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Growth and reproductive performance in cultured nearshore rockfish (*Sebastes* spp.)

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Abstract

The present study evaluates the extent to which the viviparous reproductive strategy that characterizes the genus *Sebastes* (rockfish) can be expressed in culture. In addition, the growth patterns of rockfish were examined during the early phases of growth pertinent to the culture of the species. Using grass rockfish (*Sebastes rastrelliger*) as our model, it was demonstrated that all phases of ovarian seasonal cyclicity could proceed under controlled environmental conditions. Rockfish successfully spawned in our facility and subsequently passed through successive phases of oocyte development during the normal reproductive season before follicular atresia was observed in the absence of fertilization. Fish introduced into culture in an advanced stage of vitellogenesis became pregnant in the absence of males 14–55 days later. This observation is consistent with the view that delayed fertilization occurs in rockfish and establishes that wild caught specimens for spawning purposes are not confined to pregnant females. By monitoring growth parameters in two groups of brown rockfish (*S. auriculatus*) introduced into culture during their first and second year of development a comprehensive picture of early growth was established. Overall changes in both weight and length followed a sigmoid curve comprising an early phase of exponential growth transitioning to a phase of exponential decay. The constituent phases of this curve, as expressed in the two age groups, and the combined growth data over a period of 1083 culture-days were precisely described by the Gompertz equation. This equation also described the growth of young-of-the-year copper rockfish (*S. caurinus*) with similar accuracy. Validation of the applicability of our Gompertz equation was achieved by reference to growth parameters of brown rockfish of known age raised from birth at UCSB. Our mathematical model precisely depicted growth with age from birth to the period of sexual maturity. These data on growth in relation to age may find broad application in fisheries management plans allowing for evaluation of population changes over time and be useful in determining and improving the culture potential of nearshore rockfish species.

Keywords: Rockfish; Growth; Reproduction; Culture; Fisheries

1. Introduction

The rockfish (genus Sebastes) are highly adaptive marine teleosts comprising over 110 species worldwide with distribution centers on both sides of the Northern Pacific Rim (Boehlert and Yamada, 1991). The diversity and abundance of the genus and the ease of harvesting have made rockfish an important component of the recreational and commercial fisheries on both sides of the Pacific Rim. Commercial landings of rockfish species in the U.S.A have risen dramatically in recent years to a national total of 34,034 metric tons with a value of $16.5 million (Annual Commercial Landings

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Statistics for 2004, NOAA Fisheries). The continued rise in pressure on the nearshore rockfish fishery on the Eastern Pacific Rim by both the commercial and recreational fishing industries has led to increased attention by state and federal management agencies seeking to effectively manage the populations of threatened marine species (Pacific Fishery Management Council, 2004). Nearshore rockfish in particular have received special consideration with significant restrictions implemented for the fishery. As increased attention is directed towards management of threatened rockfish populations to limit fishing wild stock, there has been developing interest in the feasibility and economic viability of culturing candidate rockfish species for commercial purposes or for remediation programs to repopulate rockfish habitat.

The potential for successful commercial culture of rockfish species has been clearly demonstrated by the development of *Sebastes schlegeli* as one of the leading marine fin-fish cultured in Korea, second only to the flounder, with production exceeding 23,711 tons in 2003 (Ministry of Maritime Affairs and Fisheries of Korea, 2003). In addition, large-scale replenishment programs for *S. schlegeli* have been established in Japan (Kusakari, 1991). The development of comparable mariculture programs for rockfish of the Eastern Pacific Rim requires the characterization of growth parameters and patterns of reproductive performance for candidate rockfish species in culture. Evaluation of the potential of individual rockfish species from this region for culture has been particularly hampered by the lack of comprehensive growth data over the pertinent size range. Field studies, where growth rates are based on size at an estimated age, deal predominantly with specimens larger than the desirable market size. Growth rates vary dramatically among different species of the *Sebastes* genus (Boehlert and Yoklavich, 1983; Woodbury and Ralston, 1991). For individual species, available evidence indicates that growth rates differ at different phases of their life-history with growth rates declining as fish mature (Love et al., 1991). There have been few and extremely limited comparisons of growth rates of individual species in the wild as compared to growth under culture conditions and the studies that have been performed in culture have been confined to small segments of early development (Kendall and Lenarz, 1987). Rockfish in the Pacific Northwest typically exhibit a single annual reproductive cycle during late winter or spring (Phillips, 1964; Wyllie-Echeverria, 1987; Love et al., 1990). They are both highly fecund and viviparous with parturition the culmination of a prolonged phase of synchronized oocyte maturation, internal fertilization, embryonic development within the ovary and the abrupt release of larvae in an advanced stage of organogenesis. The viviparous reproductive strategy seen in rockfish presents unique challenges for brood-stock management. As is the case for many oviparous teleosts, the culture of *S. schlegeli* on the Western Pacific Rim may depend on the collection and rearing of pregnant fish (Kusakari, 1991). The development of successful strategies for mating and fertilization of rockfish in culture will require more detailed information on oocyte development and the timing of maturational events in relation to successful impregnation.

The present study examines growth characteristics of local nearshore rockfish during phases of development pertinent to the culture of the species for food resource and replenishment programs. In addition, the extent to which the component phases of the reproductive cycle can be expressed normally under prolonged culture conditions is determined. Three local nearshore species, grass (*Sebastes rastrelliger*), brown (*S. auriculatus*), and copper (*S. caurinus*) rockfish were identified as having the potential for viable aquaculture. These species mature relatively early (Love and Johnson, 1998), grow at a rate close to the mean for the genus (Love et al., 1990), transport readily for the live-fish trade, and are extremely palatable. In addition they are among species primarily targeted for effective management under California's Nearshore Fishery Management Plan (California Department of Fish and Game, 2002).

2. Materials and methods

2.1. Fish sampling and maintenance

Adult grass rockfish used to assess seasonal changes in reproductive status under natural conditions and in culture were caught by commercial fishers in various coastal waters of Southern and Central California. Young brown and copper rockfish used in the growth studies were obtained by University of California collectors from the nearshore waters of the Santa Barbara Channel. All juvenile and adult fish were housed in a covered outdoor facility under natural photoperiod at the University of California, Santa Barbara in flow through fiberglass tanks. Groups of small brown and copper rockfish were separately housed in 600 l tanks while older brown and adult grass rockfish were housed in 2000 l tanks. Seawater supplying the tanks was drawn from intakes located in the Santa Barbara Channel 762 m offshore and at a depth of 15.5 m. Seawater was sand filtered to remove particulate matter down to 20 μm in size and continuously supplied to the tanks at rate that provided an exchange of water approximately every 2 h. Seawater quality was monitored with an Aquanode XL500 (Aquadyne Computer Corp. San Diego, CA) with probes to measure dissolved oxygen, temperature, conductivity and pH. Seawater temperature was maintained at ambient conditions ranging between 14–16 °C. All fish were fed commercial trout pellets (Silver Cup, Nelson & Sons, Inc., Murray, Utah). The populations of small brown and copper rockfish were fed 3/32–1/8 inch pellets in amounts adjusted monthly to 1% of fish mass per day. Larger brown rockfish were fed 1/4″ pellets daily to satiation.

2.2. Assessment of reproductive status in cultured grass rockfish

161 female adult grass rockfish ranging from 579 to 2437 g in weight and 33.0 to 50.0 cm in total length were brought into culture during all 12 months of the year. Ovarian biopsies were taken within a week of arrival and at intervals throughout the reproductive season (November–April) in order to determine gonadal condition and development in individual fish. Fish were anesthetized by immersion in tricaine methanesulfonate (MS-222; Argent Chemical Laboratories, Redmond, WA, 150 mg/l of seawater). Small samples of ovarian tissue were aspirated by inserting a length of medical grade silicon tubing (Dow Corning, Midland, MI, 2 mm outside diameter) through the genital pore and applying gentle suction with a 3 cc syringe. Tissue samples were examined either directly on acquisition or following vital staining with a 1% methylene blue solution. In both cases, digital images of ovarian samples were acquired with a Pixera 120es digital camera system (Pixera Corp., Los Gatos, CA). In addition small pieces of tissue were fixed in 2.5% glutaraldehyde, dehydrated, embedded in glycol methacrylate, sectioned at a thickness of 1–2 μm and stained for histological analysis as previously described (Moore et al., 2000).

The staging scheme used to describe embryonic development in rockfish was developed by Yamada and Kusakari (1991) for *S. schlegeli* and is based on that originally proposed by Oppenheimer (1937) for *Fundulus heteroclitus*. Specific timing as to the progression of stages over the course of pregnancy was assessed using a complete developmental table derived from longitudinal sampling (Chaillé, 2006).

2.3. Growth studies

A cohort of 14 small brown rockfish was collected in August. An additional 31 fish of closely similar size were obtained in September and the two groups combined. Changes in weight and linear dimensions were recorded at various intervals for a total of 688 days for the combined group of 45 fish. Six small copper rockfish were also caught during August and October and cultured for 236 days with parameters of growth also determined periodically. By reference to our growth curves, both groups of small rockfish were determined to be in their first year of growth at the beginning of the study (see Discussion). A group of 25 larger brown rockfish was collected in October and growth characteristics were determined over a period of 591 days. These fish were determined to be in their second year of growth at the beginning of the study (see Discussion). For ease of description, the younger and older groups of fish are referred to as fingerlings and juveniles respectively.

2.4. Growth analysis

Equations with mathematical properties applicable to the measurement of the growth of organisms were tested including the monomolecular equation developed by von Bertalanffy, the logistic equation and the Gompertz equation (Laird, 1965, review).

The model that most accurately represents the pattern of growth over the period of this study was determined using the Marquardt–Levenberg algorithm as programmed in the curve-fitting software SigmaPlot 2001 (SPSS, Chicago, IL). The best fitting model was selected using the correlation coefficient (R), the coefficient of determination (R^2) and the adjusted R^2 ($R^2_{(adj)}$). An ANOVA of the residual sum of squares due to regression allowed for further assessment of the applicability of various growth models to the data sets.

2.5. Rockfish rearing

Rockfish reared in culture in our established culture program provided validation of mathematical models of growth. Briefly, an adult brown rockfish collected in an advanced stage of pregnancy successfully gave birth in captivity in a dedicated 1000 l indoor fiberglass tank supplied with flow through filtered seawater (sand, 15 μm cartridge filter, and ultraviolet). Photoperiod and water temperature were maintained at ambient conditions (14–16 °C). After parturition the adult fish was removed from the tank and the flow adjusted to different levels adjusted in response to monitored water quality. Larvae were fed twice daily a diet comprised of enriched rotifers introduced with green water. Copepods were integrated into the larval diet and a mixture of larger zooplankton was introduced once mouth size allowed. Juvenile rockfish reared from larvae in the laboratory were fed a diet consisting of live mysid shrimp, frozen euphasids, a commercial flake food and minced squid. The wet weights and total length for juvenile brown rockfish reared successfully from birth and used for validation were taken on days 151, 175, 203, 287 and 335. Fish were anesthesized, measured, weighed and photographed using a standard digital camera.

3. Results

3.1. Reproductive development in culture

10 grass rockfish that exhibited no signs of pregnancy when collected from the field during November,

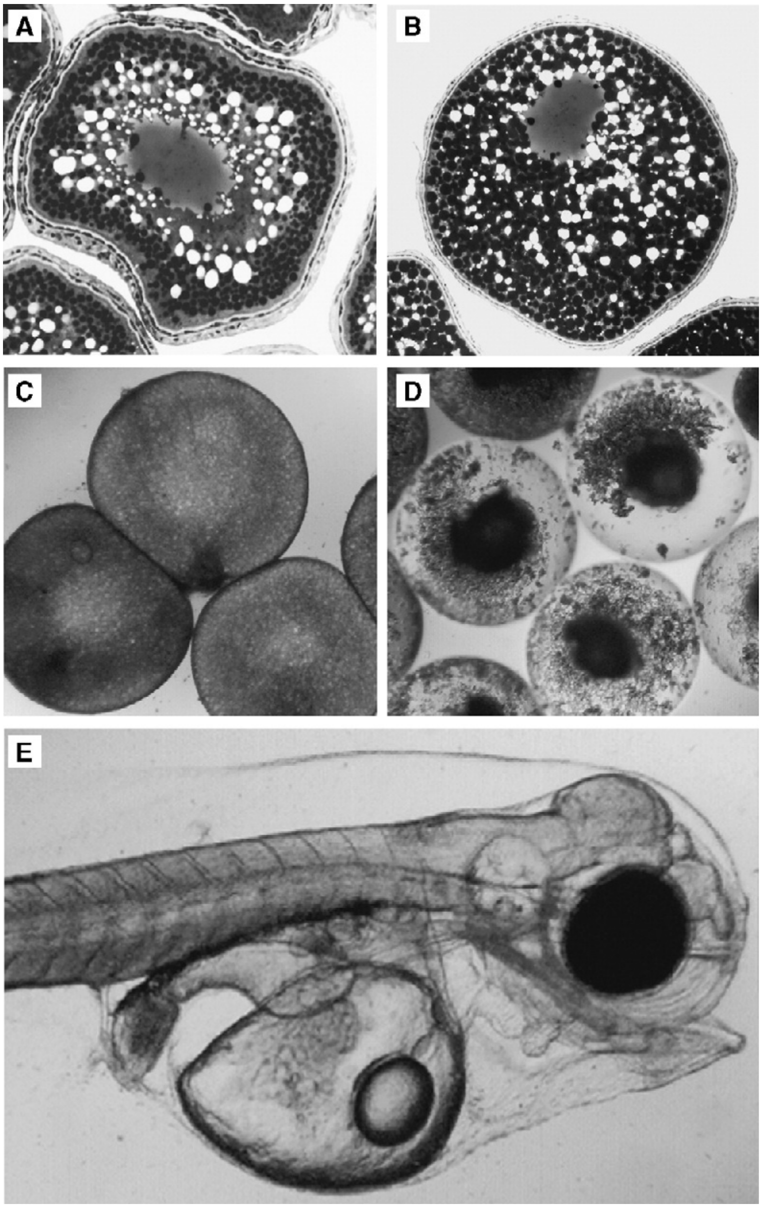

Fig. 1. Light micrographs of oocytes and larva of grass rockfish. A, histological section of a stage V oocyte from a fish recently introduced into culture that subsequently became pregnant and spawned in the absence of a male. B, histological section of a stage VI oocyte showing progression of vitellogenesis and maturation (including nuclear migration) from the condition seen in a previous biopsy, (micrograph A). C, biopsied oocytes stained with vital dye (1% methylene blue) to directly assess oocyte condition. D, atretic oocytes from a fish which had passed through stages V and VI of oocyte development in culture. Degeneration is considered to result from a failure of fertilization. E, developing embryo (7 days before parturition) aspirated from a fish introduced into culture with stage V oocytes and kept in isolation from males.

December and January became pregnant while in captivity. At capture, these fish contained oocytes in either early (7 fish) or late (3 fish) stage V of development ranging in size from 570–940 μM (mean, 697 μM; Fig. 1A). These oocytes progressed through stage VI of development prior to fertilization (Fig. 1B and C) and the establishment of pregnancy (Fig. 1E). The time between the introduction of non-pregnant rockfish into culture and the first detection of pregnancy ranged from 14–55 days with normal parturition events occurring between late December and late March.

18 grass rockfish obtained in various stages of pregnancy successfully gave birth in our facility. 2 grass rockfish that were obtained in an advanced stage of pregnancy in March gave birth during the same month (March 16 and 23). Examinations of sequential biopsies for a 12-month period following parturition revealed normal seasonal ovarian recrudescence characterized by the complete progression of vitellogenesis and oocyte development. Oocytes sampled on November 11 had developed to a stage V condition while a subsequent sample taken on January 9 contained oocytes at stage VI. During sampling on February 3 both fish were observed extruding large quantities of tissue through the genital pore. Microscopic examination showed this extrusion to contain numerous atretic oocytes comprised of a chorion enclosing an amorphous cellular mass and crystalline inclusions (Fig. 1D). Continuous extrusion followed with one fish losing 70 grams in body weight in 4 days leaving the abdomen flaccid with conspicuous stretch marks. This massive atresia of the oocyte population was considered to be the consequence of the lack of fertilization in the absence of male fish although could potentially have been enhanced as a result of handling stress.

In the two developmental situations described above, stage V oocytes were characterized by a centrally located acidophilic nucleus with several basophilic nucleoli visible on the periphery of the nuclear membrane. Numerous oil droplets surrounded the nucleus and had not yet coalesced. Vitellogenesis had begun as indicated by an outer layer of dark-staining basophilic yolk globules occupying approximately one half of the cytoplasmic volume. The follicular cells encapsulating the oocyte consisted of a single layer of granulosa cells surrounded by a single layer of theca cells. An extensive network of capillaries surrounded the follicle (Fig. 1A). Stage VI oocytes contained a migrating nucleus surrounded by an irregularly shaped nuclear membrane with several nucleoli still visible. Almost all of the cytoplasmic volume was comprised of yolk globules and the oil droplets had not yet completely coalesced (Fig. 1B). These features were sufficiently discernible in vitally stained specimens to allow rapid evaluation of oocyte development in aspirated samples (Fig. 1C).

3.2. Growth in culture

The population of 45 brown rockfish fingerlings introduced into culture during their first year of growth had an average weight of 9.47±0.53 grams when initially weighed on September 7. These fish exhibited an exponential increase in body weight over the experimental period of 688 days (Fig. 2A). During the first 34 days in culture fish grew at a rate of 0.012 g/day to a final weight of 9.87±0.48 grams. The incremental growth rate increased progressively during subsequent phases of growth to maximum values of 0.317 and 0.309 g/day recorded between days 304–573 and 574–688 days in

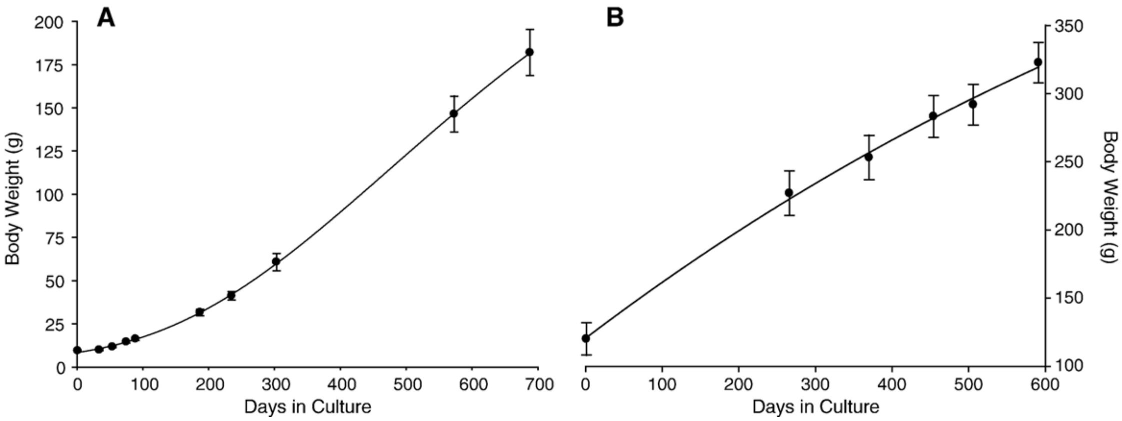

Fig. 2. Weight velocity curves of brown rockfish introduced into culture in their first (A) and second (B) year of growth.

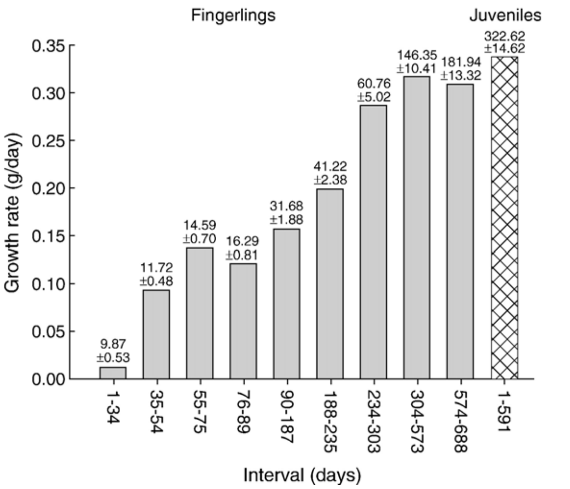

Fig. 3. Incremental growth in body weight of cultured brown rockfish. Numbers above each column are the final weight (±SEM) at the end of the interval of culture.

culture respectively with fish attaining a final weight of 181.94±13.32 g (Fig. 3).

The population of 25 brown rockfish introduced into culture during their second year at an initial weight of 120.12±11.84 g grew at an approximately constant rate (Fig. 2B) with an average incremental growth rate of 0.338 g/day over the study period of 591 days resulting in a final weight of 322.62±14.62 g (Fig. 3). This growth rate was closely similar to that recorded during the final phases of growth of the younger group of fish.

The standard length of the younger group of brown rockfish showed an early exponential increase from an initial value of 6.83±0.12 cm (Fig. 4A). The incremental growth rate rose from 0.0026 cm/day between days 1–34 to 0.020 cm/day between days 55–75 with fish attaining a length of 7.50 cm. This incremental rate was

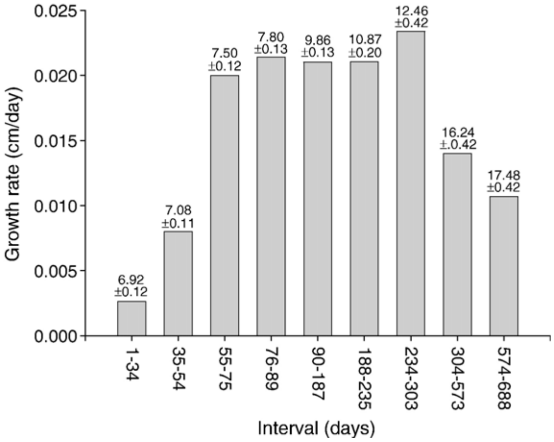

Fig. 5. Incremental growth in length of cultured brown rockfish. Numbers above each column are the final weight (±SEM) at the end of the interval of culture.

maintained constantly during the 76–89, 90–187, 188–235 and 234–303 periods of evaluation (Fig. 5). This resulted in an approximately linear phase of growth between culture days 76–303 (Fig. 4A). In subsequent age groups, the incremental growth rates declined to 0.014 cm/day and 0.011 cm/day in the 304–573 and 574–688 day age groups respectively (Fig. 5) as the length velocity curve passed the point of inflection (Fig. 4A). The population of fish introduced into culture in their second year of development showed a further decline in incremental growth from a rate of 0.0175 cm/day between days 1–266 in culture to 0.0123 cm/day in the final culture period, days 506–591 with the fish attaining a final length of 25.26±0.43 cm (Fig. 4B).

The small group of copper rockfish introduced into culture during their first year of growth showed a similar early growth pattern and comparable growth rates to those recorded in the corresponding group of fingerling

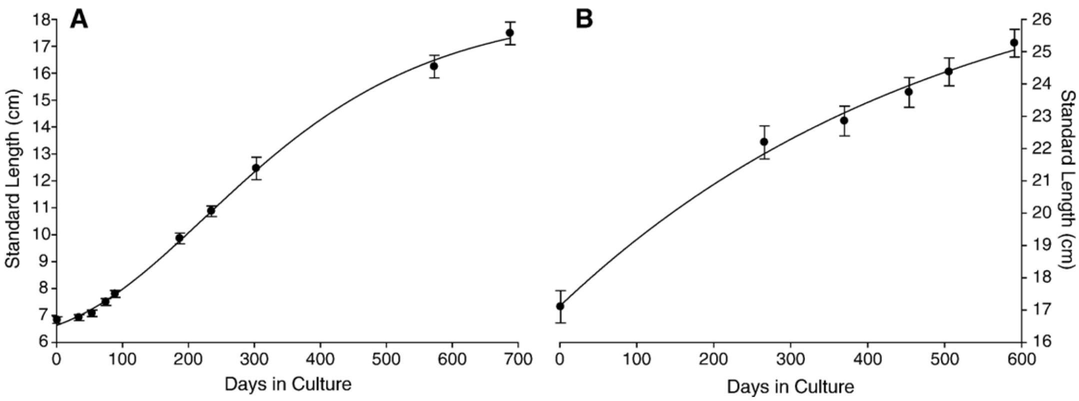

Fig. 4. Length velocity curves of brown rockfish introduced into culture in their first (A) and second (B) year of growth.

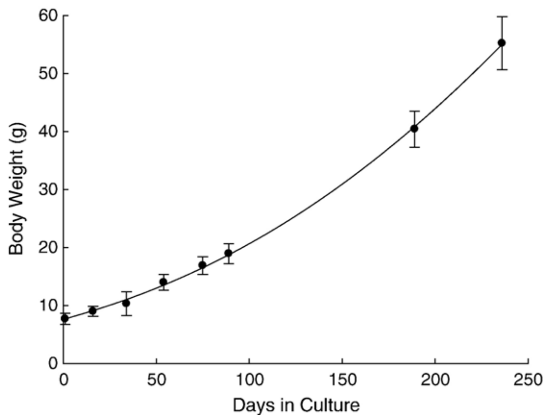

Fig. 6. Weight velocity curve of cultured copper rockfish.

brown rockfish. Body weight increased exponentially from an initial weight of 7.7±0.97 g to a final weight of 55.52±4.57 g (Fig. 6) with incremental growth rates increasing progressively from 0.0810 to 0.3150 g/day during the culture period (Fig. 7).

Among the different mathematical models used to predict growth in culture, the Gompertz curve provided the most accurate fit to our data. The formula for the 4-parameter Gompertz curve used in our analysis is: $F=y_0+a*\exp(-\exp(-(x-x_0)/b))$ where, x=days in culture; a, b, x_0 and y_0 are independent parameters.

Growth for brown rockfish introduced into culture during their first year (Figs. 2A and 4A) is represented by the Gompertz equations:

$$\text{Body weight} = 3.8561+301.1254*\exp(-\exp(-(x-475.4295)/331.4843)); R^2 = 0.999.$$

$$\text{Standard length} = 6.0826+12.3463*\exp(-\exp(-(x-224.1826)/197.7925)); R^2 = 0.999.$$

Growth for brown rockfish introduced into culture in their second year (Figs. 2B and 4B) is represented by the Gompertz equations:

$$\text{Body weight} = -1207.1391 + 1777.3363*\exp \times(-\exp(-(x-(-1119.3340))/908.36)); R^2 = 0.997.$$

$$\text{Standard length} = 71.0458 + 99.3828*\exp \times(-\exp(-(x-(-987.2279))/465.1215)); R^2 = 0.993.$$

By combining the data sets at overlapping phases of growth in fingerlings and juvenile fish, a curve was generated encompassing growth over a total of 1083 culture days. Growth for brown rockfish over this entire culture period (Figs. 8 and 9) is represented by the Gompertz equations:

$$\text{Body weight} = -1.1227 + 472.5282*\exp \times(-\exp(-(x-638.7455)/462.3457)); R^2 = 0.998.$$

$$\text{Standard length} = -1.8590 + 38.5634*\exp \times(-\exp(-(x-311.9638)/717.2898)); R^2 = 0.987.$$

3.3. Growth curve validation

The curve depicting growth in body weight over the entire culture period (Fig. 8) was validated by comparing the actual weights of juveniles reared in the laboratory at known ages to the estimated age based upon the derived Gompertz equation (Table 1). The R^2 value for comparison between actual and estimated ages using the formula was 0.989.

4. Discussion

The present study characterizes aspects of growth and reproductive performance that are of direct relevance to the culture of rockfish for commercial or remedial purposes. Our observations establish that nearshore rockfish can be maintained for prolonged periods in culture and, under appropriate environmental conditions, display characteristic patterns of reproductive activity

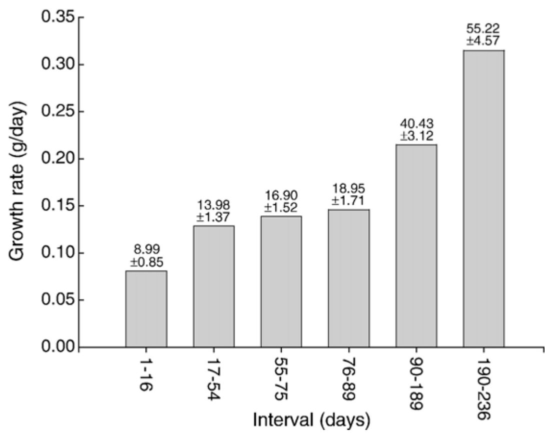

Fig. 7. Incremental growth in body weight of cultured copper rockfish. Numbers above each column are the final weight (±SEM) at the end of the interval of culture.

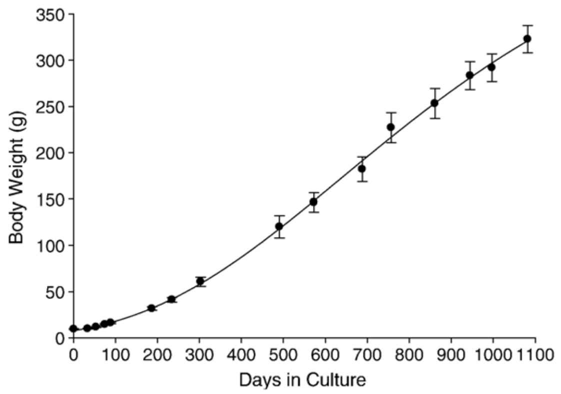

Fig. 8. Weight velocity curve constructed by combining growth data for the two age classes of cultured brown rockfish.

and somatic growth. Under ambient conditions of photoperiod and water temperature, component phases of reproductive development critical to brood stock management proceeded with a seasonal cyclicity corresponding to that observed in nearshore denizens with oocyte recruitment, vitellogenesis, fertilization, pregnancy and parturition occurring in culture during the Winter and Spring (Love and Johnson, 1998; Moore et al., 2000; Collins et al., 2001). These reproductive processes are governed by the interplay of gonadal steroids (Moore et al., 2000) and centrally acting peptide hormones (Collins et al., 2001). The preservation of normal reproductive cyclicity in culture evidences the normal expression of these complex endocrine mechanisms under appropriate environmental conditions. Rockfish introduced into culture in an advanced stage of oocyte development later established normal pregnancies while isolated from males (Fig. 1E). This observation is consistent with the view that prolonged sperm storage and delayed fertilization occur in the genus *Sebastes* (Mori et al., 2003). For aquaculture operations where successful mating in culture has not been achieved, this observation establishes that potential broodstock are not confined to captured pregnant fish but can include specimens in late vitellogenesis. The latter condition can be readily determined by reference to histological preparations (Fig. 1A and B) or vitally stained aspirated ovarian samples (Fig. 1C). Our continued focus on two aspects of reproduction, namely, recurrent seasonality and delayed fertilization is directed towards providing novel information on the reproductive biology of rockfish germane to both the development of strategies for effective management and improved technologies for aquaculture programs.

The present study elucidates patterns of growth during the initial years of rockfish life-history that are not easily estimated using field-sampling techniques. The monitoring of two rockfish populations introduced into culture in their first and second year revealed an overall sigmoidal pattern of growth characterized by an exponential increase to a point of inflection followed by a phase of decay. A comparison between the changes in linear dimensions and weight over time revealed that the length velocity curve had clearly passed the point of inflection during the first year of growth and began to decay during a period when weights were still increasing at an approximately linear rate (Figs. 2 and 4). This divergence in the changes in the two growth parameters was reflected in the incremental growth data where increases in weight in the fingerling population rose progressively to a maximum growth rate (approx. 0.3 g/day) that was sustained in fish introduced into culture during their second year of growth (Fig. 3). In contrast incremental increases in length reached maximum rates in fingerling fish during the first year in culture and fell dramatically during the remainder of the 688 day culture period (Fig. 5). Accordingly, cultured rockfish during the juvenile phase of development accrued body mass at a relatively greater rate as compared to the associated increases in body length. This observation may be of particular relevance in an aquaculture context where marketable size is assessed primarily in terms of weight.

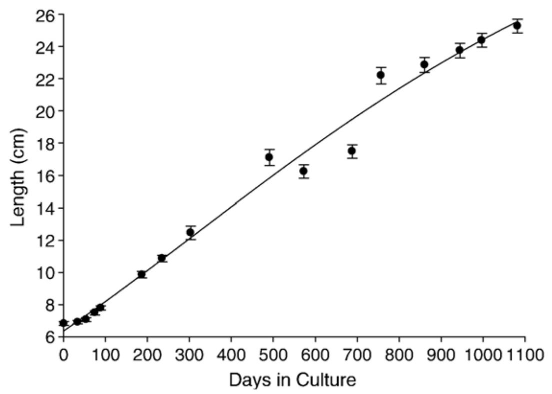

Fig. 9. Length velocity curve constructed by combining growth data for the two age classes of cultured brown rockfish.

Table 1
Estimated values for age of brown rockfish using the Gompertz equation for the combined weight velocity curve compared with the known ages of fingerling brown rockfish of given weights raised from birth in our facility at UCSB

Actual weight (g)	4.72	6.10	8.60	18.20	23.00
Actual age (days)	151	175	203	287	335
Estimated age (days)	149	170	204	295	320

R^2 value for comparison between actual and estimated age = 0.989.

A number of attempts have been made to develop equations to describe patterns of individual growth, including the von Bertalanffy, logistic, Richards and Gompertz functions (Laird, 1965; Laird et al., 1965; Ricker, 1979). In fish, the prediction of size as a function of age is most commonly addressed through the application of monomolecular type of equations such as the von Bertalanffy growth model (Von Bertalanffy, 1960). This model has been appropriately applied to rockfish in a fisheries context to generate growth curves by reference to age (usually determined by observations of otolith annuli) relative to length (Beamish and McFarlane, 1987; Laidig et al., 1991). The development of a mathematical model to describe each of the component phases of growth in rockfish is complicated by the extreme longevity of the genus. Pacific rockfishes are some of the longest-lived fishes known. Many species reach maximum ages of 50 to150 years (Archibald et al., 1981; Love et al., 1990). The longest-lived species is believed to be the rougheye rockfish (*Sebastes aleutianus*) with a recorded maximum age of 205 years (Munk, 2001; Cailliet et al., 2001). The application of the von Bertalanffy model in the back-calculation of growth rates in younger fish from parameters established in older specimens is extremely limited and the usefulness of this type of mathematical model is confined to the properties of growth in older organisms that are beyond the inflection point and have entered a phase of exponential decay in incremental growth (Laird, 1965). The von Bertalanffy growth curve model was not applicable over the early growth phases encompassed in our study. The mathematical function that provided the most useful description of growth in younger fish during the fingerling and juvenile phases of growth was the Gompertz growth model. This equation recognizes that the growth of an organism from birth to early maturity is comprised of two genetically determined processes of exponential growth and of exponential decay of the specific growth rate (Laird et al., 1965). The Gompertz equation precisely represented the growth characteristics, in terms of weight, of both brown and copper rockfish introduced into culture during the year of their birth (Figs. 2A and 6, respectively), growth of brown rockfish beginning in their second year of development (Fig. 2B) and the combined growth data for the younger and older groups of brown rockfish over a total of 1083 days in culture (Fig. 8). The Gompertz equation also accurately described the changes in length during the corresponding periods of growth in fingerling brown (Fig. 4A), fingerling copper (Fig. 6) and juvenile brown rockfish (Fig. 4B) and well-represented the pattern of overall growth (Fig. 9). The shortcomings of the von Bertalanffy growth model and the more precise applicability of the Gompertz equation in providing back-calculated growth estimates during the early stages of development have also been demonstrated in the short belly rockfish, *S. jordani* (Laidig et al., 1991).

The total age from birth was estimated by extrapolating the established Gompertz curve to the known initial weight of rockfish larvae at parturition. The younger cohort of brown rockfish was introduced into culture with an average weight of 9.47 ± 0.53 g. The initial weight of brown rockfish larvae spawned in our facility was 0.00123 ± 0.00026 g. By extrapolation to this initial value the young-of-the year fish were estimated to be 185 days old at the start of the culture period in September and would have been born in the wild in early March during the established season for parturition for the species. Brown rockfish introduced into culture during their second year of growth reached a length of 25.26 ± 0.43 cm at the end of the culture period. The estimated final age of these fish based on the length of the combined growth curve (1083 days) and the additional time from birth to the start of the culture period (185 days) was 1268 days or 3.47 years. The final size of fish in the older culture group corresponds closely with the size at which 50% of individuals of this species attain maturity in the wild (mean length 25.7 cm; Love and Johnson, 1998). Application of our combined length Gompertz equation predicts that this length would be attained, under culture conditions, 1280 days after birth or 3.5 years. This is within the broadly estimated age range for brown rockfish at first maturity in the wild of 3–6 years (Love and Johnson, 1998). Thus, the Gompertz equation developed from the combined data sets for the two cultured groups provides a mathematical model that precisely depicts growth with age from birth to sexual maturity.

The successful rearing of brown rockfish through sensitive larval stages to juveniles allowed for the validation of our growth model by reference to specimens of known age and size. Using body weight as a parameter, the Gompertz equation developed from our combined growth data for brown rockfish yielded estimated values for age which were precisely correlated with the known ages of fingerling rockfish of given weights currently being reared from birth (Table 1).

Our study establishes growth characteristics in two species of nearshore rockfish during the early phases of growth that are pertinent to the culture of the species. While our data confirms the relatively slow growth patterns of rockfish, they also indicate that a modest acceleration of growth during specific phases of development would improve the feasibility of economically viable culture of particular species in food resource or replenishment programs. Experiences with *S. schlegeli* in commercial culture operations on the Western Pacific Rim have demonstrated that optimization of dietary regimens can dramatically improve the rate of weight gain as compared to a restricted diet (Lee et al., 2000). Reference to our unique growth data set for rockfish, indicates that growth characteristics could be improved by an acceleration of the increasing incremental growth rate during the early exponential growth phase in fingerling fish and/or sustaining or increasing incremental growth once maximum growth rate is achieved in juvenile fish. The specific growth characteristics established for rockfish during the early years of rapid and exponential growth encompass a period of development when rockfish are normally recruited to the fishery. These data may be applicable in the prediction of factors affecting recruitment fluctuations and year-class success of nearshore rockfish species. In the aggregate, data from this study may find application in determining the culture potential of nearshore rockfish and in fisheries management plans requiring assessments of relationships between size and age.

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