respond to distant feeding chemical cues that are upstream because we empirically knew that sea stars aggregate to the carrion of various animals in a cage trap. This hypothesis was tested in a Y-maze trough that was constructed from plastic boards, and seawater (2 L min⁻¹) was supplied from the corners of two channels (Fig. 1). One live scallop (between 94 and 126 mm in SH) and one pair of only scallop shells were tethered at the upstream sections of each channel (Fig. 1). The shells were washed and dried for the new trial to remove the chemical cues of the internal organs. One sea star (between 113 and 226 mm in AL) was acclimatized for 24 h in a mesh cage and placed at the downstream section of the trough (Fig. 1). Observations started after the cage was removed. We recorded the behavior of the sea stars for 24 h using a digital video camera (Everio GZ-VX895, JVC Kenwood Corp. Kanagawa, Japan) set above the trough. After each trial, the scallop and shells were replaced with new ones, the channels of placement were switched, and a new sea star was placed at the downstream section for the new trial. This observation was repeated 13 times for A. amurensis and 12 times for D. nipon in the summer, and 23 times for A. amurensis in the winter. Our definition of channel selection by the sea star was when it passed through two thirds of the channel length and, via the video images, we examined which channel the sea stars selected first after the cage was removed. If the sea stars were motivated to feed and traced the chemical cue of the live scallop, they would have moved directly to the channel where the live scallop was tethered. We defined that sea stars showed predatory behavior when they covered the scallop, even if they could...
not successfully consume it and the scallop was still alive. To confirm a sea star’s response to the chemical cue of the live upstream scallop, we used Fisher’s exact test in a 2×2 contingency table to compare the frequency with which sea stars selected a channel (a live scallop or only shells) at their first migration against the types of behavior (predatory or non-predatory). If they had tracked the chemical cue of a live scallop, they would have more frequently selected the channel where the live scallop was tethered and possibly have shown predatory behavior.

To examine the effect of relative body size on the predator-prey relationship, we collected differently-sized Japanese scallops and the two sea star species. This experiment was first conducted in the winter (from December 11, 2016 to March 14, 2017) with a mean water temperature of −0.2°C (between −0.6 and 1.1°C), and then in the summer (from July 1 to August 5, 2017) with a mean water temperature of 20.2°C (between 17.4 and 23.0°C). The size of the scallops we used ranged between 47 and 124 mm in width at the base, 310 mm in height, approximately 5 mm in alveolar length (from July 1 to August 5, 2017) with a mean water temperature of 20.2°C (between 17.4 and 23.0°C). The size of the scallops we used ranged between 40 and 160 mm. The size of *D. nipon* (used for the summer experiments) ranged between 51 and 215 mm. We then experimentally examined the effect of relative size between the sea star and the scallop on their predator-prey relationship.

One sea star was put into a round basket (464 mm in diameter at the base, 310 mm in height, approximately 5×5 mm in mesh size) that was sunk in a large seawater aquarium (1200 L). As the ability of scallops to escape increases with their body size, we placed five size-matched scallops in the round basket to allow the sea star to easily access any of the five scallops without chasing a specific one. These trials were repeated by changing the size combination of one sea star and five size-matched scallops in the baskets. We made 36 combinations for *A. amurensis* during the winter experiments, and 37 and 44 combinations for *A. amurensis* and *D. nipon*, respectively, during the summer experiments. Each trial period was a maximum of 10 days in the winter and four days in the summer. Survival of the scallops was observed each day, and the trial was terminated when one or more of the five scallops died. As an experimental control, we simultaneously observed the survival of differently-sized scallops in round baskets where sea stars were not included. As all scallops survived in 11 replications of the control in the winter and only one of 140 individuals died in 28 replications of the control in summer, we concluded that the deaths of scallops in the trials were caused by sea star predation. We calculated ratios by dividing the size (SH) of the scallop by the size (AL) of the sea star in each size combination. We used the size of the largest scallop when two or more scallops were preyed on in one trial, and we used the size of the smallest scallop when all five scallops survived, although their size differences were small. To estimate the probability of scallop survival against the size ratio, we applied a logistic regression model to the binary data, i.e., survival or death, collected from each experiment in the winter and summer.

All statistical analyses were conducted with freeware R 3.4.3 (R-Development-Core-Team 2017).

### Results

The Y-maze experiments showed that both *A. amurensis* and *D. nipon* did not exhibit any significant selection behavior towards the live scallops placed upstream of the sea stars. In the summer, *A. amurensis* moved to one of the two channels in 12 trials (92%) and *D. nipon* moved to one of the channels in 10 trials (91%). Predatory behavior was observed in 10 trials with *A. amurensis* (77%) and in 9 trials with *D. nipon* (90%). In these trials, there was no significant difference between the types of behavior (predatory or non-predatory) concerning the frequency with which the sea stars selected a channel (a live scallop or only shells) in *A. amurensis* (*p*=0.52, Table 1A) and in *D. nipon* (*p*=1.00, Table 1B). In the winter, sea star movement was observed in 11 of 23 trials (48%) and predatory behavior was observed in five of 11 sea stars that moved to one of the channels (45%). In the winter trials, there was no significant difference between the two types of behavior concerning the frequency with which the sea stars selected a channel (*p*=0.44, Table 1C).

In the experiments that examined the effect of relative body size on scallop predation, both *A. amurensis* and *D. nipon* exhibited two types of predatory behavior. In one type, the sea star completely covers the scallop from above and slightly lifts the center of its body while consuming the scallop by inserting its stomach into the shell (Fig. 2A). In the other type, the sea star holds the scallop from above.

<table>
<thead>
<tr>
<th>A. Scallop Shell Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Predation 4 6 10</td>
</tr>
<tr>
<td>No predation 0 2 2</td>
</tr>
<tr>
<td>Total 4 8 12</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>B. Scallop Shell Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Predation 5 4 9</td>
</tr>
<tr>
<td>No predation 0 1 1</td>
</tr>
<tr>
<td>Total 5 5 10</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>C. Scallop Shell Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Predation 4 1 5</td>
</tr>
<tr>
<td>No predation 4 2 6</td>
</tr>
<tr>
<td>Total 8 3 11</td>
</tr>
</tbody>
</table>
the side of the scallop’s shell and then consumes it (Fig. 2B). The latter behavior was generally observed when the arm of the sea star was shorter than the SH of the scallop. The logistic models in all three experiments showed that the survival of the scallop increased with increases in the prey-to-predator size ratio (Fig. 3, Table 2). In *A. amurensis*, the ratios at which mortality was 50% ($M_{50}$) was 0.71 in the summer (Fig. 3A, Table 2A) and 0.57 in the winter.

**Table 2.** Results of the logistic models from each experiment. (A) *Asterias amurensis* in the summer, (B) *A. amurensis* in the winter, and (C) *Distolasterias nipon* in the summer. PP size ratio denotes the size ratio of prey to predator.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Estimate</th>
<th>S.E.</th>
<th>Z-value</th>
<th>P-value</th>
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<tbody>
<tr>
<td>A. Intercept</td>
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<td>6.11</td>
<td>−2.31</td>
<td>0.021</td>
</tr>
<tr>
<td>PP size ratio</td>
<td>19.88</td>
<td>8.33</td>
<td>2.43</td>
<td>0.017</td>
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<tr>
<td>Residual deviance</td>
<td>9.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>df = 34</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B. Intercept</td>
<td>−3.752</td>
<td>1.75</td>
<td>−2.04</td>
<td>0.041</td>
</tr>
<tr>
<td>PP size ratio</td>
<td>6.28</td>
<td>2.63</td>
<td>2.39</td>
<td>0.017</td>
</tr>
<tr>
<td>Residual deviance</td>
<td>26.4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>df = 34</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C. Intercept</td>
<td>−10.70</td>
<td>3.81</td>
<td>−2.81</td>
<td>0.005</td>
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<tr>
<td>PP size ratio</td>
<td>14.46</td>
<td>5.77</td>
<td>2.51</td>
<td>0.012</td>
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<tr>
<td>Residual deviance</td>
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<td>df = 42</td>
<td></td>
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</table>

(Fig. 3B, Table 2B). When the scallops were exposed to *D. nipon* in the summer, $M_{50}$ was 0.74 (Fig. 3C, Table 2C). Figure 4 shows the relationship between the size of the Japanese scallops and the prey-to-predator size ratio. The horizontal axis begins with the smallest size (30 mm) of scallops that are released into the fishing grounds of the Sea of Okhotsk. The sizes of the sea stars are displayed in 50 mm intervals (50, 100, 150, and 200 mm) that approach the maximum size used in our samples (226 mm). The area above the constant lines of $M_{50}$ in Fig. 4 suggests that the predation risk by sea stars rapidly decreases with increasing scallop size. For example, the predation risk from sea stars that are smaller than 100 mm is very low for scallops that are larger than 70 mm.

**Discussion**

This study provides basic information about the preda-
Predatory behavior of sea stars on scallops

The present study provides an important parameter in estimating the predation risk from sea stars in scallop fishing grounds. In a typical Japanese scallop maricultural year, fishermen release 1-year-old scallop juveniles to one of four designated areas at the bottom of the sea after culturing the scallop spats in a suspended cage (Nishihama 1994, Kosaka 2016). All surviving scallops are harvested three years later from the released area, and new juveniles are released to the vacant area again after the harvest. In this cyclic culture, the scallops are composed of individuals from a single year class with little size differences within each area. The minimization of the risk of predation by considering the sizes of both the scallops and sea stars has been suggested in other species of scallops and sea stars (Barbeau et al. 1996, Magnesen & Redmond 2012). We can recognize the density of all sea stars as a potential predator in each area from the relationships shown in Fig. 4. The monitoring of scallop size in each area of each fishing ground has already been conducted in the Sea of Okhotsk, and the measurement of sea star size would also be possible if scallop monitoring were conducted through photographic images (Goshima & Fujiwara 1994) because sea stars would also appear in the images. In the wild, $M_{50}$ may actually be lower than the one presented here because the scallops can escape from the sea stars. However, the values may not be very different because the densities of scallops in the fishing grounds are not low, i.e., between 15 and several individuals per m² (Goshima & Fujiwara 1994, Paturusi et al. 2002, Miyoshi unpublished data). In addition, Miyoshi et al. (2018) demonstrated that $A. amurenensis$ can move more quickly (45.9 m h$^{-1}$ maximum) than
we previously imagined, implying that sea stars would easily be able to encounter a scallop in the fishing grounds. We, therefore, believe that \( M_{50} \) provides a valid criterion for estimating the density of predatory sea stars because the current monitoring systems provide reliable data to estimate the size and density of both scallops and sea stars in the fishing grounds. It is also possible to quantify the predation risk if we could estimate not only \( M_{50} \), but also the total amount of scallops that are consumed by sea stars of different sizes.

Our results illustrate that avoiding the unnecessary removal of sea stars from scallop fishing grounds would be preferable for the conservation of the environment. *A. amurensis* is known as a generalist (Fukuyama & Oliver 1985, Ross et al. 2002, 2003). *D. nipon* also feeds on various animals such as clams and mussels (our unpublished data). It is likely that both sea star species do not exclusively feed on scallops in the fishing grounds, and that they may prefer other animals rather than scallops, as observed in *Placopecten magellanicus* (Wong & Barbeau 2005). There is a possibility that sea stars contribute to weaker competition between Japanese scallops and other animals in the fishing grounds, because the sea star may be a keystone species in their community (e.g., Paine 1966, Botto et al. 2006, Gosnell & Gaines 2012). The specific predatory impacts of both *A. amurensis* and *D. nipon* should be examined not only for the Japanese scallop but also for the communities in the fishing grounds. Unnecessary removal of the sea star may cause unfavorable changes in community structure. The results of our study will thus contribute to the effective and responsible management of Japanese scallop mariculture.

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