SIZE FREQUENCY MEASURES OF WHITE ABALONE WITH IMPLICATIONS FOR CONSERVATION

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ABSTRACT—To evaluate size structure and other population characteristics of white abalone (*Haliotis sorensoni*), survey dives were conducted in October 1999, using the Research Submersible DELTA in waters off the coast of southern California. The submersible surveyed rocky substrate at depths where recreational and commercial divers indicated white abalone populations were once abundant. Lasers projected spots in the field of view of a video camera, allowing length of items to be determined. Adults reach about 20–25 cm in length in southern California (males tend to be larger) and maximum size decreases in more southern latitudes. The mean length across all sites was 14.8 cm (n = 86). Mean length varied moderately, but significantly among the three sites with sufficient sample sizes to compare, with Tanner Bank having smaller animals than Cortes Bank and San Clemente Island. Although there were no white abalone that seemed small enough to be juveniles (<9 cm), juvenile abalone are notoriously cryptic, and detection may be difficult. The recovery of white abalone could be handicapped by recruitment failure due to low densities, which would result in populations dominated by larger, aging individuals. Although these data are insufficient to thoroughly evaluate recruitment failure, they may serve as a benchmark for future studies and restoration efforts.

Keywords: conservation, Haliotis sorensoni, recruitment failure, size, and white abalone

INTRODUCTION

Hobday and Tegner (2000) concluded that, between 1969 and 1977, legal fishing reduced white abalone (*Haliotis sorensoni*) density in the U.S. by several orders of magnitude. Fishing such as this, can lead to many important size-related changes in the exploited population (Halpern and Warner 2002). Therefore, we predict that size distribution shifts in this species are likely. Changes in size distributions can have profound effects on the ecology and evolution of a species (Halpern and Warner 2002); therefore, documenting these changes and predicting their implications are important to conservation efforts involving exploited species. Removing the largest individuals of a population may lead to a smaller average size and selection for individuals to begin to reproduce at a smaller size (Trexler and Travis 2000). This can have severe implications for the future of a stock, since the relatively low fecundity of smaller individuals can lead to a decline in the population growth rate. Low population levels may also decrease reproductive success, especially in broadcast spawners, which must be in close proximity for high fertilization rates. If recruitment failure of a stock occurs, this can conversely lead to an increase in average size as large animals grow and no small animals recruit into the population. This could eventually lead to populations dominated by larger, aging individuals.

The complexity involved in predicting size-related changes due to fishing is clear from the preceding paragraph; however, white abalone are unlikely to exhibit a reduction in average size due to the length of time since fishing ceased. By 1979, commercial fishing of white abalone declined to very low levels at the California Channel Islands and offshore banks (Karpov et al. 2000). White abalone grow at between 1.0 and 2.92 cm/year depending on size (Tutschulte 1976); therefore, in the 20 years between the cessation of intense fishing and this study, remaining animals should have grown to near the maximum size for the species. Due to this, we expect any residual size-related changes in white abalone will likely be represented by a paucity of small individuals due to a lack of recruitment.

White abalone occur between Punta Abreojos in Baja California, Mexico and Point Conception, California, USA, with Santa Catalina and San Clemente Islands the historic centers of abundance (Cox 1960, Leighton 1972). Relatively little is known of the life history of this deep dwelling species. Historically, white abalone have been most common in areas of boulders and sand (Davis et al. 1996) at depths between 25–30 m, feeding on attached and drift algae (Tutschulte 1976). Adults reached about 20–25 cm in length in southern California (males tend to be larger) and maximum size declined towards southern latitudes (Hobday and Tegner 2000). This species is of special concern, since the National Marine Fisheries Service listed white abalone as an endangered species in 2001 (NOAA 2001).

Hobday et al. (2001) and Lafferty et al. (2004) described the distribution, abundance and habitat characteristics of the remaining white abalone populations in southern California. Hobday et al. (2001) estimated the total population size at approximately 2,540 individuals with an average density of 2.73 ha^{-1} throughout southern California and Mexico. However, data from submersible dives showed that groups of white abalone were rare and that the effective population size was very small (Hobday et al. 2001), thus increasing the probability of reproductive and, therefore, recruitment failure. Lafferty et al. (2004) investigated the habitat preferences of white abalone and found that this species associated with a variety of food items and distributed themselves on rocks to facilitate the capture of drift algae. In addition, they found that white abalone density increased with distance from the nearest port, indicating that fishing pressure was likely greater at accessible islands than at more isolated offshore banks.

We describe the size distribution and ecological correlates with size of remaining populations of white abalone in southern California, observed from submersible dives, to address the following questions. First, are there differences in size between sites? Second, are offshore banks less likely to experience recruitment failure due to their isolation? The hypothesis that dramatic declines in the abundance of white abalone were a result of overfishing predicts that recruitment failure due to low densities should result in populations dominated by larger, aging individuals. Offshore banks have higher densities due to reduced fishing pressure; therefore, recruitment failure at these locations is less likely if larval transport is low. The last question involves the association between abalone size and the presence of other taxa in the community. Do the taxa that have been determined to affect white abalone densities (see Lafferty et al. 2004; eg., red urchins, fleshy algae, and coralline algae) have similar effects on white abalone size? This might indicate that some of the same processes that lead to higher densities also affect white abalone size.

STUDY AREA, MATERIALS AND METHODS

Survey dives occurred from 9 to 25 October 1999, using the Research Submersible DELTA and the Research Vessel VELERO IV in waters off the coast of southern California, including the Santa Cruz, Anacapa, Santa Barbara, Santa Catalina and San Clemente Islands and at the Osborn, Farnsworth, Tanner and Cortes offshore banks (Fig. 1). As on previous dives (Davis et al. 1996, Davis et al. 1998), the submersible surveyed rocky substrate at depths where recreational and commercial divers indicated white abalone populations were once abundant.

When over appropriate habitat (rocky substrate 30–70 m deep), the pilot moved slowly and closely over the substrate as the observer searched for live abalone and shells of abalone. During the surveys, a Hi8 video camera and light mounted to the starboard side of the submersible recorded part of the field of view, time, date and depth. Two parallel lasers set at a distance of 20 cm projected spots in the video's field of view, allowing length measurements of items from the video. Subsequent study of VHS copies of the videotape allowed the extraction of lengths and additional information. We measured the greatest shell length and distance

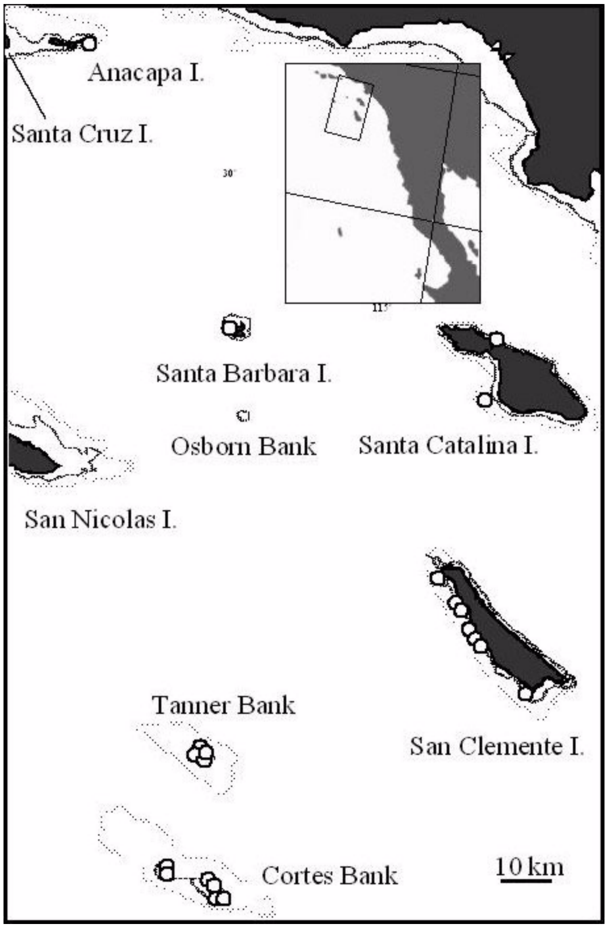

Figure 1. Map of the study area. White circles represent areas where white abalone were found. Of these locations, Tanner and Cortes Bank were classified as remote, while Anacapa, Santa Barbara, Santa Catalina and San Clemente Islands were classified as accessible. Inset map shows southern California (USA) and Baja Mexico (Mexico).

between the lasers at the point where the lasers were closest to the abalone, and converted the two lengths to the estimated shell length. Fixed parallel lasers are commonly used to estimate lengths from submersible video footage and have been found to be accurate as long as the subject is within 2.5 m of the camera (Yoshihara 1997, Yoklavich et al. 2000). White abalone greater than 2.5 m from the submersible were not measured due to this difficulty. In cases where the shell was at an angle to the video, we oriented a hand-held white abalone shell to a similar angle, and estimated the difference between the apparent shell length and the true shell length.

For each abalone on the video, we estimated the maximum dimension of the rock it occupied according to the following five size classes: 0–40, 41–80, 81–120, 121–160, and >160 cm. We noted the presence of fleshy algae, crustose coralline algae, and articulated coralline algae within 0.2 m of an abalone. The presence of neighboring red sea urchins (*Strongylocentrotus franciscanus*) was recorded if they were within 0.5 m of an abalone. We used presence data, since accurate measures of density were unavailable. Additionally, we chose the above distances (0.2 and 0.5 m) based on movement patterns of the organisms and the constraints of the video field of view. For analyses, islands and offshore banks were classified as accessible and remote (see Fig. 1), respectively, based on distance from the mainland. The offshore banks are further from ports than the more accessible islands and lack protected anchorages. Due to these two factors, fishing pressure should have been reduced at the offshore banks. This is likely the case since Hobday et al (2001) showed landings were highest at San Clemente Island, while largest populations of white abalone were found on the offshore banks. If overfishing at accessible locations has led to recruitment failure, remote locations should show a smaller mean size; therefore, a one-tailed test for significance was used to test whether white abalone size increases with site accessibility. A stepwise approach was used to construct a general linearized model (GLM) that best predicted individual white abalone size, controlling for depth, based on rock size, the presence of the above taxa, and accessibility of the location.

RESULTS

Fifty-eight of the 70 dives in 1999 were over suitable abalone habitat. We located 157 live white abalone, of which 86 could be clearly seen and measured from the video footage. The mean length of measurable white abalone, given as the maximum length of the shell, was 14.77 cm (Fig. 2; SD = 2.63, n = 86). Mean length varied moderately, but significantly among the three sites where we collected sufficient sample sizes to compare (Fig. 3). Tanner Bank (13.38 cm, SD = 2.41, n = 33) had smaller animals than Cortes Bank (15.59 cm, SD = 2.09, n = 23) and San Clemente Island (16.31 cm, SD = 2.60, n = 21; $F_{2, 74}$ = 11.40, P < 0.001, ANOVA).

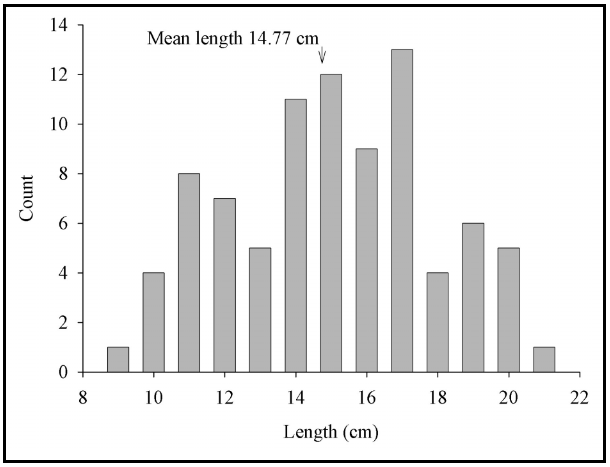

Figure 2. Distribution of the shell lengths of white abalone from all locations combined from the 1999 survey (mean length = 14.77 cm; *SD* = 2.63, *n* = 86).

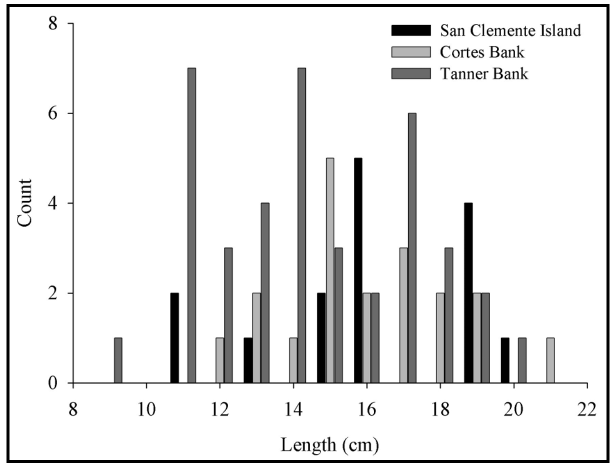

Figure 3. Distribution of the shell lengths of white abalone at San Clemente Island, Cortes Bank and Tanner Bank from the 1999 survey. Lengths varied significantly among locations ($F_{2, 70}$ = 3.29, *P* = 0.04, ANOVA).

After controlling for depth using GLM, white abalone size was not significantly associated with the presence of fleshy algae or articulated coralline algae; however site accessibility, maximum rock size, presence of nearby crustose coralline algae and red sea urchins were associated with white abalone size (R^2 = 0.36, $F_{8, 85}$ = 5.41, $P < 0.001$). The model found that white abalone size was smaller at remote sites (14.29 cm, *SD* = 2.63, *n* = 56) than at accessible sites (15.65 cm, *SD* = 2.52, *n* = 30; *F* = 2.81, *P* = 0.049). Additionally, white abalone were largest on intermediate size rocks (41–80 cm size class) and size declined as rock size increased (*F* = 5.41, $P < 0.001$). The presence of certain taxa nearby were also associated with larger white abalone, including crustose coralline algae (coralline algae: 14.81 cm, *SD* = 2.57, *n* = 83; no coralline algae: 13.48 cm, *SD* = 4.51, *n* = 3; *F* = 6.08, *P* = 0.016) and red sea urchins (urchins: 16.46 cm, *SD* = 2.52, *n* = 17; no urchins: 14.35 cm, *SD* = 2.52, *n* = 69; *F* = 14.53, P < 0.001).

DISCUSSION

Submersible surveys of white abalone populations throughout southern California documented white abalone size distributions. Although there were no white abalone observed that seemed small enough to be juveniles (<9 cm), indicating the possibility of recruitment failure, juvenile abalone are notoriously cryptic (Cox 1960), and observers could have missed animals that were present. However, the smallest individuals differed between locations, indicating that either animals become emergent at different sizes at different locations or there are real differences in the number of the smallest abalone between locations. The limited size-frequency data were consistent with Cox's (1960) account of a 20–25 cm maximum size and 13–20 cm mean size with animals smaller than 10 cm being rare. However, no individuals larger than 21 cm were observed indicating either the possibility of a decline in maximum size or that abalone as large as 25 cm have always been exceedingly rare.

White abalone populations throughout southern California showed variation in abalone size correlated with rock size and the presence of certain other taxa. These results can be compared with similar analyses of the effects of habitat characteristics on white abalone density by Lafferty et al. (2004) to determine if the same characteristics that are associated with high densities are also associated with aspects of white abalone size. White abalone were largest on intermediate size rocks, but more common on large rocks. The number of abalone on a given rock is likely limited by space; therefore larger rocks contain more abalone. However, smaller rocks likely contain fewer conspecific competitors, and due to their size, result in abalone being located closer to the sand-rock interface and sources of drift algae, both possibly leading to higher growth rates. Additionally, white abalone were both more common and larger when in close association with red sea urchins and crustose coralline algae. White abalone were more likely to be feeding when closely associated with red sea urchins (Lafferty et al. 2004). This increased feeding may have led to increased growth near red sea urchins. However, it is also possible that locations that are good for abalone growth are simply more productive for urchins. Therefore, it is likely that the some of same species that are associated with white abalone habitat selection are positively related to white abalone size, however rock size does not does not associate with habitat selection in a similar manner to abalone size.

White abalone were larger at accessible locations whereas at remote locations they were more abundant. Recruitment failure due to the isolation of remaining individuals would result in a size distribution dominated by large, aging adults and an absence of new recruits. A positive association between density and recruitment is one possible explanation for the higher proportion of small individuals at remote locations, specifically Tanner Bank, which has the highest density and had the smallest abalone observed. Intraspecific competition could also depress growth rates leading to smaller sizes in areas with the highest densities, however, this is unlikely since current population levels are much lower than the historical carrying capacity and white abalone existing in groups are rare (Hobday et al. 2001). The relative lack of smaller size classes at the accessible locations is possibly a result of some degree of recruitment failure in the areas most heavily fished.

The degree to which recruitment has failed is difficult, if not impossible, to determine due to the difficulty of surveying for cryptic juveniles at the depths at which this species lives. There are, however, some data to suggest that there has not been complete recruitment failure. In 2000 and 2001, white abalone recruits were found in artificial recruitment modules maintained by the National Park Service. Two recruits (sizes 32 and 38 mm) were found in 2000 at Yellowbanks on Santa Cruz Island, a site with few adults, and one recruit (29 mm) was found in 2001 at Yellowbanks (Kushner et al. In press, Kushner and Lerma in prep). Since the recruit found in 2001 is smaller than the two recruits found in 2000, these individuals likely represent separate recruitment events. It is probable that these recruits were produced locally, rather than dispersing as larvae from southern regions with higher white abalone densities, because abalone larvae only disperse short distances (Kinlan and Gaines 2003). For example, a direct measure of dispersal for Black lip abalone, *Haliotis rubra,* is 0.015 km and a genetic estimate of dispersal for black abalone, *Haliotis cracherodii*, is 24.2 km (Kinlan and Gaines 2003). Therefore, while dispersal can be much greater than the mean, the probability that multiple abalone larvae could disperse greater than 100 km from the southern offshore banks to Santa Cruz Island is very low. Therefore while there is evidence for some degree of recruitment failure associated with heavy fishing, some populations outside the areas with highest densities are still able to reproduce.

These data indicate that white abalone conservation efforts must address the possibility of recruitment failure in some populations. Because the effective population size of this species is extremely low due to the lack of aggregations (Hobday et al. 2001), outplanting strategies should address the need for aggregations including males and females to maximize the reproductive output of the population.

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