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Southwest monsoon effects on the growth of juvenile abalone (*Haliotis mariae* Wood, 1828) along the western Dhofar coast, Arabian Sea, Sultanate of Oman

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HIGHLIGHTS

- We quantified seasonal incremental growth in juvenile abalone.
- We established a link between seasonal upwelling and abalone growth.
- We established the relationship between seasonal temperature and growth.
- We illuminated the importance of the south west monsoon on productivity and abalone growth.

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ABSTRACT

An experimental tag and release/recapture experiment with juvenile *H. mariae* in three areas, Hassila, Haat and Raha, along the Dhofar coast of Oman demonstrated that the growth rates of *H. mariae* are driven by season and temperature. The winter NE monsoon and the summer SW monsoon have a significant effect on the monthly incremental growth of juvenile abalone (30–63 mm shell length, $p < 0.001$). The peak average growth rates, up to 7.4 (SD ± 2.5) mm and 8.4 (SD ± 2.5) mm per month, occurred in October and September, respectively, with minimal growth of <1 mm occurring from March to May. The growth increases coincided with the blooming of *Ulva sp.* when the temperatures decreased and upwelling occurred. Growth also peaked when the kelp species *Sargassum* and *Sargopsis* were abundant. Complete growth inhibition occurred during April and May when very little algal biomass is available. The peak summer growth rates were approximately 3 times the lowest winter growth rates. A close relationship was identified between the chlorophyll-a levels and abalone growth. Increases in marine productivity are reflected in both the chlorophyll-a levels and the seasonal algal diversity, and the abundance is likely the most dominant driver of increased abalone growth along the Dhofar coast.

1. Introduction

The wild abalone (*H. mariae* Wood, 1828) fishery is an integral part of the Omani fishing culture. The fishery, which lies along the western Dhofar coast between Mirbat and Hassik (Fig. 1), has been in decline for a number of years (Balkhair et al., 2013; De Waal et al., 2013; Al-Hafidh, 2006). As a result, abalone restocking research is currently underway in Oman (De Waal et al., 2013). Increased seed size increases the survival of newly seeded juveniles; therefore, seeding during periods of high growth may have positive effects on seed survival (De Waal et al., 2013; Hart et al., 2013). The objective of this study is to quantify seasonal growth to optimize survival by seeding in the correct season.

The near-shore sub tidal zone of this stretch of the Dhofar coast is highly influenced by the annual southwest (SW) monsoon that begins in June and ends in September (Piontkovski and Claereboudt, 2012; Tudhope et al., 1996; Shepherd et al., 1995; UNEP, 1985). The resulting cold upwelling and nutrient rich waters that are forced inshore (negative peak ±18 °C, Sanders, 1982) promote the growth of *Ulva sp.* and other algae, including macro algal forests of *Sargassopsis zanardinii, Sargassum spp.* and *Ecklonia radiata* (Al-Hafidh, 2006; Shepherd et al., 1995; Ormond and Banaimoon, 1994; UNEP, 1985). These seasonal macro algal communities peak during the post-monsoon season (September to October) and begin to decline during the winter months (November to January) when the northeast (NE) monsoon occurs and temperatures are in excess of 20 °C (Al-Hafidh, 2006; Shepherd

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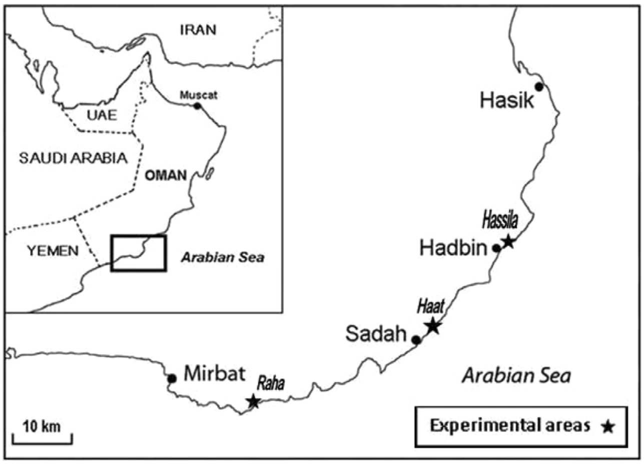

Fig. 1. The abalone rich area of the western Dhofar coast of Oman, inset map shows the Hadhramout coast along southern Yemen.

et al., 1995; Sanders, 1982). By the end of March, the majority of these macro algal species have largely disappeared. The effects of the SW monsoon also extend along the Yemeni Hadhramout coast, which supports many of the algal species found along the Dhofar coast (Ormond and Banaimoon, 1994; UNEP, 1985; Figure I) and also one species of abalone, *Haliotis pustulata* (Ali et al., 2009). The impact of the SW monsoon on the productivity along this coast is significant (Piontkovski and Claereboudt, 2012; Tudhope et al., 1996; UNEP, 1985). Satellite-derived chlorophyll a levels are a sensitive indicator of biological productivity in the offshore and coastal waters of the Arabian Sea (Piontkovski and Al-Jufaili, 2013).

A number of studies have been conducted on the growth of *H. mariae* (Balkhair et al., 2013; Al-Rashdi and Iwao, 2008; Al-Hafidh, 2006; Siddeek and Johnson, 1997; Shepherd et al., 1995; Siddeek and Johnson, 1993; Sanders, 1982). Most of these studies measured growth checks and growth rings (Shepherd et al., 1995) or used models, such as ELEFAN, that assessed the shell length frequencies of the harvested shells to calculate the growth and recruitment patterns (Siddeek and Johnson, 1993). Only a limited number of experiments were conducted in which individually tagged abalone were released into the wild to be recaptured and measured for shell length (SL) growth. In these experiments, growth was monitored for extended periods of 9 months to one year (Al-Hafidh, 2006; Shepherd et al., 1995). As a result, growth was calculated over an extended period of time and the seasonal growth patterns could not be quantified. These studies produced a range of first year growth rates, ranging from 35 to 78 mm SL, nearly linear in the first year and then beginning to taper off during the second or third year (Balkhair et al., 2013; Siddeek and Johnson, 1997; Shepherd et al., 1995; Sanders, 1982). Although these authors refer to the seasonality of growth in this species, to date, this has not been directly investigated. In this study, the growth measurements were quantified over shorter time periods and the relationship between the chlorophyll a levels and growth was clearly established.

2. Materials and methods

2.1. Seeding, sampling and measuring growth

The abalone used were all hatchery reared. Growth was measured in juvenile abalone that were large enough to survive seeding in relatively high numbers but that remained in the linear growth phase (30–63 mm SL, De Waal et al., 2013; Hart et al., 2013). Each abalone was individually tagged with a numbered colored plastic tag fixed with superglue to the central area of the shell two days prior to seeding. The SL was individually measured for all abalone prior to release. All abalone were hand seeded at a density of approximately 10 abalone m^{-2} (De Waal et al., 2013). All of the sites were <6 m deep in a habitat that was considered to be suitable for juvenile abalone, including under boulder habitat cracks and crevices (De Waal et al., 2013). Seeding was performed in three geographic areas, Hassila, just east of Hadbin; Haat, just east of Sadah; and Raha, just east of Mirbat (Fig. 1). The tagged juveniles were then recaptured and the SL was again measured. The total SL increment was divided by the number of days in the water for each abalone. This daily average was then converted to a monthly average. The data of all abalone from each area, which was measured for a specific time period, were pooled to calculate an average for that specific area and period. The same experimental procedure was followed for both the NE and the SW monsoon periods.

The diving and, therefore, seeding and sampling conditions were much better during the NE monsoon than the SW monsoon period. This was reflected by the number of abalone sampled and the experimental period between seeding and sampling during the SW monsoon period compared to the NE monsoon period (Table 1). No data were collected in March or June, and not all sites yielded data for each of the other months.

3. Data analyses

All statistical analyses were performed using the statistiXL 1.8 software. Two analyses were conducted. First, the data were pooled from each area for each month and sorted according to the season (Table 1). Two-way ANOVA was then performed to test the site versus season (Table 2). Non-parametric Mann–Whitney tests were then conducted to determine the variability in average monthly growth increments between individual months for all of the areas pooled. Because the sites were not all at the same depth, the effect of depth on growth was tested.

Depth was estimated as an average, and the maximum tidal range was approximately 3.03 m. In Hassila, the sites used during the NE monsoon varied in average depth from 0.5 to 3 m, whereas all of the sites used during the SW monsoon were approximately 2 m deep. In Haat, all of the sites used in both monsoon periods ranged between 1.5 and 2 m. In Raha, the sites used in the NE monsoon ranged from 2.5 to 5.5 m, and during the SW monsoon, they ranged from 1 to 1.5 m. This depth range was too small to produce realistic depth related growth analyses (De Waal et al., 2013); therefore, no depth related analyses were performed.

The satellite derived chlorophyll-*a* concentration data for the Western Dhofar Coast (16.757–17.319 °N, 53.265–56.152 °E) and monthly sea surface temperatures (SST) were derived directly from the GES-DISC Interactive Online Visualization and Analysis Infrastructure software and were used to show the relationship between abalone growth, SST and primary production (Figure II, Piontkovski and Claereboudt, 2012).

4. Results

During the NE monsoon (winter) months, October to May, the growth rates of all three areas grouped together ranged between 8.37 and 0.86 mm $month^{-2}$ (Table 1). During the winter months, Raha yielded slightly lower monthly growth increments than both Hassila and Haat. The measurements taken in Hassila during April and May showed a marked decrease compared to the earlier growth rates from the same area (Table 1). During the SW monsoon (summer) months, the growth rates began to increase from July, with the maximum occurring in Hassila in September (10.28 mm $month^{-2}$). The maximum temperature occurred in October during the transition between monsoon periods in both Haat and Raha (9.76 and 8.37 mm $month^{-2}$, respectively, Table 1). The November growth rate in Raha was approximately half of that