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ORIGINAL ARTICLE

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Aerial images can detect 3D small patch reefs that are potential habitats for anemonefish *Amphiprion frenatus*

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Abstract Patchy habitats often enhance species coexistence and, consequently, abundance of each species. The present study examined two indicators of potential habitats for anemonefish *Amphiprion frenatus*: total area of dark-colored patch reefs that are detectable on an aerial image with image analysis software, and total area of tall patch reefs (> 1.5 m in height) that are detectable on stereoscopic aerial images with a stereoscope. Relationships between patch reef area and anemonefish abundance, as estimated by number of host anemone *Entacmaea quadricolor*, were investigated at Shiraho Reef, Ishigaki Island, Japan. Total number of anemones was not correlated with total area of tall patch reefs but was highly correlated with total area of dark-colored patch reefs. Underwater observations confirmed that upper surface of tall patch reefs often involved bare substratum, whereas dark-colored patch reefs did not include this substratum. Because reef area approximately reflected reef volume within shallow back reefs, total area of dark-colored patch reefs that are detectable by aerial photography will reflect total volume of reef fish habitat. The present study suggests that aerial photography with a drone can provide a useful predictor of reef fish abundance.

Keywords Coral reef fish · Drone · Habitat structure · Seascape structure

Introduction

Patchy habitats often enhance species coexistence and, consequently, abundance of each species (Tilman and Kareiva 1997; Turner et al. 2001). Coral reef fish communities, which are among the most diverse animal communities in nature, occur on various sized patch reefs (e.g., Lowe-McConnell 1987; Sale 1991; Spalding et al. 2001). While species richness and abundance of individuals can be high in patchy habitats (Tilman and Kareiva 1997; Turner et al. 2001; Hattori 2002), several authors suggest that total area of habitat patches is the crucial determinant of species richness and abundance of each species (Lomolino 1994; Tjörve 2003; Fahrig 2013).

A back reef is an essential component of a mature fringing reef and harbors many coral reef fish. Back reefs are usually less than 3 m deep and include various sized patchy reefs that are formed by coral heads and outcrops dispersed throughout sandy bottom (Chave and Eckert 1974; Lowe-McConnell 1987; Spalding et al. 2001). Aerial photography at low altitude using unmanned aerial vehicles (UAV) or drones have been reported to provide detailed landscape or seascape images (Paine and Kiser 2012; Anderson and Gaston 2013). Aerial images of shallow back reefs can differentiate among the sandy bottom, submerged patch reefs and emerged patch reefs (see Hattori and Kobayashi 2007, 2009). However, aerial images usually provide two-dimensional information on habitat patches. A study that used high-resolution aerial color images as detailed field maps to assess species-area relationships of damselfish assemblages over 84 small patch reefs (> 0.75 m^2) within a back reef located at Ishigaki Island, Okinawa, Japan, found that a large patch reef harbored fewer species than small patch reefs of equivalent area (Hattori and Shibuno 2010). Subsequently, interspecific competition among territorial herbivores was found to be less intense on a tall reef (> 1.5 m in height) than on a flat reef because, on the former, inferior competitors were able to use the vertical side of the reef (Hattori and Shibuno 2013). Harborne et al. (2012) also reported that reefs with high rugosity (> 0.5 m difference in height) were found to harbor more species than reefs with low rugosity (≤ 0.5 m difference in height). Relatively low species density on large reefs may be attributed to tendency of larger reefs to be flat within shallow back reefs (Hattori and Shibuno 2010, 2013, 2015). Although high

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species richness and abundance of coral reef fishes are often related to high coral cover on coral reefs, many reef fishes inhabit structural habitats even in the absence of high coral cover (Pratchett et al. 2016). Structural complexity of seafloor influences species richness and abundance of each species (Pittman and Olds 2015). Total amount of patch reefs with high rugosity must be important for reef fish habitats.

Assessment of habitat quality of shallow back reefs is necessary to prioritize protection measures given threats from land reclamation, such as pier, airport and waterfront construction (Spalding et al. 2001; Tsuchiya et al. 2004; Hattori and Kobayashi 2007, 2009). Total amount of patch reefs with high rugosity may be an indicator of habitat quality. For example, total volume of 3D patch reefs (i.e., reef area × reef height) has been reported predictive of species richness of damselfish assemblages (Hattori and Shibuno 2015). In shallow back reefs, however, it is impractical for field ecologists or research divers to measure total volume of patch reefs, or structural complexity of seafloor, except for research using small quadrats (e.g., 5 m × 5 m), because of complex seascapes and shallowness. The present study examined whether two indicators from aerial images on a hectare scale (2.9 ha) can be used for habitat quality assessment of coral reef fish: (1) total area of dark-colored patch reefs that are detectable on an ordinary aerial photograph with image analysis software, and (2) total area of tall patch reefs (> 1.5 m in height) that are detectable on stereoscopic aerial images with a stereoscope.

Hattori and Shibuno (2010) investigated species richness and abundance of individuals of damselfishes among 84 small patch reefs and found that abundance of anemonefish *Amphiprion frenatus* was most positively correlated to damselfish species richness. In addition, Hattori and Kobayashi (2007) reported that total area of dark-colored patch reefs that were detected on aerial images reflects total number of *A. frenatus*, although they used analog type aerial photographs and did not distinguish *tall* patch reefs (> 1.5 m in height) from the dark-colored patch reefs. The objective of the present study was to examine whether total area of *tall* patch reefs (> 1.5 m in height) that are detectable on stereoscopic aerial images, as well as total area of dark-colored patch reefs that are detectable on ordinary aerial images, can be used for habitat quality assessment of the anemonefish. Total area of dark-colored patch reefs can be compared with the results of Hattori and Kobayashi (2007). Underwater observations on patch reefs were also conducted to confirm relationships between anemonefish abundance and total area of patch reefs.

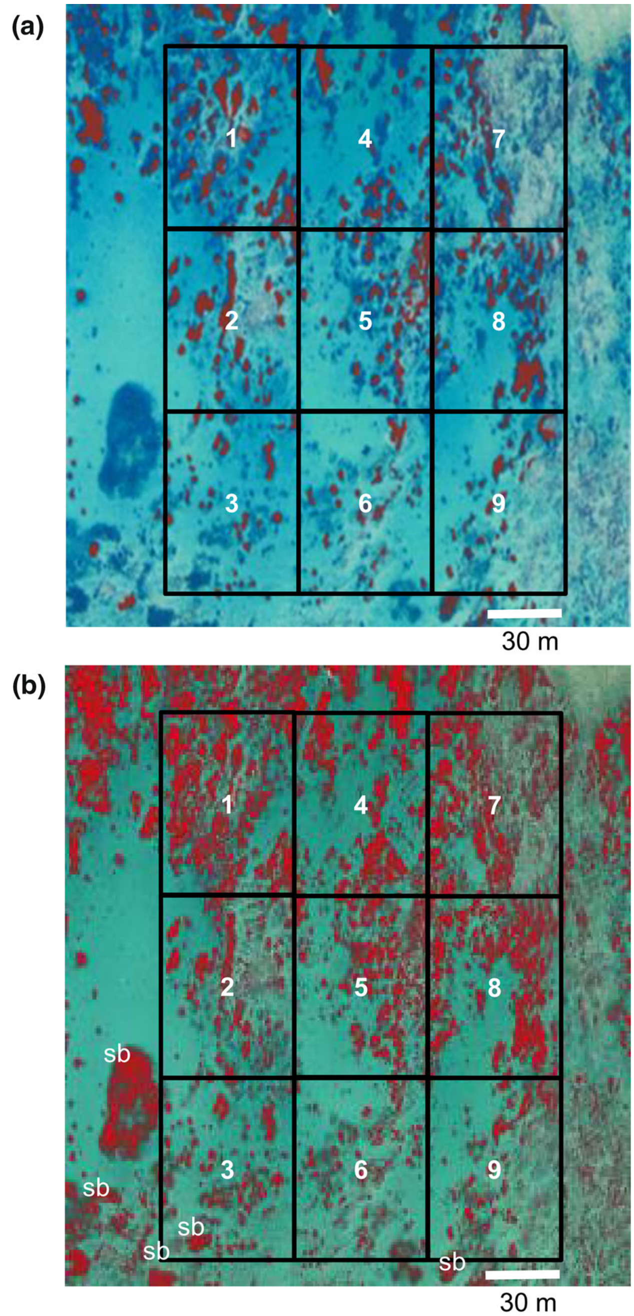

Fig. 1 Distribution of tall patch reefs (> 1.5 m in height) detected by a stereoscope (**a**) and dark-colored patch reefs (> 0.5 m in height) detected by image analysis software (**b**) on high-resolution digital aerial photographs taken in 2006. Color of seagrass beds (sb) could not be distinguished from that of dark-colored patch reefs on the aerial images. Based on field observations, areas of seagrass beds were removed from the images to measure reef areas. Squares indicate nine quadrats with quadrat number. See text for details

Materials and methods

The present study was conducted within a shallow back reef, Shiraho Reef (24°22′N, 124°15′E), located at Ishigaki Island, Okinawa, Japan, the same site (Fig. 1a, b, 151×193 m^2, maximum depth = 3 m at spring high tide) as that previously described (Hattori and Kobayashi 2007). In the present study, dark-colored patch reef was defined as natural reefs that were detectable on aerial images with image analysis software (> 0.75 m^2 in area and > 0.5 m in height, as defined in Hattori and Kobayashi 2007; Hattori and Shibuno 2010), which were formed by coral, e.g., coral patches and outcrops dispersed throughout the sandy bottom. Study site was divided into nine quadrats on aerial photographs (667 × 537 pixels, 1 m = 10.6 pixels). To detect *tall* patch reefs (> 1.5 m in height), two high-resolution digital aerial photographs taken on 20 September 2006 at an altitude of 1500 m for stereoscopic vision (a sequence of aerial photographs) to make geographical land maps (ground resolution = 8 cm, 2540 dpi, 1/10000, PASCO Co., Ishigaki C-19-1608 and C-19-1607) were examined with a stereoscope (SOKKIA, Mirror Stereoscope, Model MS27). *Tall* patch reefs on printed aerial images were marked directly with a red pencil, and the red-colored print was converted with a scanner to a digital image (Windows BMP format) of resolution 600 dpi. Pixels colored red were extracted from the image, and all other pixels were deleted using image analysis software (Adobe Photoshop 7.0). Extracted pixels were processed into binary images. Total area of *tall* patch reefs in a quadrat was measured using Image J 1.33 (a public domain program, developed at US National Institutes of Health and available on the Internet at http://www.rsb.info.nih.gov/ij/docs/index.html). Total area of dark-colored patch reefs (> 0.5 m in height) was also measured on a computer, as described (Hattori and Kobayashi 2007). Seagrass beds had the same colors as dark-colored patch reefs on aerial images. After field observations, the dark colors for seagrass beds were removed with image analysis software. To determine changes in area of dark-colored patch reefs from 1995 to 2006, percentage of each area of dark-colored patch reef in a quadrat was calculated. Perimeters of patch reefs could not be determined, be-

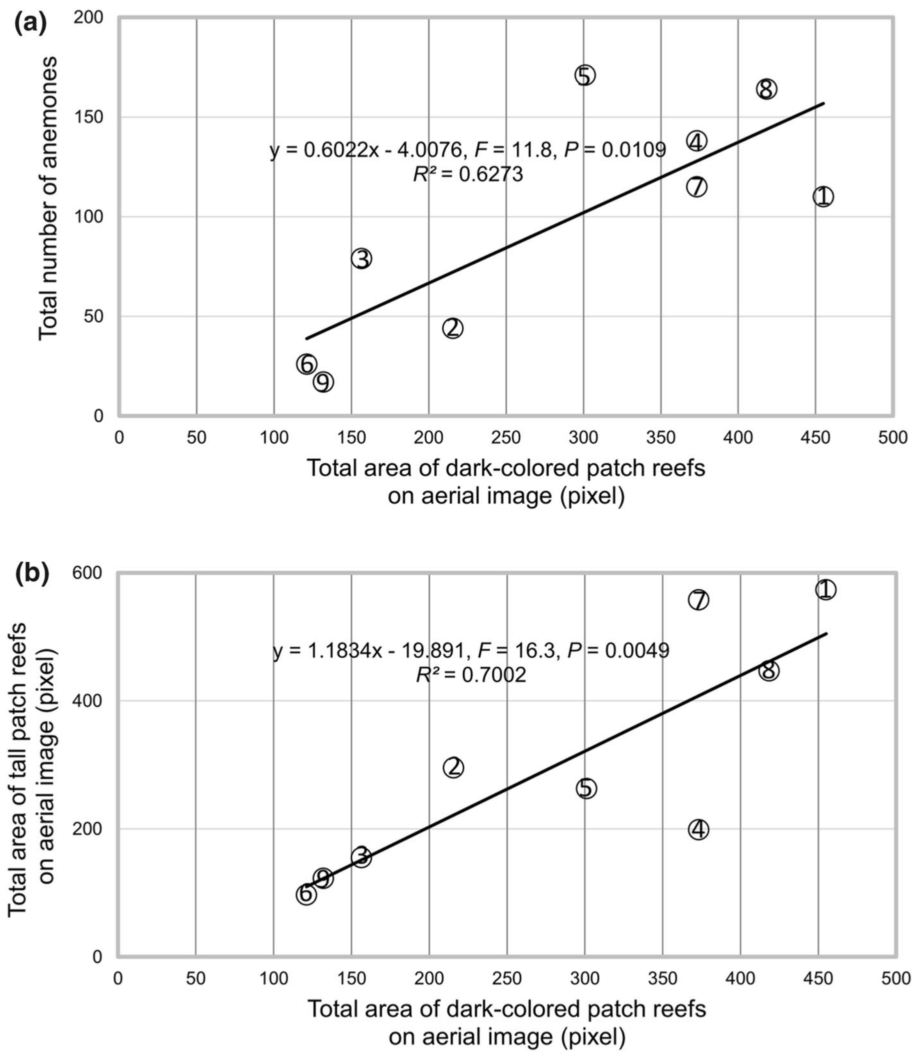

Fig. 2 Relationship between total area of dark-colored patch reefs (pixels) and total number of anemones counted in 2014 (indicator of number of anemonefish) in each of nine quadrats (**a**), and relationship between total area of dark-colored patch reefs and total area of tall patch reefs (**b**). These areas were measured with image analysis software on aerial photographs taken 2006. Number in circle indicates quadrat number

cause these pixels on high-resolution digital aerial images were too fine (like a point drawing) to provide practical edge lines.

The giant sea anemone *Entacmaea quadricolor* is an indicator species for abundance of *Amphiprion frenatus*, because this anemonefish inhabits *E. quadricolor* only (Allen 1975; Fautin and Allen 1992; Hattori 1991, 2005; Kobayashi and Hattori 2006; Hattori and Kobayashi 2007). To determine relationships between total area of patch reefs and anemonefish abundance, total number of *E. quadricolor* in each quadrat was assessed on the seascape map. That is, one part of the sequence of aerial images (C-19-1607) was enlarged, printed, waterproofed and used to map anemones in June and July 2014. While searching for anemones and plotting their location on seascape maps, environmental features were determined. Original data of Hattori and Kobayashi (2007), which were determined in 2002 using aerial images taken in 1995, were reanalyzed and compared with results of present study. All data were analyzed with R 3.0.1 statistical software (R Development Core Team 2013).

Results

Total number of anemones per quadrat in 2014 was highly correlated with total area of dark-colored patch reefs (Pearson product moment correlation coefficient: $r = 0.79$, $t = 3.43$, $P = 0.011$, $n = 9$, Fig. 2a), similar to findings in 2002 (Hattori and Kobayashi 2007). In contrast, total number of anemones per quadrat did not correlate with total area of *tall* patch reefs, both in 2014 ($r = 0.50$, $t = 1.54$, $P = 0.17$, $n = 9$) and 2002 ($r = 0.62$, $t = 2.11$, $P = 0.07$, $n = 9$). There were no significant differences in average number of anemones per quadrat (96.0 vs. 91.3, t test: $t = 0.10$, $P = 0.92$, $n = 9$) between 2014 and 2002, although total number of anemones throughout entire study site increased from 822 in 2002 to 864 in 2014.

Total area of *tall* patch reefs was highly correlated with total area of dark-colored patch reefs ($r = 0.83$, $t = 4.04$, $P = 0.004$, $n = 9$), and regression line shown in Fig. 2b could be used to predict total area of *tall* patch reefs based on total area of dark-colored patch reefs. However, total numbers of anemones in Quadrats 4 and 7, where total area of *tall* patch reefs largely deviated from regression line in Fig. 2b, were very close to total numbers of anemones predicted from total area of dark-colored patch reefs and regression line in Fig. 2a. Field observations confirmed that Quadrat 4 contained *tall* patch reefs but many dark-colored patch reefs on seafloor (see Fig. 1). Direct observations also confirmed the abundance in Quadrat 7 of shallow platforms with bare substratum (i.e., reef pavement around lowest tides level, yellowish colors on aerial images of Fig. 1). Upper surface of a large and *tall* reef was very close to the water surface, involving bare substratum (e.g., a microatoll such as a large massive *Porites*, and a shallow platform or reef pavement). In contrast, field observations revealed that bare substratum was not present at sites corresponding to dark-colored patch reefs on aerial images.

Interestingly, both small and large reefs were present in Quadrat 5 (see Fig. 1), where total number of anemones was much higher than that predicted from total area of dark-colored patch reefs using regression line in Fig. 2a. In addition, Quadrat 5 contained a larger total number of anemones in 2014 than in 2002 (Fig. 3a). In contrast, total number of anemones had largely decreased from 2002 to 2014 in Quadrat 7 (Fig. 3a), where platforms with bare substratum were widely observed (see Fig. 1) and relative area (%) of dark-colored patch reefs had decreased (Fig. 3b). Total number of anemones had decreased over time in Quadrat 6 (Fig. 3a), where field observations confirmed that populations of branching *Acropora* had decreased. In Quadrat 1, relative area (%) of dark-colored patch reefs had increased markedly over time (Fig. 3b), whereas total number of anemones had not (Fig. 3a). Underwater observations revealed that short branching *Porites* had increased over time in Quadrat 1. Relative area (%) of dark-colored patch reefs had decreased in Quadrat 8 (Fig. 3b), where the area of bare substratum had decreased because of loss of soft corals but total number of anemones had not changed markedly (Fig. 3a).

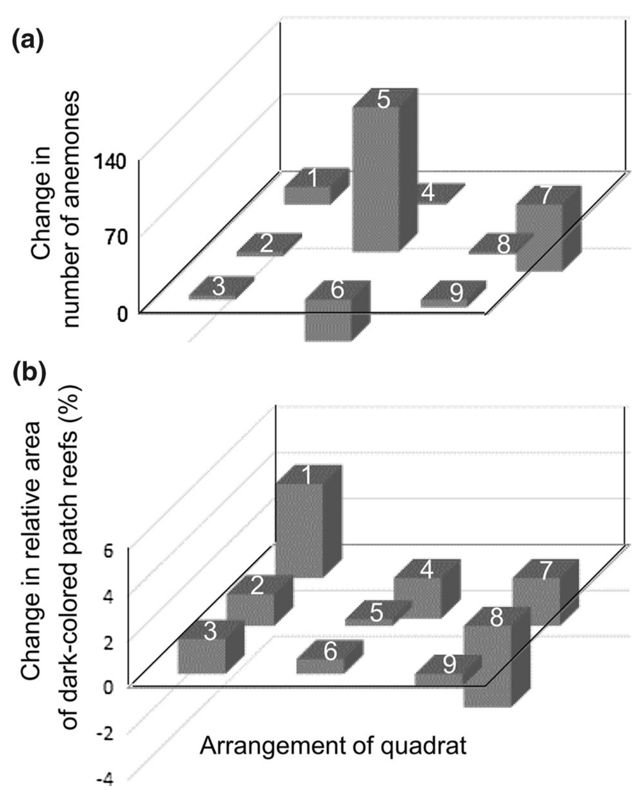

Fig. 3 Change in total number of anemones in each quadrat from 2002 to 2014 (**a**), and change in relative area (%) of dark-colored patch reefs in each quadrat from 1995 to 2006 (**b**). See text for details

Discussion

The present study demonstrated that total area of dark-colored patch reefs (> 0.5 m in reef height), as measured on aerial images, can be an indicator of anemonefish abundance, although it requires that areas of seagrass beds be removed from aerial images, based on field observations. Although number of anemones was found to show a stronger correlation with the product of total area and total perimeter of dark-colored patch reefs than with total area alone (Hattori and Kobayashi 2007), the perimeter of dark-colored patch reefs could not be determined in this study (see "Materials and methods"). After measuring height of 84 patch reefs within the present study site (2.9 ha), Hattori and Shibuno (2015) suggested that total volume ($\sum$ reef basement area × reef height) of dark-colored patch reefs is an indicator of total species richness of damselfish assemblages within shallow back reefs. Accordingly, we expected that total area of *tall* patch reefs (> 1.5 m in height) that were detected on a sequence of two aerial images with a stereoscope would indicate anemonefish abundance. However, upper surface of *tall* patch reefs, in which sessile organisms are exposed to air at lowest tides, often consisted of bare substratum, and total area of *tall* patch reefs did not relate with number of anemones (i.e., number of anemonefish). In contrast, dark-colored patch reefs that were detected on aerial images with image analysis software did not involve such bare substratum. Thus, all patch reefs taller than 0.5 m without bare substratum could be detected on aerial images without a stereoscope. In addition, comparison of total patch reef area between the present and the past aerial images could give some explanation about change in number of anemones. These indicate that unmanned aerial vehicles (UAV) or drones without stereoscopic aerial photography will be able to provide reliable information on patch reef habitats over a wide range.

Why could total area of dark-colored patch reefs reflect fish abundance in the present study? Volume of patch reef (i.e., reef area × reef height) was reported better explained by a linear than a power approximation of reef area in a shallow back reef site, although that study assessed only 84 patch reefs (Hattori and Shibuno 2015). Presuming that a small patch reef is a hemisphere of radius r, the living space around this reef is proportional to reef volume (Figs. 4a, 5a). In the present study site, large patch reefs tended to be flat (Fig. 4a; see Hattori and Shibuno 2013). Thus, if d = water depth, a large patch reef (i.e., $r > d$) should be a partial hemisphere of radius r and height d. As the basement area of a hemisphere is proportional to πr^2, the volumes of a small (i.e., $r < d$) and a large (i.e., $r \geq d$) patch reef will be proportional to $(2/3)\ \pi\ r^3$ and $(1/3)\ \pi\ d\ (3r^2 - d^2)$, respectively. At various values of r, reef volume at a place with sufficiently great water depth can be explained by a power function with the basement area (Fig. 4b). In shallow waters (d = 2 m at the lowest tide at the present study site), a linear function with the basement area was sufficient to determine reef volume (Fig. 4b). Thus, reef area approximately reflects reef volume in shallow waters, in which fish abundance correlates with total basement area (Fig. 5a) and total volume of patch reefs

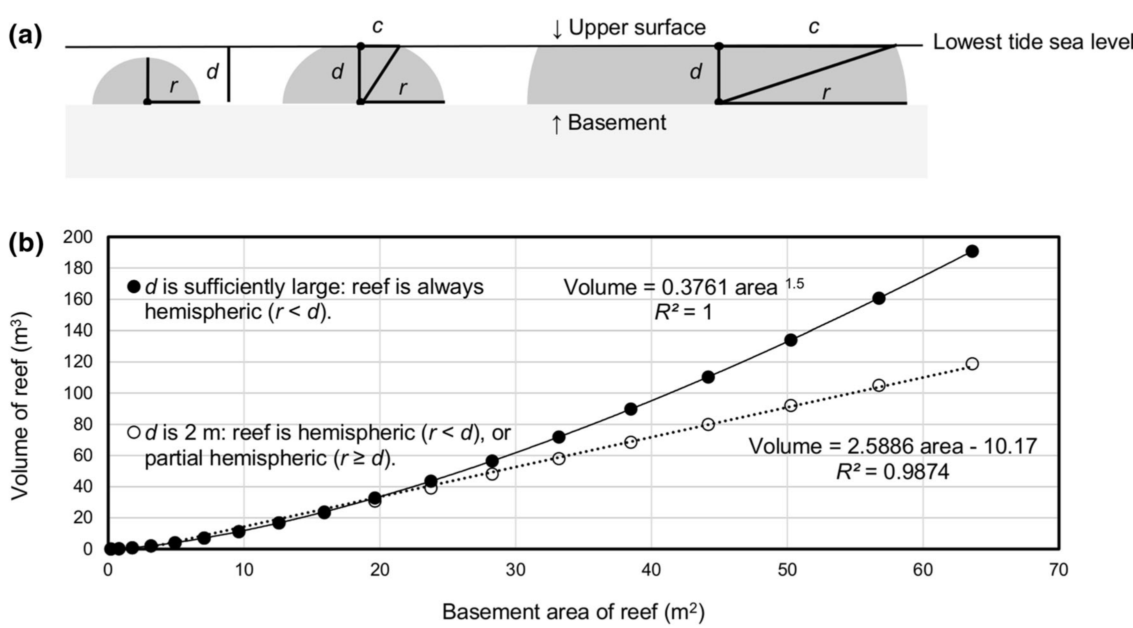

Fig. 4 A model to evaluate volume of patch reef with its basement area within a shallow back reef. d and r indicate water depth and radius of a hemisphere or partial hemisphere respectively (**a**): c indicates radius of the upper surface of the partial hemisphere but is deleted when volume is calculated. Relationship between basement area and volume of a model reef of various sizes is shown (**b**). Solid circles in the graph indicate a relationship when water depth is sufficiently large ($r < d$). Vacant circles indicate a relationship when water depth is 2 m (the lowest tide at the study site)

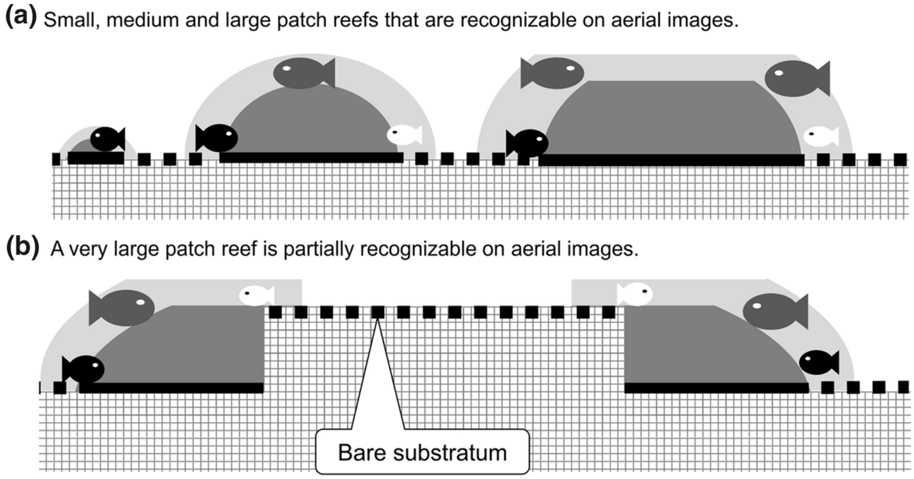

Fig. 5 A model of living space for reef fish around dark-colored patch reef that is recognizable on aerial images of shallow back reef. Living space (light grey) for reef fish around a dark-colored patch reef will be proportional to the volume (dark grey) of the reef (**a**). Basements of dark-colored patch reefs and sandy bottoms are indicated by solid lines and broken lines, respectively. On aerial images, bare substratum of a very large patch reef (**b**) is recognized as the same color as sandy bottoms, which are, therefore, distinguished from the dark-colored patch reefs (solid lines)

without bare substrata (Fig. 5b). In deeper waters, such as outside the reef slope, the total basement area of patch reefs will be unable to explain fish abundance (Belmaker et al. 2007).

Mature fringing reefs are often characterized by shallow platforms, or reef pavement with bare substratum, such as a wide platform on the reef flat (Spalding et al. 2001). On aerial images, the reef flat on a mature fringing reef appears as very large patch reefs, which will not harbor high species richness of reef fishes because living space for fish rarely include bare substratum (Fig. 5b). Because it does not contain bare substrata, total area of dark-colored patch reefs reflects total amount of reef fish habitats, which are measurable on ordinary aerial images (Fig. 5). In conclusion, aerial photography with a drone can provide a useful predictor of reef fish abundance within back reefs.

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