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ORIGINAL ARTICLE

Akihisa Hattori · Miyako Kobayashi

Configuration of small patch reefs and population abundance of a resident reef fish in a complex coral reef landscape

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Abstract Habitat use by the resident coral reef anemonefish, *Amphiprion frenatus*, was examined in the complex coral reef landscape of Shiraho Reef, Ishigaki Island, Okinawa, Japan, using an enlarged color aerial photograph processed using image analysis software as an accurate field map. The anemonefish inhabit assemblages of the host sea anemone, *Entacmaea quadricolor* (clonal type), which inhabit various patch reefs in the back reef moat. We located all patch reefs inhabited by the host in the map based on snorkel observations: 297 anemonefish were found in 93 host assemblages in the study site of 2.9 ha. These patch reefs could be recognized by the reef colors, including the shadows (blackish color) in the photograph. Using image analysis software, the colors of the patch reefs were chosen and pixels with the same color values were regarded as potential habitat patches for the fish (PHPs). PHPs were 3D patch reefs (>0.5 m in height). Total areas (TA) and total perimeters (TP) of PHPs were measured in nine quadrats in the digitized aerial photograph. Host abundance and anemonefish abundance in a quadrat showed stronger correlations with the product of TA and TP of PHPs than TA alone. A site with numerous large 3D patch reefs (≥ 0.75 m^2 in situ) can be a better habitat for the fish than other sites consisting of several huge 3D patch reefs of the same total area. The methodology applied here may be useful for assessing the quality of habitats for small resident animals in shallow subtidal reefs.

Keywords Coral bommies · Direct observations · Enlarged aerial photograph · Micro landscape structure · NHI Image J

Introduction

Habitat structure plays an important role in structuring animal communities, and a heterogeneous and patchy environment often enhances species diversity and population abundance of a species (Tilman and Kareiva 1997; Turner et al. 2001). Coral reef fish communities, which are among the richest animal communities in nature, are established in heterogeneous and patchy environments (e.g., Lowe-McConnell 1987; Sale 1991). A coral reef consists of several benthic landscapes, including reef slopes, reef crests and back reef moats, and a landscape involves landscape elements, such as a small patch reef (coral patch or bommy), sandy bottom and a mound called the reef pavement (e.g., Japanese Coral Reef Society and Ministry of the Environment 2004). For example, many fishes inhabit small patch reefs in a back reef moat (Sale 1991), and ecologically similar species can coexist in such a patchy environment (Hattori 1995, 2002).

As they are especially calm and shallow (usually less than 3-m deep at ebb tide), back reef moats are suitable habitats for reef-building corals, which form patch reefs of various sizes (e.g., Lowe-McConnell 1987; Sale 1991). For the same reason, reclamation has also been conducted (Spalding et al. 2001; Japanese Coral Reef Society and Ministry of the Environment 2004). Reclamation, as well as coral bleaching due to unusually high water temperatures, have directly destroyed fish habitats and reduced the species diversity and population abundance of coral reef fishes (Spalding et al. 2001; Roberts et al. 2002; Japanese Coral Reef Society and Ministry of the Environment 2004). To determine the order of priority for protection, it is necessary to assess the quality of the habitat: i.e., the composition, quantity and configuration of landscape elements required for the species

A. Hattori (✉)
Faculty of Liberal Arts and Education, Shiga University,
2-5-1 Hiratsu, Otsu, Shiga 520-0862, Japan
E-mail: hattori@sue.shiga-u.ac.jp
Tel.: +81-77-5377852
Fax: +81-77-5377852

M. Kobayashi
Nature Conservation Educators Association Sakishima,
Shiraho, Ishigaki, Okinawa 907-0242, Japan

present. As patch reefs are essential habitats for reef fishes in back reef moats (e.g., Lowe-McConnell 1987; Sale 1991), the total areas of patch reefs in a site may be an important indicator of the habitat quality of the site.

Remote sensing techniques, including use of aerial photographs and satellite images, are powerful tools for habitat mapping, especially on broad scales (> km^2), and spatial distribution patterns of live and dead coral communities and seagrass beds, which are important habitats for fishes, have been studied extensively in relation to biological and geological factors (e.g., Mumby et al. 1995, 2004; Sheppard et al. 1995; Spalding et al. 2001; Purkis and Pasterkamp 2004; Japanese Coral Reef Society and Ministry of the Environment 2004). However, these techniques cannot cover small fishes and their habitat use because they are too small and motile to be reflected in the photographs or images. In addition, some use small patch reefs consisting of live corals and dead coral skeletons as refuge and food sources. Thus, direct observations are necessary to record fish abundance and their habitat use, and these have been conducted in small quadrats or belt transects (less than several hundred square meters), even when aerial photographs or satellite images are used as supplementary data for inter-site comparisons on broader scales (e.g., Nanami and Nishihira 2002; Friedlander et al. 2003; Kendall et al. 2003; Chittaro 2004; Nakamura and Sano 2004). In a small quadrat or belt transect, however, it is difficult to measure the total areas of the patch reefs: a patch reef often has a complex shape consisting of smaller patches with unclear boundaries, and a continuous reef in a small quadrat may be a patch reef in a larger one. Although the effects of the surface topography and live coral cover of a site on the species richness and population abundance of reef fishes have been studied extensively using quadrat or belt transect techniques (e.g., Luckhurst and Luckhurst 1978; Bell and Galzin 1984; Sano et al. 1987; McCormick 1994; Chabanet et al. 1997), the effects of the configuration of small patch reefs consisting of dead and live corals on their species richness and population abundance have not been documented in detail and are poorly understood. Here, we describe a simple technique to measure all patch reefs inhabited by a reef fish and potential habitat patches for the fish: an enlarged aerial photograph was used as an accurate map in the field, and then data regarding the patch reefs inhabited by the fish were analyzed with image software on a computer.

Preliminary studies on community structures of damselfishes, which were conducted in back reef moats of fringing reefs around Ishigaki Island, Okinawa, Japan, using standard belt transect techniques, indicated that the anemonefish (*Amphiprion frenatus*) are almost always found in sites where species richness and population density of damselfishes are very high (Shibuno, unpublished data). The patch reefs inhabited by the anemonefish may be suitable sites for other damselfishes. The anemonefish inhabit the host anemone (*Entacmaea quadricolor*), which inhabit patch reefs in back reef moats, and anemonefish home ranges are restricted to the vicinity of the host (Hattori 1991, 2005; Kobayashi and Hattori 2006). As they are sedentary, the host anemone is a good material to detect patch reefs inhabited by the resident reef fish. The aim of this study was to determine the relationship between the patch reef configuration and the population abundance of a resident fish in a complex coral reef landscape.

Materials and methods

The field study was conducted in March, June and September 2001 and March 2002 in a back reef moat of Shiraho Reef, Ishigaki Island (24°22′N, 124°15′E), Okinawa, Japan. To observe the anemonefish (*Amphiprion frenatus*) and the host anemone (*E. quadricolor*), detailed field maps of the study site (Fig. 1a, b, 151×193 m^2, maximum depth = 3 m at spring high tide) were made based on an enlarged color aerial photograph (92×92 cm^2), which was an enlarged copy of an area (11×11 cm^2) of an aerial photograph of Shiraho Reef (23×23 cm^2, OKC-94-13, 1/10,000, 95 Ishigaki C15-34, Geographical Survey Institute, Ministry of Land, Infrastructure and Transport, Japan): these photographs were purchased from an agency of the Geographical Survey Institute, Ministry of Land, Infrastructure and Transport, Japan. The image of the study site was obtained from the enlarged copy and converted to digital images (Windows BMP format, 1,152×1,476 pixels) with a scanner at a resolution of 600 dpi. These images were waterproofed and used for mapping the anemonefish and the host. Snorkel observers located all patch reefs inhabited by the host on the maps. In this study, patch reefs in the back reef moat mean natural reefs that formed live corals and/or dead coral skeletons: e.g., coral patches, coral bommies, micro-atolls and mounds called the reef pavements. Distances between several benthic landmarks were measured in the field: a distance of 7.63 pixels on the digitized maps was equivalent to 1 m, and one pixel was much smaller than the smallest patch reef (about 0.9 m in diameter) inhabited by the host. In Shiraho Reef, *A. frenatus* inhabited assemblages (Kobayashi and Hattori 2006) or the clonal type of *E. quadricolor* (see Dunn 1981; Fautin and Allen 1992), although they use the solitary type in other places (Allen 1972; Hirose 1985; Hattori 1991, 2005). Although small solitary individuals were found in this study site, they were regarded as assemblages consisting of one host. The number of individual hosts in an assemblage was determined by counting their mouths. The water depths of the sites to which the hosts attached were measured to the nearest 5 cm by using a tape measure while snorkeling, setting the lowest sea level in a spring low tide in March 2002 at 0-m deep (the lowest sea level and the highest sea level from the local reference datum was 0.9 and 2.2 m, respectively). The water depth of the largest host in an assemblage was regarded as the water depth of the assemblage. The number of anemonefish was counted at each host assemblage.

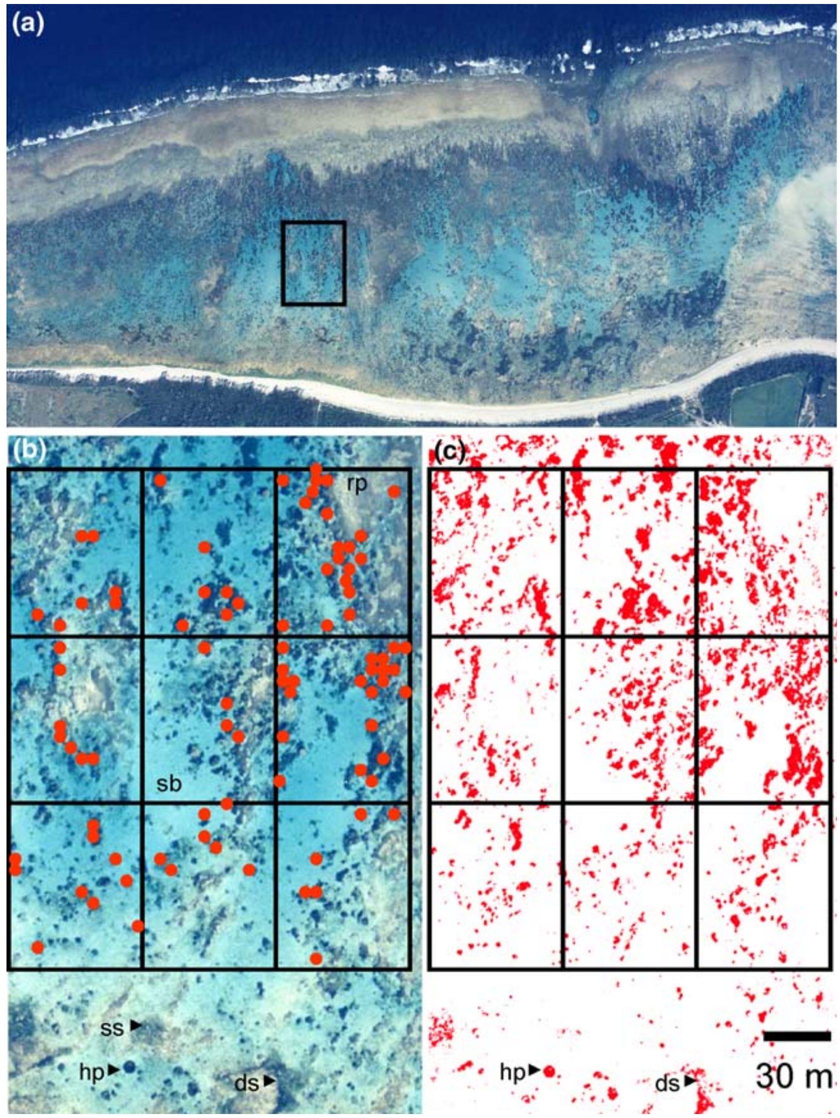


Fig. 1 **a** Location of the study site in the back reef moat of Shiraho Reef, Ishigaki Island, Okinawa, Japan (original color aerial photograph: OKC-94–13, 1/10,000, 95 Ishigaki C15–34, Geographical Survey Institute, Ministry of Land, Infrastructure and Transport, Japan). **b** Distribution of host anemone assemblages (*Entacmaea quadricolor*, *red circles*) and landscape structure of the study site, indicating several landscape elements: high patch reefs (*hp*), sandy bottoms (*sb*) including small coral rocks, reef pavement (*rp*), dense seagrass beds (*ds*) and sparse seagrass beds (*ss*). **c** The potential habitat patches (PHPs) of the anemonefish (*Amphiprion frenatus*), detected by specific color values of the high patch reefs (*hp*), which were inhabited by the host anemone. The color of dense seagrass beds (*ds*) could not be distinguished from the color of the high patch reefs. *Squares* indicate nine quadrats

To identify potential habitat patches of the anemonefish (PHPs), pixels with the colors of the patch reefs inhabited by the host assemblages were extracted from a digitized image of the study site, and the other colors were deleted using image analysis software (Adobe Photoshop 7.0). The extracted image was processed into a binary image. The study site was divided into nine quadrats (each quadrat =384×492 pixels) (Fig. 1c). The total areas (TA) and the total perimeters (TP) of PHPs in a quadrat were calculated on a computer with a public domain program (Image J 1.33, developed at the US National Institutes of Health and available on the Internet at http://www.rsb.info.nih.gov/ij/docs/index.html), using the function of Analyze Particles setting 7.63 pixels as 1-m scale. Thereafter the products of TA and TP were calculated.

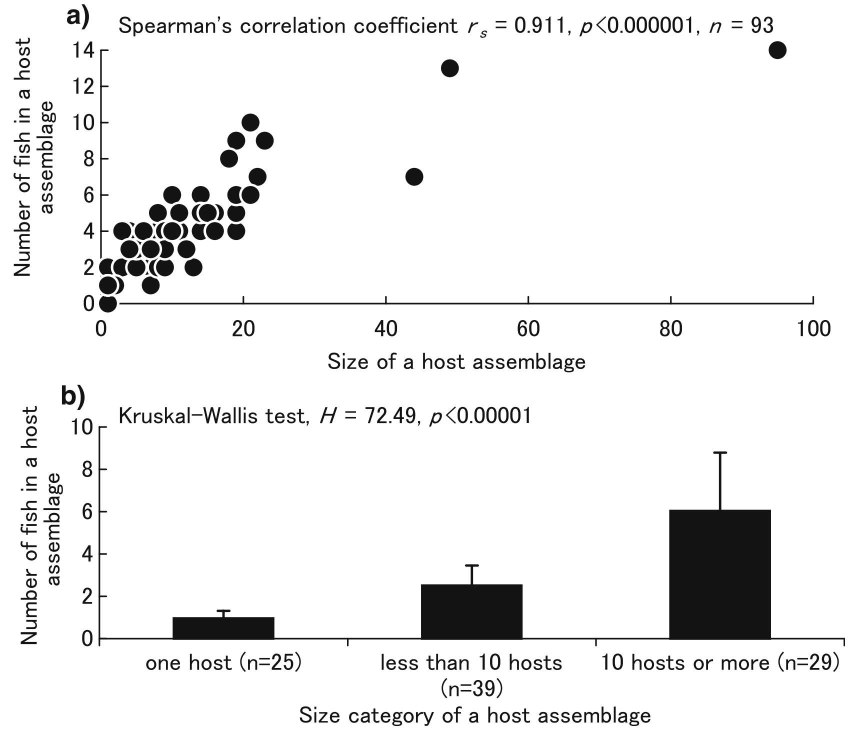
Non-parametric statistical tests were applied to data sets when data distribution differed significantly from the standardized form of normal distribution (χ^2 test).

Results

There were 93 host assemblages with 297 anemonefish (Fig. 1b), and the number of individual hosts amounted to 821 in the study site of 2.9 ha. An average assemblage consisted of 8.8 ± 12.4 hosts (range 95–1, mode 1, median 5, $n = 93$); 26.9% of the assemblages consisted of one host. The average number of anemonefish in a host assemblage was 3.2 ± 2.6 (range 14–0, mode 1, median 2, $n = 93$). The two smallest hosts were found to be without anemonefish. The number of anemonefish in a host assemblage was highly correlated with the size (i.e., the number of hosts) of a host assemblage (Fig. 2a), and there were significant differences in the number of anemonefish among the three size categories of host assemblages (Fig. 2b).

The patch reefs inhabited by host assemblages were located in the digitized image, and the colors of the

Fig. 2 **a** Relationship between the total number of the anemonefish (*Amphiprion frenatus*) in a host anemone assemblage and its size (i.e., the number of host anemones). **b** Comparison of the average number (+SD) of anemonefish among host anemone assemblages of three size categories



patch reefs were chosen (Fig. 1b). The patch reefs were not less than 44 pixels in the image (0.75 m^2 in situ) and more than 0.5 m from the bottom in the field. These high patch reefs had three-dimensional (3D) structures that could be recognized by the reef colors including the shadows (blackish color) in aerial photographs. A total of 2,066 PHPs were detected. These patches contained 220,976 pixels, corresponding to 13.0% of the area of the study site. The average area of PHPs was 1.84 ± 8.26 m^2 (range 173.5–0.017, mode 0.017, median 0.086, $n = 2{,}066$). Excluding small PHPs (<44 pixels, 4.9% of the total area of PHPs), 497 PHPs containing 210,152 pixels remained (12.4% of the area of the study site): these large PHPs were equivalent to large 3D patch reefs (≥0.75 m^2 in situ). The average area of the large PHPs was 7.3 ± 15.6 m^2 (range 173.5–0.756, mode 1.25, median 2.63, $n = 497$).

The number of host assemblages in a quadrat was not correlated with the TA of PHPs (Spearman's correlation coefficient, $r_s = 0.485$, $P > 0.05$, $n = 9$) and not correlated with the TP of PHPs ($r_s = 0.417$, $P > 0.05$, $n = 9$). However, the total number of hosts in a quadrat was highly correlated with TA (Pearson's correlation coefficient, $r = 0.832$, $P = 0.005$, $n = 9$) and also highly correlated with TP ($r = 0.707$, $P = 0.033$, $n = 9$). The strongest correlation was with the product of TA and TP (Fig. 3, $r = 0.846$, $P = 0.004$, $n = 9$). The total number of anemonefish in a quadrat was also significantly correlated with TA ($r = 0.676$, $P = 0.045$, $n = 9$) and TP ($r = 0.686$, $P = 0.041$, $n = 9$), and highly correlated with the product of TA and TP ($r = 0.768$, $P = 0.015$, $n = 9$). Excluding the small PHPs (<0.75 m^2 in situ), the total number of hosts in a quadrat was still highly correlated with TA ($r = 0.828$, $P = 0.006$, $n = 9$) and TP ($r = 0.732$, $P = 0.025$, $n = 9$), and showed the strongest correlation with the product of TA and TP (Fig. 4, $r = 0.848$, $P = 0.004$, $n = 9$).

The average water depth of a host assemblage was 59.4 ± 42.1 cm (range 185–10, mode 30, median 50, $n = 93$). The depth-frequency distribution of host assemblages showed that they were abundant in shallow substrata: 63.4 and 92.5% of the assemblages inhabited shallow substrata less than 65-cm deep and less than 125-cm deep, respectively (Fig. 5a). The depth-frequency distribution of individual hosts showed similar results: 69.3 and 96.2% of 821 hosts inhabited substrata shallower than 65-cm deep and shallower than 125-cm deep, respectively (Fig. 5b). However, only 36 individuals (4.38%) inhabited shallow substrata less than 15-cm deep.

Discussion

All patch reefs inhabited by the host anemone *E. quadricolor* could be recognized in the color aerial photograph by their reef colors including the shadows. From the colors, including shadows, 3D or high patch reefs (>0.5 m in height) could be distinguished from other substrata: i.e., sandy bottoms, sparse seagrass beds and low or flat patch reefs, such as small coral rocks and the reef pavement. The shadows of dense seagrass beds could not be distinguished from those of 3D patch reefs in the photograph, although there were no dense seagrass beds in the study site (Fig. 1). As the lengths of the shadows are dependent upon solar height, it may be

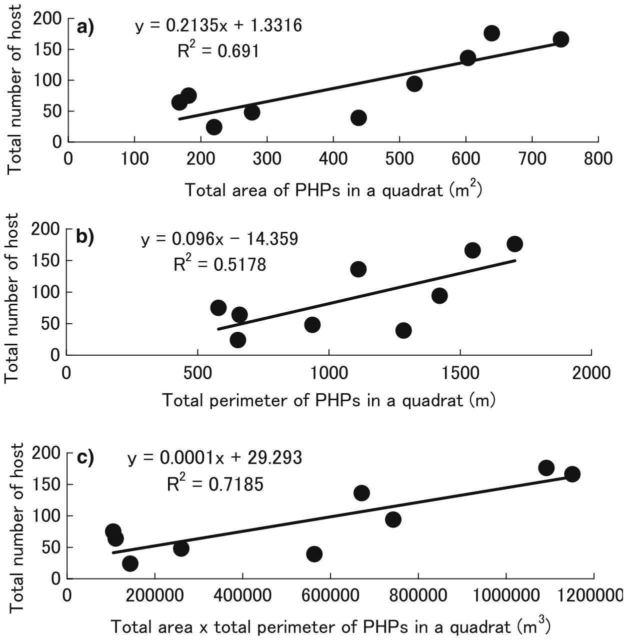


Fig. 3 Relationship between the total number of host anemones in a quadrat and the total areas (*TA*) of PHPs (**a**), the total perimeters (*TP*) of PHPs (**b**) and the product of TA and TP of PHPs (**c**)

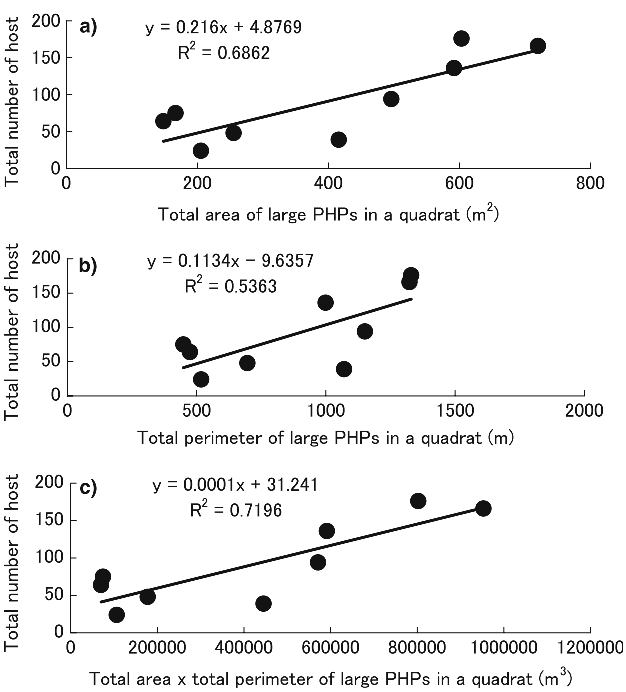


Fig. 4 Relationship between the total number of host anemones in a quadrat and the total areas (*TA*) of large PHPs (**a**), total perimeters (*TP*) of large PHPs (**b**) and the product of TA and TP of large PHPs (**c**). See text for details

difficult to detect 3D patch reefs in aerial photographs taken around noon. Further studies are necessary to confirm whether it is possible to detect 3D patch reefs in back reef moats using color aerial photographs.

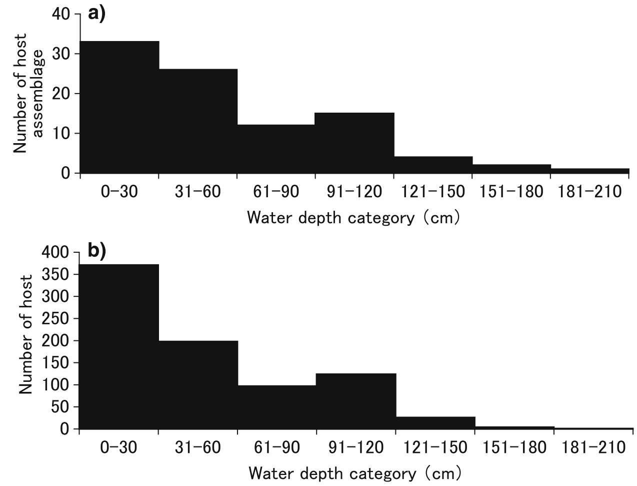


Fig. 5 a Depth-frequency distribution of host anemone assemblages. **b** Depth-frequency distributions of host anemones

In the digitized aerial photograph, the colors of the 3D patch reefs were all regarded as PHPs, which involved small PHPs less than 0.75 m^2 in situ. The host anemone did not inhabit small PHPs, but TAs of the small PHPs were only 4.9% of the TA of all PHPs. Although the total number of host assemblages in a quadrat was not significantly correlated with the TA of PHPs, the total number of hosts in a quadrat was highly correlated with the TA of PHPs. This suggests that larger 3D patch reefs harbor larger host assemblages, although they are not always inhabited by the host anemone. While the largest size of host assemblages was 95, 26.9% of the assemblages consisted of only one host. As clonal (or colonial) types of host anemones can reproduce asexually (Dunn 1981; Fautin and Allen 1992), *E. quadricolor* settled on larger 3D patch reefs may be able to form larger assemblages in this study site. The number of anemonefish was highly correlated with the size of a host assemblage, and the total number of anemonefish in a quadrat was significantly correlated with the TA of PHPs. The size of a host assemblage (i.e., the number of hosts) can be used as an indicator of anemonefish abundance.

We expected that the TA of PHPs in a quadrat would be the critical determinant of anemonefish abundance (or host abundance) because the population density of animals in a given area is usually proportional to the total area of habitat patches, although most previous studies on this subject were conducted in terrestrial ecosystems (Johnson et al. 1992; Primack 1995; Turner et al. 2001; Goodsell and Connell 2002; Pullin 2002). In the present study, however, TP was also an important factor governing host abundance: the total number of hosts showed a stronger correlation with the product of the TA and TP than with the TA only, and the host inhabited only large 3D patch reefs (≥0.75 m^2 in situ). These results suggest that a site containing numerous large 3D patch reefs can have a higher population density of the host and the anemonefish than other sites of the same total area with several huge 3D patch reefs. If the total area does not diminish, habitat fragmentation may not have a negative effect on population density in coral reef fishes because they have a drifting larval phase (Sale 1991), unlike animals in terrestrial ecosystems (Primack 1995; Turner et al. 2001; Pullin 2002).

As the product of the TA and TP of 3D patch reefs in a given area can be a better indicator of essential habitats for the host and the anemonefish than TA only, there must be some disadvantage for the host and the anemonefish inhabiting huge 3D patch reefs. In the shallow back reef moat, young coral colonies would grow to reach the water surface and then continue to grow outward on the perimeter of the colonies, and finally some large colonies would become a huge 3D patch reef. Accordingly, a huge 3D patch reef, like a micro-atoll, would have shallow flat parts on the top, where physiological stress, such as aerial exposure, extreme temperature and wave action, may be severe. Although hosts were abundant in shallow substrata, they were less abundant on the shallowest flat tops of large patch reefs (Hattori and Kobayashi, personal observations). Actually, only 4.38% of 821 individual hosts inhabited shallow substrata less than 15-cm deep. In huge 3D patch reefs, they may have been abundant in the shallow edges, not in the shallowest flat tops. Consequently, host abundance may have depended upon the product of TA and TP. A host anemone species (*Heteractis crispa*) is known to be more abundant in the shallow edges of reefs than in the shallowest parts in a fringing reef of Sesoko Island, Okinawa, because physiological stress (extreme temperature, aerial exposure and wave action) is less severe and hard and soft corals are more abundant at the reef edges, which provide the host with refuge and shelters (Hattori 2006).

In preliminary studies on damselfish communities on back reef moats around Ishigaki Island, the anemonefish were almost always found in sites where species richness and population density of damselfishes are very high (Shibuno, unpublished data). A patch reef inhabited by the anemonefish can be a suitable reef for other damselfishes. Abelson and Shlesinger (2002) studied a reef fish community on artificial reefs (3–15 m^3) with different inside structural complexities in Eilat on the Red Sea, and found a higher population density and higher species richness of reef fishes in larger reefs with a certain degree of structural complexity. As fishes, including juveniles, can move to a vacant artificial reef from natural reefs in the surrounding area, a larger reef with a certain degree of structural complexity can harbor a greater number of individual fish and higher species richness. In the present study site, as mentioned earlier, the host and the anemonefish inhabited 3D patch reefs larger than 0.75 m^2 in situ. As a natural patch reef in the back reef moat is formed by reef-building corals, the large 3D patch reef may have a degree of inside structural complexity, which can provide the host, the anemonefish and other damselfishes with refuge and shelters.

In conclusion, 3D or high patch reefs (>0.5 m in height) larger than 0.75 m^2 in situ were potential habitat patches for the host and the anemonefish in the shallow back reef moat, probably because of the inside structural complexity. In the shallowest flat tops of huge 3D patch reefs, however, physiological stress for them must be severe: they could have been abundant in the shallow edges. Therefore, the product of the TA and TP of 3D patch reefs in a given area can be a good indicator of the habitat quality. The present study suggests that based on the 'micro' landscape structures that are reflected in enlarged aerial photographs, better habitats for small resident reef animals can be detected. The methodology applied here may be useful for assessing the habitat quality: i.e., the composition, quantity and configuration of landscape elements required for resident reef animals in shallow subtidal zones, which are subject to human impacts, such as reclamation.

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