Estimating Abalone Growth and Shell Morphometrics on a Sea Ranch in South-Western Australia

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Abstract

This study estimated the growth of tagged, hatchery-reared *Haliotis laevigata* (Greenlip abalone) released ("seeded") on artificial habitats (Abitats) in Flinders Bay, south-western Australia. It also evaluated a mark in the shell detected after transferring abalone from the hatchery to the ocean as a predictor of the size-at-release for the abalone. The research was carried out as part of commercial operations on the sea ranch which limited some of the data collected. A total of 117 tagged *H. laevigata* were released on the Abitats and harvested across three areas (lines). Growth in shell length (SL) was significantly slower on one line (1.96 mm month^{-1}) than the others (2.33 mm month^{-1} and 2.44 mm month^{-1}), possibly due to different pre-seeding histories. Slower growing abalone were retained in the hatchery for an additional 74 days compared to the faster growing abalone. However, growth in wet weight did not differ significantly among lines (2.22 g month^{-1}). This study provides the first estimates of the different shell-length characteristics for juvenile abalone: the mean (± 1 SE) SL: shell width ratio was 1.31 ± 0.005 and the SL: shell depth ratio was 4.94 ± 0.057, much greater than these ratios for mature *H. rubra* in southern Australia. The hatchery mark at harvest was a significant linear predictor of the shell length at seeding and was still present in abalone at harvest size (~100 mm SL), providing a way of estimating growth in *H. laevigata* on the sea ranch without the need for tagging.

Keywords: aquaculture-based-enhancement, greenlip abalone, *Haliotis laevigata*, tagging, growth models, artificial habitats

Introduction

Recent Food and Agriculture Organization (FAO) reports and a reconstruction of global catches show that world capture fisheries plateaued since the mid-1990s or declined if estimates of illegal, unreported and unregulated catches are included (Pauly and Zeller, 2016; Food and Agriculture Organization, 2020). Overfishing has been recognised as a significant impact on fish stocks and marine ecosystems globally (Pauly et al., 2002; Worm and Branch, 2012; Kleisner et al., 2013), negatively impacting sedentary, easily accessible micro-stocks within a metapopulation such as abalone.

Globally, abalone capture fisheries have declined dramatically since the 1960s (Prince, 2004), e.g. from 19,720 tonnes in 1970 to 6,500 tonnes in 2015 (Cook, 2016). In order to arrest the global decline in abalone capture fisheries, restrictions and total closures have been put in place in some commercial and recreational fisheries in the hope of rebuilding stocks for the future (Campbell, 2000). In addition, the aquaculture and sea ranching of abalone, particularly in China, has increased global production greatly (Cook, 2016; Gao et al., 2023).

In Australia, commercial abalone fisheries began in the mid-1960s with management strategies including minimum size limits and capping the number of commercial abalone divers (Prince et al., 1998; Prince, 2004). Four *Haliotis* species are fished commercially and recreationally, namely *Haliotis rubra* W.E. Leach, 1814 (Blacklip), *Haliotis laevigata* Donovan, 1808

(Greenlip), *Haliotis conicopora* Peron, 1816 (Brownlip), and *Haliotis roei* Gray, 1826 (Roe's) (Mayfield et al., 2012). Tasmania is Australia's largest abalone producer and has an average total yield from capture fisheries (~95 %) and aquaculture (~5 %) of 1,710 t year^{-1} of *H. rubra* and *H. laevigata* since 2015/16 (Mobsby et al., 2020).

In Western Australia, three species of abalone are harvested commercially (*H. laevigata*, *H. coconicopora* and *H. roei*) producing a total commercial catch of 40.1 tonnes and an estimated recreational harvest of 14.4 tonnes in 2022–23 (Strain et al., 2023). *Haliotis laevigata* is the main commercial species with a total allowable commercial catch set at 29.9 tonnes in 2022. Since 2010, Ocean Grown Abalone (OGA, now Rare Foods Australia) have been developing a *H. laevigata* sea ranching operation in south-western Australia, which produced 75.9 tonnes in the 2020/21 financial year (Ocean Grown Abalone, 2021), nearly three times the *H. laevigata* commercial catch in Western Australia (WA) in 2022–23 (26.1 tonnes, Strain et al., 2023).

The use of aquacultured individuals to restore and rebuild fisheries, i.e. aquaculture-based-enhancement (ABE), is increasing globally (Taylor et al., 2017; Lorenzen et al., 2021). Sea ranching is one form of ABE and has been defined as "the release of cultured juveniles into open marine and estuarine environments for continued growth and harvest at a larger size, with no intention that the released animals contribute to the spawning biomass, though it may occur" (Bell et al., 2008). The immediate goal of sea ranching is to create production for the current generation (Kitada, 2018). Fisheries enhancement through sea ranching is practised over large scales for invertebrates and fish in China, Japan and South Korea (Taylor et al., 2017; Lee, 2019; Cheng et al., 2023). In these countries, sea ranching is often combined with the deployment of artificial reefs to increase production, thus combining ABE with habitat enhancement (Taylor et al., 2017; Lorenzen et al., 2021).

Sea ranching operations require good conditions for growth and low natural mortality to achieve economic success. Being able to estimate growth accurately provides a mechanism of predicting the likely yields at harvest and the returns from the ranch. It also allows conditions to be compared in different environments. Abalone growth in shell length (SL) is linear during the juvenile phase (Haddon et al., 2008) before growth in length asymptotes, and Prince (2005) showed that the growth of *H. rubra* in Tasmania is best described by a sigmoidal curve such as the Gompertz model or, alternatively, with a piecewise fit with linear growth for the juveniles up to maturity and a von Bertalanffy curve for the adults.

In Flinders Bay, south-western Australia (Fig. 1), OGA have commercialised the first abalone sea ranching venture in Australia (Taylor et al., 2017). This operation combines habitat enhancement by the use of patented concrete structures ("Abitats", Fig. 2) placed on the seafloor with "seeding" the Abitats with aquaculture produced juvenile abalone. These structures effectively trap drift algae whilst also providing a refuge for juvenile abalone to escape predation from octopus, stingray, fish and crab species (Greenwell et al., 2019). Juvenile abalone are seeded on the Abitats at a size of ~40 mm SL (age ~12–18 months) and left until harvest at an average size of 110 mm SL and 350 g ~3 years later, with no additional foods or nutrients supplied (Melville-Smith et al., 2017; B. Adams, OGA, 2020, pers. comm.).

Currently, OGA do not have any information on the variation in individual abalone growth across their lease. The aims of this study were to:

1. Estimate the growth rates of *H. laevigata* across the OGA sea ranching lease site in Flinders Bay, south-western Australia;
2. Determine the morphometric ratios between shell length: shell width and shell length: shell depth for juvenile abalone on the lease; and
3. Evaluate whether a mark laid down after moving abalone from the hatchery to the ocean environment (a hatchery mark) provides a good estimate for the size at seeding and if so, whether it can be used to accurately estimate abalone growth without tagging.

Materials and Methods

Ethical approval

The abalone tagged and harvested in this study were collected as part of commercial operations by the OGA company. As a consequence, no animal ethics approvals were required for this research.

Study site

The study area was the OGA 413 ha lease site within Flinders Bay, Augusta, off south-western Australia (Fig. 1), where *Haliotis laevigata* (Greenlip abalone) are ranched on Abitats (Fig. 2). The OGA lease area is situated on flat sandy substratum interspersed with irregular patches of sea grass including *Amphibolis antarctica*, *Amphibolis griffithii*, and *Halophila ovalis* at water depths ranging from 15 to 19 m (Greenwell et al., 2019). The southern part of Flinders Bay is characterised by fringing reefs colonised by macroalgae, particularly *Ecklonia* spp., and natural rocky reefs to the east and west of the lease site (Melville-Smith et al., 2013).

Lease configuration

In 2020 OGA had 10,000 Abitats deployed in Flinders Bay arranged in 21 "lines" of artificial reef structures, hereafter referred to as lines (B. Adams, OGA, 2020, pers. comm.). The focus of this study is on abalone growth on three lines chosen by OGA: Boranup, Bears and Puerto; located within 2.5 km of each other on the lease. Each Abitat is constructed from concrete and

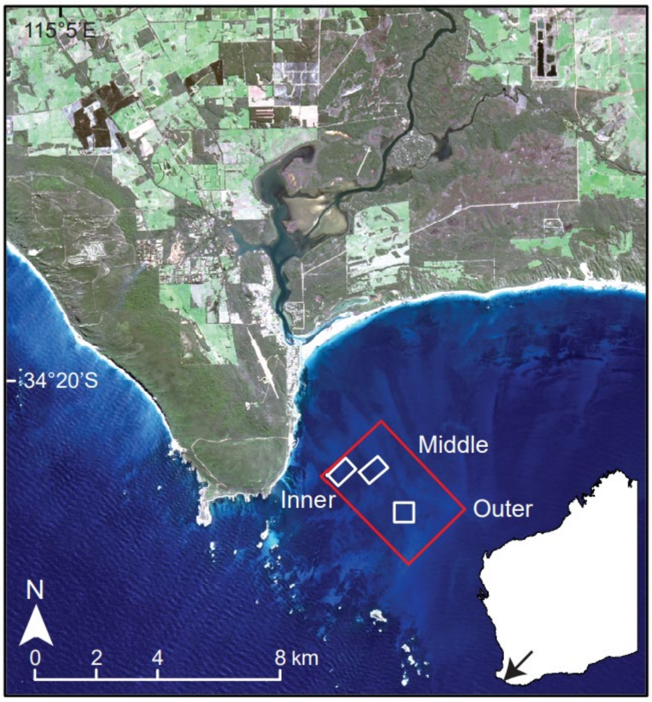

Fig. 1. Satellite image (Landsat 2016) showing the initial lease locations (inner, middle and outer), and the amalgamation of the previous leases (red rectangle) of the 413 ha sea ranching lease (B. Adams, OGA, 2020, pers. comm.) for *Haliotis laevigata* operated by Ocean Grown Abalone in Flinders Bay, south-western Australia. Inset denotes the location of Flinders Bay in Australia. Modified from Greenwell et al. (2019).

Fig. 2. The artificial reefs (Abitats) used on the abalone sea ranch in Flinders Bay, south-western Australia. Abitat dimensions: height = 0.9 m; base area = 1.4 m^2; total surface for abalone = 9.34 m^2; weight = 900 kg. (Photo supplied by B. Adams, Ocean Grown Abalone).

stands 0.9 m high, has a base footprint of 1.4 m^2 and a surface area of 9.34 m^2 for abalone habitat (Fig. 2). Lines run perpendicular to the prevailing south-westerly swells and are positioned adjacent to naturally occurring seagrass beds to best trap drift algae, maximising food availability for abalone.

Culturing abalone and seeding of Abitats

Mature abalone (broodstock) from Flinders Bay are used to produce juvenile abalone at ~40 mm SL from a commercial company, 888 Abalone in Bremer Bay, located about 480 km east of Augusta. Individuals are first placed into nursery tanks, which have been seeded with diatoms and *Ulvella* sp., 6 days after fertilisation. After 6 months abalone are graded by SL and moved into hide tanks containing concrete bricks to simulate natural habitat where they can shelter. The hide tanks are supplied with unfiltered sea water and the abalone are fed an artificial pelletised feed (Yumbah and Aquafeeds). After a further 6 months in the hide tanks abalone are again graded by SL, with those deemed large enough moved into the raceways for their final growth phase in the hatchery (J. Poad, 888 Abalone, 2021, pers. comm.). This process ensures that harvested individuals for transport to Flinders Bay and seeding on Abitats are of a similar SL, but not necessarily of a similar age.

Juvenile abalone are packed into specially designed release units holding ~200 abalone and transported to

Augusta in oxygenated tanks, where they are loaded onto OGA commercial dive vessels and taken to the lease area for seeding on Abitats. Transport from the hatchery in Bremer Bay to Augusta takes ~5 h and abalone are seeded on the Abitats within 12-24 h of their harvest. Divers secure the release units onto the Abitats, and the release units are left for 3-4 weeks to allow the juvenile abalone to move out and colonise the Abitats (B. Adams, OGA, 2020, pers. comm.).

Abalone do not receive any supplementary feeding on the Abitats, as all nutritional requirements are obtained from the natural food in the surrounding environment (Melville-Smith et al., 2013). The sea ranch supports a diverse assemblage of drift algae and seagrasses that are dominated by two brown algae (*Scytothalia dorycarpa* and *Ecklonia radiata*), two seagrasses (*Zostera tasmanica* and *Amphibolis* spp. comprising *Amphibolis antarctica* and *A. griffithii*) and two red algae (*Pollexfenia pedicellata* and *Gracilaria flagelliformis*) (Melville-Smith et al., 2017).

Tagging abalone

Abalone were tagged and measured for initial SL and wet weight (WT) at the time of seeding and then measured again at harvest. Abalone were tagged using numbered tags backed with a steel spring placed onto the growing edge of the shell with the number facing up (Fig. 3, Hart et al., 2013). After tagging, abalone are ideally left for a minimum of 20 d in order for the shell to incorporate the tag's spring into its shell matrix, securing the tag in place and helping to minimise tag loss (Hart and Strain, 2016).

Two cohorts of hatchery-reared abalone were tagged: one tagged in the 888 Abalone hatchery 74 d before their transport and release; and the other tagged at the Flinders Bay marina immediately before release (Table 1). Commercial operations prevented this cohort being tagged 20 d prior to their release on the sea. Abalone were measured for SL to the nearest millimetre, using Vernier callipers and tagged, with a random sub-sample of at least 50 from each cohort also measured for WT to the nearest gram. Abalone were returned to the raceways for another 74 d before 871 abalone were packed and transported to Flinders Bay on 28th August 2019, when tagged abalone were remeasured (SL and WT) before being transported and deployed onto 8 reference Abitats along the Boranup line by OGA divers (Table 1). A total of ~120 abalone were seeded on seven Abitats on the Boranup line.

The second cohort was tagged on the 18th June 2019 at the Flinders Bay marina (Table 1). A total of 499 abalone were tagged, measured (SL and WT), placed in release units (50 per unit with 150 untagged abalone) and deployed on 10 Abitats on the Bears and Puerto lines. Each of the Abitats received 50 tagged abalone except one on the Puerto line, which received 49.

No investigations into tag effect were conducted during this study. The tagging method was the same as that used by Hart et al. (2013), who investigated tag loss and calculated a correction factor of 1.1 for survival, but not growth. As the tags are embedded into the shell matrix very quickly, and are quite small, we assumed no effect of tagging on growth following Hart et al. (2013).

Harvest and measurements of abalone

On 20th May 2020, OGA divers harvested a sample (n = 117) of the tagged abalone from Abitats, stored all tagged abalone in a labelled bag with the Abitat number, packed them on ice in oxygenated, styrofoam boxes and transported them 3.5 h to Murdoch University in Perth (~300 km north of Augusta) where they were stored in a cool room (4 °C).

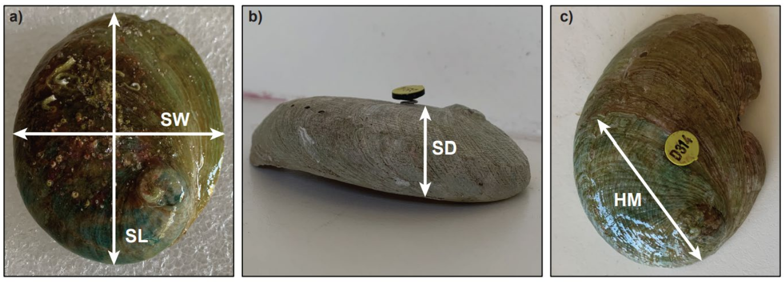

Fig. 3. Images showing the shell length measurements taken from tagged *Haliotis laevigata* from the Ocean Grown Abalone sea ranching farm in 2020. (a) shell length (SL) and width (SW), (b) shell depth (SD), and (c) the hatchery mark (HM). Spring loaded tag is also evident in b) and c). Note damage on the right hand side of shell in (c) is due to handling during harvest and transport.

Table 1. Details of tagging and seeding of abalone released on artificial habitats (Abitats) in Flinders Bay, south-western Australia.

Detail of cohort	Cohort 1	Cohort 2
Date tagged	16/6/2019	18/6/2019
Date(s) measured	16/6/2019, 28/8/2019	18/6/2019
Days between tagging and release	74	0
Release line(s)	Boranup	Bears, Puerto
Number released (Number/Abitat)	871 (120)	499 (50)
Date of harvest	20/5/2020	20/5/2020
Days on Abitats	266	337
Number harvested	75	42 (22 Bears, 20 Puerto)

The SL (Fig. 3a) and WT of harvested abalone were measured in the laboratory: SL to 0.1 mm using Vernier callipers and WT to 0.1 g using a balance (HF-300G, A&D, Japan). Shell width (SW, Fig. 3a) and shell depth (SD, Fig. 3b) were also measured using Vernier callipers. Each abalone foot was harvested and weighed to 0.1 g (FW). Shells were cleaned for epiphytes, and the width of a mark laid down after the abalone was transferred from the hatchery to the Abitats, termed the hatchery mark (HM, Fig. 3c), was measured. This mark is recognised by a change in shell colouration from light green inner shell during the time in the hatchery to a darker outer shell during the time on the sea ranch. Eight tagged abalone shells harvested at commercial size (108 to 128 mm SL, median SL = 113.5 mm) were also collected during commercial operations and their HM and SL were measured. These abalone had been in the ocean for between 1008 d (2.76 years) and 1104 d (3.02 years).

Environmental conditions

Temperature and dissolved oxygen (mg.L^{-1} and % saturation), were measured for part of the growing period at three locations on the OGA lease (the South Point, AC1 and Boranup lines) using miniDot loggers (Precision Measurement Engineering, Vista, California). These locations were chosen to span the width of the abalone ranching lease site and, except for the Boranup line, differ from those where abalone were seeded (Bears and Puerto). Loggers were set to record temperature and dissolved oxygen every 10 min, and were deployed on the 20th March 2020 and retrieved on the 31st May 2020, 72 d later. The R statistical package (R Core Team, 2020) and packages gt (Iannone et al., 2020) and ggplot2 (Wickham, 2016) were used to calculate descriptive statistics and visualise the environmental data over the 72 days of deployment. Data on monthly sea-surface temperatures (SST) were retrieved from the NOAA grid including Flinders Bay for the months when abalone were on the Abitats.

Abalone data analyses

Abalone were measured for SL and WT at the time of seeding and at the time of harvest from each of the Boranup, Bears and Puerto lines (n = 75, 22, and 20, respectively, at harvest) to determine an estimated growth rate during their ocean growth phase. Though the harvest date was the same for all lines (20th May 2020), the time of seeding differed among lines. Abalone were seeded on the Bears and Puerto lines on 18th June 2019 and were in the ocean for 337 d, while those on the Boranup line (seeded 28th August 2019) had 266 d in the ocean. Individual abalone growth rates were calculated from the increase in growth during the time in the ocean (harvest SL – seeding SL), divided by the number of days in the ocean to calculate daily and "monthly" (i.e. 30 d) growth rates. Differences in mean growth rates (SL and WT) among lines were tested using a one-way ANOVA.

The relationship between SL and WT was calculated for all abalone tagged at seeding and at harvest (n = 1487) and expressed in the form:

$$log_e\,(WT_i) = \beta_0 + \beta_1\, log_e(SL_i) + \epsilon_i$$

where WT_i denotes total WT, SL_i denotes SL, and $\epsilon_i \sim N\,(0, \sigma^2)$ is the error term for some constant measure of variability σ^2.

The ratios of SL:SD and SL:SW at the time of harvest were calculated, as these ratios have been used to differentiate fast and slow growing larger abalone (Saunders et al., 2008).

To determine the effectiveness of using the post-harvest HM as a proxy for SL at seeding, a linear model of the form:

$$SL_i = \beta_0 + \beta_1 HM_i + \epsilon_i$$

was fitted to the data for the measured SL (SL_i) and the length of the HM (HM_i) for abalone *i* (measured after harvest), where $\epsilon_i \sim N\,(0, \sigma^2)$ is the error term for some constant measure of variability σ^2.

The growth rates of the eight tagged, commercial size abalone were also estimated using the SL at harvest and three estimates of the SL at seeding: 1) the measured SL; 2) the predicted SL at seeding from the linear regression above; and 3) the measured hatchery mark at seeding.

Results

Environmental conditions

The short term logger data from March to May 2020 followed a similar pattern at the three stations on the OGA lease (Fig. 4). Water temperatures were consistently higher in March (19.7–22.1 °C) than May (18.6–20.6 °C), which had the most variation in temperature (Fig. 4a). The minimum dissolved oxygen recorded was 5.8 mg.L^{-1} (25 April), which was also the time of lowest oxygen saturation (85 %, Fig. 4b).

The range of temperatures from the logger data were within the range of temperatures from the NOAA sea surface temperature (SST) monthly data, which ranged from 17.9 (September 2019) to 21.91 °C (April 2020) (data not shown) from the time when abalone were seeded on Abitats to their harvest.

Estimated abalone growth rates

The mean sizes of *H. laevigata* seeded on the Bears and Puerto lines in June 2019 were ~41 mm SL (range: 29 to 60 mm), with a mean WT of ~10 g (2 to 30.5 g). The abalone held for 74 d in the hatchery before transport and seeding on the Boranup line were ~11 mm longer (mean SL = 52.4 mm, range: 41 to 60 mm) and 9 g

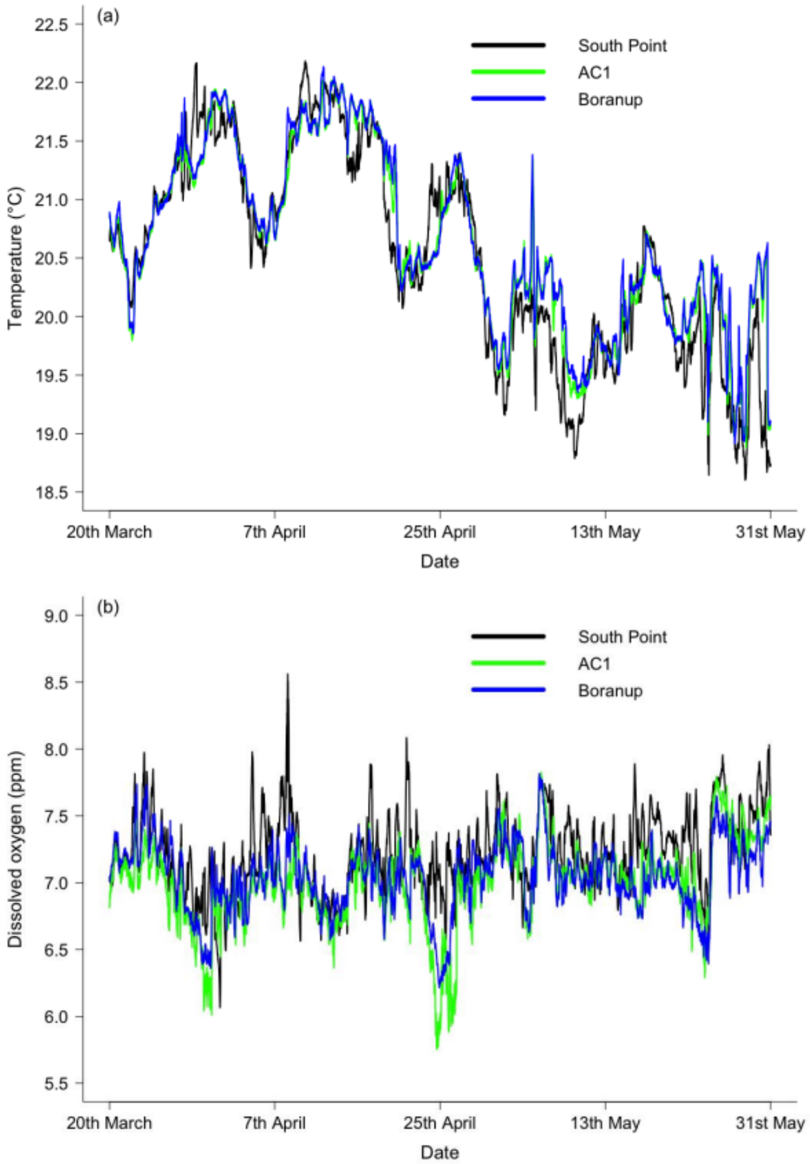

Fig. 4. Individual logger data for (a) bottom temperature (°C) and (b) dissolved oxygen (ppm) recorded every 10 minutes from three locations on the Ocean Grown Abalone sea ranching lease site in Flinders Bay, south-western Australia from 20th March 2020 to 31st May 2020.

heavier (mean WT = 19.4 g, range: 10 to 34 g) at seeding than those on Bears and Puerto.

At harvest, the mean SL of the abalone from the Bears line and Puerto lines were almost identical (67.6 and 67.7 mm), and the mean WTs were similar (38.48 and 35.5 g). The mean SL and WT of abalone harvested from the Boranup line were ~2 mm longer (69.8 mm) than those on the other two lines and similar in mean WT (38.1 g) to that on the Bears line.

The mean growth rate in SL across all three lines was 2.11 mm month^{-1}, ranging from 1.96 mm month^{-1} (Boranup) to 2.44 mm month^{-1} (Puerto, Table 1, Fig. 6). The overall mean growth in WT was 2.22 g month^{-1}, ranging from 2.11 g month^{-1} (Boranup) to 2.53 g month^{-1} (Bears, Table 1). ANOVA showed that the mean SL growth rate on Boranup was significantly slower ($F_{2,114}$ = 12.02, P < 0.0001) than those on Bears (post-hoc Tukey test, P = 0.003) and Puerto (P = 0.0001), which did not differ significantly from each other (P = 0.70) (Fig. 5, Table 2). In contrast to SL, the WT growth rate did not differ significantly among the three lines at a 5% significance level, although the P - value was still relatively small ($F_{2,114}$ = 2.548, P = 0.0827). Growth in WT tended to be slower on Boranup (2.11 g month^{-1}) than on Bears (2.53 g month^{-1}) and Puerto (2.28 g month^{-1}) (Table 2).

Length-weight relationship and morphometric data

The relationship between the log transformed data for SL and WT during the ocean growth phase was; $\ln(WT) = -7.87 + 2.73\ln(SL)$ and was highly significant (R^2 = 0.95, P < 0.0001, n = 1487), with SL accounting for 94.5 % of the variation in WT. From this relationship, the predicted WTs of abalone at SLs of 40, 60, and 80 mm, are 8.9, 26.8 and 58.6 g, respectively. If this growth rate is

Table 2. Mean growth rate (± 1 SE) in (a) shell length and (b) total weight for each line and the overall growth rate for the *Haliotis laevigata* seeded onto the Ocean Grown Abalone sea ranching site in Flinders Bay, south-western Australia.

Line	n	Growth rate		*P* and Tukey test
		Per day	Per month	groups
a) Shell length (mm)				
Boranup	75	0.0654 ± 0.00170[b]	1.961 ± 0.051	b
Bears	22	0.0775 ± 0.00375[a]	2.326 ± 0.113	a
Puerto	20	0.0812 ± 0.00274[a]	2.437 ± 0.082	b
Overall	117	0.0704 ± 0.00151	2.111 ± 0.045	<0.0001
b) Weight (g)				
Boranup	75	0.0705 ± 0.00299	2.114 ± 0.090	a
Bears	22	0.0841 ± 0.00614	2.525 ± 0.184	a
Puerto	20	0.0761 ± 0.00420	2.282 ± 0.126	a
Overall	117	0.0740 ± 0.00238	2.220 ± 0.0715	=0.083

Significance (*P*) of one-way ANOVA shown on overall row and *post-hoc* Tukey test groups shown by letters for each line.

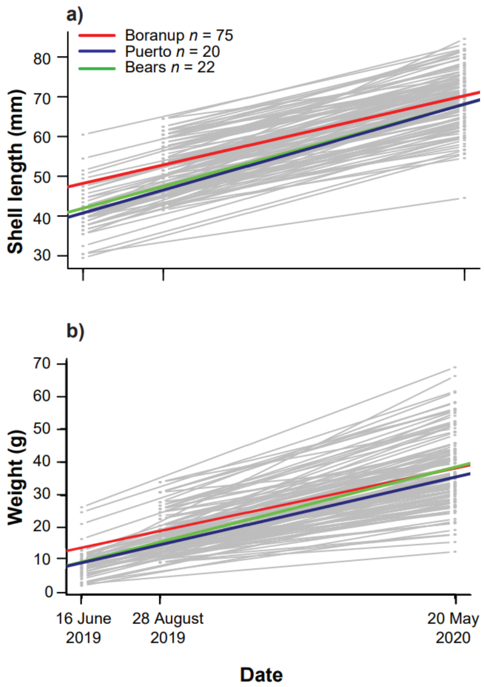

Fig. 5. Individual changes in (a) shell length (mm) and (b) weight (g) for *Haliotis laevigata* during their ocean growth phases (grey lines and dots). Overlaid lines = regression lines of best fit; green = Bears; red = Boranup; blue = Puerto.

maintained through to maturity, the predicted WT at a SL of 100 mm would be 107.7 g. Note this projected weight has been extrapolated beyond the range of the data for SL (maximum SL = 84 mm).

The mean shell width (SW) at harvest ranged from 51.8 mm (Puerto) to 53.5 mm (Boranup), with an overall mean (± 1 SE) of 53.2 ± 0.552 mm. The mean shell depth (SD) of abalone at harvest from all lines in May 2020 was 14.2 ± 0.216 mm, ranging from a mean of 13.5 mm (Puerto) to 14.4 (Boranup). The mean SL:SW ratio ranged from 1.28 on Bears to 1.31 on Puerto (overall mean = 1.300 ± 0.005) and the overall mean SL:SD ratio was 4.94 ± 0.057 (range = 4.88 [Boranup] to 5.15 [Puerto]).

Hatchery mark as an indicator of size at seeding

The mean length of the hatchery mark (HM ± 1 SE) of harvested abalone (47.0 ± 0.48 mm) was within 0.9 mm of the mean measured SL at seeding (46.1 ± 0.48 mm). The equation for the relationship between SL at seeding and HM was:

$$SL = 11.61 + 0.73(HM)$$

which was highly significant ($P < 0.001$, n = 117), with HM accounting for 53.5 % of the variation in SL at seeding (Fig. 6).

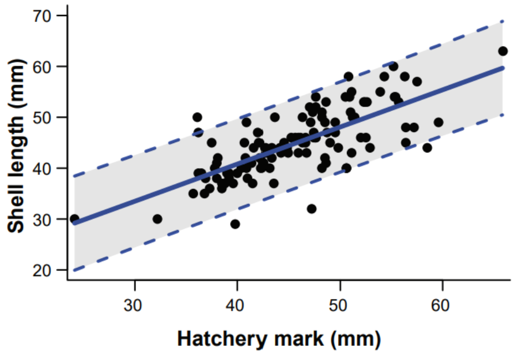

Fig. 6. The relationship between hatchery mark measured at harvest, and shell length at the time of seeding for *Haliotis laevigata* on the Ocean Grown Abalone sea ranching site in Flinders Bay, south-western Australia. Blue line = line of best fit; dashed blue lines = 95% confidence interval. (n =117, r^2 = 0.535).

The hatchery mark was still evident in eight abalone harvested at commercial size, about three years after seeding on the Abitats. The mean SLs at seeding (± 1 SE) estimated from the three methods were: 53.4 ± 1.26 mm for the measured size at seeding; 52.8 ± 1.70 mm for the measured HM; and 50.1 ± 1.24 mm for the predicted SL (from HM). The estimated growth rates per year for the three measures of SL at seeding varied by only 0.21 mm (21.4 ± 0.35, 21.6 ± 0.62 and 21.61 ± 0.53 mm.y^{-1} for the SL, HM and predicted SL at seeding, respectively). The estimated annual growth rates from the HM and predicted SL at seeding were within 1 % of the growth rate estimated from the measured SL at seeding.

Discussion

This research provides the first quantitative estimates of individual *Haliotis laevigata* (Greenlip abalone) growth on the sea ranching lease site Flinders Bay, south-western Australia and shows that the hatchery mark, laid down when the abalone are transferred from the hatchery to the ocean, provides a means of estimating growth without the need for tagging.

Growth rates

The individual growth rates in abalone shell length varied significantly among the three lines on the Flinders Bay lease, with slower growth on the Boranup line than either Bears or Puerto. This variation in growth rates may be due to the difference in pre-seeding histories of the abalone or environmental conditions at the time of seeding (June vs August). In terms of pre-seeding history, abalone on the Boranup line were tagged in the hatchery and retained for an additional 74 d before harvest, transport, and seeding on Abitats; this contrasts with the abalone seeded on the Bears and Puerto lines that were tagged immediately before seeding on the Abitats i.e. immediately after harvest from the hatchery and transport to Flinders Bay. The variation in growth among these three lines is unlikely to be due to variation in the environment or food resources as water temperature and dissolved oxygen were relatively homogenous across the lease. These study locations are separated by distances of <2.5 km between the lines and two of them (Bears and Puerto) are only 0.5 km apart.

The minimum and maximum individual growth rates for shell length recorded during the current study were from the Boranup and Bears line (1.14 mm $month^{-1}$ and 3.93 mm $month^{-1}$ respectively), with the maximum growth rate 3.4 times faster than the minimum. This large variation in individual growth may be the result of genetic differences between individuals, and being able to identify this in the hatchery growth phase and select fast growers for seeding on Abitats would enhance production during the ocean growth phase.

If the growth rates in shell length recorded in the current study continue to larger sizes, *H. laevigata* would take ~2.1 to 2.6 years reach maturity at ~100 mm after being seeded onto Abitats at 40 mm shell length. The slower growth in SL recorded on the Boranup line has not previously been recorded in this location on the ranch, which suggests that the longer hatchery phase for these abalone may have had a detrimental effect on their ability to withstand the stresses associated with transport and seeding processes, culminating in a reduced ability to quickly adapt to oceanic conditions.

Climate change projections for this region of south-western Australia predict that marine heatwave events will become more common in the future due to anthropogenic factors contributing to the current warming trend (Oliver et al., 2018). For example, in the summer of 2010/11 a strong *La Niña* event created an extreme marine heat wave event that affected 2000 km of coastline for 66 days in the mid-west of Western Australia (Pearce et al., 2011; Hobday et al., 2018; Caputi et al., 2019). Water temperatures rose between 2–4 °C, which resulted in mass mortalities of *H. roei* (Roes Abalone) at the northern end of its range and spawning stocks remain very low (Caputi et al., 2019). As *H. laevigata* is at the northern end of its range in Augusta, OGA needs to consider the consequences of further warming events for their future abalone production in the region.

Morphometric measurements

This study is apparently the first to record detailed morphometric measurements of small, juvenile abalone ranging in size from ~20–80 mm shell length (SL). The ratios of shell dimensions i.e. shell length: shell width (SL:SW) and SL: shell depth (SL:SD), have been used to determine whether an adult abalone population was stunted or non-stunted in growth in natural systems (Saunders et al., 2008). Little variation was found in the mean ratios on the three lines SL:SW (overall mean, range of means = 1.30, 1.28 to 1.31) and the SL:SD ratios (4.94, 4.89 to 5.15). No information is available for the SL:SD ratios for adult *H. laevigata*, however, the mean ratios for blacklip abalone (*H. rubra*) >90 mm SL in South Australia (3.0–3.7) (Saunders et al., 2008) are much smaller than those for the juvenile *H. laevigata* in the current study. The larger, mature blacklip abalone have broader and deeper shells relative to their lengths than the juvenile greenlip abalone in the current study, probably related to the onset of maturity and investment in gonad development. In juvenile life stages, abalone allocate energy to growth in shell length and typically display longer, thinner shells than larger, maturing individuals (Prince et al., 1998; Jennings et al., 2009), resulting in greater SL:SD ratios. The shell morphometric measurements may be used to make quick, non-invasive measures to evaluate growth on sea ranches and compare them with ranches in other locations or to natural abalone populations.

Hatchery mark as an indicator of size at seeding

At harvest, a colour differentiation was evident on the *H. laevigata* shells (Fig. 3) that probably indicates the size at which the abalone were moved from the hatchery to the ocean, associated with a major change in food sources from pelleted food in the hatchery to macroalgae in the ocean. Shell length at seeding was linearly related to the hatchery mark measured at harvest, with a slope of <1, possibly because the hatchery mark is demarcated sometime after the abalone have been seeded on Abitats, when they have fully assimilated the new diet in the ocean. The small sample of tagged, commercial-sized abalone (n = 8, SL = 108–118 mm) harvested after the main study showed that the hatchery mark was still evident at the time of harvest, about three years after seeding on the Abitats. The estimated annual growth of these individuals based on the hatchery mark at harvest was within 1 % of the estimate using the measured size at seeding. These findings show that measuring the hatchery mark at harvest provides a fast, non-invasive way of estimating individual growth rates of harvested abalone seeded at different times and locations. It avoids the need for measuring and tagging the abalone before seeding them on Abitats, which is costly, time-consuming and may potentially have negative effects on growth (McShane et al., 1988; Gorfine et al., 1998; Wang, 1998).

Conclusion

This study has shown that *H. laevigata* released onto the OGA sea ranching lease site in Flinders Bay, south-western Australia, varied in individual growth in shell length. However, the slower growth recorded on one line is possibly related to seeding abalone onto the Abitats at a larger size after a longer duration in the hatchery environment. As the conditions at the three locations within the sea ranch were homogeneous, they are unlikely to have contributed to the slower growth. Results from this study suggest that individual variability in size at seeding is maintained throughout the sea ranching growth phase, with smaller individuals taking longer to reach the size at harvest than larger ones. Shell morphometric measurements have been established for juvenile *H. laevigata* for the first time and the ratios of SL:SW and SL:SD provide other measures of abalone growth for comparison with other sea ranch systems or with abalone in natural conditions. The hatchery mark, and its relationship with the size at seeding, has great potential for estimating individual growth rates from different areas on the farm at the time of harvest. The measurements of hatchery mark from 8 individuals at the commercial-size of harvest confirm that the hatchery mark provides a means of estimating growth without the need for tagging and making comparisons in growth rates between locations on the sea ranch and between different sea ranches.

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