Short-term population dynamics of high-latitude 
Alveopora japonica in Tateyama Bay, Japan

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Abstract To assess the effectiveness of the temperate coral, Alveopora japonica as an impact indicator, we examined the effects of various environmental variables on the coral’s short-term population dynamics in Tateyama Bay, Chiba, Japan. We measured coral cover, colony density and colony size of A. japonica in June, August and November 2013. Newly identified colonies were recorded separately. We analyzed the relationships between colony density, substrate types, and seawater temperature using a generalized linear mixed model. Both coral cover and colony density decreased between August and November, showing high mortality during this period. In November, a decrease in mean colony size and skewness of colony size distribution, compared with August, was attributed to mortality of large colonies and an increase in the abundance of small colonies. Newly identified small colonies were observed in August and November. The presence of these colonies may be in part due to accelerated planulation (i.e., recruitment). The generalized linear mixed model showed a significant trend of increasing colony density with seawater temperature rise, potentially resulting from recruitment during the high-temperature period. In addition, there was a negative effect of sand substrate on colony density. Since the sand substrate abundance was significantly correlated with typhoon occurrence, we suggest that typhoons could be one of the major factors affecting the short-term population dynamics of A. japonica in Tateyama Bay.

Keywords Alveopora japonica, coral population, fluorescence, typhoon, substrate

Introduction

Tateyama Bay, Chiba, Japan is at the northern limit of zooxanthellate coral distribution on the western side of the Pacific Ocean. Twenty-four scleractinian coral species (20 genera) have been recorded around Tateyama (Veron 1992). Alveopora japonica, an endemic species around Korea and Japan (Veron 2000), is one of the dominant temperate scleractinian coral species in this region (Hagiwara 2003). The species is found at Tanegashima (Veron 1992), Miyake-jima (Tribble and Randall, 1986) and Tateyama (Veron 1992) on the western side of the Pacific Ocean, and in the Amakusa Islands (Nozawa et al. 2008; Sugihara et al. 2009), Iki Islands (Yamano et al. 2004), and Jeju Island, Korea (Denis et al. 2013; Sugihara et al. 2014) in the Sea of Japan. The growth-forms of the colonies are small (generally less than 10 cm in diameter) hemispherical or massive (Veron 2000). The colonies are sometimes densely distributed over small areas (Denis et
al. 2013), likely because of their reproductive strategy (brooding species), whereby they release planula larvae that settles within a relatively short time (Harii et al. 2001). Recently, a population increase was reported in *A. japonica* around Jeju Island (33.41°N, Denis et al. 2013, 2015), which was also suspected to be due to a seawater temperature rise (Denis et al. 2015). High-latitude corals can be used as impact indicators of environmental changes, especially seawater temperature rise caused by global warming (Yamano 2008). Information on population structure and short-term dynamics is necessary to assess the effectiveness of a coral species as an impact indicator; however, such information on *A. japonica* is currently limited (Nozawa et al. 2008; Denis et al. 2013, 2015; Vieira et al. in press).

In this study, we examined the effects of various environmental variables on the short-term population dynamics of *A. japonica*. We measured coral cover, colony density and colony size of *A. japonica* along the coast of Tateyama Bay, and analyzed the relationships among colony density, substrate, and seawater temperature.

**Materials and methods**

**Benthic surveys and image processing**

The study site was located at 5 m depth on the west side of Tateyama Bay (34°58′37″N, 139°46′36″E), where the substrate is a mix of rock and sand (Matsumoto et al. 2012). In June, August and November 2013, quadrat surveys were carried out at the study site by SCUBA. A transect line (10.4 m length) was attached to the seabed at the study site using stainless steel pegs. Photo-quadrat surveys were conducted during the day for quantifying substrate, and during the night for accurate measurements of the number and size of coral colonies. Photo-quadrats were performed at a constant camera distance (0.8 m), by fixing a digital camera (Sony Co., NEX-5) in a waterproof housing on top of a stainless steel quadrat (D×W×H: 0.4×0.5×0.8 m). The quadrat was placed on both sides of the transect line without any empty space (52 quadrat images, 10.4 m²). Two coral species (*A. japonica* and *Hydnophora exesa*) were observed during the survey, however, *A. japonica* was the only one species identified within our quadrats. The daytime surveys were conducted between 14:00 and 15:00, while nighttime surveys started just after sunset and finished within 1 hour. For nighttime surveys, we used a UV-induced fluorescence method. This method can detect small changes in colony abundance (Baird et al. 2006; Piniak et al. 2005; Schmidt-Roach et al. 2008; Matsumoto et al. 2012; Fig. 1). The excitation light source was an underwater UV-LED light (Nichia Co., NSHU551A, Wavelength: 375 nm±5 nm).

The number of colonies was counted to determine coral density. Colony area was measured to an accuracy of at least 0.001 cm² as “colony size”, using the number of pixels in the region of each colony detected from all of the fluorescent quadrat imagery. Coral cover per quadrat was calculated as a percentage of the colony area to the quadrat area. The same colonies were identified from imagery obtained through the three temporal surveys. All colonies that did not show green fluorescence in August and November were considered to be dead. Partial mortality of colonies was not detected. Newly identified colonies were recorded separately. To understand the temporal changes in substrate, the substrate type (i.e. rock, sand) was visually determined from the daytime imagery, and the sand area per quadrat was measured to an accuracy of at least 0.001 cm². In addition, the substrate types of each quadrat were classified into three categories “Rock (R: sand area 0 to 25%)”, “Rock and Sand (R-S: 26 to 75%)” and “Sand (S: 76 to 100%)” based on the percentage of sand area per quadrat. Image processing and measurements were performed using the image processing software ImageJ (ver. 1.47, National Institutes of Health, MD, USA).

**Statistical analysis**

Significant temporal changes in colony density and coral cover were determined by one-way repeated measures ANOVA tests. If the ANOVA was significant, differences between individual surveys were identified by Bonferroni test for post-hoc comparisons. Colony size distribution was analyzed in the logarithmic scale, which is considered to better reflect the size structure of the corals (Bak and Meesters 1998; Meesters et al. 2001; Vermeij and Bak 2003). Mean colony size and skewness of size distribution were used to evaluate temporal
changes in the population structure of this species (Nozawa et al. 2008). Significant temporal changes in colony size were determined by a Kruskal–Wallis test. Differences with a $P$ value of $<$0.05 were considered significant. In addition, to examine the effects of temporal changes in environmental conditions on this species, we carried out model selection based on a generalized linear mixed model (GLMM). To avoid multicollinearity (Graham 2003), substrate and seawater temperature were used as explanatory variables in this analysis. Seawater temperature was measured in water pumped into Tateyama Station, Field Science Center of Tokyo University of Marine Science and Technology from the seabed (3 m depth), about 500 m west of the study site. Measurements were taken daily at 09:00 for the 6-month study period using a mercury thermometer (accuracy of at least 0.1°C). Average seawater temperature, from 80 days prior to each survey date near the study site, was used. Temperature anomalies were the differences between the recorded value and the average value from the same month from 1982 to 2012 (http://www.agri-kanagawa.jp/suisoken/Kaikyozu/TokyoWanko.asp). Sand area per quadrat was used as the substrate. We also examined the number of typhoons close to the study site (http://www.jma.go.jp/jp/typh/). “Typhoon approached” was defined as when the center of the typhoon had entered within a 300 km radius from the study site, in accordance with the Japan Meteorological Agency. The international typhoon scale is based on 10-minute average wind speed (Tropical storm: 17 to 25 m/s, Severe tropical storm: 25 to 33 m/s., Typhoon: $\geq$33 m/s). However, in this study, a wind speed of 17 m/s or more was considered as a “Typhoon”, in accordance with the Japanese typhoon scale. In the analysis, colony density was the response variable. The ID number of the quadrat, which denoted the same location in the three temporal surveys, was included in the model as a random effect. A negative binomial distribution was applied to the response variable. Akaike information criterion (AIC) was used for model selection, with the model that showed the lowest AIC chosen as the best model. These analyses were performed by the statistical analysis software R (Ver. 3.1.0, R Development Core Team, 2014, R Foundation for Statistical Computing, Vienna, Austria), with the lme4 package (Ver. 1.1-6, Bates et al. 2014) used for the estimation of the GLMM coefficient.

**Results and Discussion**

Both the mean colony density and coral cover were changed significantly through the temporal surveys (Repeated-measures ANOVA, density: $F=4.09, P<0.05$, cover: $F=5.05, P<0.01$). The increasing trend in colony density was seen between June and August (Table 1), but the trend was not significant ($P=0.06$). The decreasing trend between August and November was significant (Table 1, $P<0.05$). The coral cover was highest in August, and was significantly higher than in other months ($P<0.05$). The mean size of live colonies was 2.31, 2.43 and 1.79 cm$^2$ in June, August and November, respectively (Fig. 2). A decreasing trend in colony size was seen between August and November, but the trend was not significant (Kruskal–Wallis test, $H=2.16, P=0.34$). The skewness of colony size distribution was 0.14, 0.13, and $-0.03$ in June, August and November, respectively. No colony mortality was found between June and August, but was estimated to be 15.6 inds./m$^2$ between August and November (Fig. 2). A decreasing trend in colony size was seen between August and November, but the trend was not significant (Kruskal–Wallis test, $H=2.16, P=0.34$). The skewness of colony size distribution was 0.14, 0.13, and $-0.03$ in June, August and November, respectively. No colony mortality was found between June and August, but was estimated to be 15.6 inds./m$^2$ between August and November (Fig. 2). Small colonies of less than 0.125 cm$^2$ accounted for 41.8% of the colony mortality. The newly identified colonies were observed in August and November (Fig. 2).

Seawater temperature near the study site ranged from
19.8 to 27.5°C between June and August (average: 22.8°C, anomaly: +0.4°C) (Fig. 3). By November, seawater temperature had declined to 18.9°C (average: 23.7°C, anomaly: +0.2°C). The number of typhoons that approached the study site was 0, 2 and 8 between March and June, June and August, and August and November, respectively. A correlation was observed between the number of typhoons and the substrate cover in individual quadrats (Spearman rank correlation: $r_s=0.44$, $P<0.01$). Therefore, this increase in sand substrate (i.e., sedimentation) could have been induced by typhoons, with colony mortality occurring as a consequence of sedimentation. In GLMM analysis, model selection based on AIC included both substrate and temperature as explanatory variables in the best model. From the estimated coefficients of the explanatory variables, there was a positive effect of temperature, and a negative effect of substrate type, on colony density (Table 2).

Although coral cover was extremely low in comparison with other high-latitude locations (67–75% in Jeju Island; Denis et al. 2013; Vieira et al. in press), a short-term
change was observed in both coral cover and colony density of this species. The high variations in colony density suggest that recruitment of this brooding species is patchy, because of its short precompetent period of planula larvae (Harii et al. 2001; Tioho et al. 2001; Denis et al. 2015). In Japan, the planulation of this species occurs between September and October (Harii et al. 2001; Nozawa et al. 2006), and thus our observation of newly identified colonies in the summer is likely to be too early for recruitment. However, it was also reported that planulation in 1994 (September) was earlier than 1995 (October), when the seawater temperature was relatively low in the latter (Harii et al. 2001). The positive anomaly in our study (+0.9°C) was higher than in 1994 (+0.4°C [difference between the average value of same period of 1982 to 1993]). In addition, planulation of this species was observed in August at Suo-Nada, Yamaguchi Prefecture, Japan (Matsumoto pers. comm.). Furthermore, the seawater temperature in Suo-Nada from March to June 2013 (16.4°C) was lower than in our study site (17.6°C). Therefore, planulation in our study site could have been earlier during summer 2013, compared to 1994. Although the newly identified colonies in the summer might include small colonies that were overlooked at the former survey (June) due to a cover of sand and seaweed, we can assume that both the increase in colony density in the summer and the positive effect of temperature in the GLMM may be in part due to accelerated planulation (i.e., recruitment).

If sedimentation rate was low, it could be removed by coral mucus secretion (Hubbard and Pocock 1972). However, large amounts would induce colony mortality (Woodley et al. 1981; Fabricius et al. 2008; Hongo and Yamano 2013). Generally, sedimentation affects small colonies by inhibiting recruitment (Gilmour 1999), and in serious cases, large colonies may also be affected (Gilmour et al. 2006). Since mortality of both small and large colonies was found in this study, the effect of sedimentation could be a relevant factor affecting the population dynamics of A. japonica. As the small colony mortality was dominant, mortality could also be related to strong wave action during typhoons (Hongo et al. 2012). Observations of coral skeletons on the seabed during the daytime surveys in November also suggest that some live colonies were removed by strong water flow occurring during typhoons. Overall, our results show a negative effect of sedimentation induced by typhoons. These findings are important in the context of increasing typhoon intensity (Oouchi et al. 2006). With coral colonies threatened by both sand and mechanical damage, and the need for the protection of temperate coastal ecosystems, including temperate corals (Makino et al. 2014), it is essential that we increase our knowledge of short-term population dynamics of temperate corals.

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