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The evolution of extreme longevity in modern and fossil bivalves

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Abstract: The factors involved in promoting long life are extremely intriguing from a human perspective. In part by confronting our own mortality, we have a desire to understand why some organisms live for centuries and others only a matter of days or weeks. What are the factors involved in promoting long life? Not only are questions of lifespan significant from a human perspective, but they are also important from a paleontological one. Most studies of evolution in the fossil record examine changes in the size and the shape of organisms through time. Size and shape are in part a function of life history parameters like lifespan and growth rate, but so far little work has been done on either in the fossil record. The shells of bivavled mollusks may provide an avenue to do just that. Bivalves, much like trees, record their size at each year of life in their shells. In other words, bivalve shells record not only lifespan, but also growth rate. Being abundant both on the surface of the planet today, and in the geologic record, bivalves provide a vessel by which we can explore the factors that influence lifespan from two different perspectives.

Mean body size in marine animals has increased more than 100 fold since the Cambrian. Associated with this increase in body size is thought to be an overall shift in the metabolic rates of organisms as well. Both factors bring attention to the key life history parameters of lifespan and growth rate. Variation in these parameters is not well understood among modern taxa, much less in deep time. Therefore, in Chapter 1, I present a global database of modern bivalve lifespans and growth rates in order to understand if latitudinal patterns exist in life history parameters in today's oceans. The database consists of over 1,000 entries from 297 species compiled by latitude. The data indicate that 1) lifespan increases, and growth rate decreases, with latitude, both across the group as a whole and within well-sampled species, 2) growth

rate, and hence metabolic rate, correlates inversely with lifespan, and 3) opposing trends in lifespan and growth combined with high variance obviate any demonstrable pattern in body size with latitude. These observations suggest that the proposed increase in metabolic activity and demonstrated increase in body size of organisms over the Phanerozoic, should be accompanied by a concomitant shift towards faster growth and/or shorter lifespan in marine bivalves.

Clear latitudinal patterns in both lifespan and growth rate documented in Chapter 1 suggest a role for some environmental factors in promoting lifespan. From a physiological perspective, cool temperatures and low/seasonal food availability are thought to promote long lifespan. However, on the planet today, these two factors covary with latitude so separating their influence using modern organisms is difficult. Fortunately, Earth's fossil record offers a chance to tease apart these factors. In Chapter 2, I turn to fossils from the Cretaceous and Eocene of Seymour Island, Antarctica. During these times, Antarctica was situated in almost the same latitude as today, but temperatures resembled those of modern day mid-latitude environments (e.g, North Carolina). In this unique setting, I found several co-occurring, unrelated, slow growing, long-lived species of bivalve. Cool temperatures cannot explain these impressive longevities. However, the high latitude setting would have resulted in extended periods of no sunlight and suggests that caloric restriction may be the driving factor in extreme longevity.

Chapters 1 and 2 suggest that growth rate could be the factor through which long-life is selected in the evolution of extreme longevity. Studies of growth rates of bivalves living at similar latitudes, under similar environmental conditions through long spans of geologic time, could help shed light on this question. However, determining growth rates and lifespans of bivalves requires cross-sectioning individuals to reveal internal growth bands. Such methods are time intensive and destructive sampling is often not permitted by museum curators. An alternative method could be to determine age by simply measuring the size of individuals without cross-sectioning, but the nature of growth in bivalves (long-lived in particular) is such that a few millimeters of growth could equate to several decades and introduces a large degree of error. In Chapter 3 then, I explore probabilistic methods for determining age from size in order to constrain population growth parameters without cutting large numbers of individuals. From a small original sample size, I use the relationship between parameters of the von Bertalanffy growth equation to constrain the theoretical age/size distributions of a population of modern *Spisula solidissima*. From these distributions, age can be assigned to an individual of any given size by drawing at random from the corresponding age/size distribution. This method works extremely well in reconstructing population growth parameters in a modern bivalve and should be applicable to the fossil record as well.

With the three chapters presented here, the foundation has been laid to study life history parameters in the fossil record. Currently, life history data are missing from studies of body size and energetics of organisms through time. The growth rate parameter k of the von Bertalanffy growth equation is the variable that will add a new dimension to our understanding of these fundamental patterns in the history of life on Earth. The conclusions from Chapter 1 predict that the temporal trend in body size is driven by an increase in k through time. The methods in Chapter 3 allow for study of k values through time in the fossil record. Chapter 2 examines lifespans and growth rates of fossil bivalves and provides significant revelations into the factors that influence extreme longevity. Though bivalves have been on the planet for over 500 million years, only a handful of studies have examined their life histories in the fossil record. Besides those presented, other fascinating areas where life history information is needed include studies of survival at mass extinction events and the transitions associated with the Mesozoic Marine Revolution. Incorporation of life history data into paleontological studies can and will provide fascinating insights in the evolution of life on Earth.

THE EVOLUTION OF EXTREME LONGEVITY IN MODERN AND FOSSIL BIVALVES

by

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To my friends in the department I thank you for keeping me sane. To all of the Earth Sciences graduate students I want to thank you for following my lead in the formation of the Geology Graduate Organization (GeoGO). I know that what we started will have a significant impact on the quality of life for future graduate students.

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Chapter 1:

Lifespan, growth rate, and body size across latitude in marine Bivalvia, with implications for Phanerozoic evolution

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Abstract

Mean body size in marine animals has increased more than 100 fold since the Cambrian, a discovery that brings to attention the key life history parameters of lifespan and growth rate that ultimately determine size. Variation in these parameters is not well understood on the planet today, much less in deep time. Here, we present a new global database of maximum reported lifespan (MLSP) and shell growth coupled with body size data for 1,148 populations of marine bivalves and show that 1) lifespan increases, and growth rate decreases, with latitude, both across the group as a whole and within well-sampled species, 2) growth rate, and hence metabolic rate, correlates inversely with lifespan, and 3) opposing trends in lifespan and growth combined with high variance obviate any demonstrable pattern in body size with latitude. Our observations suggest that the proposed increase in metabolic activity and demonstrated increase in body size of organisms over the Phanerozoic, should be accompanied by a concomitant shift towards faster growth and/or shorter lifespan in marine bivalves. This prediction, testable from the fossil record, may help to explain one of the more fundamental patterns in the evolutionary and ecological history of animal life on this planet.

Introduction

Animals living at high latitudes have long been suspected to live longer and grow more slowly than those in the tropics, but this contention is based on sparse and largely anecdotal data, and virtually nothing is known of how these parameters have changed over time. Bivalve molluscs are distributed pole to pole, are abundant in the fossil record, and their accretionary shells typically preserve records of age-at-size for every year of an animal's life. As such, they offer an ideal vessel by which to constrain these parameters for marine ectotherms over Earth's surface today. Faster growth and longer life offer two avenues by which to attain larger size, but they have contrasting implications for the metabolic and ecologic changes hypothesized to drive a mean size increase over time (Bambach 1993, Finnegan et al. 2011, Heim et al. 2015, Payne et al. 2009, Smith et al. 2016). In addition, 'faster' life histories allow for more rapid evolutionary change, and so any documented trend with latitude will have implications for gradients in diversity and ecology. An examination of spatial variation in life history parameters may therefore provide insight into modern biodiversity patterns as well as lay the groundwork for interpreting trends through time.

Our dataset (available online at Proceedings B website) derives from an exhaustive search of the peer-reviewed literature and consists of measures of maximum reported lifespan (MLSP), growth, and maximum body size from 1,148 local populations of living marine bivalves spanning the tropics to the polar regions. Data encompass 297 species in 158 genera and include members of nearly half (45) of all extant marine bivalve families (97). Not surprisingly, families that serve as fisheries targets (e.g., Veneridae, Pectinidae, Mytilidae) are represented by greater numbers of populations in the published literature. Fewer populations are recorded from low latitudes; however, these observations account for over 140,000 individuals. Only data from "wild" populations are included; aquacultural and experimental studies were omitted. Growth is approximated by k, the von Bertalanffy growth coefficient, a measure of how fast maximum adult size is attained and a consistent proxy for shell growth across disparate taxa. Maximum body size of individuals within populations is approximated by L_{∞}, the asymptotic size derived from the von Bertalanffy growth equation. See the Supplement for details on the dataset and the von Bertalanffy growth equation (von Bertalanffy 1938).

Results

The data reveal that most bivalves are short lived and that there is a pattern in the distribution of lifespan and growth, but not body size, with latitude.

Maximum reported lifespans for populations of the Bivalvia are exponentially distributed; in more than half the sampled populations, the oldest individuals live for fewer than 11 years (Fig. 1). While most bivalves by far are short-lived (the modal lifespan of species is 3 years), a not insignificant number of species have MLSPs that exceed 20 years, and at least 9 centenarian taxa are documented, including the record-holding *Arctica islandica,* at 507 years (Butler et al. 2013) (Table S1). Note that "maximum" lifespan is in part a function of sampling effort, and reported values should be treated as estimates.

Population-level data plotted by latitude reinforce the preponderance of short-lived bivalves but also demonstrate a strong tendency for populations with longer-lived individuals to be found at higher latitudes (Fig. 2A). Because frequency distributions of population MLSPs, both for the whole dataset (Fig. 1) and for subsets of populations divided by latitude (Fig. S1), are exponentially distributed, standard parametric descriptive statistics can be used to compare population variables across latitude. The mean and standard deviation of MLSPs reported for populations increase with increasing latitude. Populations of tropical (< 30°) bivalves record a mean MLSP of 7.9 years, whereas those in the mid- to high-latitudes have a mean MLSP of 24.7 years. Outliers for low latitudes include the photosymbiotic giant clams (*Tridacna*) and the chemosymbiotic vent clam *Bathymodiolus.* No other low-latitude species have populations with MLSPs longer than 30 years. Individual taxa represented by at least 15 sampled populations spanning >10° of latitude show a similar pattern of increasing lifespan with latitude

(Fig. S2), suggesting a cause that acts both within and across species. Growth (k) shows a similar, but inverse, relationship with latitude (Fig. 2B). Low-latitude bivalves are characterized by significantly higher and more variable growth coefficients than those in the mid and high latitudes.

The potential for these observed patterns to arise simply from uneven sampling with latitude is evaluated by comparing observed data to modeled distributions where lifespan and k in fact have no relationship to latitude. For each variable, we generate exponential distributions using a rate term (slope on a log plot) equal to 1/mean of all observed values (a better approximation of the actual distribution than the best-fit to the discretized histogram), draw values from the modeled distributions at random, and randomly assign them to each of our sampled-population latitudes, thus eliminating any preferred tendency with latitude. We then bin modeled data by latitude and calculate the mean and standard deviation of lifespan and k in each bin. After 1000 trials, we compare the distributions of modeled lifespans and k values in each bin, where there is no relation with latitude but sampling is still non-uniform, to the observed data. Despite being undersampled, observed lifespans are significantly shorter and less variable in the tropics, and higher and more variable near the poles, than seen in the randomized trials (Fig. 3A,B). Likewise, the observed mean and standard deviation of growth/metabolic rate are significantly higher in the tropics and lower toward the poles (Fig. 3C,D).

Plotting k versus lifespan reveals a significant log-log relationship ($p<0.001$) such that slower growing bivalves tend to have longer lifespans than fast growing forms (Fig. 4), corroborating a relationship suggested earlier from a limited dataset (Ridgway et al. 2011a).

Data grouped by order (Fig. 4) or family exhibit the same negative lifespan-growth relationship, suggesting that causal factors act universally across taxa, rather than the pattern being merely an epiphenomenon of specialization for distinct physiologies or habitats. Because shell growth, more-so than soft-tissue growth, provides a strong proxy for metabolic rate (Lewis and Cerrato 1997), these data also indicate that short-lived (tropical) bivalves have faster metabolisms than long-lived (polar) species, an inference supported by oxygen consumption data for bivalves across a range of habitats (Vladimirova et al. 2003).

The exponential fits to frequency distributions of population MLSPs grouped into 16° latitudinal bands (Fig. S1) illustrate the increasing proportion of populations with longer-lived individuals as latitude increases. Such a pattern requires a systematic decrease in the exponent of the exponential equation (slope on a log scale) with latitude (Fig. S1F). This value corresponds to the probability of death; higher slopes at low latitudes reflect higher overall rates of bivalve mortality (Fig. 5). This pattern is evident whether grouping data into bins of equal latitude or equal numbers of observations.

While lifespan and growth rate demonstrate clear trends with latitude, the combined result of these two variables, body size, does not. Using the von Bertalanffy parameter L_∞ as a proxy for maximum size within populations reveals no significant relationship between body size and latitude (Fig. 2C, Fig. 3E, F), lifespan, or growth rate (Fig. S3A, B). Populations of slower growing, longer lived, high latitude species show a similar range of sizes overall to those of faster growing, short-lived, tropical species. This lack of a consistent pattern in bivalve body size with latitude, within or across taxa, is supported by earlier work and has been discussed at some length (e.g., Berke et al. 2013, Roy et al. 2000).

Note that R^2 values for the relationships described above are low; latitude alone is a poor predictor of lifespan and growth. To be sure, the lifespans and growth rates exhibited within a population are controlled by a myriad of factors (e.g., see the discussion below), and this complexity contributes to the high variance exhibited in these relationships. Nevertheless, highly significant p values indicate that, despite the variance, latitude and its correlates contribute in a substantive way to an explanation of lifespan and growth across marine Bivalvia today, and hence can be expected to have done so in the past as well.

Potential Causal Factors

Strong trends in lifespan and growth coefficient with latitude, both within and across taxa, require an explanation consistent with factors that vary systematically with latitude. Environmental variables such as temperature and light (and hence primary production, or food availability) are perhaps the most obvious – both have strong impacts on physiology through their influence on metabolism, and metabolic rate is widely suspected to relate causally to lifespan (Speakman 2005, Van Voorhies 2001). Indeed, our documentation of the relationship between lifespan and growth coefficient in bivalves lends further support to that hypothesis. The decrease in temperature that accompanies increasing latitude has a profound influence on biology; as temperature decreases, so too does metabolic rate in both plants and animals (Gillooly et al. 2001). Metabolic rate is also influenced by the availability of food. For the dominantly filter-feeding bivalves, food constitutes phytoplankton and other suspended particles, and phytoplankton production is strongly tied to solar insolation. Studies on a range of animals have shown that caloric restriction increases lifespan, likely through a reduction in metabolic rate (Fontana et al. 2010). Today, high-latitude bivalves like *Arctica islandica* experience not only cold temperatures but also a limited and highly seasonal supply of food. Deconvolving their influence is difficult, but work with austral sea urchins demonstrates that the effect on metabolism of starvation in winter is far more significant than that of cold temperature (Brockington and Clarke 2001). In either case, long lifespan might simply be a side consequence of limited metabolism rather than a true adaptation to high-latitude environments. Alternatively, if trophic constraints are severe enough that successful reproduction in any given year is unlikely, then long life would be adaptive for organisms that spawn only once per year.

A decrease in disturbance frequency with latitude might also play a role in growth/lifespan trends because long-lived bivalves tend to delay the onset of reproduction for years or even decades (Ridgway et al. 2011a), not a viable life history strategy when an early death due to some calamity is probable. While physical/environmental disturbances such as storms or sediment gravity flows are unlikely to show a consistent relationship with latitude, ecological disturbances like predation could. Such has been postulated (Vermeij 1978), and, while not observed everywhere (Kelley and Hansen 2007, Vermeij et al. 1989), studies have demonstrated a decrease in both drilling (Visaggi and Kelley 2015) and skeleton-crushing (Bertness et al. 1981) predation on bivalves with increasing latitude and extremely low predation in shallow Antarctic ecosystems (Aronson et al. 2007, Harper and Peck 2003, Harper and Peck 2016, Martinelli et al. 2013). Our data are consistent with the hypothesis that fast growth, and consequently shorter life, in the tropics is an adaptation to higher predation frequency. A general, though not universal, decrease in predation with latitude would allow for increasing variation in life history strategies. While diversity and ecological interactions have a strong influence on local trophic structure (e.g., Hairston and Hairston 1993), a putative latitudinal trend in predation intensity may itself also derive in part from the distribution of temperature and light over Earth's surface.

Note that temperature and food supply in the oceans decrease not only with latitude, but also with water depth. There is evidence, too, that predation pressure decreases with increasing depth (Harper and Peck 2003, Oji 1996). While not the focus of our study, water depth was reported for 425 of the populations in our dataset. Data are sparse, strongly skewed to shallow shelf depths, and often reported as ranges of values, but a tendency toward longer lifespan with increasing water depth is suggested (Fig. S4A). There does not appear to be a relationship with growth rate or, perhaps less surprising given the lack of a latitudinal pattern as well, body size (Fig. S4B,C). Nevertheless, the limitations of the available data require caution when interpreting pattern (see discussion in SI). Additional targeted sampling might help to clarify the nature of these relationships.

Implications for Phanerozoic Evolution

We document a clear global pattern in the latitudinal distribution of life history parameters in today's oceans for a pervasive marine ectotherm, animals that also dominate the post-Paleozoic fossil record and range back to the Cambrian. Is there a temporal trend in the expression of this pattern, and what might it mean for the evolution and ecology of marine ecosystems over the deep history of life? Despite the relative ease with which bivalve lifespans and growth rates can be determined from their shells, the longevities of fossil bivalves have only been reported in a handful of studies. Anecdotal data are consistent with today's broad latitudinal pattern persisting back through the Phanerozoic: subtropical mollusks live only a few years in the Eocene (Haveles and Ivany 2010), mid-latitude (~40°N) Jurassic gryphaeid bivalves live upwards of 20 years, and early Permian high-latitude faunas contain bivalves with lifespans of several to many decades (Ivany and Runnegar 2010), all consistent with the modern trend. The degree to which temperature is driving this pattern will determine how sensitive the gradient is to global climate change over time. Early in the Cenozoic, for example, the poles were a good deal warmer than today, yet bivalve centenarians are still present in austral polar faunas (Buick and Ivany 2004). Such non-analog settings, where temperature and light/food limitation are not as tightly correlated as they are today, can offer critical tests of their relative causal roles.

The pace of life – growth rate and life span – has significant implications for the interpretation of macroevolutionary trends. Not only is this at the heart of resolving modes of heterochronic change in the evolution of individual lineages (Jones 1988, Jones and Gould 1999), but there are potential connections to global Phanerozoic trends in body size, energetics and diversity. Causal hypotheses for aspects of each of these can be tested using life history data from the fossil record now that patterns in Modern oceans are understood.

An increase in the mean body size of animals through time is now well documented (Heim et al. 2015, Payne et al. 2014), a trend manifest within bivalves as well (Fig. S5). Today, consistent relationships between body size and latitude (Fig 2), body size and lifespan (Fig S3A) or body size and growth rate (Fig. S3B) cannot be demonstrated in marine bivalves, obfuscating the driving factor behind a temporal increase in body size using a space-for-time substitution argument. However, the relationship between lifespan and growth rate predicts that even limited new data on one variable or the other can bring greater clarity on how a trend toward larger body size comes about. The scenarios of increasing lifespan or growth rate bear rather different implications for the macroecological history of bivalves, hence these types of data are critical complements to existing data on body size evolution.

An increase in the metabolic rate of marine organisms is an inherent prediction of broad ecological hypotheses such as Seafood through Time and escalation during the Mesozoic Marine Revolution (Bambach 1993, Vermeij 1977). This prediction is supported by Finnegan et al. (Finnegan et al. 2011), who use the metabolic model of Gillooly et al. (Gillooly et al. 2001) to relate increasing body size in post-Paleozoic gastropods to faster metabolic rates through time and provide the first quantitative test of the energetics hypothesis. A subsequent analysis by Payne et al. (2014) using size data of bivalves over the Phanerozoic suggests a similar increase in metabolic rates. The necessary assumptions that accompany the application of this model to extinct organisms in deep time call for some caution in interpreting the results. However, because shell growth correlates with both metabolic rate and lifespan, one could validate the Finnegan et al. (Finnegan et al. 2011) and Payne et al. (2014) results, and hypotheses about energetics though time, with a targeted study of von Bertalanffy k values and/or lifespans of shells sampled from similar paleolatitudes over time. To the degree that lifespan/growth gradients are sensitive to temperature, our data also predict that polar faunas may become more ‘escalated’ during times of global warmth. Antarctic faunas during the warm Eocene are ecologically more similar to low latitude assemblages than they become once temperature begins to fall (Aronson et al. 2009). Comparison of Eocene life history traits with those from more recent cooler times could test this prediction.

Another fundamental biological pattern, the latitudinal diversity gradient, may not be unrelated to the distribution of life history parameters with latitude. Speciation rates are in part dependent upon the rates of mutation, and taxa with shorter generation times have the potential to accumulate more variation in a given interval of time (Thomas et al. 2010). Because slow-growing bivalves also tend to delay the onset of sexual maturity (Ridgway et al. 2011a), polar taxa might be less likely to spin off new species than are fast-growing tropical taxa. It is therefore not unreasonable to suggest that life history parameters in fact contribute to the maintenance of the latitudinal diversity gradient. Such is consistent with observations of preferential bivalve origination in the tropics during the Neogene (Jablonski et al. 2006). Furthermore, a connection might be made with the modest rise in sample-standardized diversity seen over the Phanerozoic (Alroy et al. 2008).

While the potential for testing hypotheses about relationships between life history traits and spatio-temporal macroevolutionary trends using the modern and fossil record is high, little work has thus far been done. This may be the next frontier of paleobiological research.

Figures

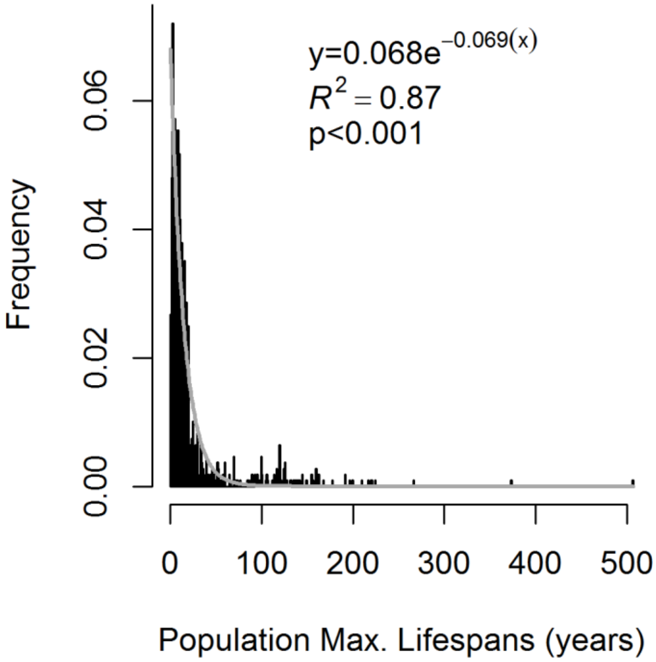


Figure 1. Distribution of maximum reported lifespans of individuals within all populations of the Bivalvia in the database. Minimum = 0.25 yrs (*Donax variabilis*), maximum = 507 yrs (*Arctica islandica*). Dataset provided in the Supplement. N = 1,084.

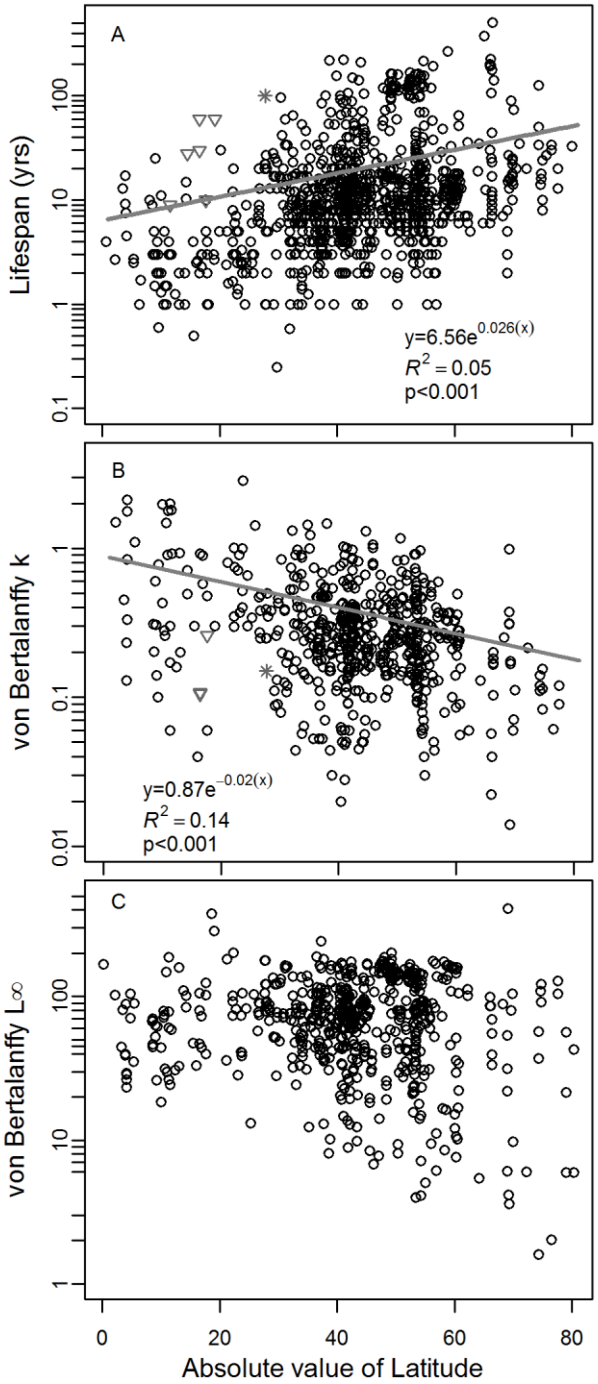


Figure 2. Relationships between latitude and life history parameters in local populations of marine bivalves. A) Maximum lifespan; N=1077. B) Growth as measured by the von Bertalanffy growth parameter, k; N=613. C) Body size as measured by the von Bertalanffy L∞ parameter;

N=636. ∇= *Tridacna*, a photosymbiotic taxon; * = *Bathymodiolus*, a chemosymbiotic taxon from a hydrothermal vent setting.

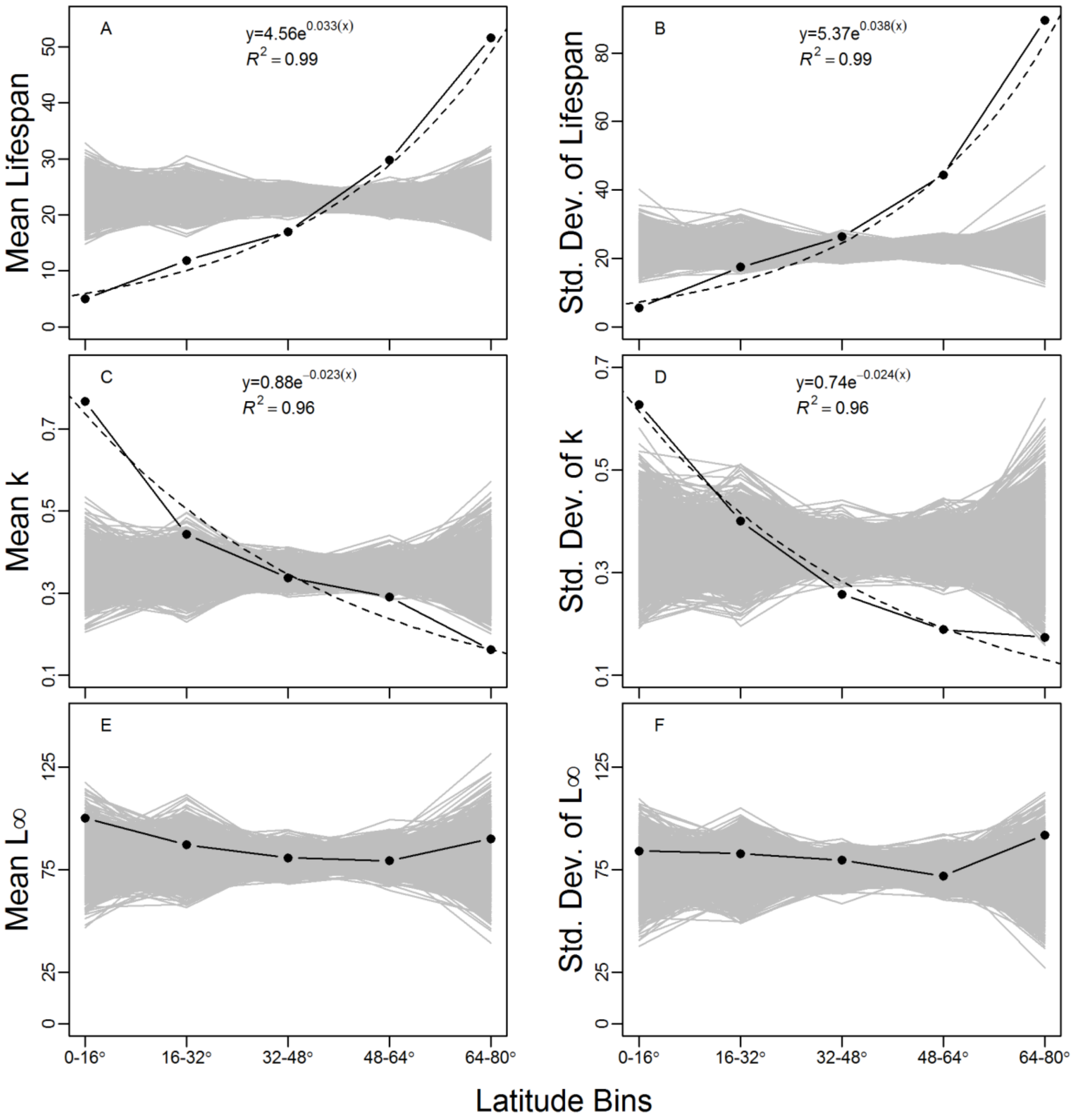


Figure 3. Results of resampling procedures to evaluate statistical significance of relationships between latitude and life history parameters. Gray lines connect resampled values assuming no relationship with latitude. Black lines are the observed trends in values and their best-fit lines. A) Mean and B) standard deviation of maximum lifespan vs. latitude. Mean observed lifespan = 22.47 for entire database. C) Mean and D) standard deviation of von Bertalanffy k

values vs. latitude. Mean observed k = 0.35 for entire database. Tropical and polar bivalves fall well outside the range of randomized trials for both lifespan and k. E) Mean and F) standard deviation of L_{∞}. Observed values fall within the range of randomized trials suggesting no significant relationship.

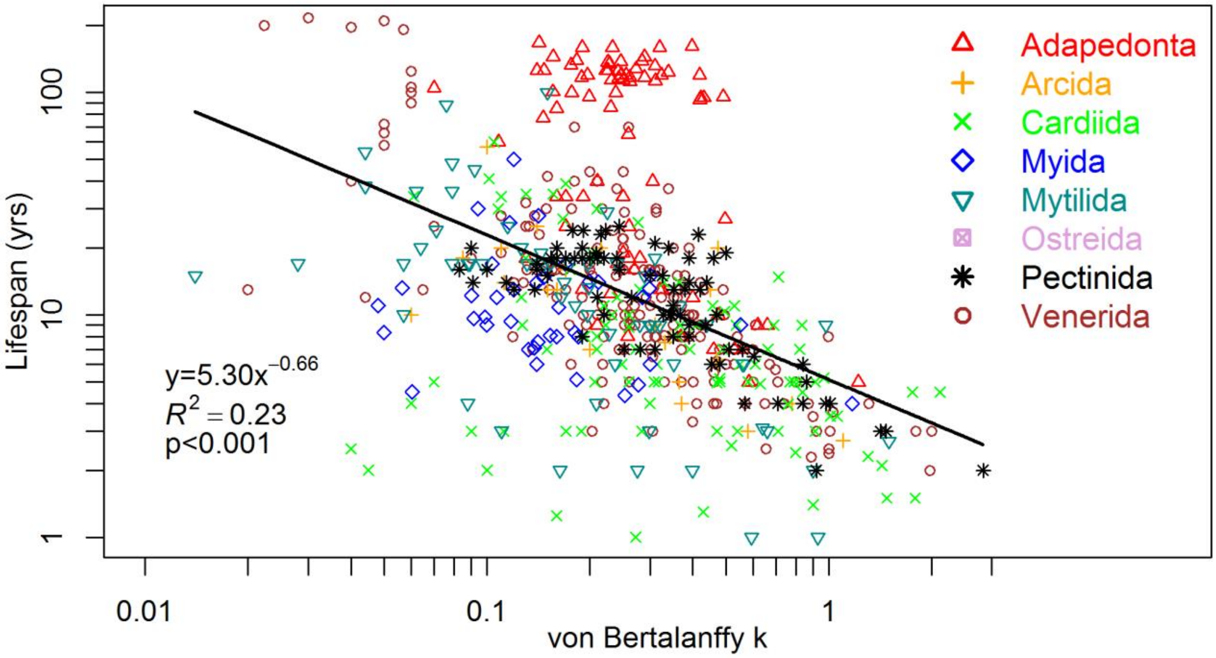


Figure 4. Relationship between the von Bertalanffy k growth coefficient and lifespan, with data points coded by Order within the Bivalvia. Only orders with >20 observations are included. Six-hundred and thirteen populations contain data on both lifespan and growth rate.

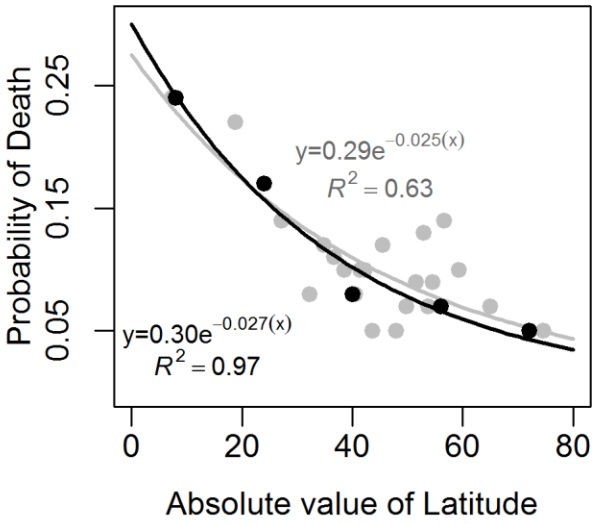


Figure 5. Probability of death versus latitude based on exponential fits to frequency distributions of populations MLSPs (Fig. S1). Lifespan observations are binned by equal latitude (in black, 16° bins) or by equal number of observations (in grey, 50 lifespans per bin except last with 26). Total number of observations on lifespan =1078. Absolute value of latitude is plotted as the midpoint of each bin. Note that both approaches yield essentially the same relationship (p<0.01).

Supplementary Material for Chapter 1:

Methods

We identified and searched the entire publication runs of 30 peer-reviewed journals (Table S2) likely to contain articles reporting lifespan and/or growth rate data on marine bivalves. We tracked down additional references cited therein, and also retrieved articles cited in previous molluscan lifespan compilations (Comfort 1957, Heller 1990, Kidwell and Rothfus 2010, Powell and Stanton 1985, Robertson 1979). A full list of references is provided at the end of this Supplement. Our database differs from previous attempts in that all entries are derived solely from primary sources, based on natural populations, and we record not only maximum reported lifespan (MLSP), but also von Bertalanffy growth parameters and latitude and longitude of the population sampled. Water depth was also tabulated if provided, along with other population metadata (Table S3). The database consists of observations derived from 1,148 populations. Not all variables are recorded for all populations, but 1,084 report maximum lifespan, 673 report von Bertalanffy k values, and 613 report both of these.

Parameters from the von Bertalanffy growth equation (von Bertalanffy 1938) can be used to describe the growth of many marine invertebrates. The standard form of the von Bertalanffy growth equation can be written as:

$$L_t = L_\infty(1-e^{-k(t-t_0)})$$

where L_t = shell length at time t, L_∞ = asymptotic size, or the size at which growth rate is essentially zero, k = rate at which L_∞ is attained, and t_0= age at which the bivalve has a size of zero (the x intercept on a plot of size as a function of age). In organisms with indeterminate growth, such as bivalves, a maximum size may not be biologically appropriate, though L_∞ is often treated as such in the literature. Where only age-size data were provided but not curve-fit, we calculated von Bertalanffy growth parameters using the nls procedure in R.

Taxonomy for all entries in the database was verified using the World Online Register of Marine Species (http://www.marinespecies.org/). Representatives from 45 bivalve families are included in the database (Table S4), accounting for nearly half of all described families. The most numerous are the Veneridae (n=223), Mytilidae (n=121), Pectinidae (n=116), and Hiatellidae (n=70).

Results and Discussion

Lifespan and growth within taxa

An examination of lifespan versus latitude in species with at least 15 observations spanning more than 10°of latitude (Fig. S2) makes apparent that the pattern in Fig. 2A is not driven by one or a few taxa, but rather is a feature present across the Bivalvia, both within and across taxa. In 11 of 12 well-sampled species spanning 9 families, the slope of the relationship between maximum within-population lifespan and absolute latitude exceeds zero at a significance of $p < 0.10$. The lower slope of the best-fit line for *Mercenaria* may be an artifact of sampling mainly shallow-water populations along the U.S. Atlantic Coast, which have historically been heavily harvested (Quitmyer and Jones 1997, Rice 1992). The oldest specimen of *Mercenaria mercenaria*, a 106-year-old individual, was collected in water deeper (15m) than had been investigated before (Ridgway et al. 2011b), suggesting the potential for a different age-latitude relationship in less impacted, deeper-water populations. See discussion on depth below.

Depth versus lifespan, growth rate, and size

Nutrient availability and temperature decrease with depth as they do with latitude, and thus the depth at which an organism lives may also relate to its longevity and growth. In addition, deep-water ecosystems have been described as ecologically distinct from those on the shelf due in part to different evolutionary histories (Jablonski et al. 1983), and this could be reflected in differences in lifespan and growth (e.g., Koslow 2000 for fishes). Sources report depths for fewer than half of all populations (N = 425), and those are often given as approximations or broad ranges. It is possible, therefore, that water depth could introduce variation that is unaccounted for and obscures patterns in lifespan and growth with latitude. Reported data, however, are strongly skewed toward shallow shelf settings (modal depth = 10 m; only 7 populations are recorded from ≥200 meters), and there is no reason to believe the remainder to be any different, particularly given that most come from fisheries targets harvested on the shelf. Patterns we report are therefore likely to characterize shallow shelf faunas – there is no systematic bias associated with including a large number of slope or deep sea taxa from particular regions that could color our results.

While the vast majority of our data come from shelf settings, it is nonetheless possible that effects associated with water depth could be present in the data. Jones et al. (Jones et al. 1978a), e.g., presented data suggesting differences in longevity, growth, and body size between shallow and deep populations of *Spisula solidissima* off New Jersey, but few other systematic studies exist. We restricted our analysis to the well-sampled mid-latitudes (30-60° N and S) so as to minimize conflation with covariates of latitude as much as possible. The relationship between depth and lifespan is positive and significant, but there is no demonstrable relationship between depth and either growth rate or body size (Fig. S4). These results should be treated with caution. Observations from many more populations along broad depth transects at constant latitude are needed to establish the presence or absence of pattern with confidence.

Supplementary Figures

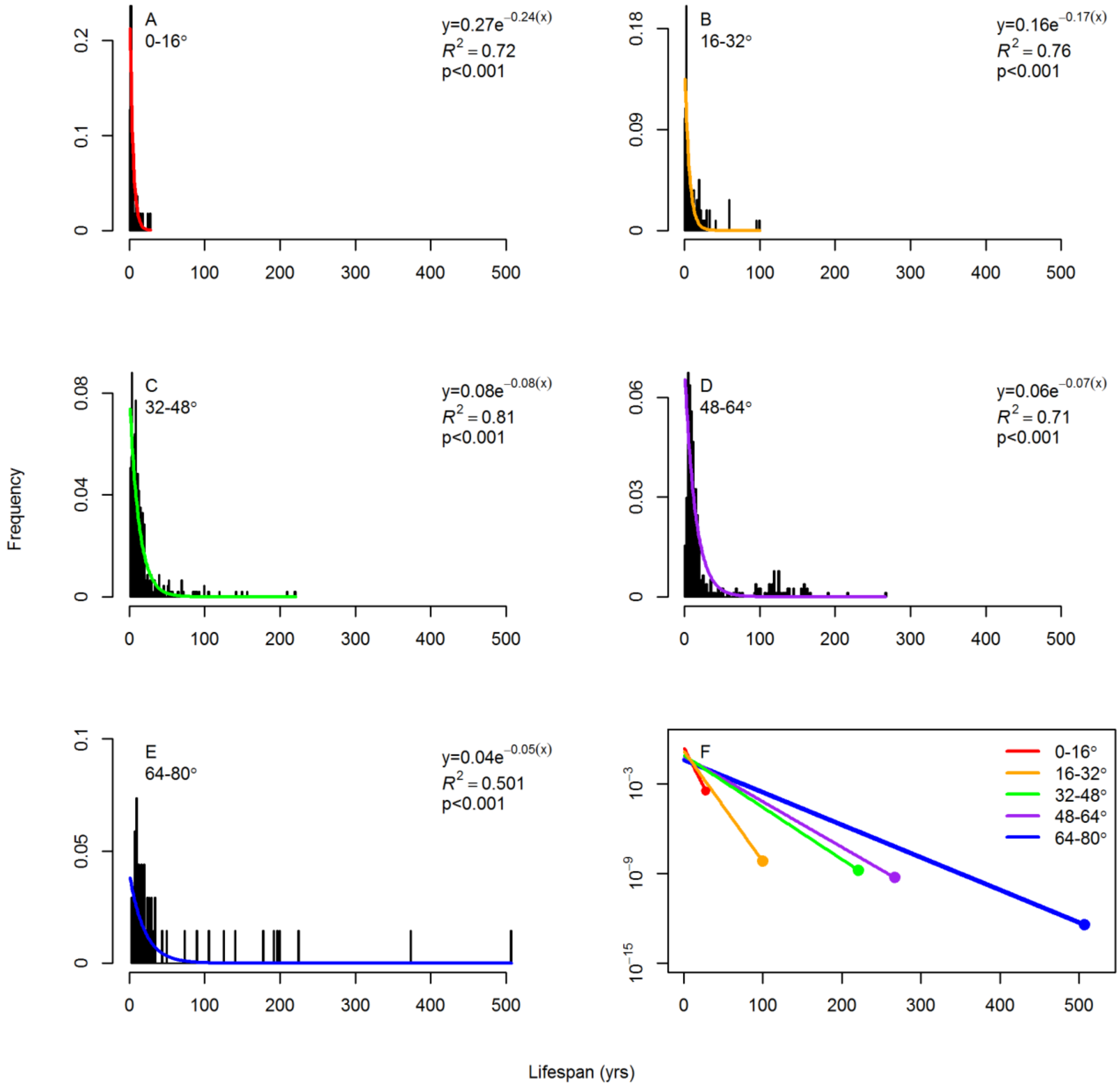


Figure S1. Histograms of population-level maximum lifespans for each 16° latitude bin. Curves are best fit exponential equations. Y-axes vary to best show fits to distribution. Panel F shows all 5 regressions on a log scale, truncated at the observed maximum lifespan for that bin, to illustrate differences in slope (probability of death) with latitude and maximum lifespan. See main text for more discussion.

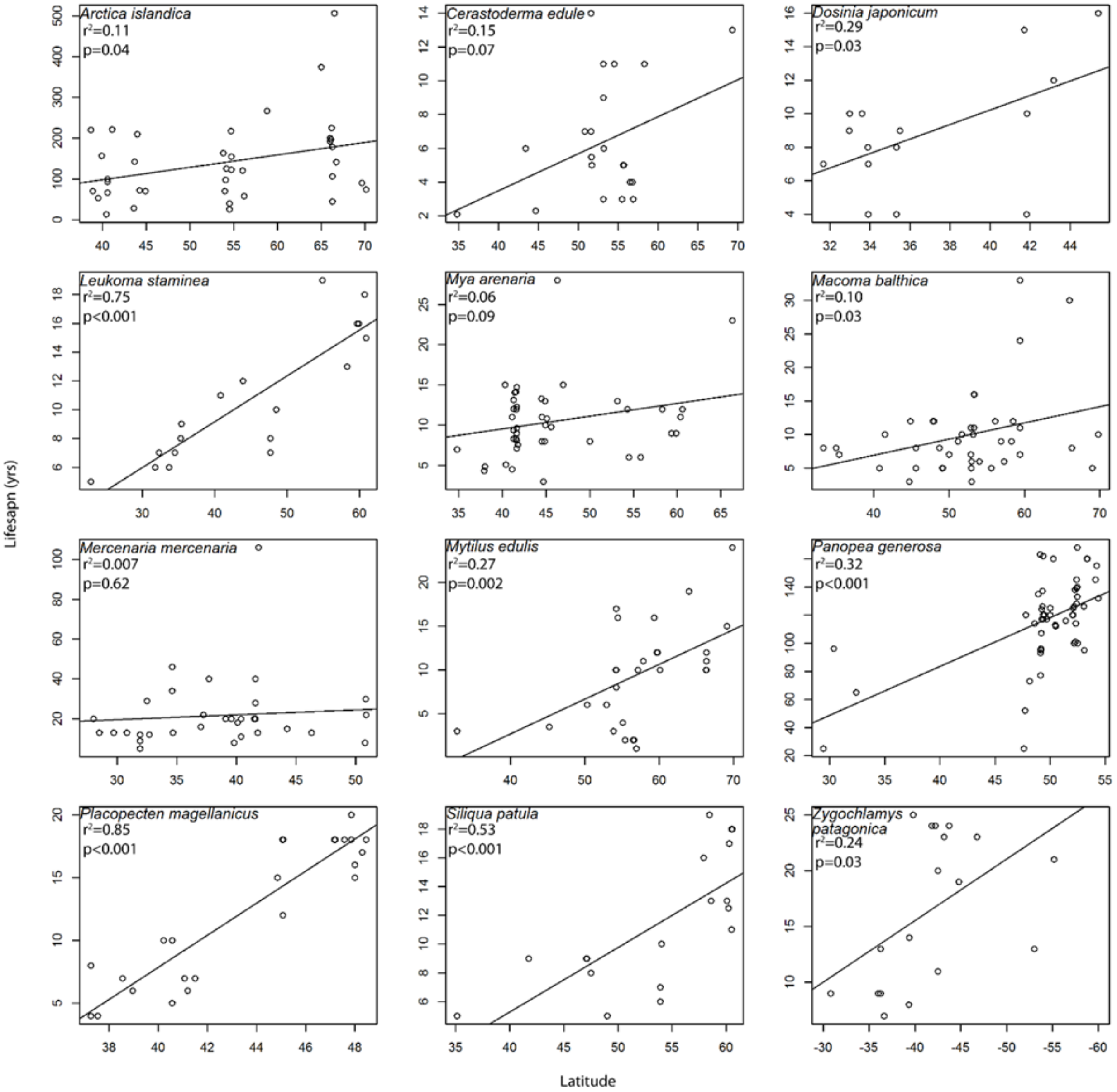


Figure S2. Relationship between latitude and lifespan in 12 species with at least 15 populations spanning >10° of latitude. All but one of the regressions (*Mercenaria*) are significant at the 0.01 level.

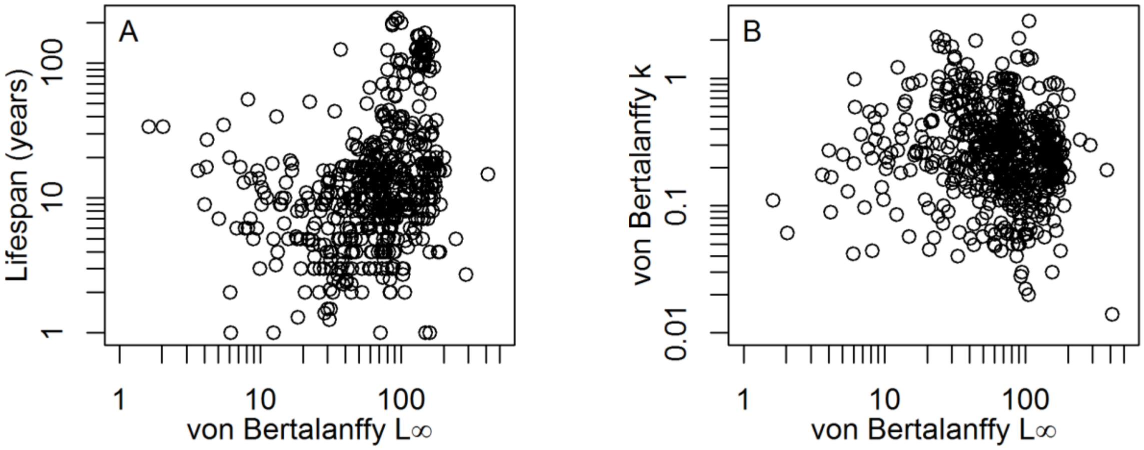


Figure S3. Relationships between maximum body size (approximated by L∞) and lifespan (A) and growth rate (B). Neither of the relationships are statistically significant.

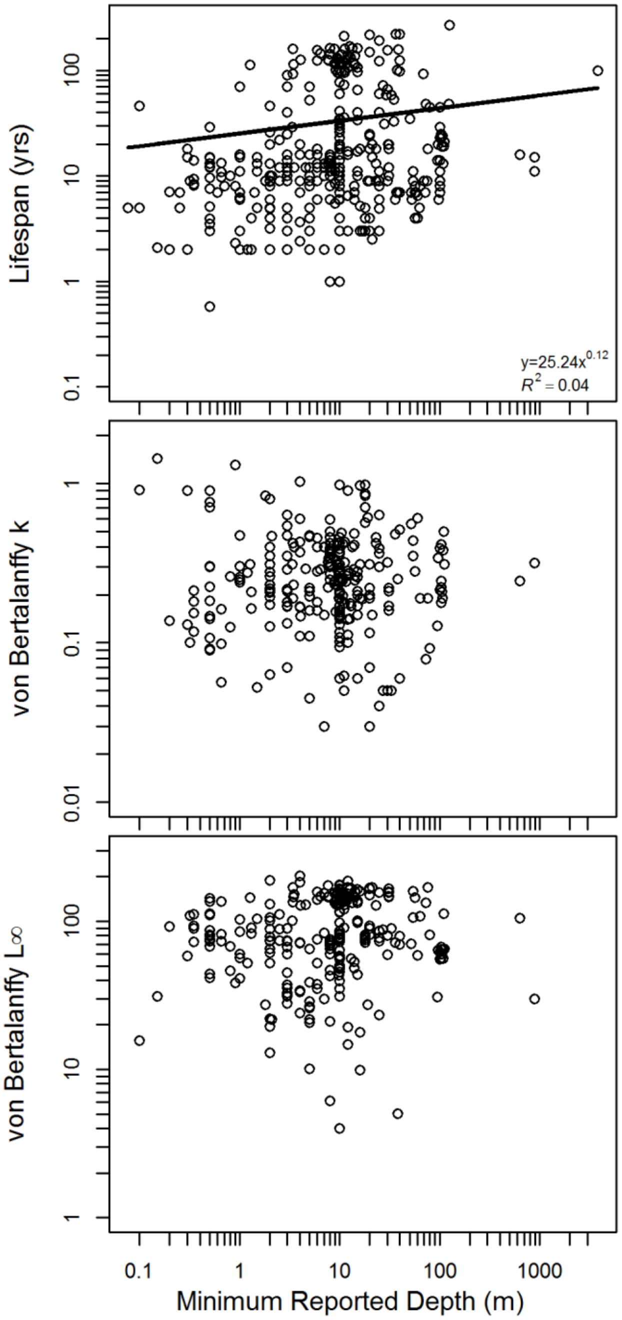


Figure S4. Relationship between water depth and A) maximum lifespan, N=411 observations, B) growth rate, N=278 observations, and C) body size, N=278 observations, for populations between 30° and 60° N and S latitude. Only the trend with lifespan is significant ($p \leq 0.01$).

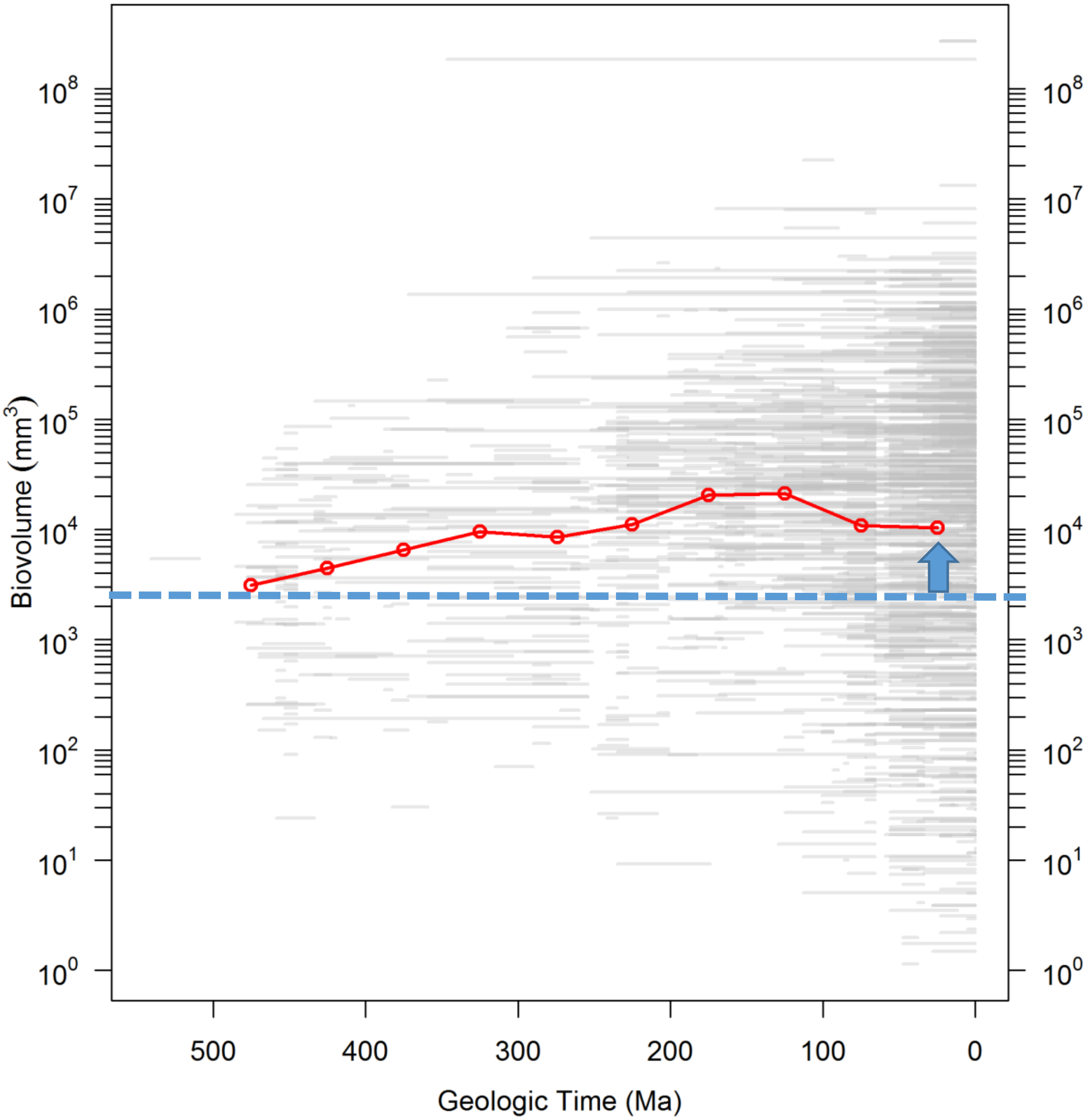


Figure S5. Biovolume of bivalve genera through the Phanerozoic derived from Heim et al. (Heim et al. 2015), plotted as body size of the largest measured species within each genus over the geologic range of the entire genus. Gray bars are geologic ranges. Red line shows the trend in mean biovolume towards the Recent for 50-million-year time bins, an increase perhaps first noticed by Runnegar (Runnegar 1985).

Supplementary Tables

Table S1. Maximum reported lifespans (MLSP) for species represented in database. References provided in Appendix 1.

Species	MLSP (yrs.)
Abra alba	4
Abra nitida	8.8
Abra prismatica	1.8
Abra tenuis	2.5
Adacnarca nitens	20
Adamussium colbecki	20
Aequipecten opercularis	8
Aligena elevata	7
Amarilladesma mactroides	8
Amiantis purpurata	25
Amusium pleuronectes	2
Amygdalum glaberrimum	1
Anadara broughtonii	20
Anadara cornea	4
Anadara inaequivalvis	7
Anadara nobilis	4
Anadara tuberculosa	25
Anodontia alba	2
Anomalocardia flexuosa	2.6
Anomalodiscus squamosus	3
Arca noae	16
Arca ventricosa	10
Arca zebra	10
Arctica islandica	507
Arcuatula arcuatula	1.5
Arcuatula senhousia	2
Argopecten irradians	2
Argopecten irradians concentricus	2
Argopecten purpuratus	6
Arvella manshurica	9
Asaphis deflorata	7
Astarte arctica	9
Astarte borealis	10
Astarte elliptica	20
Astarte warhami	3
Atrina vexillum	11
Aulacomya atra	18
Austrovenus stutchburyi	9
Barbatia trapezina	6.29
Barnea candida	4
Barnea parva	6
Bathymodiolus childressi	100
Brachidontes variabilis	5
Callista chione	18
Calyptogena magnifica	4
Carditamera affinis	17.25
Cavatidens omissa	1
Cerastoderma edule	14
Cerastoderma glaucum	6
Chamelea gallina	12
Chamelea striatula	11
Chione cancellata	6
Chione cortezi	8
Chione elevata	11
Chione undatella	2
Chionista fulctifraga	16
Chlamys islandica	35
Chlamys tehuelcha	5
Choromytilus chorus	1.25
Choromytilus meridionalis	9
Ciliatocardium ciliatum	35
Clinocardium nuttallii	16
Corbicula fluminea	4
Corbula gibba	2
Crassostrea ariakensis	5
Crassostrea bilineata	4
Crassostrea gigas	7
Crassostrea glomerata	1.25
Crassostrea rhizophorae	1
Crassostrea virginica	6
Crassula aequilatera	5
Crenella decussata	7
Crenomytilus grayanus	150
Cumingia tellinoides	4
Cyclocardia ventricosa	12
Cyrtodaria siliqua	105
Cytrodaria kurriana	19
Decatopecten radula	8
Diplodon chilensis patagonicus	90
Diplodonta aleutica	6

Table S1 cont.

Species	**MLSP (yrs.)**	**Species**	**MLSP (yrs.)**
Divaricella irpex	1	*Hiatella arctica*	126
Donax cuneatus	3	*Katelysia opima*	3
Donax denticulatus	1.5	*Keenocardium californiense*	9
Donax dentifer	4.5	*Kurtiella bidentata*	7
Donax faba	2	*Lasaea adansoni*	4
Donax gouldi	3	*Laternula elliptica*	36
Donax hanleyanus	5.18	*Leiosolenus patagonicus*	15
Donax incarnatus	2	*Leukoma antiqua*	16
Donax serra	2	*Leukoma grata*	14
Donax sordidus	1.4	*Leukoma jedoensis*	6
Donax spiculum	0.6	*Leukoma staminea*	19
Donax striatus	2.4	*Leukoma thaca*	9
Donax trunculus	5	*Liocyma fluctuosa*	23
Donax variabilis	1	*Lissarca miliaris*	7
Donax vittatus	8	*Lissarca notorcadensis*	18
Dosinia concentrica	3	*Lithophaga lithophaga*	54
Dosinia elegans	6	*Loripes lucinalis*	4.9
Dosinia exoleta	12	*Lunarca ovalis*	3
Dosinia hepatica	9	*Lyonsia arenosa*	7
Dosinia japonicum	16	*Lyonsia vniroi*	10
Dosinia lupinus	15	*Macoma balthica*	33
Ensis directus	8.5	*Macoma calcarea*	18
Ensis macha	9	*Macoma lama*	8
Ensis magnus	18	*Macoma loveni*	11
Ensis siliqua	10	*Macoma middendorffi*	19
Eontia ponderosa	15	*Macoma nobilis*	3
Equichlamys bifrons	13	*Mactra chinensis*	12
Eurhomalea exalbida	70	*Mactromeris polynyma*	60
Eurhomalea rufa	2.5	*Megapitaria maculata*	10
Ezocallista brevisiphonata	52	*Megapitaria squalida*	2.5
Fragum fragum	5	*Megayoldia thraciaeformis*	15
Gafrarium pectinatum	3	*Mercenaria campechiensis*	28
Gaimardia trapesina	5	*Mercenaria mercenaria*	106
Gari solida	14.83	*Meretrix casta*	3
Gemma gemma	6	*Mesodesma arctatum*	24
Geukensia demissa	24	*Mimachlamys gloriosa*	4
Glossocardia obesa	8	*Mimachlamys varia*	6
Glycymeris bimaculata	57	*Mizuhopecten yessoensis*	15
Glycymeris glycymeris	192	*Modiolus modiolus*	48
Glycymeris nummaria	20	*Mulinia edulis*	7

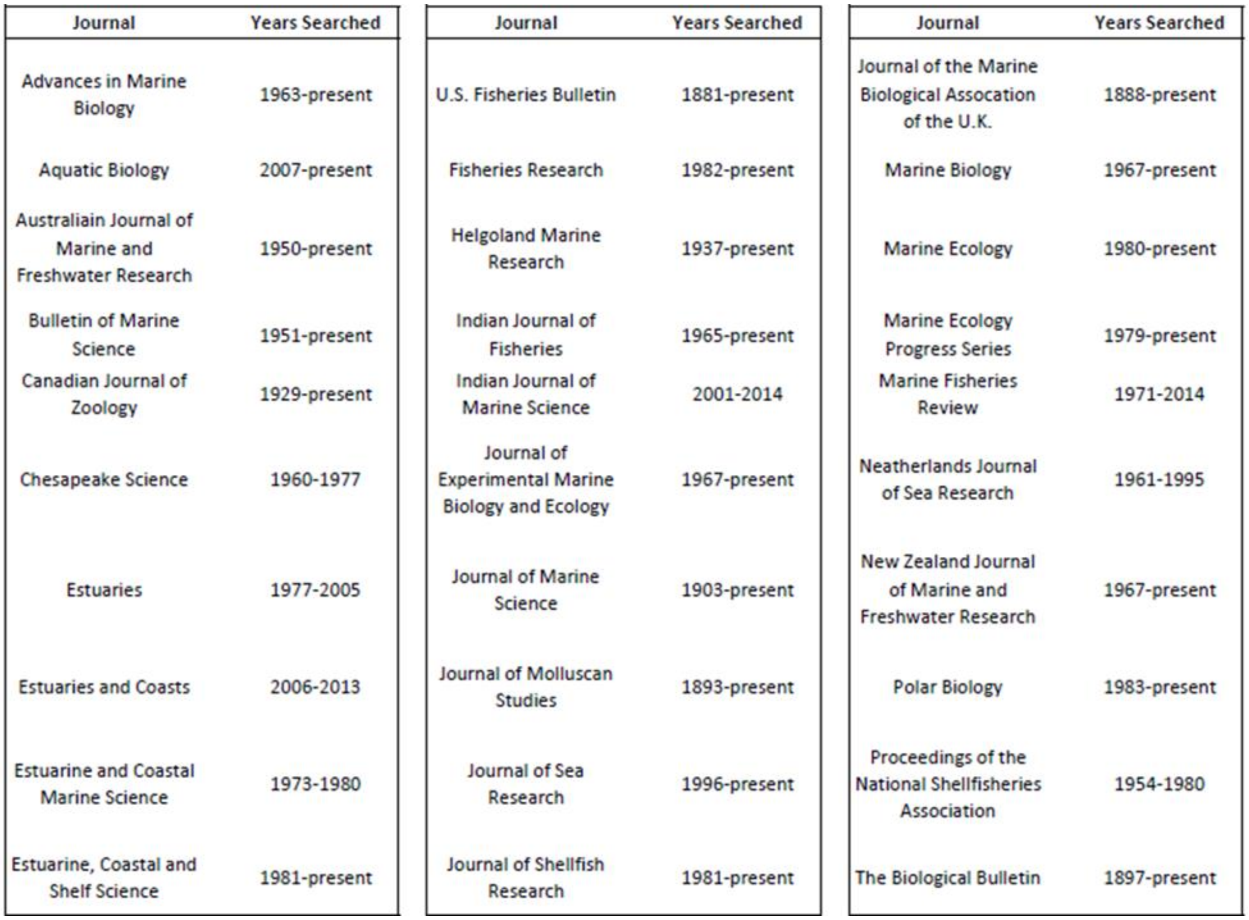
Table S1 cont.

Species	**MLSP (yrs.)**	**Species**	**MLSP (yrs.)**
Mulinia lateralis	0.58	*Pholas dactylus*	14
Musculus discors	9	*Phreagena kilmeri*	16
Musculus niger	19	*Pillucina neglecta*	1.5
Mya arenaria	28	*Pinctada imbricata*	7
Mya baxteri	30	*Pinctada imbricata fucata*	6
Mya pseudoarenaria	26	*Pinctada imbricata radiata*	4
Mya truncata	50	*Pinctada margaritifera*	5
Mysella cuneata	4	*Pinctada maxima*	20
Mysella kurilensis	9	*Pinna bicolor*	12
Mysella planulata	4	*Pinna nobilis*	26
Mytilus californianus	6	*Placopecten magellanicus*	20
Mytilus coruscus	29	*Polititapes aureus*	5
Mytilus edulis	24	*Polititapes rhomboides*	11
Mytilus edulis planulatus	3	*Portlandia arctica*	7
Mytilus galloprovincialis	20	*Potamocorbula adusta*	1.71
Mytilus trossulus	13	*Protapes gallus*	3
Nucula paulula	1	*Protothaca euglypta*	15
Nucula turgida	10	*Pteria colymbus*	1
Nuculana minuta	9	*Pteria penguin*	2.7
Nuculana pernula	11	*Ptericolaria pholadiformis*	10
Ostrea chilensis	8	*Rangia cuneata*	8
Ostrea edulis	16	*Reloncavia chilencia*	1
Ostrea puelchana	6.5	*Ruditapes decussatus*	8
Panomya ampla	11	*Ruditapes philippinarum*	16
Panopea abbreviata	86	*Saxidomus gigantea*	20
Panopea generosa	168	*Saxidomus purpurata*	9
Panopea globosa	60	*Scrobicularia plana*	18
Panopea zelandica	85	*Semele lenticularis*	13
Paphia laterisulca	3	*Semele solida*	9
Paphia undulata	3	*Senilia senilis*	30
Paphies donacina	5	*Septifer virgatus*	12
Paphies ventricosa	7	*Serripes groenlandicus*	39
Parvicardium exiguum	1	*Siliqua alta*	18
Patinopecten caurinus	19	*Siliqua patula*	19
Pecten albus	3	*Siliqua pulchella*	2
Pecten fumatus	16	*Solemya sp.*	1
Pecten jacobaeus	13	*Sphenia sincera*	3
Pecten maximus	22	*Spisula discors*	9
Perna perna	9.03	*Spisula murchisoni*	7
Perna viridis	3	*Spisula sachalinensis*	70

Table S1 cont.

Species	**MLSP (yrs.)**
Spisula solida	13
Spisula solidissima	37
Spisula solidissima similis	5.5
Spisula subtruncata	4
Spisula voyi	52
Spondylus limbatus	16
Tagelus divisus	2.5
Tagelus dombeii	10
Tawera elliptica	23
Tawera mawsoni	14
Tawera sphaericula	9
Tegillarca granosa	7.5
Tellina capsoides	3
Tellina cuspis	4
Tellina exotica	1
Tellina fabula	6
Tellina liliana	1
Tellina lutea	41
Tellina martinicensis	2
Tellina piratica	2
Tellina tenuis	7
Teredo navalis	2
Theora lubrica	1.8
Thracia septentrionalis	11
Thyasira flexuosa	3.2
Thyasira gouldi	2
Timoclea micra	1
Tindaria callistiformis	100
Tivela mactroides	3.3
Tivela stultorum	53
Tresus capax	16
Tresus nuttallii	16
Tridacna crocea	60
Tridacna dersa	30
Tridacna gigas	60
Tridacna maxima	28
Venerupis bruguieri	6.5
Venerupis corrugata	10
Venerupis japonica	10
Venus verrucosa	16
Xenostrobus pulex	3
Ylistrum balloti	3
Ylistrum japonicum	2
Yoldia amygdalea hyperborea	9
Yoldia eightsi	65
Yoldia limatula	4
Yoldia myalis	11
Yoldia notabilis	17
Yoldia seminuda	14
Zirfaea pilsbryi	7
Zygochlamys patagonica	25

Table S2. List of journals and years for which exhaustive searches were completed.



Journal	Years Searched
Advances in Marine Biology	1963-present
Aquatic Biology	2007-present
Australiain Journal of Marine and Freshwater Research	1950-present
Bulletin of Marine Science	1951-present
Canadian Journal of Zoology	1929-present
Chesapeake Science	1960-1977
Estuaries	1977-2005
Estuaries and Coasts	2006-2013
Estuarine and Coastal Marine Science	1973-1980
Estuarine, Coastal and Shelf Science	1981-present
U.S. Fisheries Bulletin	1881-present
Fisheries Research	1982-present
Helgoland Marine Research	1937-present
Indian Journal of Fisheries	1965-present
Indian Journal of Marine Science	2001-2014
Journal of Experimental Marine Biology and Ecology	1967-present
Journal of Marine Science	1903-present
Journal of Molluscan Studies	1893-present
Journal of Sea Research	1996-present
Journal of Shellfish Research	1981-present
Journal of the Marine Biological Assocation of the U.K.	1888-present
Marine Biology	1967-present
Marine Ecology	1980-present
Marine Ecology Progress Series	1979-present
Marine Fisheries Review	1971-2014
Neatherlands Journal of Sea Research	1961-1995
New Zealand Journal of Marine and Freshwater Research	1967-present
Polar Biology	1983-present
Proceedings of the National Shellfisheries Association	1954-1980
The Biological Bulletin	1897-present

Table S3. Parameters recorded in the lifespan database (see Proceedings B website), as provided by the authors.

Family- Accepted family
Given genus – Genus supplied in text
Given species –Species supplied in text
Accepted genus – Genus according to WoRMS
Accepted species –Species according to WoRMS
MLSP – Maximum lifespan of each population presented in source
IP- Scale of study, I=Individual, P=population
N- number of individuals if population
Location – Geographic name
Latitude – Decimal degrees
Longitude – Decimal degrees
Minimum depth - meters
Maximum depth - meters
Linf – Parameter of von Bertalanffy growth equation
K – Parameter of von Bertalanffy growth equation
t_0- Parameter of von Bertalanffy growth equation
Vbmeth – Method of estimating von Bertalanffy growth equation; L=length frequency analysis, M=growth bands produced at shell margin, H=growth bands in hinge, R=mark and recapture
Author
Year
Paper title
Journal
Comments – from enterer

Table S4. Number of observations for each family recorded in the database.

Family	n	Family	n	Family	n
Veneridae	223	Astartidae	10	Vesicomyidae	2
Mytilidae	121	Philobryidae	10	Lasaeidae	1
Pectinidae	116	Yoldiidae	9	Nassariidae	1
Cardiidae	73	Glycymerididae	7	Nuculidae	1
Hiatellidae	70	Montacutidae	7	Solemyidae	1
Mactridae	70	Pholadidae	5	Spondylidae	1
Tellinidae	68	Nuculanidae	5	Teredinidaeá	1
Myidae	51	Psammobiidae	4	Thraciidae	1
Donacidae	42	Carditidae	3	Tindariidae	1
Arcticidae	39	Corbulidae	3	Trapezidae	1
Arcidae	28	Thyasiridae	3	Undulinidae	1
Semelidae	28	Latemulidae	3		
Pharidae	24	Ungulinidae	3		
Ostreidae	24	Cyamiidae	2		
Pinnidae	22	Cyrenidae	2		
Pteriidae	14	Lucinidae	2		
Mesodesmatidae	12	Lyonsiidae	2		
Solenidae	11	Solecurtidae	2		

Chapter 2:

High latitude settings promote extreme longevity in fossil bivalves

Chapter 2 has been prepared in the format of the journal *Paleobiology*. It will be submitted with co-authors Linda C. Ivany, John Schnue, Robert B. Silver, and Emily Artruc.

Abstract

The longest lived, non-colonial animal on the planet today is a bivalve that can attain lifespans in excess of 500 years and lives in a cold, seasonally nutrient limited setting. Separating the influence of temperature and food availability on lifespan in modern settings is difficult, as the two covary. Fortunately, the lifespans of fossil animals can provide insights into the role of environment in the evolution of extreme longevity that are not available from studies of modern taxa. Earth's deep past encompasses a range and combination of environmental conditions not currently represented on the surface today, thus providing opportunities to test hypotheses about how particular variables might relate to life history. Here we examine bivalves from the unique, non-analog, warm and high-latitude setting of Seymour Island, Antarctica, during the greenhouse intervals of the late Cretaceous and Eocene. All ten species we examine here are both slow growing and long-lived, especially when compared to modern bivalves living in similar temperature settings. Cool temperatures have long been thought to be a key factor in promoting long lifespan, but our findings suggest an important role for caloric restriction driven by the low and extremely seasonal food availability at high latitude settings. Our life history data, from multiple species across three different families of the Bivalvia that otherwise do not typically exhibit long life, emphasize that longevity is at least in part governed by environment, rather than phylogenetic or ecologic factors particular to a given taxon. Such findings have implications for both modern and ancient latitudinal diversity gradients, as a common correlate of slow growth and long life is delayed reproduction and longer generation times that limit the potential for evolutionary change. While lifespans of modern bivalves are well studied, data on lifespans of fossil bivalves are sparse and largely anecdotal, although

methods for ontogenetic age determination have been in practice for over half a century. Life histories of organisms from deep time can not only elucidate the controls on lifespan, but will also add a new dimension to our understanding of macroevolutionary patterns.

Introduction

What controls lifespan? Today, the longest-lived**,** non-colonial animal on the planet is the ocean quahog, *Arctica islandica*, with a maximum reported lifespan of 507 years (Butler et al. 2013, Wanamaker et al. 2008). Along the Atlantic Coast of the United States, 200-year-old individuals of *Arctica* are common, but thus far, individuals of 300 years or older have only been found off the coast of Iceland and northern Norway (Butler et al. 2013, Mette et al. 2016, Schöne et al. 2011). The pattern of longer lifespans at higher latitudes is not only evident in the long-lived *Arctica*, but is a feature consistent across the Bivalvia today (Moss et al. 2016). Such a strong pattern suggests that an environmental control may facilitate long life. Cool temperatures and caloric restriction are thought to be first order controls on lifespan. Water temperature and food availability (driven by the extremely seasonal light regime in polar settings) covary with latitude so separating their influence is difficult. Fortunately, Earth's history offers a range of conditions far broader than those that exist on the planet today, including non-analog settings that present opportunities to deconvolve these two factors and test hypotheses related to the role of environment in bringing about extreme longevity.

Here, we use the skeletal archives of fossil bivalves from just such a non-analog setting, the warm, high-latitude, nearshore marine sediments of the Cretaceous and Paleogene on Seymour Island, Antarctica, to argue that high-latitude settings do indeed seem to be characterized by taxa exhibiting extreme longevity, but that this effect is evidently not primarily brought about by cold temperatures. Rather, we argue that the low and seasonal availability of food resulting from extended periods of no sunlight may be the driving factor behind the link between latitude and lifespan. Our findings suggest that latitudinal patterns in life history traits may be a persistent feature throughout the Phanerozoic, and that they have consequences for macroevolution.

Background

Geologic Setting

Seymour Island, off the Antarctic Peninsula (64° 17'S, 56° 45'W), has long been the subject of geologic investigation. Being one of the very few places in the high southern latitudes where Meso-Cenozoic fossiliferous sediments are exposed, the stratigraphy, paleontology, and paleoclimate history of the island's sedimentary record have been well studied (see sources in Feldmann and Woodburne 1988 and those cited below). The Cretaceous and Paleogene marine section includes three formations consisting mostly of sands, muds, and shell beds. The Lopez de Bertodano and Sobral Formations are exposed on the southern portion of the island and represent one of the most expanded K-Pg sections currently known (Marshall 1995, Tobin et al. 2012, Witts et al. 2015, Witts et al. 2016, Zinsmeister et al. 1989). The Lopez de Bertodano Formation is a deepening-upward sequence from shallow water deltaic/estuarine deposits to middle to outer shelf deposits, while the overlying Sobral Formation consists of progradational deltaic facies (Macellari 1988, Zinsmeister 1982). The Eocene La Meseta Formation is a shallow-marine succession that overlies the dominantly non-marine Cross Valley

Formation (Porebski 1995, 2000, Sadler 1988). A thorough investigation of Mesozoic and Cenozoic molluscan systematics has documented several hundred species (e.g., Beu 2009, Macellari 1984, 1988, Stilwell and Zinsmeister 1992, Tobin and Ward 2015, Tobin et al. 2012, Witts et al. 2015, Zinsmeister 1984, Zinsmeister et al. 1989, Zinsmeister and Macellari 1988).

Global greenhouse climates prevailed throughout the Cretaceous and Paleogene periods. Pole to equator temperature gradients were low (Hay and Floegel 2012, Huber and Sloan 2001) and the high latitudes were relatively warm and largely ice free until the Eocene-Oligocene transition (Zachos et al. 2001, Zachos et al. 2008). Proxy data from Seymour Island suggest that the Antarctic peninsula experienced cool-to-warm temperate conditions with mean annual temperatures similar to the mid-latitudes today, ranging from 5-17 °C (Douglas et al. 2014, Dutton et al. 2007, Dutton et al. 2002, Francis and Poole 2002, Ivany et al. 2008, Kemp et al. 2014, Tobin et al. 2012). Thus, the Cretaceous and Paleogene bivalves of Seymour Island were living in an environment not currently represented anywhere on Earth – a high-latitude setting with near darkness for half the year, but where waters were comparatively warm and ice-free (Buick and Ivany 2004).

Determination of bivalve lifespans

Bivalves have accretionary and indeterminate growth and, akin to trees, record not only their size at each year of growth throughout their ontogeny, but also the environmental conditions in which they lived (e.g., Beierlein et al. 2015, Jones 1983, Lutz and Rhoads 1980, Pannella and MacClintock 1968, Rhoads and Lutz 1980, Rhoads and Pannnella 1970, Schöne and Gillikin 2013). As benthic organisms that are generally incapable of significant movement to track preferred conditions, bivalves are subject to changes in their local environment. Such changes result in temporary slow- or shut-downs in shell growth and lead to the formation of the two major classes of growth bands: disturbance and periodic. Disturbance lines result from events such as storms or predation attacks and form with no particular periodicity (i.e, they are random), whereas periodic lines form regularly at a known or detectable frequency (Clark 1974). Growth lines on the exterior surface of bivalve shells are often of the former type and were initially (and often erroneously) relied upon for estimates of age (e.g., as pointed out by Krantz et al. 1984 on scallops). Internal growth bands, revealed in cross-section, are typically of the latter and provide much more accurate age estimates if the periodicity of formation is known. At least five different types of periodic growth bands have been documented: semi-daily, daily, fortnightly, monthly, and annual (e.g., Clark 1974, Goodwin et al. 2001, Pannella 1976, Richardson et al. 1980, Schone et al. 2005).

Desire for documenting the periodicity of formation of internal growth bands grew out of an emerging shellfish industry in the early 1900s (Belding 1910) and a post-World War II effort to supply a much needed alternate source of protein (Neville 1945). One of the oldest methods for determining periodicity of formation in modern bivalves are mark and recapture experiments. In these studies, specimens are tagged or marked and in some cases caged and observed at set intervals of time (e.g., Jones 1980, Jones et al. 1978b, MacDonald and Thomas 1980, Peterson et al. 1983, Sejr et al. 2002a). The downfall of mark and recapture studies is that frequent sampling is required in order to accurately determine periodicity of formation and the limit to constraining the timing of formation is directly related to the interval between observations. An alternative route, which is particularly useful for fossil bivalves, is to sample ontogenetic variations in the oxygen isotope value of bivalve shell carbonate (Jones and Quitmyer 1996). Isotope profiles through growth increments that are annual in nature show variations that approximate the sinusoidal (seasonal) variation in environment (Ivany 2012). This phenomenon was first documented by Williams et al. (1982) and Jones et al. (1983) in shells of modern *Spisula solidissima* collected from New Jersey. These values showed that during the spring and summer *S. solidissima* grows rapidly and deposits a wide, opaque growth band in transmitted light (white in reflected light), whereas a narrow, translucent (dark) band is deposited in late summer when growth slows or stops. Dark bands are typically associated with spawning periods and/or temperature extremes, which tend to be annual in nature (Jones et al. 1978b, Thompson et al. 1980). These methods have been successfully applied to not only modern (just to name a few Hallmann et al. 2008, Jones et al. 1989), but also fossil bivalves (e.g., Buick and Ivany 2004, Ivany and Runnegar 2010, Jones and Gould 1999).

The primary controls on growth band formation are environmental parameters like temperature and food availability and as a result bivalves living in highly seasonal environments today form unambiguous annual growth bands (e.g., Ambrose et al. 2011, Brey and Mackensen 1997, Lomovasky et al. 2002, Sejr et al. 2002b, Witbaard et al. 1994). The same is true of bivalves from the fossil record. Buick and Ivany (2004) and Ivany et al. (2008) documented annual growth bands in *Cucullaea raea* and *Eurhomaela antarctica* from the Eocene of Seymour Island, Antarctica, and Beard et al. (2015) and Ivany and Runnegar (2010) do the same with early Permian bivalves from SE Australia. In the past and today, the polar regions are characterized by extreme seasonality in light regime and hence phytoplankton production. Water temperatures are more consistently cold today, but become increasingly seasonal as climate warms. Given that the primary controls on growth band formation are environmental, and that paleoenvironmental conditions were highly seasonal during the Cretaceous and Paleogene greenhouse, we presume the additional Seymour Island taxa studied here formed annual bands as well.

Materials and Methods

Ten species of infaunal marine bivalves were selected from the Cretaceous Lopez de Bertodano and Eocene La Meseta Formations on Seymour Island for investigation: *Cucullaea ellioti, C. antarctica, Nodenskjoldia nodenskjoldia,* and *Lahillia larseni* from the Cretaceous, and *C. raea, C. donaldi, Eurhomalea antarctica, E. newtoni, Eumarcia robusta,* and *L. wickensi* from the Eocene. These ten were chosen because they are common in collections made by previous researchers (e.g., Macellari 1984, Stilwell and Zinsmeister 1992), their shell material is preserved sufficiently well to reveal internal growth bands, and they are well represented in archival research collections. While several additional common taxa are noted in field surveys, these were evidently smaller and not typically collected. Regardless, the 10 taxa examined here are dominant elements of assemblages both in the field and in collections, and hence they serve as representatives of the Seymour Island bivalve fauna in general. Specimens used for analysis were drawn from collections at the Florida Museum of Natural History (FMNH), the Paleontological Research Institution (PRI), and Syracuse University (SU).

Lifespans and growth rates are determined through examination of annual bands as revealed in cross section. In order to prevent damage to the shell (and loss of data) during cutting, individuals selected for sectioning were imbedded in an epoxy resin before cross-sectioning along the maximum growth axis with a Buehler Iso-Met 1000 low speed saw. We explored three successively more time-intensive methods as needed for visualizing annual bands in cross section. Thick sections were polished using silicon carbide sanding discs and finished with 1.0 and 0.05 micron aluminum oxide powder to yield a smooth glassy surface, and images were captured under plane white light with an AxioCam ERc5s camera coupled to a Zeiss Discovery V.8 stereomicroscope at 1.25x magnification. One specimen of *E. antarctica* was prepared by staining with Mutvei's solution, a procedure common in the field of sclerochronology and outlined in Schöne et al. (2005). Images for this specimen were captured using a Nikon Coolpix 995 digital camera mounted to a Wild M3 stereomicroscope at 10x magnification. Thin sections of *C. raea* were imaged using a petrographic microscope equipped with an AxioCam ERc5S camera. Up to 75 images were stitched together to create a complete montage of each shell using Photoshop®. Once adequate images were obtained, we used the open source software ImageJ to count and measure growth bands to determine lifespan and growth rate of each individual. Because bivalve shells have some degree of curvature in their thickness, the length of cumulative growth band widths measured in cross-section will be greater than the umbo-to-commissure distance measured using calipers on an uncut individual. We therefore transformed cumulative growth band widths to straight line measured distances by dividing each band by the total cumulative size and multiplying that by the straight line measured distance. This procedure allows us to compare growth curves from cross-sections with sizes of individuals measured using calipers in museum collections.

As the methodology for recovering lifespan and growth rate is deemed "destructive" by collections managers, we were limited in the subset of individuals available for sectioning. In most cases we were not permitted to section the largest specimens in collections, which hinders our ability to estimate ‘maximum’ longevity for these taxa. In order to put our data into context of the population and get closer to this objective, we also measured the maximum height (dorsal to ventral distance) of all individuals present in the three collections. In total, we sectioned 34 individuals and measured 1,058 intact shells from 10 different species. Care should be taken not to over interpret size distributions. While tempting to draw inferences about population dynamics from size (or age) distributions, these specimens were collected by a number of individuals at a number of localities during field seasons spanning several decades. Some collecting was selective and opportunistic, including float specimens, some was systematically conducted to reflect the whole fauna, and some targeted large numbers of particular taxa. While some plotted distributions may in fact approximate those in the actual fossil assemblage, we use them here only to describe what is in collections and how our sectioned individuals compare to them in terms of size.

Growth rates of modern bivalves have been shown to correlate with longevity (Moss et al. 2016, Ridgway et al. 2011a) through their relationship with metabolic rate (Camus et al. 2005, Speakman 2005). They are therefore a crucial component of any analysis of lifespan and life history. To determine growth rates for Seymour Island bivalves, growth curves for each sectioned individual were generated by plotting the cumulative distance between growth bands in the outer shell layer against the corresponding year of growth and fitting a modified von Bertalanffy growth equation (MVBG):

$$L_t = L_\infty(1-e^{-k\,(t)})$$

where L_t = shell length at time t, L_∞ = asymptotic size, or the size at which growth rate is essentially zero, and k = rate at which L_∞ is attained. The standard form of the von Bertalanffy growth equation (von Bertalanffy 1938) contains an additional term, t_0 , which is the size of the organism at age 0, or in other words, where the growth curve crosses the x-axis. For organisms such as whales with substantial size at birth, this term is appropriate, but bivalve size at 'birth' is essentially zero, hence the term is unnecessary. There is little difference in parameter values of the modified and standard form of the equation fitted to individuals in our samples. Here, we report all MVBG parameters for each of the cross-sectioned individuals and examine the relationship between k and lifespan for these fossil taxa. We compute mean growth curves for each taxon by averaging von Bertalanffy parameters for all individuals. Finally, we compare k values of Seymour Island taxa to those of modern bivalves distributed across latitude and temperature as compiled by Moss et al. (2016) so as to identify where in the distribution of values from modern bivalves the Seymour fossil taxa best fall.

Because methods for precisely determining the age of bivalves require cross-sectioning to reveal internal growth bands, we explore methods of estimating age from size measured with calipers. The von Bertalanffy growth equation is typically written with age as the dependent variable and size as the independent variable. However, the equation can be solved algebraically such that size (L_t) is the predictor and age (t) is the response variable:

$$t= (-1/k)*(\ln(1-(L_t/ L_\infty)))$$

Thus, given a von Bertalanffy growth equation established from some sample of individuals, age can be estimated from a simple size measurement of un-sectioned individuals. However, a few non-trivial issues arise when using this approach. First, predictions from the von Bertalanffy growth equation are deterministic. That is, all ages predicted using the equation will necessarily fall on the line it establishes. As a result, any natural variation in age at size in the original population is lost. Second, and perhaps most important, is that for sizes (L_t) that are greater than L_∞, age cannot be predicted, as the equation would call for taking the natural log of a negative number, a mathematically invalid operation. This could result in significant numbers of individuals for which age cannot be estimated from size. Though the bivalve aging community is well aware of these issues, no readily available solutions appear to exist. In most cases the 'L_∞ problem' is acknowledged, but individuals of greater size (potentially the longest lived) are typically removed from analyses (e.g., Dexter and Kowalewski 2013) and age estimates for those less than L_∞ are recognized as "crude" (Ridgway et al. 2014). Both approaches are wholly unsatisfactory.

We explore two alternative methods for aging shells by size alone using both cross-sectioned and measured individuals of *Cucullaea raea*, the species for which we have the greatest number of cross-sectioned individuals. In the first method to avoid issues created by L_∞, we use three different von Bertalanffy growth curves derived from age-size relations in sectioned individuals to predict ages for measured museum specimens: the mean of parameters from all 11 individuals and the parameter values from the individuals with the largest and smallest L_∞ value. The three curves were then used to predict ages for individuals less than or equal to their L_∞ values. Our second approach avoids the deterministic nature of von Bertalanffy growth equations and instead uses a probabilistic approach to the age-at-size problem. We model the theoretical age/size distribution for *C. raea* using the linear relationship between logged values of k and L_∞ from sectioned individuals. From these modeled values, we ‘grew’ 50,000 individuals of *C. raea* to the maximum lifespan reported here and then constrained the age distributions for each size in the population. Finally, we assigned ages to each measured individual by selecting at random an observation from the appropriate age/size distribution. We compare the resulting age histograms for measured individuals using the two approaches.

Results

Size Distributions

In most cases, the individuals selected for ‘destructive’ analysis were not the largest of any taxon in any collection (Fig. 1). Size distributions in collections reveal that sectioned individuals, for which lifespans can be confidently assigned, range from 53% to 100% of the size of the largest measured specimen. For some species, like *C. raea,* we were able to section some of the largest individuals in the collections; for others like *C. antarctica* we were only able to section individuals near the median size in museum collections.

Longevities

Annual growth bands in all species are well preserved, distinct, and virtually unambiguous (Fig. 2). Even though the most prominent growth bands are clearly annual in nature, several species (e.g., *L. larseni, C. raea,* and *E. antarctica*) also reveal sub-annual growth banding, providing attractive prospects for high resolution intra-annual studies (Goodwin et al. 2001) detailing shell growth under these unusual environmental conditions. Imaging techniques allow for discrimination of even the most closely spaced annual bands near the commissure of the shell (Fig. 2).

All of the species examined reached ages greater than 20 years, and nine of the ten had lifespans greater than 50 years (Table 1). *C. raea, C. antarctica,* and *N. nodesnkjoldia* record maximum measured lifespans of 120, 101, and 131 years, respectively. Given restrictions on the number of individuals we were permitted to section and the fact that these shells did not typically include the largest individuals of any species in the collections, the lifespans documented here should be considered minimum estimates for that potentially attained by their taxa.

Growth Parameters

Values for the parameter k (the growth constant) of the MVBG equation range from 0.05 to 0.37 (Table 1). There is a relationship between k and lifespan in the Seymour bivalves, with slower growing individuals living longer than faster growing individuals (Fig. 3). While sample size is small, there is a tendency for this pattern to hold true within species as well as across. Mean growth curves for all species show rapid growth early in ontogeny followed by many years of much slower growth later in life (Fig. 4).

Age from size in C. raea

Using the three different modified von Bertalanffy growth equations, 10 of the 163 measured individuals were unable to be assigned an age because their lengths were greater than the maximum L_∞ value. For those that could be assigned, their ages were constrained to each of the three curves (Fig. 5A). The maximum age that can be predicted for each curve is that at which the curve essentially reaches L_∞. Predicted ages from measured individuals are significantly less than the actual ages of sectioned individuals of almost identical size. The resulting age distribution of all measured individuals using this approach predicts a large number of very young *C. raea,* with only one individual greater than 40 years old (Fig. 5C), highly unlikely given that some sectioned shells demonstrably attained ages of over 100 years.

The probabilistic approach yields more satisfactory results. Because age predictions here are not constrained by the L_∞ of any of the three curves, there is much more variation in predicted ages at any given size in the population (Fig. 5B). This variation also approximates the natural shape expected in the age-size relationships of *C. raea*. In addition, this approach avoids the 'L_∞ problem' and all measured individuals are able to be assigned an age. The distribution of predicted ages here shows fewer short-lived individuals and is more right skewed than that using only the three modified von Bertalanffy growth curves (Fig. 5D).

Discussion

Limitations and Assumptions

We face two non-trivial problems when using fossil (or modern) shells from existing collections to study lifespan and growth. First is a limitation on the number of specimens permitted for 'destructive' analysis. This is understandably an issue when working with museum collections, particularly when material is rare or comes from remote or no longer accessible field areas. This means that the maximum observed lifespans for the ten species examined here are surely underestimates. In addition, some species, like *N. nodenskjoldia,* are rare in museum collections (n=15), so the likelihood of finding a longer-lived individual than what is observed (here, 131 years) will increase significantly with more intensive sampling. In each respect, it is highly likely that individuals older than those reported are present in existing collections, and virtually certain that they are present in the field waiting to be discovered. Not only is this true of our understanding of lifespan, but it is also true of growth rate, as even in our small samples there is a significant variation in von Bertalanffy k values. Finally, we were limited in this study not only to the number of individuals of a given species, but also to the number of species in total we were permitted to section, placing limits on our ability to reconstruct the full spectrum of life histories exhibited at this setting.

Even more difficult to circumvent is the problem of estimating 'maximum lifespan' itself, whether it be based on direct measurement from specimens or calculated from an age-size relationship. Lifespan for an individual is relatively easy to determine from shell cross sections, but the limitations on sample size and availability discussed above ensure that the oldest individuals will almost never be sectioned. One is therefore left with inferring an age for the largest available specimens based on the relationship between shell growth and age seen in one or a few sectioned specimens. Slow growth over many years though, as is typical of the longest-lived taxa, obfuscates the determination of age from size, for a few millimeters of growth near the margin could represent many decades (e.g., in Figure 2A, the last 5 millimeters of growth in *L. larseni* represent almost 20 of the 39 years of its full lifespan). Maximum age cannot be estimated simply by using the von Bertalanffy growth equation either because, as discussed above, the 'L_∞ problem' combined with restrictions on destructive sampling nearly always prevents age predictions for the largest individuals. However, the probabilistic methods for estimating age from size described here may provide some relief. Modeling a significant number of values for growth parameters should ensure that the entire theoretical age/size distribution is captured and thus age can be predicted for any size. Note though, that predicted ages are probabilistic and change with each iteration such that a range of ages is produced for any individual. Using the probabilistic approach with *C. raea* reveals an age distribution that suggests the common occurrence of 'old' individuals. In other words, the individuals we selected for cross-sectioning were not outliers in the population, and it is likely that shells in that size range routinely attain ages well over 50 years.

Comparison with living bivalves

When the life histories of these high-latitude fossil taxa are considered in comparison with living taxa, the unusual nature of the fauna becomes apparent. While a number of Recent taxa can attain lifespans in excess of 50 years, the modal value of maximum reported lifespan for bivalve species today is three years (Moss et al. 2016). The shortest-lived species from Seymour Island reached lifespans of at least 22 years. The longevity of bivalves in this assemblage, even as established from such a restricted sample, is impressive. In addition, modern bivalves have k values that range as high as 3, while the sectioned Seymour specimens all revealed k values <0.4, on the lowest end of the modern distribution and representing extremely slow growth. Within this sample of slow-growing, long-lived fossil individuals, the relationship between k and lifespan seen in modern populations is also apparent: those exhibiting slower growth tend to have lived longer lives.

When the life histories of modern taxa are considered in the context of latitude (Moss et al. 2016), however, the Seymour taxa become part of a general global pattern. Species living at tropical latitudes tend to be fast growing (k values range as high as 3) and short lived (most <20 years). As latitude increases, the bivalve fauna includes progressively more taxa with much longer lifespans, and growth universally slows until k values at high latitudes are nearly all less than 0.5. The Seymour Island taxa examined here plot within the range of lifespans and k values exhibited at high latitudes today (Fig. 6A), consistent with a high-latitude position (64° S) that has changed little if at all over the past 100 million years (e.g., Lawver et al. 1992, Norton and Sclater 1979, Torsvik et al. 2008).

Despite a general decrease toward the poles, a wide range of k values is evident at any latitude today. To determine the range of modern latitudes most consistent with observed Seymour Island data, we used resampling techniques that compare observed data with an equal number of k values drawn at random from a modern global dataset of k values published elsewhere (Moss et al. 2016). We draw at random, without replacement, 34 observations from the available data within a twenty-degree latitudinal band, calculate their mean, and repeat 1000 times, yielding a range of mean k values expected today for that window of latitude. We step the twenty-degree latitude window by 1° of latitude from equator through to the poles, each time drawing k values and calculating means 1000 times, then plot those means against latitude for comparison to the fossil data (Fig. 6B). For each random draw, we also assess the significance of the difference between the fossil versus modern k values in that latitude bin using a t-test for independent samples. Results from the t-tests show that insignificant tests (no difference between the means of randomly sampled and Seymour Island k values) predominate in latitude bins with midpoints greater than 60° (Fig. 6C). These results confirm that the life histories of fossil taxa are consistent with those of modern high-latitude taxa, despite the substantial difference in the thermal environment in which they are each living.

The bivalve fauna of Seymour Island is diverse and includes species with a range of ecologies. As modal lifespan in modern assemblages is still on the low side at any latitude, it is likely that short lived species are present in the fossil fauna as well, although we have not sampled them here. In keeping with data from today's high-latitude bivalves, however, we would expect any short-lived fossil taxa discovered to nonetheless have relatively low k values.

In sum, bivalves today tend to grow slower and live longer as the latitude at which they live increases. High-latitude bivalves living during past intervals of polar warmth exhibit the same long lifespans and slow growth as bivalves living in those regions today, suggesting a set of causes deriving from latitude but independent of large-scale swings in global climate.

What influences longevity?

From a physiological perspective, two of the most often cited mechanisms for long life are thermal stress (cold temperature) (e.g., Brey and Clarke 1993, Peck and Conway 2000, Sejr et al. 2002b), and caloric restriction (e.g., Masoro 2000), both of which vary systematically with latitude and work through a reduction in metabolic rate (see below). In addition to physiology, ecology could also be a driver of long lifespan. Organisms living in areas where predation events are frequent would be expected to benefit from a life history strategy characterized by fast growth and early reproduction. Given the demonstrated relationship between lifespan and growth rate (Moss et al. 2016; Fig 3), those taxa would also likely have short lifespans in comparison to those where predation is rare. While there are data to suggest that predation frequency is high in the tropics and decreases with latitude (e.g., Bertness et al. 1981, Freestone et al. 2011, Schemske et al. 2009, Visaggi and Kelley 2015), the pattern may not be as clear as once thought (e.g., Dudley and Vermeij 1980, Harper and Peck 2016, Kelley and Hansen 2007, Vermeij et al. 1989). We elaborate below on these three factors and discuss their relative importance to the Seymour Island fauna.

A widely accepted principle in the research community studying the aging process is that individuals with low metabolic rates typically live longer than those with higher metabolic rates (Van Voorhies 2001). This relationship was first described over a century ago in mammals (Rubner 1908) and has since been expanded to include numerous animal groups. Metabolic activity results in the production of free-radicals and reactive oxygen species, which are thought to promote cell damage and ultimately cell death. In modern bivalves, growth rate is correlated with metabolic rate (Lewis and Cerrato 1997), and there is a strong relationship between von Bertalanffy k (a proxy for growth rate) and lifespan (Moss et al. 2016). Seymour Island fossil bivalves (and living high-latitude bivalves) exhibit lower k values than most other living bivalves, thus, their impressive longevities could be facilitated by slow growth and correspondingly low metabolic rates. Metabolism, in turn, within a given taxonomic group is affected by body size, temperature, and food supply (Brockington and Clarke 2001, Gillooly et al. 2001). While bivalve body size shows no systematic trend with latitude (Berke et al. 2013, Moss et al. 2016, Roy et al. 2000) temperature and food supply do.

Metabolic rates are the summation of chemical reactions in the body, and chemical reactions typically proceed faster at high temperatures where activation energies are lower.

Consequently, the Universal Temperature Dependence model for metabolism states that individuals living at higher temperatures typically have higher metabolic rates than those living at lower temperatures (Gillooly et al. 2001). Experimental work has shown that tropical bivalves have higher metabolic rates than mid- and high latitude species (Vladimirova et al. 2003), a fact not unrelated to the high k values of tropical bivalves. Modern Antarctic organisms, living in water temperatures that hover around 0°C, typically have lower metabolic and growth rates than their mid- and low-latitude counterparts (Clarke et al. 2004, Peck et al. 2006, Sato-Okoshi and Okoshi 2007, Vladimirova et al. 2003). Though the Seymour Island fossil taxa lived in relatively warm water, their k values are a good deal lower than those of mid latitude (comparably warm water) taxa today, suggesting that temperature is not the driving factor behind their growth.

Research on caloric restriction suggests that limiting food intake lowers metabolic rate and brings about cellular changes that in turn decrease the accumulation of free radicals and reactive species. Studies spanning a range of invertebrate and vertebrate taxa show that caloric restriction can promote fewer age-related disorders and longer lifespans (e.g., Austad 1989, Brandhorst et al. 2015, Colman et al. 2014, Fanestil and Barrows 1965, Klass 1977, Lakowski and Hekimi 1996, McKay et al. 1935, Verdone-Smith and Enesco 1982, Woodhead 1985). For bivalves living on the seafloor, their primary food sources come from phytoplankton and suspended food particles in the water column. Because of the tilt of the Earth’s axis, high latitude settings are characterized by extremely seasonal light regimes, with the majority of their sunlight received during an approximately four month period. In the Antarctic today, phytoplankton and other suspended particles are only available in appreciable quantities during this four month period (Peck et al. 2006).

The low and extremely seasonal availability of food in the Antarctic has dramatic effects on the organisms that live there. Like those reported here, the von Bertalanffy k values for modern fish (e.g., Brodte et al. 2006, Burchett et al. 1984), brachiopods (e.g., Brey et al. 1995, Peck et al. 1997), gastropods (e.g.,Clarke et al. 2004, Picken 1980), and bivalves (e.g., Brey and Hain 1992, Brey et al. 2011, Philipp et al. 2006) are all extremely low, suggesting a common environmental control. In the bivalve *Laternula elliptica,* Ahn et al. (2003) and Brockington (2001) both demonstrated dramatic decreases in metabolic rate associated with the austral winter food shortage. Additionally, in an experimental study, Brockington and Clarke (2001) showed that the significant increase in springtime metabolic activity seen in Antarctic sea urchins was primarily brought about by the increase in food availability rather than rising temperatures. The presence of food is evidently a primary driver of growth and metabolism in organisms living in Antarctica today, and this is controlled by the extremely seasonal light regime. Without a Phanerozoic-scale vector in the seasonal insolation cycle, Cretaceous and Paleogene settings on Seymour Island would have experienced similarly extreme variation in the availability of food resources. Thus, limitations on primary production brought about by the high-latitude light regime is likely the more important factor promoting the slow growth and long life of the Seymour Island taxa.

While physiology affects lifespan through its influence on metabolism, ecological factors such as predation pressure could play a role as well. Shallow burrowing infaunal bivalves like those studied here are largely sedentary and have only their shell to offer protection from predators. Today, predation frequencies in the Antarctic are extremely low and predation events often take much longer to complete than in more temperate waters. The gastropod *Trophon lonstaffi*, for example, takes 20-30 days to complete a drill hole depending on the type of prey (Harper and Peck 2003). Drilling predation on Eocene Antarctic bivalves may have also been rare, as Aronson et al. (2009) found completed drill holes on only 5% of prey shells. In measuring sizes of museum specimens from both Cretaceous and Eocene samples, we also find predation to be rare, as only 2% of the more than 1,000 individuals measured had drill holes. In combination with a slow metabolism due to food stress, low rates of predation may help to permit extreme longevity in modern and fossil Antarctic bivalves.

One plausible influence on longevity can be ruled out in the case of the Seymour Island fauna – that of taxonomic affinity. Members of at least one family of living bivalves, the Hiatellidea, may typically live longer for a given k value than other bivalves (Moss et al. 2016). This might be a correlate of their deep burrowing habit, but one could argue that their unusually long lifespan is a life history trait inherited from a common ancestor, regardless of the environment in which populations or species are found today. If the Seymour taxa belonged to such a group, the argument for an environmental driver would be less strong. However, the taxa exhibiting slow growth and long life in this fossil assemblage belong to three different families in three different orders (Table 1), and living taxa in these groups are dominantly shorter-lived and faster growing (Moss et al. 2016). In addition, within both higher taxa and individual species, longer-lived individuals are found at higher latitudes today (Moss et al. 2016), suggesting that even if a taxon has an ecology generally pursuant to long life, a latitude-related variable nonetheless governs the lifespan typical of its populations. These observations make clear that the primary variable associated with long life in these fossil bivalves as well as in living taxa is not phylogeny but rather is related to latitude.

The latitudinal driver of life history

Consistency of life history parameters between Seymour Island fossil bivalves and those of modern species living at similar high latitudes, regardless of their taxonomic affinity, suggests that the set of factors influencing lifespan and growth at those latitudes today were operating in a similar way in the deep past, despite large differences in climate. In addition, the distinct relationship between latitude and lifespan, and latitude and growth rate, exhibited on the modern Earth requires a set of causes that vary systematically with latitude. As discussed above and by Moss et al. (2016), causal factors related to latitude might derive from some combination of physical variables such as temperature and insolation and/or ecological variables such as predation pressure, as all three of these correlate, to a greater or lesser degree, with latitude today.

The Seymour Island fossils offer an opportunity to evaluate the relative influence of each of these factors on the life histories of bivalves because, while latitude and insolation have not changed over time, temperature and predation pressure have. Estimated mean paleotemperatures on the Cretaceous and Eocene shelf at Seymour Island range from around 8 °C (Tobin et al. 2012) to 17 °C (Douglas et al. 2014), far warmer than similar latitudes today, at -0.5° to 1° C (Locarnini et al. 2013). In addition, Aronson et al. (1997) and Aronson et al. (2009) have argued that the Antarctic benthos during greenhouse times were functionally more similar to modern lower-latitude faunas and subject to higher durophagous predation pressure than they are today. If temperature and/or predation pressure were the dominant drivers behind the ancient data and modern latitudinal trend, we would expect the life histories of these ancient bivalves to be more similar to those at lower latitudes today. They are not. Instead, the data are more consistent with life histories exhibited above a latitude of approximately 60° today (Fig. 6). Given that the controls on extreme longevity in both modern and fossil high latitude settings appear to derive more from food availability via insolation, these settings may be characterized by slow growth and extreme longevity throughout Earth's history. Today, the longest lived bivalve on the planet attains lifespans in excess of five centuries and lives in cold, seasonally food limited, high latitude settings. Similarly, during the Cretaceous and Eocene, several bivalves attained lifespans in excess of 100 years, but in the warm, extremely seasonal, high-latitude settings of Antarctica. Slow growth characterizes bivalves in both settings and hence could be the variable through which long life is selected for at higher latitudes.

The slow pace of life in both modern and fossil high latitude settings, coupled with much lower rates of predation, may also play a role in both modern and fossil latitudinal diversity gradients (LDG). The modern LDG is one of the most pervasive patterns of life on the planet; in almost all animal groups, in both marine and terrestrial settings, species diversity decreases with increasing latitude (Hillbebrand 2004). Such a pattern is likely to have characterized life throughout the Phanerozoic (Alroy 2010). Though we currently have no clear way to detect the age at sexual maturity of fossil bivalves (but see Sato 1994, 1995, Sato 1999 for a possibility), a correlate of long life is delayed reproduction (Ridgway et al. 2011a). In a wide range of invertebrates, short generation times correlate with higher mutation rates (Thomas et al. 2010). Thus the higher speciation rates of low-latitude bivalves might be a side consequence of fast growth and early reproduction driven by a constant, year round food supply. Limited food supply at high latitudes might therefore be a driver not only of longevity, but of latitudinal diversity gradients today and in the past.

Conclusions

The geochemcial tools to study lifespans and growth rates of modern bivalves have been developed over the past half century by the sclerochronological and paleoclimatological communities. Their application to the fossil record has already been tested by several studies, and methods for determination of periodicities of growth bands in the shells of fossil bivalves are now well understood and relatively easy to implement. Here, with a fairly small sample of bivalves from a non-analog, warm, high paleolatitude setting, we shed a bit more light on what is perhaps one of the most intriguing questions from a human perspective: what controls lifespan? The life history data from these fossil shells, in concert with a much larger database of bivalve lifespans and growth rates, suggest that the pattern of increasing lifespan with latitude on the planet today is likely a result of low and seasonal food availability at high latitude settings that results in slow growth and low metabolic rate. Given that insolation has varied little throughout Earth's history, we predict that a similar latitudinal pattern of life history parameters exists throughout the Phanerozoic. The shells of bivalved mollusks hold a wealth of information to address this and other fascinating questions. As the early paleontologists once produced copious volumes on the taxonomy of fossil mollusks from every corner of the globe, we now have the ability to do the same with their life histories – both in space and through time. Modern paleobiologists have certainly profited from early taxonomic studies and their subsequent revisions – a good deal of the paleontological literature aims to answer questions about diversity through time and the rate and mode of evolution. Future paleobiologists will likely benefit from a comparable effort to document lifespans and growth rates of fossil organisms and connect them to macroevolutionary studies.

Tables

Table 1. Lifespans (LSP, years) and von Bertalanffy growth parameters of species examined. Oldest individuals of each taxon are indicated in bold.

Family	Species	Period/Epoch	Specimen #	LSP	k	L_∞
Cucullaeidae	*Cucullaea antarctica*	Cretaceous	PRI 583113	**101**	0.07	57.52
	Cucullaea donaldi	Eocene	SU 01-56-C2	**55**	0.26	47.05
			SU 01-53-C3	50	0.26	34.97
			SU 01-56-C1	36	0.27	43.78
			SU 03-012	34	0.08	50.47
			SU 01-85-C1	18	0.22	33.98
			SU 02-82-C1	15	0.39	45.95
			Mean		0.25	42.70
	Cucullaea ellioti	Cretaceous	PRI 58448	**36**	0.22	46.21
			PRI 62371	35	0.10	40.45
			Mean		0.16	43.33
	Cucullaea raea	Eocene	UF 124613-I	**121**	0.15	75.62
			SU 01-43-C3	118	0.10	84.29
			SU 001-C2	108	0.09	81.16
			SU 01-43-C2	102	0.20	79.83
			UF 124605-I	90	0.12	88.44
			SU 001-C1	73	0.13	83.51
			SU 01-43-C1	65	0.08	90.59
			SU 01-28-C1	43	0.15	93.27
			UF 124605-III	38	0.20	77.52
			SU 01-42-C2	36	0.13	76.54
			UF 124605-II	31	0.33	77.33
			Mean		0.15	82.55
	Cucullaea sp.	Eocene	SU 01-54-C2	**92**	0.11	35.51
	Nodenskjoldia nodenskjoldia	Cretaceous	PRI 61339-B	**131**	0.05	61.41
			PRI 61339-A	47	0.29	49.22
			Mean		0.17	55.32

Table 1. Cont'd.

Family	Species	Period/Epoch	Specimen #	LSP	k	L∞
Lahilliidae	*Lahillia larseni*	Cretaceous	PRI 58774	**58**	0.16	85.35
			<u>PRI 60667</u>	<u>39</u>	<u>0.18</u>	<u>82.16</u>
			Mean		0.17	83.76
	Lahillia wilckensi	Eocene	PRI 59522	**71**	0.19	78.85
			<u>PRI 59425</u>	<u>55</u>	<u>0.29</u>	<u>95.05</u>
			Mean		0.24	86.95
Veneridae	*Eumarcia robusta*	Eocene	PRI 62912	**38**	0.05	80.55
	Eurhomalea antarctica	Eocene	SU 01-43-E3	**83**	0.04	34.76
			UF 124959-II	35	0.15	56.83
			UF 124961-I	31	0.30	63.39
			<u>PRI 59548</u>	<u>26</u>	<u>0.21</u>	<u>60.81</u>
			Mean	43.75	0.18	53.95
	Eurhomalea newtoni	Eocene	PRI 58961	**22**	0.33	45.19
			<u>PRI 59658</u>	<u>11</u>	<u>0.24</u>	<u>42.85</u>
			Mean		0.29	44.02

Figures

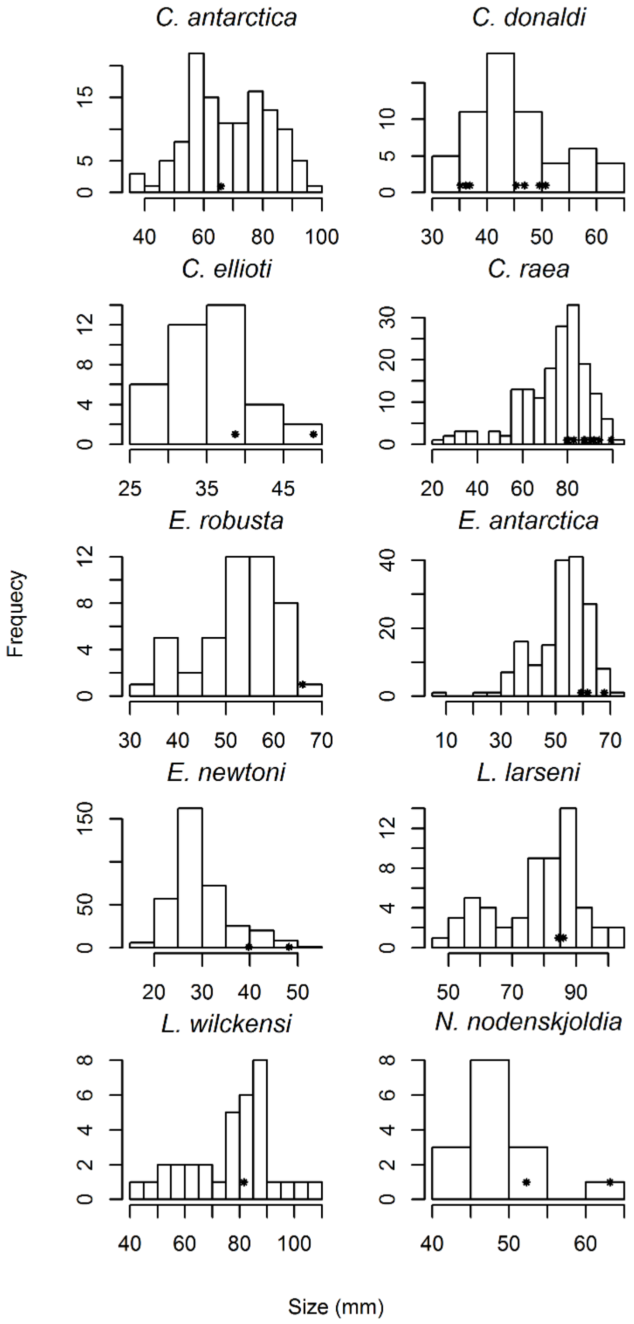


Figure 1. Umbo-to-commissure sizes of individuals measured in musuem collections. * = size of cross-sectioned individuals.

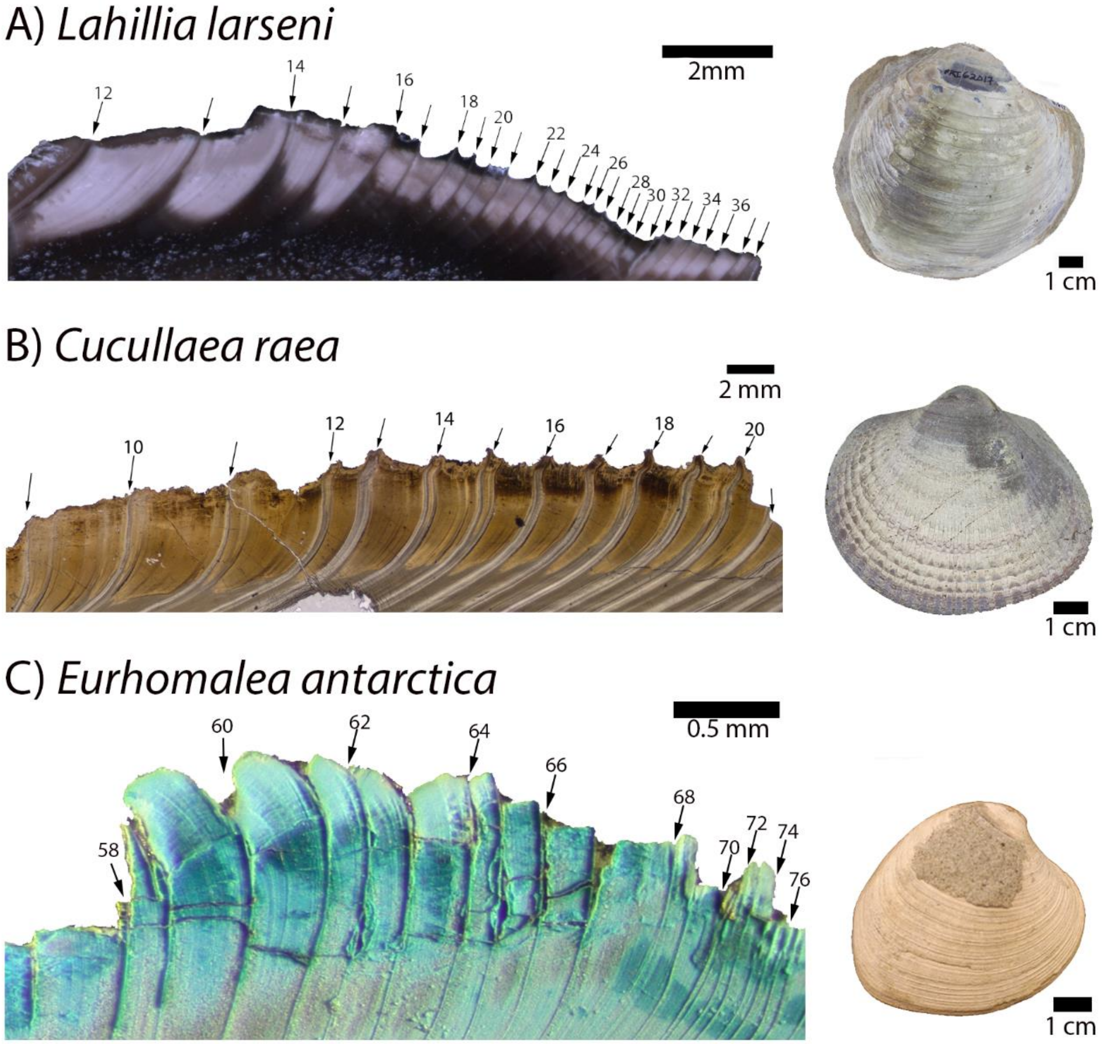


Figure 2. Annual growth banding in three species of Seymour Island bivalve. Shell cross sections encompass portions of their ontogenies, with years of growth indicated above the shell. Banding is illustrated using three different preparation techniques A) Polished thick section under reflected light (Lahillia larseni, Cretaceous), B) Polished thin section under polarized light (Cucullaea raea, Eocene), C) Thick section stained with Mutvei's solution (Schöne et al. 2005) (Eurhomalea antarctica, Eocene).

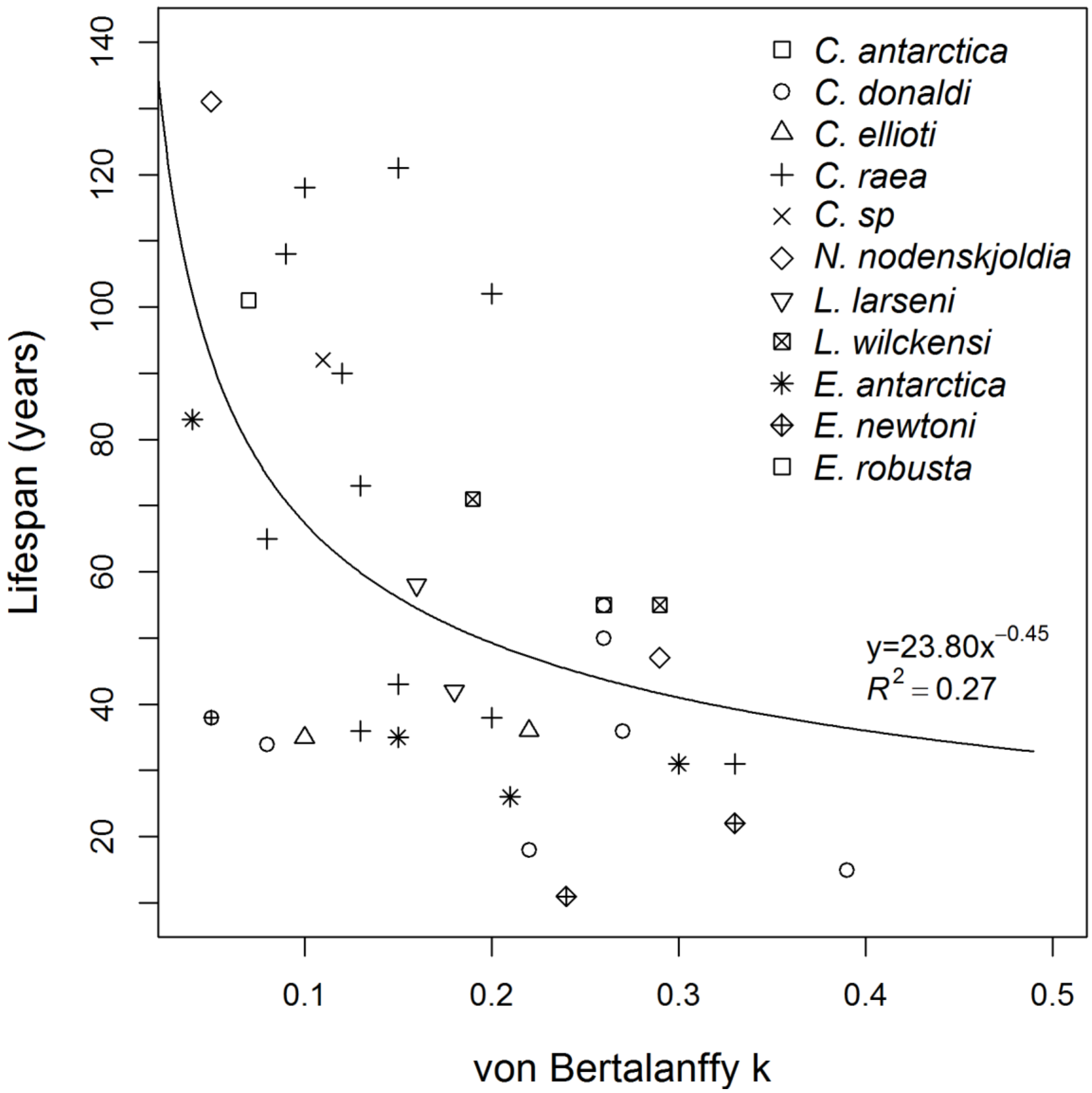


Figure 3. Relationship between growth rate (k) and lifespan in Seymour Island taxa ($p<0.01$).

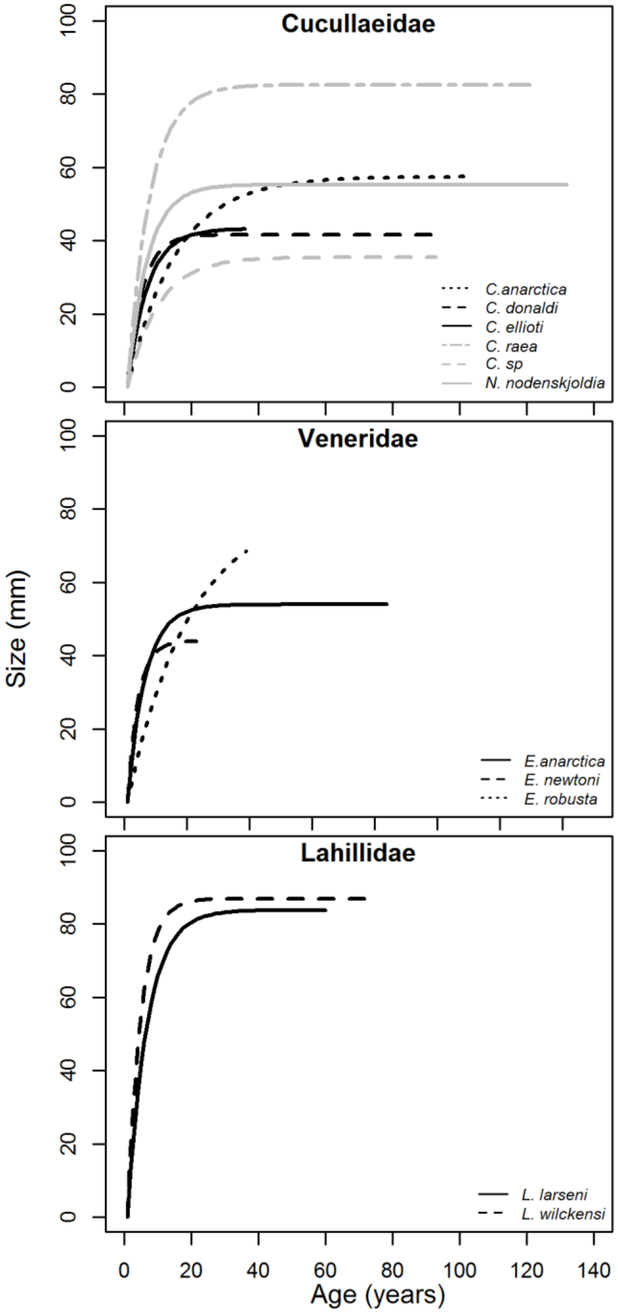


Figure 4. Growth curves for eleven taxa using the mean von Bertalanffy growth parameters in Table 1. Growth curves are extended to the maximum recorded age for species.

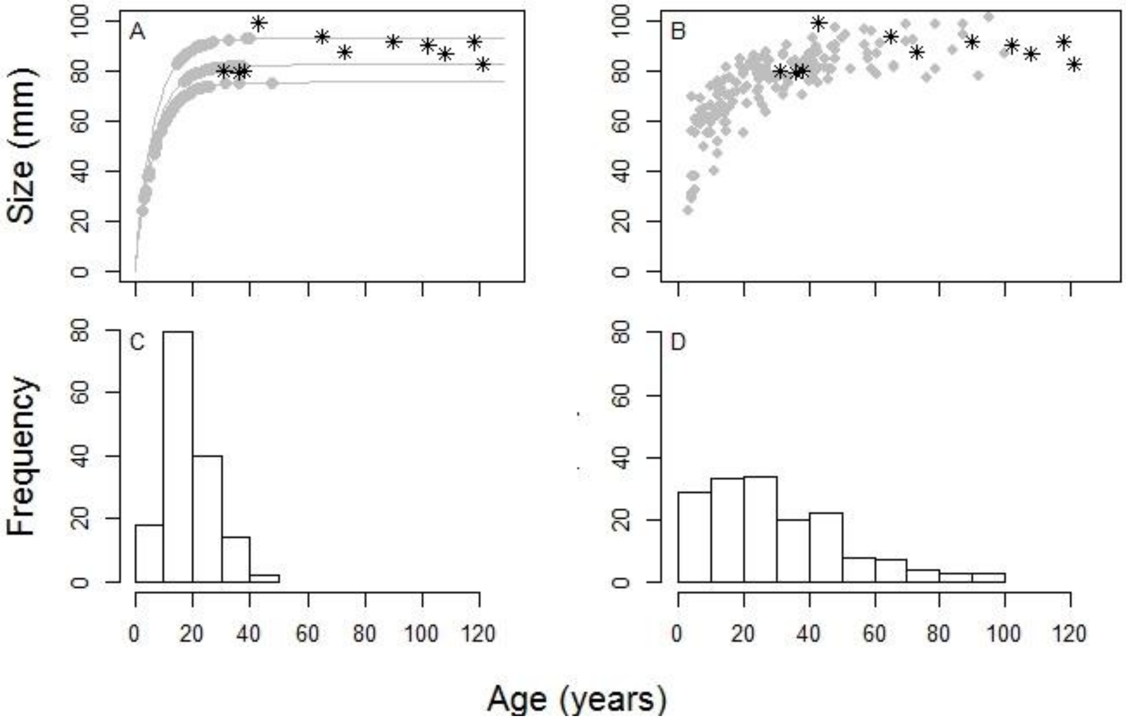


Figure 5. Results of two different methods of predicting age from size in measured individuals of *Cucullaea raea* (see Fig. 1 for size distribution). A) and C) predictions from three von Bertalanffy growth curves. B) and D) predictions from probabilistic method. * = actual age size relationships from cross sectioned individuals. ● = predicted ages from sizes of specimens measured in museum collections.

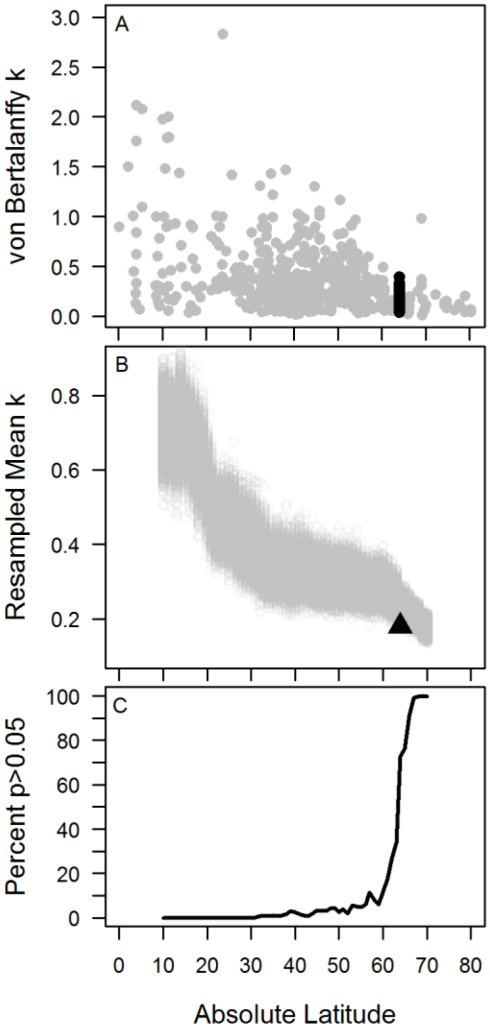


Figure 6. Growth rate of Seymour Island fossil bivalves in comparison to modern bivalves plotted by absolute (paleo)latitude. A) Growth rates (k) of modern bivalves (gray; Moss et al. 2016) and Seymour Island individuals (black) B) Mean of resampled k values for 20° bins with a 1 degree moving window for 1000 iterations (grey) and mean of Seymour Island k values (black) C) Number of t-tests (out of 1000) that fail to establish a significant difference between resampled k values and observed Seymour Island k values. Most tests are insignificant above about 60 degrees of latitude.

Chapter 3:

Estimating von Bertalanffy growth parameters using a probabilistic approach to the age-size relationship in *Spisula solidissima*

Abstract

Obtaining population life history parameters such as lifespan and growth rate from bivalves requires cross-sectioning large numbers of individuals to reveal internal growth bands. Such methods are often time intensive and not possible with species that are endangered or with specimens from hard to access locations. One of the most common equations for describing bivalve growth, the von Bertalanffy growth equation, has significant limitations when predicting age from size and typically results in the largest specimens in a population being excluded from analysis. To circumvent this problem, we develop probabilistic methods to determine age from size using a modern data set of *Spisula solidissima*. Our model uses the relationship between parameters of a modified von Bertalanffy growth equation to constrain the theoretical age/size distributions for a population. From these distributions, ages are assigned by drawing at random from the appropriate age/size distribution. The resulting age/size predictions can then be used to determine population growth rates from a large number of measured individuals.

Introduction

Accurate characterization of life history parameters, such as growth rate and lifespan, in bivalves is vital for both modern resource management and the newly-emerging field of study of life histories in the fossil record (Moss et al. 2016). The former represents a multi-billion dollar industry in the United States, whereas the latter represents a largely untapped field of research in paleobiology. Bivalves record in their shells their size at each year of their life and methods for determining life history parameters of both modern and fossil bivalves are well understood and relatively straight forward to implement (e.g., Ivany 2012, Jones 1983, Jones and Quitmyer 1996, Pannella and MacClintock 1968). Unfortunately, revealing internal growth bands is a time intensive process and may also require sacrificing live and/or potentially rare individuals. In endangered species (e.g., Hastie 2006) or fossil organisms from localities that are either difficult and/or expensive to access, or are no longer accessible due to anthropogenic influences, such “destructive” sampling is often not feasible or permitted by museum curators. Thus a non-destructive method for determining age from size is needed.

Here we develop a probabilistic approach to estimate age from size using a dataset of modern *Spisula solidissima.* Our approach can be used to approximate growth parameters on a population level without cross-sectioning and counting growth bands of the entire population. We presume that at each size in a population there is a knowable distribution of ages that changes in a predictable manner throughout ontogeny. For example, at small sizes, it is more likely that an individual is of a ‘young’ age than it is an ‘old’ age. The converse is true as well; at larger sizes it is more likely than an individual is of an ‘old’ age than a ‘young’ age. In order to constrain these age/size distributions we first fit a modified von Bertalanffy growth equation (MVBG, see methods) to plots of age versus cumulative growth band width to individuals in our dataset. We then use the relationship between these parameters to model growth in 50,000 *S. solidissima* in order to constrain theoretical age/size distributions. From these distributions, we then assign an age to a specimen of any given size by drawing at random from its corresponding age distribution. We compare the MVBG parameters estimated when using the entire known dataset to that of the predicted age/size relationships. In addition, because our ultimate goal is to only cross-section a small number of individuals and use probabilistic methods to assign age to specimens measured with calipers, we also explore these methods using sampling procedures with subsets of 5, 15, and 30 individuals from the original dataset.

Background

Determining annual nature of growth bands

While not at the heart of this paper, a brief review of the methods for determining periodicity of bivalve growth band formation is warranted. Though for a much more detailed review, the reader is referred to Pannella and MacClintock (1968), Jones and Quitmyer (1996), Ivany (2012), Schöne and Gillikin (2013) and the references therein. Desire for documenting the periodicity of formation of internal growth bands grew out of an emerging shellfish industry in the early 1900s (Belding 1910) and a post-World War II effort to supply a much needed alternate source of protein (Neville 1945). Mark and recapture experiments are one of the oldest methods for determining periodicity of growth band formation. In these studies, specimens are tagged or marked and in some cases caged and observed at set intervals of time (e.g., Jones 1980, Jones et al. 1978b, MacDonald and Thomas 1980, Sejr et al. 2002a). The downfall of mark and recapture studies is that frequent sampling is required in order to accurately determine periodicity of formation as many species record growth bands at a wide range of periodicities (e.g., daily, tidally, annually), and the limit to constraining the timing of formation is directly related to the interval between observations. Recapture rates are often quite low and in one example from the ocean quahog, *Arctica islandica,* of 41,000 marked specimens, only 60 were recovered the following year (Jones 1983). Furthermore, there is also some suggestion that the act of marking and releasing can often result in a disturbance line that can obfuscate the perceived signal (Clark 1974). Fortunately though, the carbonate in bivalve shells records variation in oxygen isotopes which can be used to determine periodicity of formation. Clear sinusoidal variations in oxygen isotope values between growth bands can indicate annual formation. This phenomenon was first documented in bivalve shells by Williams et al. (1982) and Jones et al. (1983) using the surf-clam, *Spisula solidissima*, from New Jersey. There the authors found that the striking, alternating pattern of opaque and translucent bands revealed in cross-section corresponded to oxygen isotope variations recording seasonal temperatures. In addition, they were also able to understand that shell growth is most rapid in the spring and slows considerably in the winter months. Such studies can confirm the annual periodicity of growth band formation in both modern and fossil bivalves and should be undertaken before the methods described below are implemented.

Spisula solidissima

The data used here come from *Spisula solidissima,* which is commonly referred to as the “surf clam.” This species is a conspicuous component of waters of the northeast Atlantic Coast of the United States and is a large, infaunal, suspension feeder. It is found from the Gulf of Saint Lawrence, Canada to Cape Hatteras, North Carolina in shallow subtidal water depths down to approximately 70 meters in depth (Ropes 1979). While Native Americans and colonials likely consumed surf clams, fishing in earnest began in the late 1800’s and the “modern” industry developed on Long Island, NY with the introduction of power dredging in the 1920’s. Today, an extensive industry exists from the Delmarva Peninsula to Massachusetts with the heaviest fishing off the coast of New Jersey.

Given the existence of an extensive and profitable fishery today, much work has been done on the lifespans and growth rates of *S. solidissima* throughout its geographic range. Twenty year old surf clams are common throughout its distribution. As with other bivalves, there appears to be a latitudinal cline in lifespan (Moss et al. 2016) as individuals from southern waters have maximum reported lifespans around 30 years (e.g., Cerrato and Keith 1991, Jones 1980, Jones et al. 1978a, Weingber 1999), while at the northern limit off Prince Edward Island, the maximum reported lifespan is 37 years (Sephton and Bryan 1990). Such a pattern, however, may not be present in growth rates of *S. solidissima* as it has been heavily impacted by the intense fishing activity off the Delmarva Peninsula (Weinberg and Helser 1996)

Age length keys in fish

Over 70 years ago, Fridriksson (1934) developed Age-length keys (ALKs) to estimate age from size in fish. ALKs are constructed by first taking a subsample of a fish population, recording their size, and determining their ages using growth increments recorded in internal otoliths (see Campana 2001 for review). The proportion of different ages in each length-group (usually 5 mm categories) of the subsample are used to assign ages to all fish in each length-group of the unknown sample (Bettoli and Miranda 2001). There are various methods by which to do this and even within the literature there is debate on which method is most appropriate (Bartoo and Parker 1983, Kimura 1977, Westrheim and Ricker 1978). However, there are several factors which limit the use of ALKs for our purpose here. First, they rely on a large number of initial samples to characterize the age/size relationships of an entire population, which would not avoid the issue of destructive sampling and significant amounts of time.

Second, if there is significant overlap in size among age groups, ALKs tend to be biased and yield unreliable results (Westrheim and Ricker 1978). Finally, the range of sizes for which age can be approximated using an ALK is determined by the original subsample. This means that an individual larger than any length category in the subsample either cannot be assigned an age or is sometimes assigned the age of the largest subsampled specimen. Our goal here is to be able to approximate the age of any individual in a population of bivalves based on a small subsample. Once we have age/size relationships for a large number of individuals, we should be better able to constrain population life history parameters like growth rate. While a simple application of ALKs will not solve our problems, we can borrow some of their methods. Though assignment of age in ALKs is constrained by the original proportions of the subsample, the actual assignment of age to an individual of a given size is stochastic. We must first develop a way to describe the theoretical age distributions at each size that is not limited by the original subsample.

The age at size problem in bivalves

In marine bivalves, one of the most common representations of relations between size and age is the von Bertalanffy growth equation (VBG) (von Bertalanffy 1938):

$$L_t = L_\infty (1-e^{-k\,(t-t0)}) \qquad (1)$$

where L_t = shell length at time t; L_∞ = maximum or asymptotic size, the size at which growth rate is essentially zero; k = rate at which L_∞ is attained; and t_0 = age at which the bivalve has a size of zero (the x intercept on a plot of size as a function of age). Equation 1 can be applied both at the individual and population levels. For an individual, plots of age versus cumulative growth band width can be fitted for a single individual throughout its ontogeny, whereas for a population, the final age and size of a number of individuals is fit using non-linear least squares regression. Given a VBG for a population Equation (1) can be rearranged such that a prediction of age can be made for an individual of a given size:

$$t = t_0 - (1/k) * \ln (1 - L_t/L_\infty) \qquad (2)$$

Equation (2) is deterministic in that there is only one age predicted for a given size. This means that any natural variation around the best fit equation is lost in such predictions. Furthermore, when the length of a measured individual (L_t) is greater than L_∞ the right side of Equation (2) calls for taking the natural log of a negative number which is a mathematically invalid operation. This could result in a large number of individuals which VBG cannot be used to predict age from size (e.g., Bartoo and Parker 1983, Dexter and Kowalewski 2013, Ridgway et al. 2014) and does not alleviate issues caused by ALKs. However, if we can determine the relationship between parameters of the VBG, we should be able to use those to model growth in a large number of individuals to constrain the potential age/size relationships.

Methods

Assigning Age from Size using MVBG

The dataset contains a total of 321 individuals of *Spisula solidissima* collected near Barneat Light and Point Pleasant New Jersey in the late 1970s from commercial fishing vessels. The data are divided into inshore (n=149) and offshore (n=172) populations based on their distance from shore and have been published elsewhere (Jones et al. 1978a, Jones et al. 1983). For each population, a modified form of the von Bertalanffy growth equation (MVBG) is used to approximate growth:

$$L_t = L_\infty(1-e^{-k\,(t)}) \qquad (3)$$

thus omitting the t_0 parameter found in the standard form (1). This parameter essentially controls where the curve intercepts the x-axis and can be thought of as the size at birth. In organisms like fish and whales that have a meaningful size at birth its use is appropriate, but for bivalves, whose size at settlement is extremely small, this is a numerically-meaningless term.

Our first step was to fit a modified MVBG to the cumulative growth band widths of all indivdiuals using non-linear least squares regression in R. Despite not having the extra parameter (t_0) R^2 values for both populations are extremely high (mean inshore =0.97, mean offshore = 0.98) and the MVBG describes individual growth quite well. Our dataset, though containing a significant number of individuals, does not represent the entire age/size distribution theoretically possible for *S. solidissima*. Values of k and L_∞ are lognormally distributed, so in order to model that potential distribution we first determined the best fit linear relationship between logged values of k and L_∞. To model L_∞ values we use the equation:

$$mL\infty = (\sum_{n=0}^{1} i = 12) - 6)^* \ (\sigma\ (\log(L\infty)) + \mu\ (\log(L\infty)) \qquad (4)$$

which creates a log normal distribution by adding Gaussian noise to a distribution with a mean and standard deviation of the distribution of L∞ values in the dataset. A similar process is used to model values of k but here, in addition to Gaussian noise, we use the best fit linear relationship between logged k and L∞ values:

$$mk= (\sum_{n=0}^{1} i = 12) - 6)^* \ (\sigma\ (\text{residuals}(k)) + ((-1.15^*(mL\infty) + 1.74)) \qquad (5)$$

From these values we modeled clam growth to the maximum age reported for *S. solidissima* from New Jersey (31 years). These curves are somewhat unnatural for *S. solidissima* as the species does not tend to add multiple increments less than 1 mm for a significant portion of its lifespan and are also unrealistic in that 30+ year old individuals of the species are not common (Weinberg and Helser 1996, Weingber 1999). We therefore, introduce a “kill coefficient” to terminate growth of modeled clams. This coefficient terminates the growth of an individual when the addition of an increment results in less than a predetermined amount of growth. As this number could somewhat be construed as arbitrary, we compare results using kill coefficients of 1, 0.5, and 0.25 mm.

The large number of modeled clams gives us a sufficient sample size to examine age distributions of *S. solidissima* throughout its entire theoretical size range. From these distributions, we produced a matrix of ages at every size (rounded to 0 digits) represented in the modeled curves that can be used when assigning age to an individual of any size.

The known dataset of inshore and offshore clam sizes and ages provided an opportunity to test the ability of our method to reconstruct growth parameters for the population from probabilistic assignments of age from size. To the size of each individual in the original dataset, we assigned an age by sampling at random from the modeled age distribution for that size, which results in new age size relationships. Because this process is probabilistic, the predicted age-size relationships will vary with each iteration. Therefore, we repeated the process of assigning ages for 1000 iterations of both inshore and offshore populations and each time we fit a MVBG to the predicted age-size relationships. We evaluate the ability of our approach to faithfully reconstruct population level MVBG parameters by comparing the mean and standard deviation of predicted k and $L\infty$ values to the observed original MVBG values.

How many individuals are needed?

The procedures outlined above use all of the individuals from both inshore and offshore populations (N=321) to constrain the theoretical age size distributions for each population of *S. solidissima*. Such a large sample is extremely time intensive to collect and would not be practical for large scale studies of von Bertalanffy growth parameters through time. Therefore we test the robustness of our method by repeating the procedure above with sample sizes of 5, 15, and 30 individuals from the inshore population. For each sample size, we selected at random the number of individuals and then determined the relationship between their logged k and L_∞ values and used Equations (4) and (5) to model growth of 50,000 clams from which an age at size matrix was produced. Using this matrix, we then assign ages to the sizes of inshore individuals and fit a MVBG to the predicted age-size relationship. After 100 iterations for each sample size we used an ANOVA to compare the means of the predicted distributions of k values using the entire dataset and the sampled runs.

Results

Actual k and L_∞ values for individuals in the known dataset are lognormally distributed (Figure 1) and there is a significant relationship between the two parameters (Figure 2). Offshore individuals grow slower (have lower k values) and attain larger sizes (have higher L_∞ values) than inshore individuals. Modeled growth curves with a kill coefficient of 1, approximate the shape of the growth curves for both populations (Figure 3). Most importantly though, they span a significantly wider range of values in sizes at every age in the population. Though not applied directly here, it would allow for us to approximate the age of an individual larger than any in the original sample. As expected, age distributions of this species (and presumably others) change shape with increasing size from right to left skewed. This conforms to the assumption that at small sizes, it is more likely than an individual is of a young than an old age.

While inherent in our model design, but not the ultimate goal, each iteration of our model results in a predicted age distribution. Our sample size in the original dataset is actually relatively small to get a complete picture of an age distribution, but because we run our model for 1000 iterations, we can get a sense of what a population age distributions might look like (Figure 4). The average age predicted for inshore clams is 8.7 years, which is slightly lower than the actual average age of 11.4 years, while the maximum predicted age of 20 years is slightly higher than the actual maximum age of 18 years. Offshore predicted ages on the other hand are more widely distributed than those for inshore individuals. The average age predicted for offshore clams is 12.8 years, which is less than the actual mean of 18.4 years, while the maximum predicted age of 29 years is almost identical to the actual maximum age of 28 years.

Our model then, seems to slightly over predict ages for inshore clams but under predicts for offshore clams.

Though there is some discrepancy in actual and predicted ages for both populations, the predicted k and L∞ values for 1000 iterations of assigning age based on size are extremely close to the actual growth curve for each population (Figure 5). In fact, for both inshore and offshore simulated k values, there is a difference of only 0.01 in the mean predicted and the actual k value (Figure 6). Changing the kill coefficient to 0.5, and 0.25 mm resulted in little difference between the predicted and observed k and L∞ values. This indicates that our approach to estimating age from size and approximating population growth parameters is robust.

When we repeated our procedure with samples of 5, 15, and 30 individuals and compared distributions of k values from 100 iterations, we found no significant difference between the means of each distribution. However, the standard deviation of each distribution decreased with increasing sample size from 0.10 with 5 samples, to 0.05 with 30 samples (Figure 7). This suggests that a remarkably small sample size can on average predict accurate MVBG parameters for an entire population, but that as expected, with larger sample sizes the range of predicted k values decreases significantly.

Discussion

Much more complex models for approximating von Bertalanffy growth parameters exist but their application to the fossil record would be extremely difficult. Models developed by Hofmann et al. (2006), Hart and Chute (2009), Narváez et al. (2015), and Munroe et al. (2016), and many others account for a wide range of environmental parameters to characterize growth of bivalve populations. However, the benefit of our model is that it is simplistic. It can be applied to both modern and fossil bivalves independent of any environmental knowledge. Though it is simplistic, results presented here show that our model works remarkably well when predicting von Bertalanffy growth parameters for both populations of *Spisula solidissima*. In both inshore and offshore populations the mean of our k values from age size relationships predicted using probabilistic methods are within 0.01 of the actual value for each population. Previous workers had suggested that offshore *S. solidissima* from New Jersey and elsewhere along the Atlantic Coast grow faster than inshore individuals (Ambrose et al. 1980, Jones et al. 1978a), but our results do not support this claim. The k values, a proxy for how fast $L\infty$ is attained, are much higher on average for inshore than offshore clams. Across the bivalvia, k is inversely related to lifespan in that bivalves with higher k values tend to live shorter than those with lower k values. Thus, the much larger sizes attained by offshore *Spisula* are likely a result of their longer lifespans (28 versus 18 years).

One important aspect of our model is that it requires a relatively small number (15-30) of individuals to reproduce accurate von Bertalanffy growth parameters for a population. Not only is this important for studies of modern organisms that are threatened or endangered, such as many of the long-lived freshwater species, but it is also important for studies of life history parameters of bivalves in deep time. Heim et al. (2015) document an increase in the mean body size of marine animals over the Phanerozoic, a trend manifest in bivavles as well. However, no work has been done on the life history parameters, lifespan and growth rate, that ultimately determine body size, though the capabilities to determine the periodicity of bivalve growth bands in the fossil record have existed for quite some time. Other authors have suggested an increase in organism energetics since the Mesozoic (Bambach 1993, Finnegan et al. 2011, Vermeij 1977), which implies that faster growth may be driving the observed trends in body size. If that is true, then we would expect to see an increase in the von Bertalanffy k values of marine bivalves over this time interval. Our method, in concert with geochemical techniques to determine annual periodicity of growth bands makes a study of k values of this magnitude possible. With only a moderate number of samples from each species and quick size measurements in the field of large numbers of individuals, application of our method can provide not only a mean and standard deviation of k, but also a reasonable approximation of the age distribution.

Though the model works remarkably well for predicting growth parameters, it is not without limitations. One drawback is that a reasonable estimate of the maximum lifespan for a population of species is needed. Today, clear latitudinal patterns in the increasing lifespan and decreasing growth rate both across the bivalvia and within species have been documented (Moss et al 2016). Thus for our model to work with any certainty, a reasonable estimate of the maximum lifespan of the population in question must be known. For modern species that are fisheries targets where population demographics are reasonably known this is not an issue. However, when dealing with fossil species the problem becomes more complex. For more recent intervals in geologic time (e.g., Pleistocene), lifespan estimates from modern taxa could be used but for much older intervals, such estimates may not be useful as lifespan could be a trait that evolves over time.

Conclusions

Determining age from size in large numbers of bivalves using internal growth bands is a time intensive process. Here we have developed a model that uses a small subsample of a population to create theoretical distributions of age for each possible size. In combindation with a probabilistic method of assigning age from size, our methods work remarkably well when approximating von Bertalanffy growth parameters for two distinct populations of *S. solidissima*. We have only used our methods on a single species, but the same procuedure should be applicable to other species whose growth is described by the von Bertalanffy growth equation as well. Our methods should be of significant use to not only study of endangered species, but also study of growth rate and lifespan of fossil bivalves as well.

Figures

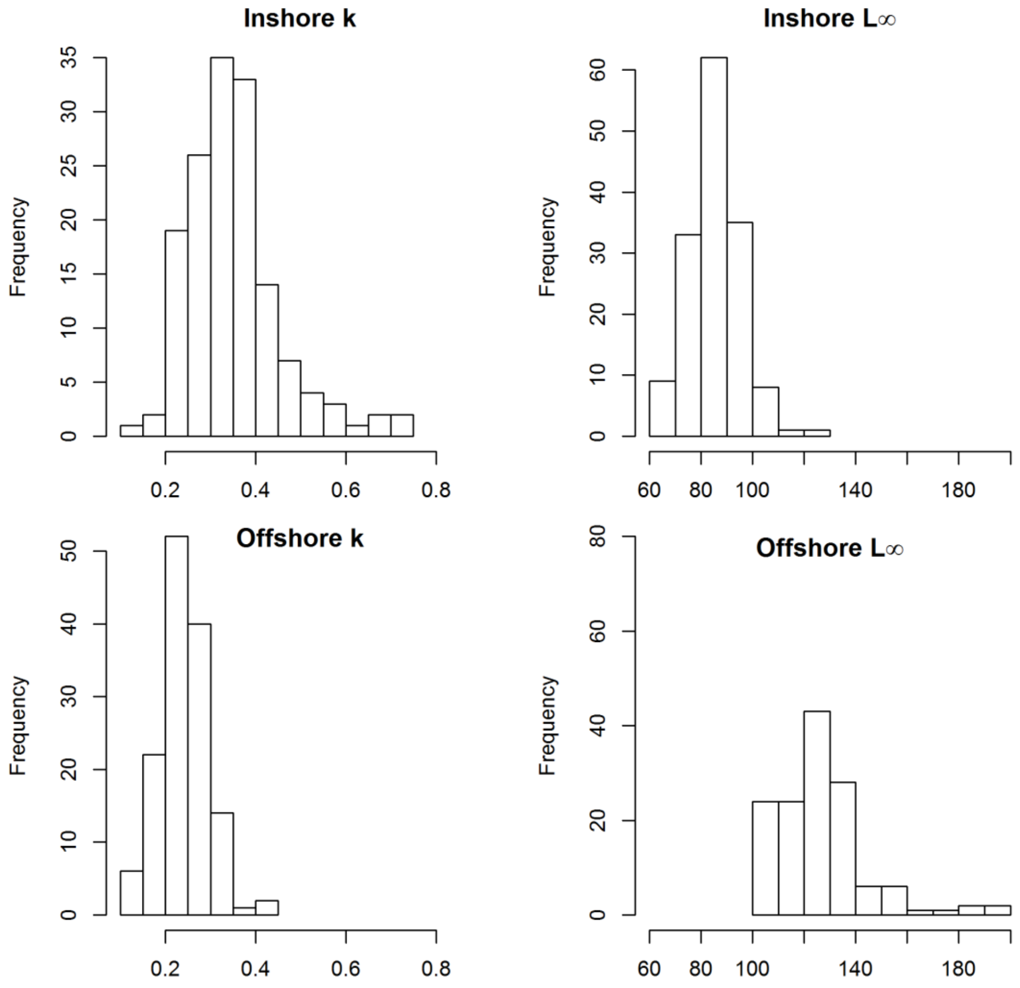


Figure 1. Parameters of the MVBG for inshore and offshore populations of *Spisula solidissima* from New Jersey.

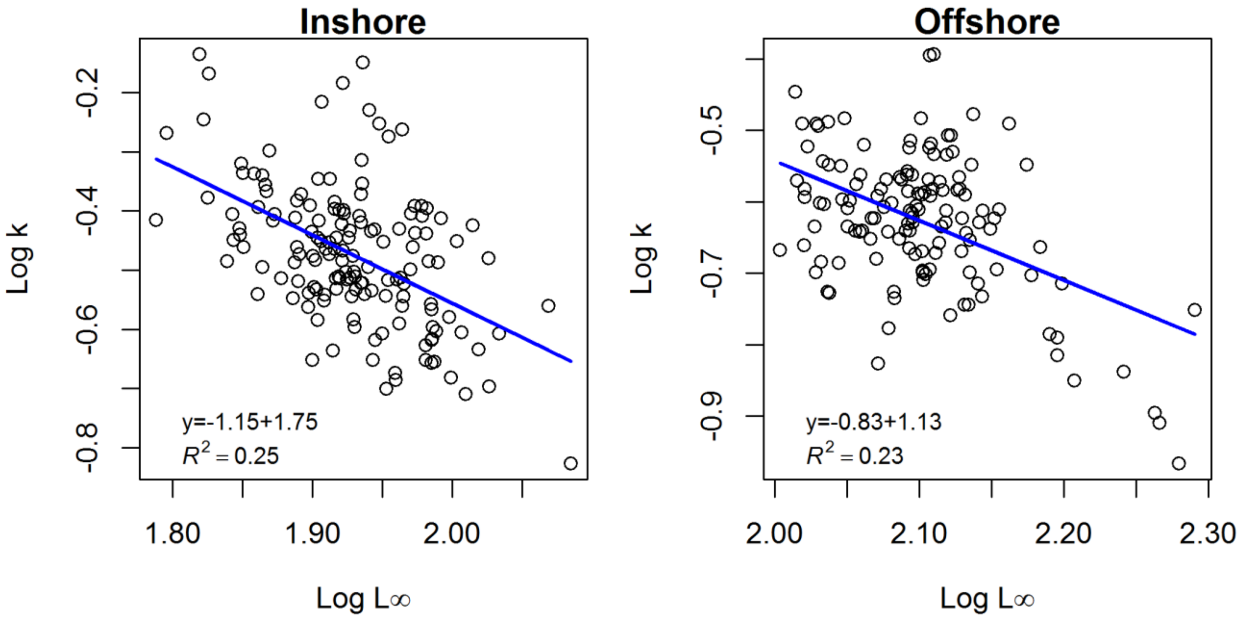


Figure 2. Log-log relationship between k and L∞ used to model additional MVBG parameters.

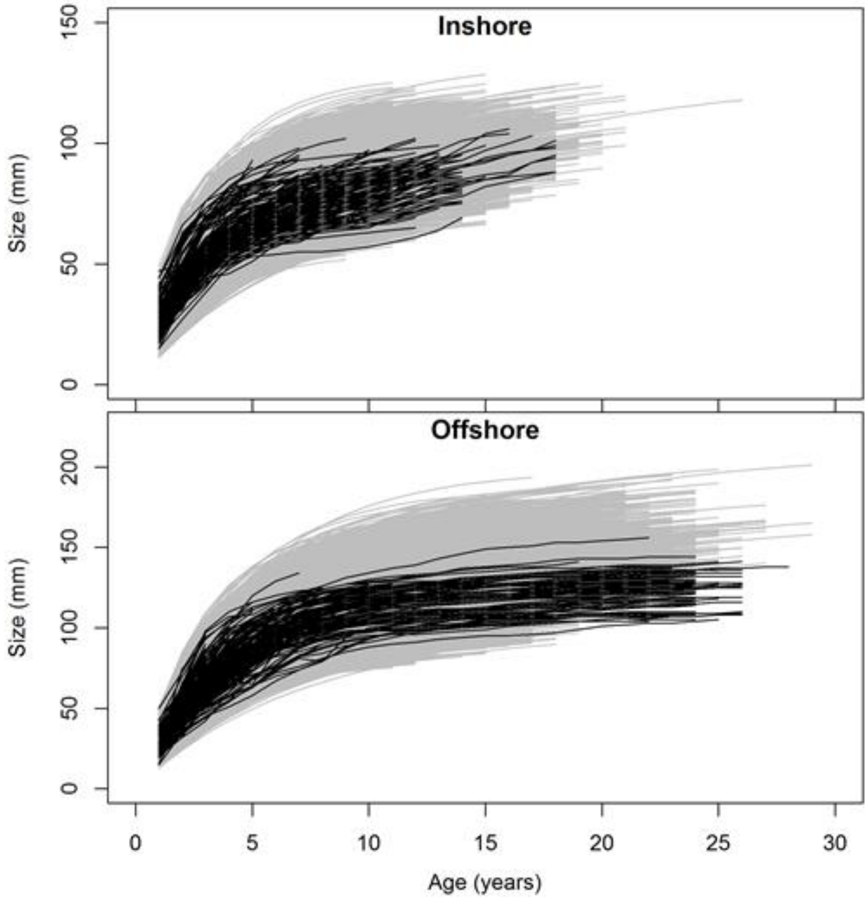


Figure 3. Actual (black) and 50,000 modeled (grey) growth curves for inshore and offshore populations of *S. solidissima*.

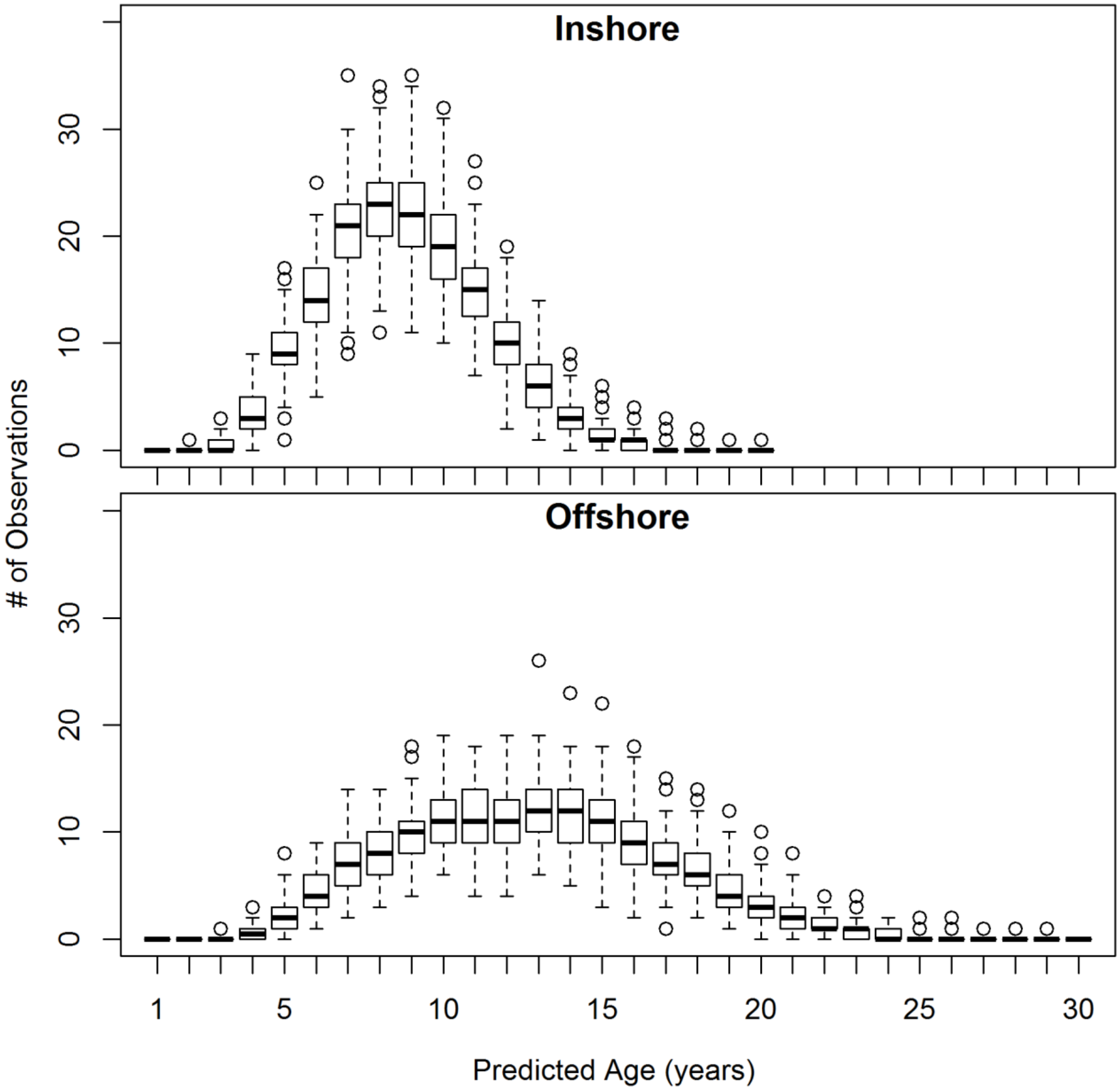


Figure 4. Range of ages predicted for sizes of both inshore and offshore clams from 1000 iterations of the model.

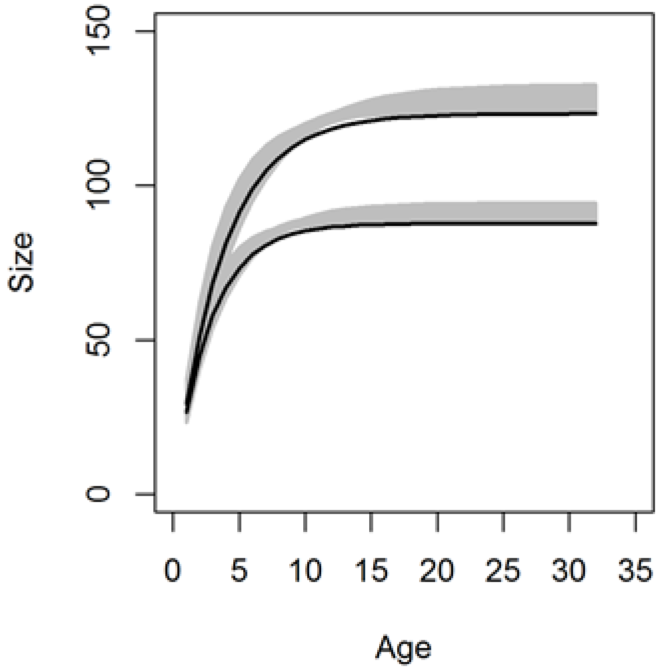


Figure 5. Range of predicted MVBG curves for 1000 iterations of age from size for Inshore (lower curve) and Offshore (upper curve). Black is actual MVBG for population, grey is predicted values.

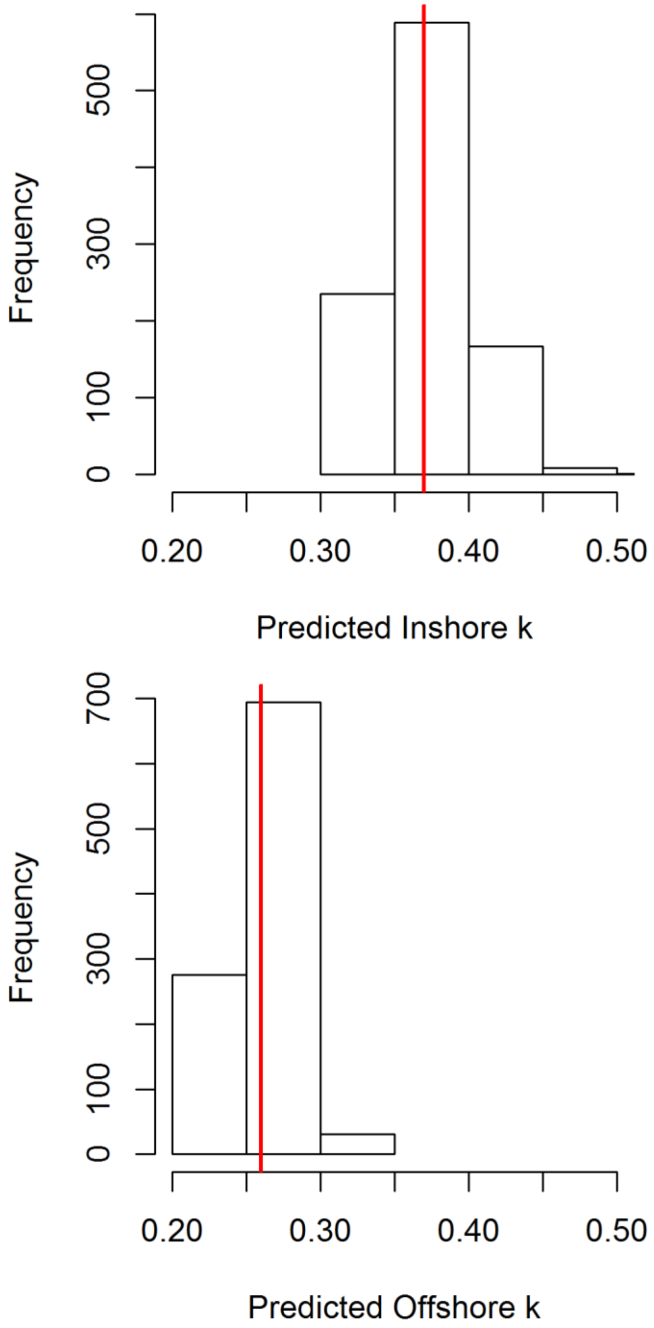


Figure 6. MVBG k values predicted from 1000 iterations of age from size. Red lines are the actual k values for each population.

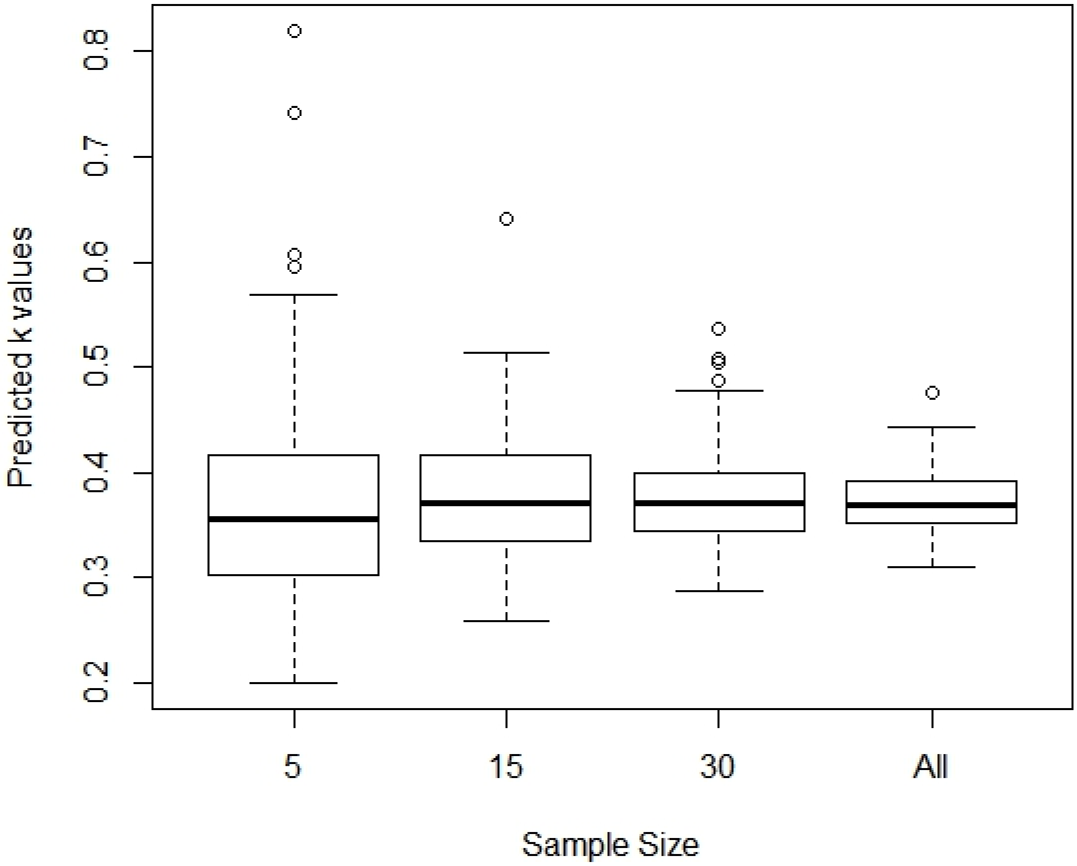


Figure 7. MVBG k values predicted from differing sample sizes for 100 iterations. There is no significant difference between the means of 15, 30 and all samples.

Appendix 1: References for Lifespan database in Chapter 1

Abada-Boudjema, Y.-M., and J.-C. Dauvin. 1995. Recruitment and life span of two natural mussel populations *Perna perna* (Linnaeus) and *Mytilus galloprovincialis* (Lamarck) from the Algerian coast. Journal of Molluscan Studies 61:467-481.

Abada-Boudjema, Y., J. Altes, and M. Moueza. 1984. Growth of two species of mussels, *Mytilus galloprovincialis* and *Perna perna* in a natural mussel bed in the Bay of Algiers. Haliotis 14:33-38.

Abele, D., J. Strahl, T. Brey, and E. E. Philipp. 2008. Imperceptible senescence: ageing in the ocean quahog Arctica islandica. Free Radic Res 42(5):474-80.

Adam, M. E. 1990. Shell growth in some Nile bivalves. Journal of Molluscan Studies 56:301-308.

Al-Barwani, S. M., A. Arshad, S. M. N. Amin, S. B. Japar, S. S. Siraj, and C. K. Yap. 2007. Population dynamics of the green mussel *Perna viridis* from the high spat-fall coastal water of Malacca, Peninsular Malaysia. Fisheries Research 84(2):147-152.

Alagarswami, K. 1966. Studies on some aspects of biology of the wedge-clam, *Donax faba* Gmelin from Mandapam Coast in the Gulf of Mannar. Journal of the Marine Biological Association of India 8(1):56-75.

Aldrige, D. C. 1999. The morphology, growth and reproduction of Unionidae (Bivalvia) in a Fenland waterway. Journal of Molluscan Studies 65:47-60.

Allen, J. A. 1952. Observations on *Nucula turgida* Marshall and *N. moorei* Winckworth. Journal of the Marine Biological Association of the United Kingdom 31:515-529.

Allen, J. A. 1969. Observations on size composition and breeding of Northumberland populations of *Zirphaea crispata* (Pholadidae : Bivalvia). Marine Biology 3:269-275.

Amaro, T., G. Duineveld, M. Bergman, and R. Witbaard. 2003. Growth variations in the bivalve *Mya truncata*: a tool to trace changes in the Frisian Front macrofauna (southern North Sea)? Helgoland Marine Research 57(2):132-138.

Ambrogi, R., and A. O. Ambrogi. 1985. The estimation of secondary production of the marine bivalve *Spisula subtruncata* (Da Costa) in the area of the Po River Delta. Marine Ecology 6(3):239-250.

Ambrose, W. G., P. E. Renaud, W. L. Locke, F. R. Cottier, J. Berge, M. L. Carroll, B. Levin, and S. Ryan. 2011. Growth line deposition and variability in growth of two circumpolar bivalves (Serripes groenlandicus, and Clinocardium ciliatum). Polar Biology 35(3):345-354.

Ansell, A. D. 1961. Reproduction, growth and mortality of *Venus striatula* (Da Costa) in Kames Bay, Millport. Journal of the Marine Biological Association of the United Kingdom 41:191-215.

Ansell, A. D. 1972. Distribution, growth and seasonal changes in biochemical composition for the bivalve *Donax vittatus* (da Costa) from Kames Bay, Millport. Journal of Experimental Marine Biology and Ecology 10:137-150.

Ansell, A. D., and F. Lagardere. 1980. Observations on the Biology of *Donax trunculus* and *D. vittatus* at Ile d'Oleron (French Atlantic Coast). Marine Biology 57:287-300.

Ansell, A. D., A. H. Parulekar, and J. A. Allen. 1978. On the rate of growth of *Nuculana minuta* (Muller) (Bivalvia; Nuculanidae). Journal of Molluscan Studies 44:71-82.

Ansell, A. D., P. Sivadas, B. Narayanan, and A. Trevallion. 1972. The ecology of two sandy beaches in South West India. III. Observations on the population of *Donax incarnatus* and *D. spiculum*. Marine Biology 17:318-322.

Anthony, J. L., D. H. Kesler, W. L. Downing, and J. A. Downing. 2001. Length-specific growth rates in freshwater mussels (Bivalvia:Unionidae): extreme longevity or generalized growth cessation? Freshwater Biology 46:1349-1399.

Antipova, T. V. 1978. Production of populations of some bivalves in the southeastern Barents Sea and the southern Kara Sea. Okeanologiia 18(4):737-741.

Anwar, N. A., C. A. Richardson, and R. Seed. 1990. Age determination, growth rate and population structure of the horse mussel *Modiolus modiolus*. Journal of the Marine Biological Association of the United Kingdom 70:441-457.

Appledoorn, R. S. 1983. Variation in the growth rate of *Mya arenaria* and its relationship to the environment as analyzed through principal components analysis and the omega paramters of the von Bertalanffy equations. Fishery Bulletin 81(1):75-84.

Appledoorn, R. S. 1995. Covariation in life-history parameters of soft-shell clams (*Mya arenaria*) along a latitudinal gradient. ICES Marine Science Symposium 199:19-25.

Appukuttan, K. K., C. M. Aravindan, T. M. Yohanan, and N. K. Balasubramanian. 1999. Population dynamics of an exploited stock of the clam *Paphia malabarica* of Astamudi Estuary (South India). The Fourth Indian Fisheries Forum Proceedings:31-34.

Aragón-Noriega, E. A., L. E. Calderon-Aguilera, and S. A. Pérez-Valencia. 2015. Modeling growth of the Cortes Geoduck *Panopea globosa* from unexploited and exploited beds in the northern Gulf of California. Journal of Shellfish Research 34(1):119-127.

Argente, F. A. T., and J. Estacion. 2014. Effect of different harvesting practices on the dynamics of *Paphia textile* (Gmelin 1792) (Bivalvia: Veneridae) populations at two sites in

Zamboanga del Norte, Southern Philippines. Environmental and Experimental Biology 12:113-120.

Arneri, E., G. Giannetti, and B. Antolini. 1998. Age determination and growth of *Venus verrucosa* L. (Bivalvia: Veneridae) in the southern Adriatic and the Aegean Sea. Fisheries Research 38:193-198.

Arnold, W. S., D. C. Marelli, T. M. Bert, D. S. Jones, and I. R. Quitmyer. 1991. Habitat-specific growth of hard clams *Mercenaria mercenaria* (L.) from the Indian River, Florida. Journal of Experimental Marine Biology and Ecology 147:245-265.

Arrieche, D., and A. Prieto. 2006. Parametros poblacionales del guacuco *Tivela mactroides* (Bivalvia:Veneridae) de Playa Caicara, Estado Anzoategui, Venezuela. Ciencias Marinas 32(2):285-296.

Bachelet, G. 1980. Growth and recruitment of the Tellinid bivalve *Macoma balthica* at the southern limit of Its geographical distribution, the Gironde Estuary (SW France). Marine Biology 59:105-117.

Bachelet, G. 1989. Recruitment in *Abra tenuis* (Montagu) (Bivalvia, Semelidae) a species with direct development and a protracted meiobenthic phase. 23rd Eurpoean Marine Biology Symposium. School of Biological Sciences, University of Wales.

Bagur, M., C. A. Richardson, J. L. Gutiérrez, L. P. Arribas, M. S. Doldan, and M. G. Palomo. 2013. Age, growth and mortality in four populations of the boring bivalve *Lithophaga patagonica* from Argentina. Journal of Sea Research 81:49-56.

Bailey, R. C., and R. H. Green. 1988. Within-basin variation in the shell morphology and growth rate of a freshwater mussel. Canadian Journal of Zoology 66(7):1704-1708.

Baird, M. S. 2000. Life History of the Spectaclecase, Cumberlandia monodonta Say, 1829 (Bivalvia, Unionoidea, Margaritiferidae). Southwestern Missouri State University.

Baird, R. H. 1966. Notes on an escallop (*Pecten maximus*) population in Holyhead Harbour. Journal of the Marine Biological Association of the United Kingdom 46:33-47.

Balasubramanian, K., and R. Natarajan. 1988. Age and growth of *Meretrix casta* (Chemnitz) in Vellar Estuary, Parangipettai. CMFRI Bulletin 1:145-147.

Baquiero-Cardenas, E., and J. Masso-Rojas. 1988. Variaciones poblacionales y reproduccion de dos poblacion de *Chione undatella* (Sowerby, 1835), bajo diferentest regimenes de pesca en la Bahia de La Paz, B.C.S., Mexico. Ciencia Pesquera 6:51-67.

Barkai, A., and G. M. Branch. 1989. Growth and mortality of the mussels *Choromytilus meridionalis* (Krauss) and *Aulacomya ater* (Molina) as indicators of biotic conditions. Journal of Molluscan Studies 55:329-342.

Barry, J. P., P. J. Whaling, and R. K. Kochevar. 2007. Growth, production, and mortality of the chemosynthetic vesicomyid bivalve, *Calyptogena kilmeri* from cold seeps off central California. Marine Ecology 28(1):169-182.

Bauer, G. 1983. Age structure, age specific mortality rates and population trend of the freshwater pearl mussel (*Margaritifera margaritifera*) in North Bavaria. Archive fur Hydrobiologie 98(4):523-532.

Bauer, G. 1987. Reproductive strategy of the freshwater pearl mussel *Margaritifera margaritifera*. Journal of Animal Ecology 56(2):691-704.

Bayne, B. L., and C. M. Worrall. 1980. Growth and production of mussels *Mytilus edulis* from two populations. Marine Ecology Progress Series 3:317-328.

Beal, B. F. 2006. Biotic and abiotic factors influencing growth and survival of wild and cultured individuals of the softshell clam (*Mya arenaria* L.) in eastern Maine. Journal of Shellfish Research 25(2):461-474.

Bechtol, W. R., and R. L. Gustafson. 1998. Abundance, recruitment and mortality of Pacific littleneck clams *Protothaca staminea* at Chugachik Island, Alaska. Journal of Shellfish Research 17(4):1003-1008.

Begum, S., L. Basova, O. Heilmayer, E. Philipp, D. Abele, and T. Brey. 2010. Growth and energy budget models of the bivalve *Arctica islandica* at six different sites in the northeast Atlantic relam. Journal of Shellfish Research 29(1):107-115.

Belding, D. 1909. The growth and habits of the sea clam (*Mactra solidissima*) Reports of the Commissioner of Fish and Game:26-41.

Berg., C. J., and P. Alatalo. 1985. Biology of the tropical bivalve *Asaphis deflorata* (Linne, 1758). Bulletin of Marine Science 37(3):827-838.

Bergh, G. 1974. Production of *Macoma balthica* (L.) (Lamellibranchiata) and notes on other ecologically important animals in Tvaren Bay in the Baltic. Zoon 2(143-152).

Berkman, P. A. 1990. The population biology of the Antarctic scallop, Adamussium colbecki (Smith 1902) at New Harbor, Ross Sea. Pp. 281-288. Antarctic Ecosystems. Springer Berlin Heidelberg.

Bert, T. M., W. S. Arnold, A. E. Wilbur, S. Seyoum, A. L. McMillen-Jackson, S. P. Stephenson, R. H. Weisberg, and L. A. Yarbro. 2014. Florida Gulf Bay Scallop (*Argopecten irradians concentricus*) population genetic structure: form, variation, and influential factors. Journal of Shellfish Research 33(1):99-136.

Bertness, M. D. 1980. Growth and mortality in the ribbed mussel *Geukensia demissa* (Bivalvia:Mytilidae). The Veliger 23(1):62-69.

Beukema, J. J. 1989. Bias in estimates of maximum lifespan, with an example of the edible cockle, *Cerastoderma edule*. Netherlands Journal of Zoology 39:79-85.

Beukema, J. J., and R. Dekker. 1995. Dynamics and growth of a recent invader into European coastal waters: The American razor clam *Ensis directus*. Journal of the Marine Biological Association of the United Kingdom 75:351-362.

Blanchard, A., and H. M. Feder. 2000. Shell growth of *Mytilus trossulus* Gould, 1850, in Port Valdez, Alaska. The Veliger 43(1):34-42.

Blicher, M. E., M. K. Sejr, and S. Høgslund. 2013. Population structure of *Mytilus edulis* in the intertidal zone in a sub-Arctic fjord, SW Greenland. Marine Ecology Progress Series 487:89-100.

Boltacheva, N. A., and S. A. Mazlumyan. 2003. The growth and longevity of *Chamelea gallina* (Mollusca, Veneridae) in the Black Sea. Vestnik Zoologii 37(3):71-74.

Bonham, K. 1965. Growth rate of giant clam *Tridacna gigas* at Bikini Atoll as revealed by radioautography. Science 149:300-302.

Borrero, F. J., and T. J. Hilbish. 1988. Temporal variation in shell and soft tissue growth of the mussel *Geukensia demissa*. Marine Ecology Progress Series 42:9-15.

Bourget, E., and V. Brock. 1990. Short-term shell growth in bivalves: individual, regional and age-related variations in the rhythm of deposition of *Cerastoderma (=Cardium) edule*. Marine Biology 106:103-108.

Bourne, N. 1982. Distribution, reproduction, and growth of Manila clam, *Tapes phillipinarum* (Adams and Reeves), in British Columbia. Journal of Shellfish Research 2(1):47-54.

Bourne, N., and D. Quayle. 1970. Breeding and growth of razor clams in British Columbia. Fisheries Research Board of Canada.

Bourne, N., and D. W. Smith. 1972. Breeding and growth of the horse clam, *Tresus capax* (Gould), in southern British Columbia. Proceedings of the National Shellfisheries Association 62:38-46.

Boyden, C. R. 1972. Relationship of size to age in the cockles *Cerastoderma edule* and *C. glaucum* from the River Crouch Estuary, Essex. Journal of Conchology 27:475-489.

Bradley, W. H., and P. Cooke. 1959. Living and ancient populations of the clam *Gemma gemma* in a Maine coast tidal flat. Fishery Bulletin 137:306-334.

Brady, F. 1943. The distribution of the fauna of some intertidal sands and muds on the Northumberland coast. Journal of Animal Ecology 12(1):27-41.

Breed-Willeke, G. M., and D. R. Hancock. 1980. Growth and reproduction of subtidal and intertidal populations of the gaper clam Tresus capax (Gould) from Yaquina Bay, Oregon. Proceedings of the National Shellfisheries Association 70:1-13.

Breen, P., C. Gabriel, and T. Tyson. 1991. Preliminary estimates of age, mortality, growth, and reproduction in the Hiatellidae clam *Panopea zelandica* in New Zealand. New Zealand Journal of Marine and Freshwater Research 25(3):231-237.

Brethes, J.-C. F., G. Desrosiers, and G. Fortin Jr. 1986. Croissance et production du bivalve *Mesodesma arctatum* (Conrad) sur la cote nord du golfe du Saint-Laurent. Canadian Journal of Zoology 64(1914-1919).

Brey, T., W. E. Arntz, D. Pauly, and H. Rumorh. 1990. *Arctica (Cyprina) islandica* in Kiel Bay (Western Baltic): growth, production and ecological significance. Journal of Experimental Marine Biology and Ecology 136:217-235.

Brey, T., and S. Hain. 1992. Growth, reproduction and production of *Lissarca notorcadensis* (Bivalvia: Philobryidae) in the Weddell Sea, Antarctica. Marine Ecology Progress Series 82:219-226.

Bricelj, V., and M. Krause. 1992. Resource allocation and population genetics of the bayscallop, *Argopecten irradians irradians*; effects of age and allozyme heterozygosity on reproductive output. Marine Biology 113:253-261.

Bricelj, V. M., J. Epp, and R. E. Malouf. 1987. Comparative physiology of young and old cohorts of bay scallop *Argopecten irradians irradia* (Lamarck) : mortality, growth, and oxygen consumption. Journal of Experimental Marine Biology and Ecology 112:73-91.

Broom, M. J. 1982. Analysis of the growth of *Anadara granosa* (Bivalvia: Arcidae) in natural, artificially seeded and experimental populations. Marine Ecology Progress Series 9:69-79.

Brousseau, D. J. 1979. Analysis of growth rate in *Mya arenaria* using the Von Bertalanffy equation. Marine Biology 51:221-227.

Brousseau, D. J. 1984. Age and growth rate determinations for the Atlantic ribbed mussel, *Guekensia demissa* Dillwyn (Bivalvia:Mytilidae). Estuaries 7(3):233-241.

Brousseau, D. J., and J. A. Baglivo. 1987. A comparative study of age and growth in *Mya arenaria* (soft-shell clam) from three populations in Long Island Sound. Journal of Shellfish Research 6(1):17-24.

Brown, A., O. Heilmayer, and S. Thatje. 2010. Metabolic rate and growth in the temperate bivalve *Mercenaria mercenaria* at a biogeographical limit, from the English Channel. Journal of the Marine Biological Association of the United Kingdom 90(05):1019-1023.

Bruenderman, S. A., and R. J. Neves. 1993. Life history of the endangered fine-rayed pigtoe *Fusconaia cuneolus* (Bivalvia:unionidae) in the Clinch River, Virginia. American Malacological Bulletin 10(1):83-91.

Buchanan, J. B., and R. M. Warwick. 1974. An estiamte of benthic macrofaunal production in the offshore mud of the Northumberland Coast. Journal of the Marine Biological Association of the United Kingdom 54:197-222.

Buick, D. P., and L. C. Ivany. 2004. 100 years in the dark: Extreme longevity of Eocene bivalves from Antarctica. Geology 32(10):921-924.

Bureau, D. 2002. Age, size structure and growth parameters of geoducks (*Panopea abrupta*, Conrad 1849) from 34 locations in British Columbia sampled between 1993 and 2000. Fisheries and Oceans Canada.

Bureau, D., W. Hajas, C. M. Hand, and G. Dovey. 2003. Age, size structure and growth parameters of geoducks (*Panopea abrupta*, Conrad 1849) from seven locations in British Columbia sampled in 2001 and 2002.

Burke, M., and K. Mann. 1974. Productivity and production: Biomass ratios of bivalve and gastropod populations in an Eastern Canadian estuary. Journal of the Fisheries Research Board of Canada 31:167-177.

Bušelić, I., M. Peharda, D. J. Reynolds, P. G. Butler, A. R. González, D. Ezgeta-Balić, I. Vilibić, B. Grbec, P. Hollyman, and C. A. Richardson. 2015. *Glycymeris bimaculata* (Poli, 1795) — A new sclerochronological archive for the Mediterranean? Journal of Sea Research 95:139-148.

Butler, A. J., and F. J. Brewster. 1979. Size distributions and growth of the fan-shell *Pinna bicolor* Gmelin (Mollusca:Eulamellibranchia) in South Australia. Australian Journal of Marine and Freshwater Research 30(1):25-39.

Cadee, G. C. 1989. Size-selective transport of shells by birds and its palaeoecological implications. Palaeontology 32(2):429-437.

Calderon-Aguilera, L. E., E. A. Aragón-Noriega, C. M. Hand, and V. M. Moreno-Rivera. 2010. Morphometric relationships, age, growth, and mortality of the geoduck clam, *Panopea generosa*, along the Pacific coast of Baja California, Mexico. Journal of Shellfish Research 29(2):319-326.

Campbell, A., N. Bourne, and W. Carolsfeld. 1990. Growth and size at maturity of the Pacific gaper *Tresus nuttallii* (Conrad 1837) in southern British Columbia. Journal of Shellfish Research 9(2):273-278.

Campbell, A., and M. D. Ming. 2003. Maturity and growth of the Pacific geoduck clam, *Panopea abrubta*, in southern British Columbia, Canada. Journal of Shellfish Research 22(1):85-90.

Campbell, A., C. W. Yeung, G. Dovey, and Z. Zhang. 2004. Population biology of the Pacific geoduck clam, *Panopea abrupta*, in experimental plots, southern British Columbia, Canada. Journal of Shellfish Research 23(3):661-673.

Cardoso, J. F. M. F., S. Santos, J. I. J. Witte, R. Witbaard, H. W. van der Veer, and J. P. Machado. 2013. Validation of the seasonality in growth lines in the shell of *Macoma balthica* using stable isotopes and trace elements. Journal of Sea Research 82:93-102.

Cardoso, J. F. M. F., J. I. J. Witte, and H. W. van der Veer. 2007. Habitat related growth and reproductive investment in estuarine waters, illustrated for the tellinid bivalve Macoma balthica (L.) in the western Dutch Wadden Sea. Marine Biology 152(6):1271-1282.

Carmichael, R. H., A. C. Shriver, and I. Valiela. 2004. Changes in shell and soft tissue growth, tissue composition, and survival of quahogs, *Mercenaria mercenaria*, and softshell clams, *Mya arenaria,* in response to eutrophic-driven changes in food supply and habitat. Journal of Experimental Marine Biology and Ecology 313(1):75-104.

Carroll, M. L., W. G. Ambrose, B. S. Levin, S. K. Ryan, A. R. Ratner, G. A. Henkes, and M. J. Greenacre. 2011. Climatic regulation of Clinocardium ciliatum (bivalvia) growth in the northwestern Barents Sea. Palaeogeography, Palaeoclimatology, Palaeoecology 302(1-2):10-20.

Carroll, M. L., B. J. Johnson, G. A. Henkes, K. W. McMahon, A. Voronkov, W. G. Ambrose, Jr., and S. G. Denisenko. 2009. Bivalves as indicators of environmental variation and potential anthropogenic impacts in the southern Barents Sea. Marine Pollution Bulletin 59(4-7):193-206.

Cassie, R. M. 1955. Population studies on the toheroa, *Amphidesma ventricosum* Gray (Eulamellibranchiata). Australian Journal of Marine and Freshwater Research 6(3):348-391.

Cassista, M. C., and M. W. Hart. 2007. Spatial and temporal genetic homogeneity in the Arctic surfclam (*Mactromeris polynyma*). Marine Biology 152(3):569-579.

Cataldo, D., and D. Boltovskoy. 1999. Population dynamics of *Corbicula fluminea* (Bivalvia) in the Parana River Delta (Argentina). Hydrobiologia 380:153-163.

Cayre, P. 1978. Etude de la molue *Perna perna* L. et des possibilites de mytiliculture en Republique Populaire du Congo. Cahiers ORSTOM Serie Oceanographie 16:9-17.

Ceccherelli, V. U., and R. Rossi. 1984. Settlement, growth and production of the mussel *Mytilus galloprovincialis*. Marine Ecology Progress Series 16:173-184.

Cerrato, R. M., and D. L. Keith. 1992. Age structure, in the Atlantic from estuarine growth, and morphometric variations surf clam, *Spisula solidissima*, and inshore waters. Marine Biology 114:581-593.

Chamberlain, T. K. 1931. Annual growth of freshwater mussels. Bulletin of the Bureau of Fisheries 46:713-739.

Chambers, M. R., and H. Milne. 1975. The production of *Macoma balthica* (L.) in the Ythan Estuary. Estuarine and Coastal Marine Science 3:443-455.

Chauvaud, L., G. Thouzeau, and Y.-M. Paulet. 1998. Effects of environmental factors on the daily growth rate of *Pecten maximus* juveniles in the Bay of Brest (France). Journal of Experimental Marine Biology and Ecology 227:83-111.

Chellam, A. 1988. Growth and biometric relationship of pearl oyster *Pinctada fucata* (Gould). Indian Journal of Fisheries 25:77-83.

Chiantore, M., R. Cattaneo-Vietti, and O. Heilmayer. 2003. Antarctic scallop (*Adamussium colbecki*) annual growth rate at Terra Nova Bay. Polar Biology 26:416-419.

Choo, P. S., and G. Speiser. 1979. An estimation of the growth parameters and mortality of *Mytilus viridis* Linnaeus (Mollusca, Mytilidae) cultured in a suspended plastic in Jelutong, Penang. The Malaysian Agricultural Journal 52:9-16.

Christian, A. D., C. L. Davidson, W. R. Posey II, P. J. Rust, J. L. Farris, J. L. Harris, and G. L. Harp. 2000. Growth curves of four species of commercially valuable freshwater mussels (Bivalvia:Unionidae) in Arkansas. Journal of the Arkansas Academy of Sciences 54:41-50.

Chung, E.-Y., D.-K. Ryou, and J.-H. Lee. 1994. Gonadal development, age and growth of the shortnecked clam, *Ruditapes philippinarum* (Pelecypoda:Veneridae) , on the coast of Kimje, Korea. Korean Journal of Malacology 10(1):38-54.

Chute, A. S., S. C. Wainright, and D. R. Hart. 2012. Timing of shell ring formation and patterns of shell growth in the sea scallop *Placopecten magellanicus* based on stable oxygen isotopes. Journal of Shellfish Research 31(3):649-662.

Ciocco, N. 1991. Differences in individual growth rate among scallop (*Chlamys tehuelcha* (d'Orb.)) populations from San Jose Gulf (Argentina). Fisheries Research 12:31-42.

Claereboudt, M. R., and J. H. Himmelman. 1996. Recruitment, growth and production of giant scallops (*Placopecten magellanicus*) along an environmental gradient in Baie des Chaleurs, eastern Canada. Marine Biology 124:661-670.

Clasing, E., T. Brey, R. Stead, J. Navarro, and G. Asencio. 1994. Population dynamics of *Venus antiqua* (Bivalvia: Veneracea) in the Bahia de Yaldad, Isla de Chilok, Southern Chile. Journal of Experimental Marine Biology and Ecology 177:171-186.

Cobb, J. C., S. P. Stephenson, and W. S. Arnold. 2011. Reproductive cycle and recruitment patterns of the coquina clam *Donax variabilis* Say along the central Gulf Coast of Florida. Journal of Shellfish Research 30(1):25-34.

Coe, W. R. 1947. Nutrition, growth and sexuality of the Pismo clam. Journal of Experimental Zoology 104(1):1-24.

Coe, W. R. 1955. Ecology of the bean clam *Donax gouldi* on the coast of Southern California. Ecology 36(3):512-514.

Coe, W. R., and J. E. Fitch. 1950. Population studies, local growth rates and reproduction of the Pismo clam. Journal of Marine REsearch 9(3):188-210.

Coe, W. R., and D. L. Fox. 1944. Biology of the California sea-mussel (*Mytilus californianus*). III. Environmental conditions and rate of growth. The Biological Bulletin 87(1):59-72.

Coelho, J. P., M. Rosa, E. Pereira, A. Duarte, and M. A. Pardal. 2006. Pattern and annual rates of *Scrobicularia plana* mercury bioaccumulation in a human induced mercury gradient (Ria de Aveiro, Portugal). Estuarine, Coastal and Shelf Science 69(3-4):629-635.

Çolakoğlu, S., and M. Palaz. 2014. Some population parameters of *Ruditapes philippinarum* (Bivalvia, Veneridae) on the southern coast of the Marmara Sea, Turkey. Helgoland Marine Research 68(4):539-548.

Cole, H. A. 1956. A preliminary study of growth-rate in cockles (*Cardium edule* L.) in relation to commercial exploitation. ICES Journal of Marine Science 22(1):77-90.

Commito, J. A. 1982. Effects of Lunatia heros predation on the population dynamics of *Mya arenaria* and *Macoma baithica* in Maine, USA. Marine Biology 69:187-193.

Conan, G., and M. S. Shafee. 1978. Growth and biannual recruitment of the black scallop *Chlamys varia* (L.) in Lanveoc area, Bay of Brest. Journal of Experimental Marine Biology and Ecology 35:59-71.

Coon, T. G., J. W. Eckblad, and P. M. Trygstad. 1977. Relative abundance and growth of mussels (Mollusca:Eulamellibranchia) in pools 8,9 and 10 of the Mississippi River. Freshwater Biology 7:279-285.

Coutts, P. J. F. 1974. Growth characteristics of the bivalve *Chione stutchburyi*. New Zealand Journal of Marine and Freshwater Research 8(2):333-339.

Cranfield, H. J., and K. P. Michael. 2001. Growth rates of five species of surf clams on a southern North Island beach, New Zealand. New Zealand Journal of Marine and Freshwater Research 35(5):909-924.

Cranfield, H. J., K. P. Michael, and R. I. C. C. Francis. 1996. Growth rates of five species of subtidal clam on a beach in the South Island, New Zealand. Mairne and Freshwater Resarch 47:773-784.

Crooks, J. A. 1996. The population ecology of an exotic mussel, *Musculista senhousia*, in a southern California bay. Coastal and Estuarine Research Federation 19(1):42-50.

Crowley, T. E. 1957. Age determination in *Anodonta*. Journal of Conchology 24:201-207.

Cruz-Vásquez, R., G. Rodríguez-Domínguez, E. Alcántara-Razo, and E. A. Aragón-Noriega. 2012. Estimation of individual growth parameters of the Cortes geoduck *Panopea globosa* from the central Gulf of California using a multimodel approach. Journal of Shellfish Research 31(3):725-732.

Cudney-Bueno, R., and K. Rowell. 2008. Establishing a baseline for management of the rock scallop, *Spondylus calcifer* (Carpenter 1857): Growth and reproduction in the upper Gulf of California, Mexico. Journal of Shellfish Research 27(4):625-632.

da Silva, C. F., G. N. Corte, L. Q. Yokoyama, J. R. Abrahão, and A. C. Z. Amaral. 2015. Growth, mortality, and reproduction of *Tagelus plebeius* (Bivalvia: Solecurtidae) in Southeast Brazil. Helgoland Marine Research 69(1):1-12.

Dalgiç, G., İ. Okumuş, and S. Karayücel. 2010. The effect of fishing on growth of the clam *Chamelea gallina* (Bivalvia: Veneridae) from the Turkish Black Sea coast. Journal of the Marine Biological Association of the United Kingdom 90(02):261-265.

Dame, R. F. 1976. Energy flow in an intertidal oyster population. Estuarine and Coastal Marine Science 4:243-253.

Dang, C., X. de Montaudouin, M. Gam, C. Paroissin, N. Bru, and N. Caill-Milly. 2010. The Manila clam population in Arcachon Bay (SW France): Can it be kept sustainable? Journal of Sea Research 63(2):108-118.

Dauvin, J. C., and F. Gentil. 1989. Long-term changes in populations of subtidal bivalves (*Abra alba* and *A. prismatica*) from the Bay of Morlaix (Western English Channel). Marine Biology 103:63-73.

Davis, J. P., and J. G. Wilson. 1982. The population sturcutre and ecology of *Nucula turgida* (Leckenby and Marshall) in Dublin Bay. Progress in Underwater Science 8:53-60.

de Goeij, P., and P. Luttikhuizen. 1998. Deep-burying reduces growth in intertidal bivalves: field and mesocosm experiments with *Macoma balthica*. Journal of Experimental Marine Biology and Ecology 228:327-337.

Defeo, O. 1996. Experimental management of an unexploited sand beach bivalve population. Revista Chilena de Historia Natural 69:605-614.

Defeo, O., and N. Gutiérrez. 2003. Geographical patterns in growth estimates of the scallop *Zygochlamys patagonica*, with emphasis on Uruguayan waters. Journal of Shellfish Research 22(3):643-646.

Defeo, O., E. Ortiz, and J. C. Castilla. 1992. Growth, mortality and recruitment of the yellow clam *Mesodesma mactroides* on Uruguayan beaches. Marine Biology 114:429-437.

Degraer, S., P. Meire, and M. Vincx. 2007. Spatial distribution, population dynamics and productivity of *Spisula subtruncata*: implications for *Spisula* fisheries in seaduck wintering areas. Marine Biology 152(4):863-875.

Dekker, R., and J. J. Beukema. 1993. Dynamics and growth of a bivalve, *Abra tenuis*, at the northern edge of its distribution. Journal of the Marine Biological Association of the United Kingdom 73(497-511).

Dekker, R., and J. J. Beukema. 1999. Relations of summer and winter temperatures with dynamics and growth of two bivalves, *Tellina tenuis* and *Abra tenuis*, on the northern edge of their intertidal distributions. Journal of Sea Research 42:207-220.

Dekker, R., and J. J. Beukema. 2012. Long-term dynamics and productivity of a successful invader: The first three decades of the bivalve *Ensis directus* in the western Wadden Sea. Journal of Sea Research 71:31-40.

Del Norte, A. G. 1988. Aspects of the growth, recruitment, mortality and reproduction of the scallop *Amusium pleuronectes* (Linne) in the Lingayen Gulf, Philippines. Ophelia 29(2):153-168.

Deval, M. C. 2001. Shell growth and biometry of the striped Venus *Chamelea gallina* (L.) in the Marmara Sea, Turkey. Journal of Shellfish Research 20(1):155-159.

Deval, M. C., and D. Göktürk. 2008. Population structure and dynamics of the cut trough shell *Spisula subtruncata* (da Costa) in the Sea of Marmara, Turkey. Fisheries Research 89(3):241-247.

Deval, M. C., and I. K. Oray. 1998. The annual shell increments of Bivalvia *Chamelea gallina* L. 1758 in the northern Sea of Marmara. Oebalia 24:93-109.

Devillers, N., A. Eversole, and J. Isely. 1998. A comparison of four growth models for evaluating the growth of the northern quahog *Mercenaria mercenaria* (L.). Journal of Shellfish Research 17(1):191-194.

Dewarumez, J. M. 1979. Etude biologique D' *Abra alba,* Wood (mollusque lamellibranche) du littoral de la Mer du Nord. Universite des Sciences et Techniques de Lille.

Dinamani, P. 2010. Reproductive cycle and gonadial changes in the New Zealand rock oyster *Crassostrea glomerata*. New Zealand Journal of Marine and Freshwater Research 8(1):39-65.

Dolbeth, M., I. Viegas, F. Martinho, J. C. Marques, and M. A. Pardal. 2006. Population structure and species dynamics of *Spisula solida*, *Diogenes pugilator* and *Branchiostoma lanceolatum* along a temporal–spatial gradient in the south coast of Portugal. Estuarine, Coastal and Shelf Science 66(1-2):168-176.

Dolmer, P. 1997. Seasonal and spatial variability in growth of *Mytilus edulis* L. in a brackish sound: comparisons of individual mussel growth and growth of size classes. Fisheries Research 34:17-26.

Duval, D. 1963. The biology of *Ptericola pholadiformis* Lamark (Lamellibranchiata Petricolidae). Proceedings of the Malacological Society of London 35:89-100.

Eagar, R. M. C., N. M. Stone, and P. A. Dickson. 1984. Correlations between shape, weight and thickness of shell in four populations of *Venerupid rhomboides* (Pennant). Journal of Molluscan Studies 50:19-38.

Easwaran, C. R., K. R. Narayanan, and M. S. Michael. 1969. Pearl fisheries in the Gulf of Kutch. Journal, Bombay Natural Hist. Society 66(2):338-344.

Edie, S. M., and D. Surge. 2013. Deciphering Annual Growth Features in Chione Elevata Shells Using Isotope Sclerochronology. Palaios 28(2):93-98.

Edward, J. K. P., and K. Ayyakkannu. 1991. Temporal variation in annual production of *Tellina nobilis* and *Tellina cuspis* in a tropical estuarine environment. Mahasagar 24(1):21-29.

Emerson, C. W., T. E. Minchinton, and J. Grant. 1988. Population structure, biomass, and respiration of *Mya arenaria* L. on temperate sandflat. Journal of Experimental Marine Biology and Ecology 115:99-111.

Epple, V., T. Brey, R. Witbaard, H. Kuhnert, and J. Patzold. 2006. Sclerochronological records of *Arctica islandica* from the inner German Bight. The Holocene 16:763-769.

Erlenkeuser, H., and G. Wefer. 1981. Seasonal growth of bivalves from Bermuda recorded in their O-18 profiles. Pp. 643-648. Proceedings of the Fourth International Coral Reef Symposium. Manila.

Escati-Peñaloza, G., A. M. Parma, and J. M. Orensanz. 2010. Analysis of longitudinal growth increment data using mixed-effects models: Individual and spatial variability in a clam. Fisheries Research 105(2):91-101.

Evans, S. V., and B. O. Tallmark. 1977. Growth and biomass of bivalve molluscs on a shallow, sandy bottom in Gullmar Fjord (Sweden). Zoon 5:33-38.

Eversole, A. G., N. Devillers, and W. D. Anderson. 2000. Age and size of *Mercenaria mercenaria* in Two Sisters Creek, South Carolina. Journal of Shellfish Research 19(1):51-56.

Evtushenko, Z. S., O. N. Lukyanova, and N. N. Belcheva. 1990. Cadmium bioaccumulation in organs of the scallop *Mizuhopecten yessoensis*. Marine Biology 104(247-250).

Ezgeta-Balić, D., M. Peharda, C. A. Richardson, M. Kuzmanić, N. Vrgoč, and I. Isajlović. 2010. Age, growth, and population structure of the smooth clam *Callista chione* in the eastern Adriatic Sea. Helgoland Marine Research 65(4):457-465.

Fahy, E., M. L. Alcantara, M. Norman, R. Browne, V. Roantree, and N. Pfeiffer. 2002. Mortalities of *Ensis arcuatus* (Jeffreys) (Solenacea) in western Ireland. Journal of Shellfish Research 21(1):29-32.

Fahy, E., J. Carroll, M. O'Toole, and J. Hickey. 2003. A preliminary account of fisheries for the surf clam *Spisula solida* (L) (Mactracea) in Ireland. Fisheries Bulletin 21:1-27.

Fairbridge, W. S. 1953. A population study of the Tasmanian "commercial" scallop, *Notovola meridionalis* (Tate) (Lamelli-Branchiata, Pectinidae). Australian Journal of Marine and Freshwater Research 4(1):1-40.

Fassatoui, C., A. Ben Rejeb Jenhani, and M. S. Romdhane. 2014. Geographic pattern of shell morphology in the endemic freshwater mussel *Unio ravoisieri* (Bivalvia: Unionidae) from northern Tunisia. Journal of Molluscan Studies 81(1):152-160.

Feder, H. M., and A. J. Paul. 1974. Age, growth and size-weight relationships of the soft-shell clam *Mya arenaria,* in Prince William Sound, Alaska. Proceedings of the National Shellfisheries Association 64:45-52.

Feder, H. M., A. J. Paul, and J. Paul. 1976. Growth and size-weight relationships of the pinkneck clam *Spisula polynyma*, in Hartney Bay, Prince William Sound, Alaska. Proceedings of the National Shellfisheries Association 66:21-25.

Feder, H. M., A. J. Paul, and J. M. Paul. 1979. The pinkneck clam *Spisula polynyma* in the eastern Bergin Sea growth, mortality, recruitment and size at maturity. Pp. 717-721. Alaska Fisheries: 200 years and 200 Miles of Change. Proceedings of the 29th Alaska Science Conference. University of Alaska, Fairbanks.

Fevolden, S. E. 1992. Allozymic variability in the Iceland scallop *Chlamys islandica:* geographic variation and lack of growth-heterozygosity correlations. Marine Ecology Progress Series 85:259-268.

Filippenko, D., and E. Naumenko. 2014. Patterns of the growth of soft-shell clam *Mya arenaria* L. (Bivalvia) in shallow water estuaries of the southern Baltic Sea. Ecohydrology & Hydrobiology 14(2):157-165.

Fiori, S., and O. Defeo. 2006. Biogeographic patterns in life-history traits of the Yellow clam, *Mesodesma mactroides*, in sandy beaches of South America. Journal of Coastal Research 224:872-880.

Flores, L., R. Licandeo, L. A. Cubillos, and E. Mora. 2014. Intra-specific variability in life-history traits of *Anadara tuberculosa* (Mollusca: Bivalvia) in the mangrove ecosystem of the Southern coast of Ecuador. Revista de Biología Tropical 62(2):473-482.

Foster, T. 1932. Observation on the life history of the fingernail shell of the genus *Sphaerium*. Journal of Morphology 53:473-497.

Franz, D. R. 1973. The ecology and reproduction of a marine bivalve *Mysella planulata* (Erycinacea). The Biological Bulletin 144:93-106.

Franz, D. R. 1996. Size and age at first reproduction of the ribbed mussel *Geukensia demissa* (Dillwyn) in relation to shore level in a New York salt marsh. Journal of Experimental Marine Biology and Ecology 205:1-13.

Franz, D. R. 2001. Recruitment, survivorship, and age structure of a New York ribbed mussel population (*Geukensia demissa*) in relation to shore level: A nine year study. Estuaries 24(3):319-327.

Fraschetti, S., A. Covazzi, M. Chiantore, and G. Albertelli. 1997. Life-history traits of the bivalve *Spisula subtruncata* (da Costa) in the Ligurian Sea (North-Western Mediterranean): The contribution of newly settled juveniles. Scientia Marinia 61(Supl. 2):25-32.

Fraser, C. 1931. Notes on the ecology of the cockle *Cardium corbis* Martyn. Transactions of the Royal Society of Canada 25:59-72.

Fraser, C. M., and G. M. Smith. 1928. Notes on the ecology of the butter clam, *Saxidomus giganteus* Deshayes. Proceedings and Transactions of the Royal Society of Canada 22:271-284.

Fraser, T. 1967. Contributions to the biology of *Tagelus divisus* (Tellinacea:Pelecypoda) in Biscayne Bay, Florida. Bulletin of Marine Science 17(1):111-132.

Fritz, L. W. 1991. Seasonal condition change, morphometrics, growth and sex ratio of the ocean quahog, *Arctica islandica* (Linnaeus, 1767) off New Jersey, U.S.A. Journal of Shellfish Research 10(1):79-88.

Gagayev, S. Y. 1989. Growth and production of mass species of bivalves in Chaun Bay (East Siberian Sea). Oceanology 29(4):504-507.

Gage, J. 1968. The mode of life of *Mysella cuneata,* a bivalve 'commensal' with *Phascolion strombi* (Sipunculoidea). Canadian Journal of Zoology 46:919-934.

Galinou-Mitsoudi, C., and A. I. Sinis. 1995. Age and growth of *Lithophaga lithophaga* (Linnaeus, 1758) (Bivalvia:Mytilidae), based on annual growth lines in the shell. Journal of Molluscan Studies 61:435-453.

Galinou-Mitsoudi, S., G. Vlahavas, and O. Papoutsi. 2006. Population study of the protected bivalve *Pinna nobilis* (Linnaeus, 1758) in Thermaikos Gulf (North Aegean Sea). Journal of Biological Research 5:47-53.

Gallardo, C. S. 1993. Reproductive habits and life cycle of the small clam *Kingiella chilenica* (Bivalvia: Cyamiidae) in an estuarine sand flat from the South of Chile. Marine Biology 115:595-603.

Gam, M., X. de Montaudouin, and H. Bazairi. 2010. Population dynamics and secondary production of the cockle *Cerastoderma edule:* A comparison between Merja Zerga (Moroccan Atlantic Coast) and Arcachon Bay (French Atlantic Coast). Journal of Sea Research 63(3-4):191-201.

Garcia-March, J. R., A. M. García-Carrascosa, and A.-L. Pena. 2002. In situ measurement of *Pinna nobilis* shells for age and growth studies: A new device. Marine Ecology 23(3):207-217.

García-March, J. R., A. M. García-Carrascosa, A. L. Peña Cantero, and Y. G. Wang. 2007. Population structure, mortality and growth of *Pinna nobilis* Linnaeus, 1758 (Mollusca, Bivalvia) at different depths in Moraira Bay (Alicante, Western Mediterranean). Marine Biology 150(5):861-871.

Garcia-March, J. R., A. Marquez-Aliaga, Y.-G. Wang, D. Surge, and D. K. Kersting. 2011. Study of *Pinna nobilis* growth from inner record: How biased are posterior adductor muscle scars estimates? Journal of Experimental Marine Biology and Ecology 407(2):337-344.

Garcia, N., A. Prieto, R. Alzola, and C. Lodeiros. 2003. Growth and size distribution of *Donax denticulatus* (Mollusca:Donacidae) in Playa Brava, Peninsula de Araya, Sucre State, Venezuela. Revista Cientifica 13:464-470.

Gardner, J. P. A., and M. L. H. Thomas. 1987. Growth, mortality and production of organic matter by a rocky intertidal population of *Mytilus edulis* in the Quoddy Region of the Bay of Fundy. Marine Ecology Progress Series 39:31-36.

Gaspar, M. B., R. Ferreira, and C. C. Monteiro. 1999. Growth and reproductive cycle of *Donas trunculus* L., (Molusca:Bivalvia) off Faro, southern Portugal. Fisheries Research 41:309-316.

Gaspar, M. B., A. M. Pereira, P. Vasconcelos, and C. C. Monteiro. 2004. Age and growth of *Chamelea gallina* from the Algarve Coast (Southern Portugal): Influence of seawater temperature and gametogenic cycle on growth rate. Journal of Molluscan Studies 70:371-377.

Genelt-Yanovskiy, E., A. Poloskin, A. Granovitch, S. Nazarova, and P. Strelkov. 2010. Population structure and growth rates at biogeographic extremes: a case study of the common cockle, *Cerastoderma edule* (L.) in the Barents Sea. Marine Pollution Bulletin 61(4-6):247-53.

George, E. L., and N. B. Nair. 1974. The growth rates of the estuarine mollusc *Musculista arcuatula* Yamamoto and Habe (Bivalvia:Mytilidae). Hydrobiologia 45(2):239-248.

Gerasimova, A. V., and N. V. Maximovich. 2013. Age–size structure of common bivalve mollusc populations in the White Sea: the causes of instability. Hydrobiologia 706(1):119-137.

Gerasimova, A. V., N. V. Maximovich, and N. A. Filippova. 2015. Cohort life tables for a population of the soft-shell clam, *Mya arenaria* L., in the White Sea. Helgoland Marine Research 69(2):147-158.

Ghent, A. W., R. Singer, and L. Johnson-Singer. 1978. Depth distributions determined with SCUBA, and associated studies of the freshwater unionid clams *Elliptio complanata* and *Anodonta grandis* in Lake Bernard, Ontario. Canadian Journal of Zoology 56:1654-1663.

Gibbs, P. E. 1984. The population cycle of the bivalve *Abra tenuis* and its mode of reproductions. Journal of the Marine Biological Association of the United Kingdom 64:791-800.

Gibson, F. 1956. Escallops (*Pecten maximus* L.) in Irish waters. The Scientific Proceedings of the Royal Dublin Society 27:2553-270.

Gil, G. M., and J. W. Thome. 2000. Estudo do crescimento em comprimento de *Donax hanleyanus* Philippi, 1847 (Mollusca, Bivalvia, Donacidae). Biociencias 8(2):163-175.

Gilbert, M. A. 1973. Growth rate, longevity and maximum size of *Macoma balthica* (L.). The Biological Bulletin 145:119-126.

Gillilan, W. 1964. Pismo clam survey. Outdoor California 25(2):10-11.

Goong, S. A., and K. K. Chew. 2001. Growth of butter clams, *Saxidomus giganteus* Deshayes, on selected beaches in the state of Washington. Journal of Shellfish Research 20(1):143-147.

Gosselin, M., C. E. Lazareth, and L. Ortlieb. 2013. Sclerochronological studies in the Humboldt Current system, a highly variable ecosystem. Journal of Shellfish Research 32(3):867-882.

Grave, B. H. 1928. Natural history of shipworm, *Teredo navalis*, at Woods Hole, Massachusetts. Biological Bulletin 55(4):260-282.

Grave, B. H. 1933. Rate of growth, age at sexual maturity, and duration of life of certain sessile organisms at Woods Hole, Massachusetts. Biological Bulletin 65(3):375-386.

Green, J. 1957. The growth of *Scrobicularia plana* (Da Costa) in the Gwendraeth estuary. Journal of the Marine Biological Association of the United Kingdom 36:41-47.

Green, R. H. 1973. Growth and mortality in an Arctic intertidal population of *Macoma balthica* (Pelecypoda, Tellinidae). Journal of the Fisheries Research Board of Canada 30:1345-1348.

Green, R. H., and K. D. Hobson. 1970. Spatial and temporal structure in a temperate intertidal community, with special emphasis on *Gemma gemma* (Pelecypoda: Mollusca). Ecology 51(6):999-1011.

Gribben, P. E., and R. G. Creese. 2005. Age, growth, and mortality of the New Zealand geoduck clam, *Panopea zelandica* (Bivalvia: Hiatellidae) in two North Island populations. Bulletin of Marine Science 77(1):119-135.

Grier, N. M. 1922. Observation on the rate of growth of shell of lake dewelling fresh water mussels. American Midland Naturalist 8(6):129-148.

Griffiths, C. L., and J. A. King. 1979. Energy expended on growth and gonad output in the ribbed mussel *Aulacomya ater*. Marine Biology 53:217-222.

Griffiths, R. J. 1981. Population dynamics and growth of the bivalve *Choromytilus meridionalis* (Kr.) at different tidal levels. Estuarine, Coastal and Shelf Science 12:101-118.

Grizzle, R. E., and R. A. Lutz. 1988. Descriptions of macroscopic banding patterns in sectioned polished shells of *Mercenaria mercenaria* from southern New Jersey. Journal of Shellfish Research 7(3):367-370.

Gruffydd, L. D. 1974. An estimate of natural mortality in an unfished population of the scallop *Pecten maximus* (L.). Journal du Conseil Permanent Internatinal pour l’Exploration de la Mer 35(2):209-210.

Guerreiro, J. 1998. Growth and production of the bivalve *Scrobicularia plana* in two southern European estuaries. Vie Milieu 48(2):121-131.

Guillou, J., and P. G. Sauriau. 1985. Some observations on the biology and the ecology of a *Venus striatual* population in the Bay of Douarnenez, Brittany. Journal of the Marine Biological Association of the United Kingdom 65:889-900.

Gutiérrez, N. L., and O. Defeo. 2005. Spatial patterns in population dynamics of the scallop *Psychrochlamys patagonica* at the northern edge of its range. Journal of Shellfish Research 24(4):877-882.

Gutsell, J. 1930. Natural history of the bay scallop. Bulletin of the Bureau of Fisheries 46:569-632.

Gwyther, D., and P. E. McShane. 1988. Growth rate and natural mortality of the scallop *Pecten alba* Tate in Port Phillip Bay, Australia, and evidence for changes in growth rate after a 20-year period. Fisheries Research 6:347-361.

Haag, W. R., and A. L. Rypel. 2011. Growth and longevity in freshwater mussels: evolutionary and conservation implications. Biol Rev Camb Philos Soc 86(1):225-47.

Hall Jr., C. A., W. A. Dollase, and C. E. Corbato. 1974. Shell growth in *Tivela stultorum* (Mawe, 1823) and *Callista chione* (Linnaeus, 1758) (Bivalvia): Annual periodicity, latitudinal differences, and diminution with age. Palaeogeography, Palaeoclimatology, Palaeoecology 15:33-61.

Hallmann, N., M. Burchell, B. R. Schöne, G. V. Irvine, and D. Maxwell. 2009. High-resolution sclerochronological analysis of the bivalve mollusk *Saxidomus gigantea* from Alaska and British Columbia: techniques for revealing environmental archives and archaeological seasonality. Journal of Archaeological Science 36(10):2353-2364.

Hallmann, N., B. R. Schöne, A. Strom, and J. Fiebig. 2008. An intractable climate archive — Sclerochronological and shell oxygen isotope analyses of the Pacific geoduck, Panopea abrupta (bivalve mollusk) from Protection Island (Washington State, USA). Palaeogeography, Palaeoclimatology, Palaeoecology 269(1-2):115-126.

Hamner, W. N., and M. S. Jones. 1976. Distribution, burrowing, and growth rates of the clam *Tridacna crocea* on interior reef flats. Oecologia 24(3):207-227.

Hanekom, N. 1986. Growth and somatic production estimates of *Dosinia hepatica* (Lamark) (Mollusca: Bivalvia) in the Swartkops estuary, South Africa. S.-Afr. Tydskr. Dierk. 21(4):325-330.

Hanks, R. W., and D. B. Packer. 1985. A new species of *Sphenia* (Bivalvia:Myidae) from the Gulf of Maine. The Veliger 27(3):320-330.

Hanlon, S. D., and J. F. Levine. 2004. Notes on the life history and demographics of the savannah lilliput (*Toxolasma pullus*) (Bivalvia: Unionidae) in University Lake, NC. Southeastern Naturalist 3(2):289-296.

Hanson, J. M., W. C. Mackay, and E. E. Prepas. 1988. The effects of water depth and density on the growth of a unionid clam. Freshwater Biology 19:345-355.

Harding, J. M. 2007. Northern Quahog (=Hard Clam) *Mercenaria mercenaria* age at length telationships and growth patterns in the York River, Virginia 1954 to 1970. Journal of Shellfish Research 26(1):101-107.

Harding, J. M., and R. Mann. 2006. Age and growth of wild Suminoe (*Crassostrea ariakensis*, Fugita 1913) and Pacific (*C. gigas,* Thunberg 1793) oysters from Laizhou Bay, China. Journal of Shellfish Research 25(1):73-82.

Harding, J. M., R. Mann, and M. J. Southworth. 2008. Shell length-at-age relationships in James River, Virginia, oysters (*Crassostrea virginica*) collected four centuries apart. Journal of Shellfish Research 27(5):1109-1115.

Harding, J. M., R. Mann, M. J. Southworth, and J. A. Wesson. 2010. Management of the Piankatank River, Virginia, in support of oyster (*Crassostrea virginica*,Gmelin 1791) fishery repletion. Journal of Shellfish Research 29(4):867-888.

Harrington, R. J. 1987. Skeletal growth histories of *Protothaca staminea* (Conrad) and *Protothaca grata* (Say) throughout their geographic ranges, Northeastern Pacific. The Veliger 30(2):148-158.

Hart, A. M., and L. M. Joll. 2006. Growth, mortality, recruitment and sex-ratio in wild stocks of silver-lipped pearl oyster *Pinctada maxima* (Jameson) (Mollusca: Pteriidae), in Western Australia. Journal of Shellfish Research 25(1):201-210.

Harvey, M., and B. Vincent. 1990. Density, size distribution, energy allocation and seasonal variations in shell and soft tissue growth at two tidal levels of a *Macoma balthica* (L.) population. Journal of Experimental Marine Biology and Ecology 142:151-168.

Harvey, M., B. Vincent, and Y. Gratton. 1993. Spatial variability of length-specific production in shell, somatic tissue and sexual products of *Macoma balthica* in the Lower St. Lawrence Estuary. Marine Biology 115:421-433.

Hastie, L. C. 2006. Determination of mortality in exploited freshwater pearl mussel (Margaritifera margaritifera) populations. Fisheries Research 80(2-3):305-311.

Haukioja, E., and T. Hakala. 1978. Measuring growth from shell rings in populations of *Anodonta piscinalis* (Pelecypoda, Unionidae). Annales Zoologici Fennici 15(1):60-65.

Hawes, I., T. Lasiak, M. L. Smith, and C. Oengpepa. 2011. The status of silverlip pearl oyster *Pinctada maxima* (Jameson) (Mollusca, Pteridae) in the Solomon Islands after a 15-year export ban. Journal of Shellfish Research 30(2):255-260.

Hayes, P. F., and R. W. Menzel. 1981. The reproductive cycle of early setting *Crassostrea virginica* (Gmelin) in the Northern Gulf of Mexico, and its implications for population recruitment. The Biological Bulletin 160:80-88.

Heald, D. I., and N. Caputi. 1981. Some aspects of growth, recruitment and reproduction in the southern saucer scallop, *Amusium balloti* (Bernardi, 1861) in Shark Bay, Western Australia. Fisheries Research Bulletin Western Australia 25.

Heilmayer, O., T. Brey, M. Chiantore, R. Cattaneo-Vietti, and W. E. Arntz. 2003. Age and productivity of the Antarctic scallop, *Adamussium colbecki*, in Terra Nova Bay (Ross Sea, Antarctica). Journal of Experimental Marine Biology and Ecology 288(2):239-256.

Heilmayer, O., T. Brey, D. Storch, A. Mackensen, and W. E. Arntz. 2004. Population dynamics and metabolism of *Aequipecten opercularis* (L.) from the western English Channel (Roscoff, France). Journal of Sea Research 52(1):33-44.

Helama, S., and B. C. Hood. 2011. Stone Age midden deposition assessed by bivalve sclerochronology and radiocarbon wiggle-matching of Arctica islandica shell increments. Journal of Archaeological Science 38(2):452-460.

Henderson, S. M., and C. A. Richardson. 1994. A comparison of the age, growth rate and burrowing behaviour of the razor clams, *Ensis siliqua* and *E. ensis*. Journal of the Marine Biological Association of the United Kingdom 74:939-954.

Hendriks, I. E., L. Basso, S. Deudero, M. Cabanellas-Reboredo, and E. Álvarez. 2012. Relative growth rates of the noble pen shell *Pinna nobilis* throughout ontogeny around the Balearic Islands (Western Mediterranean, Spain). Journal of Shellfish Research 31(3):749-756.

Henry, K. M., and R. M. Cerrato. 2007. The annual macroscopic growth pattern of the northern quahog [=hard clam, *Mercenaria mercenaria* (L.)], in Narragansett Bay, Rhode Island. Journal of Shellfish Research 26(4):985-993.

Henry, K. M., and S. W. Nixon. 2008. A half century assessment of hard clam, *Mercenaria mercenaria*, growth in Narragansett Bay, Rhode Island. Estuaries and Coasts 31(4):755-766.

Hernández-Otero, A., M. B. Gaspar, G. Macho, and E. Vázquez. 2014. Age and growth of the sword razor clam *Ensis arcuatus* in the Ría de Pontevedra (NW Spain): Influence of environmental parameters. Journal of Sea Research 85:59-72.

Herrington, H. B. 1948. Further proof that *Sphaerium occidentale* does not attain full growth in one year. The Canadian Field Naturalist 62:74-75.

Herrmann, M., J. E. F. Alfaya, M. L. Lepore, P. E. Penchaszadeh, and W. E. Arntz. 2011. Population structure, growth and production of the yellow clam *Mesodesma mactroides* (Bivalvia: Mesodesmatidae) from a high-energy, temperate beach in northern Argentina. Helgoland Marine Research 65(3):285-297.

Herrmann, M., M. L. Lepore, J. Laudien, W. E. Arntz, and P. E. Penchaszadeh. 2009. Growth estimations of the Argentinean wedge clam *Donax hanleyanus:* A comparison between length-frequency distribution and size-increment analysis. Journal of Experimental Marine Biology and Ecology 379(1-2):8-15.

Hibbert, C. J. 1976. Biomass and production of a bivavle community on an intertidal mud-flat. Journal of Experimental Marine Biology and Ecology 25:249-261.

Hibbert, C. J. 1977. Growth and survivorship in a tidal-flat population of the bivalve *Mercenaria mercenaria* from Southampton water. Marine Biology 44:71-76.

Hidalgo-De-La-Toba, J. A., S. S. González-peláez, E. Morales-Bojórquez, J. J. Bautista-Romero, and D. B. Lluch-Cota. 2015. Geoduck *Panopea generosa* growth at its southern distribution limit in North America using a multimodel inference approach. Journal of Shellfish Research 34(1):91-99.

Higgs, N. D., A. J. Reed, R. Hooke, D. J. Honey, O. Heilmayer, and S. Thatje. 2009. Growth and reproduction in the Antarctic brooding bivalve *Adacnarca nitens* (Philobryidae) from the Ross Sea. Marine Biology 156(5):1073-1081.

Hily, C., and H. Le Bris. 1984. Dynamics of an *Abra alba* population (bivalve-scrobiculariidae) in the Bay of Brest. Estuarine, Coastal and Shelf Science 19:463-475.

Hoffmann, A., A. Bradbury, and C. L. Goodwin. 2000. Modeling geoduck, *Panopea abrupta* (Conrad, 1849) population dynamics. 1. Growth. Journal of Shellfish Research 19(1):57-62.

Hopkins, H. S. 1930. Age differences and the respiration in muscle tissues of mollusks. The Journal of Experimental Zoology 56(2):209-239.

Hornbach, D. J., and T. E. Wissing. 1982. Life-history characteristics of a stream population of the freshwater clam *Sphaerium striatinum* Lamarck (Bivalvia: Pisidiidae). Canadian Journal of Zoology 60:249-260.

Hove, M. C., and R. J. Neves. 1994. Life history of the endangered James spinymussel *Pleurobema collina* (Conrad, 1837) (Mollusca: Unionidae). American Malacological Bulletin 11(1):29-39.

Howarth, L. M., C. M. Roberts, J. P. Hawkins, D. J. Steadman, and B. D. Beukers-Stewart. 2015. Effects of ecosystem protection on scallop populations within a community-led temperate marine reserve. Marine Biology 162(4):823-840.

Hughes, S. E., and N. Bourne. 1981. Stock assessment and life history of a new disovered Alaska surf clam (*Spisula polynyma*) resource in the southeastern Bering Sea. Canadian Journal of Fisheries and Aquatic Sciences 38(10):1173-1181.

Humphreys, J., R. W. G. Caldow, S. McGrorty, A. D. West, and A. C. Jensen. 2007. Population dynamics of naturalised Manila clams *Ruditapes philippinarum* in British coastal waters. Marine Biology 151(6):2255-2270.

Hutchings, J. A., and R. L. Haedrich. 1984. Growth and population structure in two species of bivalves (Nuculanidae) from the deep sea. Marine Ecology Progress Series 17:135-142.

Iglesias, J. I. P., and E. Navarro. 1991. Energetics of growth and reproduction in cockles (*Cerastoderma edule*): seasonal and age-dependent variations. Marine Biology 111:359-368.

Ignell, S., and E. Haynes. 2000. Geographic patterns in growth of the giant Pacific sea scallop, *Patinopecten caurinus*. Fishery Bulletin 98(4):849-853.

Isla, M. S., and S. Gordillo. 1996. Age and growth of the clam *Tawera gayi* (Hupe) from Golondrina Bay (Beagle Channel, Tierra del Fuego). Naturalia patagonica. Ciencias biologicas 4:33-40.

Jagadis, I., and S. Rajagopal. 2007. Age and growth of the venus clam *Gafrarium tumidum* (Roding) from south-east coast of India. Indian Journal of Fisheries 54(4):351-356.

Jensen, A. C., J. Humphreys, R. W. G. Caldow, C. Grisley, and P. E. J. Dyrynda. 2004. Naturalization of the Manila clam (*Tapes philippinarum*), an alien species, and establishment of a clam fishery within Poole Harbour, Dorset. Journal of the Marine Biological Association of the United Kingdom 84:1069-1073.

Jensen, J. N. 1990. Increased abundance and growth of the suspension-feeding bivalve *Corbula gibba* in a shallow part of the eutrophic Limfjord, Denmark. Netherlands Journal of Sea Research 27(1):101-108.

Jensen, K. T. 1992. Dynamics and growth of the cockle, *Cerastoderma edule*, on an intertidal mud-flat in the Danish Wadden Sea: Effects of submersion time and density. Netherlands Journal of Sea Research 28(4):335-345.

Jimenez, M., A. Prieto, L. Ruiz, B. Marin, and T. Allen. 2004. Distribucion de tallas, crecimiento y mortalidad de *Anadara notabilis* (Bivalvia:Arcidae) en la Bahia de Mochima Estado Sucre, Venezuela. Boletín del Instituto Oceanográfico de Venezuela 43:41-47.

Johannessen, O. 1973. Length and weight relationships and the potential production of the bivalve *Venerupis pullastra* (Montagu) on a sheltered beach in Western Norway. Sarsia 53:41-48.

Jonasson, J. P., G. Thorarinsdottir, H. Eiriksson, J. Solmundsson, and G. Marteinsdottir. 2007. Collapse of the fishery for Iceland scallop (*Chlamys islandica*) in Breidafjordur, West Iceland. ICES Journal of Marine Science 64(2):298-308.

Jones, D. S. 1980. Annual cycle of shell growth increment formation in two continental shelf bivalves and its paleoecologic significance. Paleobiology 6(3):331-340.

Jones, D. S. 1988. Sclerochronlogy and the size versus age problem. Pp. 93-108. *In* M. L. McKinney, ed. Heterochrony in evolution. Plenum Publishing Corporation.

Jones, D. S., M. A. Arthur, and D. J. Allard. 1989. Sclerochronlogical records of temperature and growth from shells of *Mercenaria mercenaria* from Narragansett Bay, Rhode Island. Marine Biology 102:225-234.

Jones, D. S., and S. J. Gould. 1999. Direct measurement of age in fossil *Gryphaea*: the solution to a classic problem in heterochrony. Paleobiology 25(2):158-187.

Jones, D. S., I. R. Quitmyer, and C. F. T. Andrus. 2004a. Seasonal shell growth and longevity in *Donax variabilis* from Northeastern Florida: Evidence from oxygen isotopes. Journal of Shellfish Research 23(3):707-714.

Jones, D. S., I. R. Quitmyer, W. S. Arnold, and D. C. Marelli. 1990. Annual shell banding, age and growth rate of hard clams (*Mercenaria* spp.) from Florida. Journal of Shellfish Research 9(1):215-225.

Jones, D. S., I. Thompson, and W. Ambrose. 1978. Age and growth rate determinations for the Atlantic surf clam *Spisula solidissima* (Bivalvia: Mactracea), based on internal growth lines in shell cross-sections. Marine Biology 47:63-70.

Jones, D. S., D. F. Williams, and C. S. Romanek. 1986. Life history of symbiont-bearing giant clams from stable isotope profiles Science 231(4733):46-48.

Jones, J. W., R. J. Neves, S. A. Ahlstedt, and R. A. Mair. 2004b. Life history and propagation of the endangered dromedary pearlymussel (*Dromus dromas*) (Bivalvia:Unionidae). Journal of the North American Benthological Society 23(3):515-525.

Josefson, A. B. 1982. Regulation of population size, growth, and production of a deposit-feeding bivalve: A long-term field study of three deep-water populations off the Swedish west coast. Journal of Experimental Marine Biology and Ecology 59:125-150.

Joseph, M. M., and P. S. Joseph. 1985. Age and growth of the oyster *Crassostrea madrasensis* (Preston) in Mulki Estuary, west coast of India. Indian Journal of Marine Sciences 14:184-186.

Kafanov, A. I. 1985. Growth and production of the bivalve mollusk *Macoma balthica* in Nabil' Lagoon (Northeastern Sakhalin). Biologiya Morya-Marine Biology 6:23-31.

Kalyanasundaram, M., and R. Kasinathan. 1983. Age and growth in the estuarine clam *Katelysia opima* (Gmelin) from the Vellar Estuary. Indian Journal of Marine Sciences 12:247-248.

Kamermans, P., H. W. Van der Veer, J. Witte, and E. Adriaans. 1999. Morphological differences in *Macoma balthica* (Bivalvia, Tellinacea) from a Dutch and three southeastern United States estuaries. Journal of Sea Research 41:213-224.

Kang, Y. J., and C. K. Kim. 1983. Studies on the structure and production processes of biotic communities in the coastal shallow waters of Korea. Bulletin of the Korean Fisheries Society 16(2):82-87.

Kato, Y., and I. Hamai. 1975. Growth and shell formation of the surf clam, *Spisula sachalinensis* (Schrenck). Bulletin of the Faculty of Fisheries Hokkaido University 25(4):291-303.

Katsanekvakis, S. 2006. Population ecology of the endangered fan mussel *Pinna nobilis* in a marine lake. Endangered Species Research 1:51-59.

Katsanevakis, S. 2009. Population dynamics of the endangered fan mussel *Pinna nobilis* in a marine lake: a metapopulation matrix modeling approach. Marine Biology 156(8):1715-1732.

Kautsky, N. 1982. Growth and size structure in a Baltic *Mytilus edulis* population. Marine Biology 68:117-133.

Keller, N., D. Del Piero, and A. Longinelli. 2002. Isotopic composition, growth rates and biological behaviour of *Chamelea gallina* and *Callista chione* from the Bay of Trieste (Italy). Marine Biology 140(1):9-15.

Kennish, M., and R. Loveland. 1980. Growth models of the northern quahog *Mercenaria mercenaria* (Linne). Proceedings of the National Shellfisheries Association 70:230-239.

Kevrekidis, T., and A. Koukouras. 1992. Population dynamics, growth and productivity of *Abra ovata* (Mollusca, Bivalvia) in the Evros Delta (North Aegean Sea). Internationale Revue der gesamten Hydrobiologie und Hydrographie 77(2):291-301.

Khim, B.-K. 2001. Stable isotope profiles of *Serripes groenlandicus* shells. II. Occurrance in Alaskan coastal water in South St. Lawrence Island, Northern Bering Sea. Journal of Shellfish Research 20(1):275-281.

Khim, B.-K., K. S. Woo, and J.-G. Je. 2000. Stable isotope profiles of bivalve shells: seasonal temperature variations, latitudinal temperature gradients and biological carbon cycling along the east coast of Korea. Continental Shelf Research 20:843-861.

Kilada, R. W., S. E. Campana, and D. Roddick. 2007a. Validated age, growth, and mortality estimates of the ocean quahog (*Arctica islandica*) in the western Atlantic. ICES Journal of Marine Science 64(1):31-38.

Kilada, R. W., S. E. Campana, and D. Roddick. 2009. Growth and sexual maturity of the northern propellerclam (*Cyrtodaria siliqua*) in Eastern Canada, with bomb radiocarbon age validation. Marine Biology 156(5):1029-1037.

Kilada, R. W., D. Roddick, and K. Mombourquette. 2007b. Age determination, validation, growth and minimum size of sexual maturity of the Greenland smoothcockle (*Serripes groenlandicus,* Bruguiere, 1789) in eastern Canada. Journal of Shellfish Research 26(2):443-450.

Kim, B. K. 1985. Studies on the spawning and growth of Hen Clam, *Mactra sulcataria* (Reeve). Bulletin of Fisheries Research Devision Agency 34:157-164.

Kim, J.-H., J.-S. Kim, Y.-H. Kim, E.-Y. Chung, and D.-K. Ryu. 2003. Age and growth of the jedo venus clam, *Protothaca jedoensis* on the west coast of Korea. Korean Journal of Malacology 19(2):125-132.

Kitamura, A., K. Tada, S. Sakai, N. Yamamoto, T. Ubukata, T. Miyaji, and T. Kase. 2011. Age and growth of *Glossocardia obesa*, a "large" bivalve in a submarine cave within a coral reef, as revealed by oxygen isotope analysis. The Veliger 51(2):59-65.

Kraeuter, J. N., G. Flimlin, M. J. Kennish, R. Macaluso, and J. Viggiano. 2009. Sustainability of northern quahogs (= hard clams) *Mercenaria mercenaria*, Linnaeus in Raritan Bay, New Jersey: Assessment of size specific growth and mortality. Journal of Shellfish Research 28(2):273-287.

Kraeuter, J. N., S. Ford, and M. Cummings. 2007. Oyster growth analysis: A comparison of methods. Journal of Shellfish Research 26(2):479-491.

Krantz, D. E., D. S. Jones, and D. F. Williams. 1984. Growth rates of the sea scallop, *Placopecten magellanicus*, determined from the 18O/16O record in shell calcite. The Biological Bulletin 167:186-199.

Kraus, M. G., B. F. Beal, S. R. Chapman, and L. McMartin. 1992. A comparison of growth rates in *Arctica islandica* (Linnaeus, 1767) between field and laboratory populations. Journal of Shellfish Research 11(2):289-294.

Kube, J. 1996. Spatial and temporal variations in the population structure of the soft-shell clam *Mya arenaria* in the Pommeranian Bay (Southern Baltic Sea). Journal of Sea Research 35(4):335-344.

Kunitzer, A. 1989. Factors affecting the population dynamics of *Amphiura filiformis* (Echinodermata:Ophiuroidea) and *Mysella bidentata* (Bivalvia:Galeommatacea). Pp. 395-406. *In* J. S. Ryland, and P. A. Tyler, eds. Reproduction, genetics and distribution of marine organisms

Lammens, J. J. 1967. Growth and reproduction in a tidal flat population of *Macoma balthica* (L.). Netherlands Journal of Sea Research 3(3):315-382.

Landry, T., T. W. Sephton, and D. A. Jones. 1993. Growth and mortality of northern quahog, (Linnaeus 1758) *Mercenaria mercenaria* in Prince Edward Island. Journal of Shellfish Research 12(2):321-327.

Lastra, M., J. Palacio, and J. Mora. 1993. Population dynamics and secondary production of *Abra alba* (Wood) (Bivalvia) in the Santanger Bay, northern Spain. Sarsia 78(1):35-42.

Laudien, J., T. Brey, and W. E. Arntz. 2003. Population structure, growth and production of the surf clam *Donax serra* (Bivalvia, Donacidae) on two Namibian sandy beaches. Estuarine, Coastal and Shelf Science 58:105-115.

Lavaud, R., J. Thébault, A. Lorrain, M. van der Geest, and L. Chauvaud. 2013. *Senilia senilis* (Linnaeus, 1758), a biogenic archive of environmental conditions on the Banc d'Arguin (Mauritania). Journal of Sea Research 76:61-72.

Lavoie, R., J.-L. Tremblay, and G. Filteau. 1968. Age et croissance de Macoma balthica L. a cacouna-est dans L'estuaire du St-Laurent. Le Naturaliste canadien 95:887-895.

Laxmilatha, P. 2013. Population dynamics of the edible clam *Meretrix casta* (Chemnitz) (International Union for Conservation of Nature status: Vulnerable) from two estuaries of North Kerala, south west coast of India. International Journal of Fisheries and Aquaculture 5(10):253-261.

LeBlanc, K., M. Ouellette, G. Chouinard, and T. Landry. 2005. Commercial harvest and population structure of a northern quahog, (*Mercenaria mercenaria* Linnaeus 1758) population in St. Mary's Bay, Nova Scotia, Canada. Journal of Shellfish Research 24(1):47-54.

Lee, A. M., A. J. Williams, and P. C. Southgate. 2007. Modelling and comparison of growth of the silver-lip pearl oyster *Pinctada maxima* (Jameson) (Mollusca: Pteriidae) cultured in West Papua, Indonesia. Marine and Freshwater Research 59:22-31.

Lee, S. Y. 1985. The population dynamics of the green mussel, *Perna viridis* (L.) in Victoria Harbour, Hong Kong - Dominance in a polluted environment. Asian Marine Biology 2:107-118.

Lefort, Y. 1994. Growth and mortality of the tropical scallops: *Annachlamys flabellata* (Bernardi), *Comptopallium radula* (Linne) and *Mimachlamys gloriosa* (Reeve) in Southwest Lagoon of New Caledonia. Journal of Shellfish Research 13(2):539-546.

LeGallo, J.-M., and J.-C. Moreteau. 1988. Croissance et productivite d'une population du *Sphaerium corneum* (L.) (Bivalvia : Pisidiidae). Canadian Journal of Zoology 66:439-445.

Leontarakis, P. K., and C. A. Richardson. 2005. Growth of the smooth clam, *Callista chione* (Linnaeus, 1758) (Bivalvia: Veneridae) from the Thracian Sea, northeastern Mediterranean. Journal of Molluscan Studies 71(2):189-192.

Lewandowski, K., and A. Stancykowska. 1975. The occurrance and role of bivalves of the family Unionidae in Mikolajskie Lake. Ekologia Polska 23(2):317-334.

Lewis, C. V. W., J. R. Weinberg, and C. S. Davis. 2001. Population structure and recruitment of the bivalve *Arctica islandica* (Linnaeus, 1767) on Georges Bank from 1980-1999. Journal of Shellfish Research 20(3):1135-1144.

Lewis, J. B., S. Saleh, H. M. Reiswig, and C. M. Lalli. 1982. Growth, production and biomass of the burrowing protobranch mollus *Yoidia limatula* in the Bideford River, Prince Edward Island, Canada. Marine Biology 70:173-179.

Lim, H. S., and L. Chang-Il. 2004. Growth pattern of soft clam (*Mya arenaria oonogai*) (Mollusca:Bivalvia) from a mud flat on the southwest coast of Korea. Journal of Korean Fisheries Society 37(2):105-115.

Lochead, J., Z. Zhang, and C. Hand. 2012. The impact of increased accuracy in geoduck (*Panopea generosa*) age determination on recommended exploitation rates. Journal of Shellfish Research 31(4):969-976.

Lodeiros, C. J., J. J. Rengel, and J. H. Himmelman. 1999. Growth of *Pteria colymbus* (Roding, 1798) in suspended culture in Golfo de Cariaco, Venezuela. Journal of Shellfish Research 18(1):155-158.

Loesch, J. G., and D. S. Haven. 1974. Estimated growth functions and size-age relationships of the hard clam, *Mercenaria mercenaria*, in the York River Virginia. The Veliger 16(1):76-81.

Lomovasky, B. J., A. Baldoni, P. Ribeiro, G. Alvarez, M. Lasta, S. Campodónico, and O. Iribarne. 2011. Exploring the causes of differences in growth rate of the Patagonian scallop *Zygochlamys patagonica* along its commercial bed distribution in the SW Atlantic. Journal of Sea Research 66(2):162-171.

Lomovasky, B. J., T. Brey, A. N. A. Baldoni, M. Lasta, A. Mackensen, S. CampodÓNico, and O. Iribarne. 2007. Annual shell growth increment formation in the deep water Patagonian scallop *Zagochlamys patagonica*. Journal of Shellfish Research 26(4):1055-1063.

Lomovasky, B. J., T. Brey, and E. Morriconi. 2005. Population dynamics of the venerid bivalve Tawera gayi (Hupe, 1854) in the Ushuaia Bay, Beagle Channel. Journal of Applied Ichthyology 21:64-69.

Lomovasky, B. J., T. Brey, E. Morriconi, and J. Calvo. 2002. Growth and production of the venerid bivalve *Eurhomalea exalbida* in the Beagle Channel, Tierra del Fuego. Journal of Sea Research 48:209-216.

Lomovasky, B. J., M. Lasta, M. Valiñas, M. Bruschetti, P. Ribeiro, S. Campodónico, and O. Iribarne. 2008. Differences in shell morphology and internal growth pattern of the Patagonian scallop *Zygochlamys patagonica* in the four main beds across their SW Atlantic distribution range. Fisheries Research 89(3):266-275.

Lopez-Jamar, E., G. Gonzalez, and J. Majuto. 1987. Ecology, gorwth, and production of *Thyasira flexuosa* (Bivalvia, Lucinacea) from Ria de la Corun, northwest Spain. Ophelia 27(2):111-126.

Lucero, C., J. Cantera, and R. Neira. 2012. Pesquería y crecimiento de la piangua (Arcoida: Arcidae) *Anadara tuberculosa* en la Bahía de Málaga del Pacífico colombiano, 2005-2007. International Journal of Tropical Biology and Conservation 60(1):203-217.

Luckens, P. A. 1990. Distribution, size-frequency, and growth-ring analyses of *Tawera mawsoni* (Bivalvia: Veneridae) at Macquarie Island. New Zealand Journal of Marine and Freshwater Research 24(1):59-73.

Luckens, P. A. 1991. Distribution, growth rate, and death from octopod and gastropod predation of *Tawera bollonsi* (Bivalvia: Veneridae) at the Auckland Islands. New Zealand Journal of Marine and Freshwater Research 25(3):255-268.

Lutz, R. A., and M. Castagna. 1980. Age composition and growth rate of a mussel (*Geukensia demissa*) population in a Virginia salt marsh. Journal of Molluscan Studies 46:106-115.

MacDonald, B. A., and N. F. Bourne. 1987. Growth, reproductive output, and energy partitioning in weathervane scallops, *Patinopecten caurinus*, from British Columbia. Canadian Journal of Fisheries and Aquatic Sciences 44:152-160.

MacDonald, B. A., and M. L. H. Thomas. 1980. Age determination of the soft-shell clam *Mya arenaria* using shell internal growth lines. Marine Biology 58:105-109.

MacDonald, B. A., and R. J. Thompson. 1985. Influence of temperature and food availability on the ecological energetics of the giant scallop *Placopecten magellanicus*. I. Growth rates of shell and somatic tissue. Marine Ecology Progress Series 25:279-294.

MacDonald, B. A., and R. J. Thompson. 1986. Production, dynamics and energy paritioning in two populations of the giant scallop *Placopecten magellanicus* (Gmelin)*. Journal of Experimental Marine Biology and Ecology 101:285-299.

MacDonald, B. A., and R. J. Thompson. 1988. Intraspecific variation in growth and reproduction in latitudinally differentiated populations of the giant scallop *Placopecten magellanicus* (Gmelin). The Biological Bulletin 175:361-371.

Mackie, G. L. 1979. Growth dynamics in natural populations of Sphaeriidae clams (*Sphaerium, Musculium, Pisidium*). Canadian Journal of Zoology 57(2):441-456.

Mackie, G. L., and L. A. Flippance. 1983. Life history variations in two populations of *Sphaerium rhomboideum* (Bivalvia: Pisidiidae). Canadian Journal of Zoology 61:860-867.

Mancera, E., and J. Mendo. 1996. Population dynamics of the oyster *Crassostrea rhizophorae* from the Cienaga Grande de Santa Marta, Colombia. Fisheries Research 26:139-148.

Mane, U. H. 1974. Growth and breeding habits of the clam, *Katelysia opima* in the Kalbadevi Estuary at Ratnagiri. Indian Journal of Fisheries 21(2):386-398.

Mane, U. H., and R. Nagabhushanam. 1979. Studies on the growth and density of the clam *Paphia laterisulca* at Kalbadevi Estuary, Ratnagiri, on the West Coast of India. Malacologia 18:297-313.

Marali, S., and B. R. Schöne. 2015. Oceanographic control on shell growth of Arctica islandica (Bivalvia) in surface waters of Northeast Iceland — Implications for paleoclimate reconstructions. Palaeogeography, Palaeoclimatology, Palaeoecology 420:138-149.

Marcano, J., A. Prieto, A. Larez, and H. Salazar. 2003. Crecimiento de *Donax denticulatus* (Linne 1758) (Bivalvia:Donacidae) en la ensenada La Guardia, Isla de Margarita, Venezuela. Zootecnia Tropical 21(3):237-260.

Margosian, A., F. C. Tan, D. Cai, and K. H. Mann. 1987. Seawater temperature records from stable isotopic profiles in the shell of *Modiolus modiolus*. Estuarine, Coastal and Shelf Science 25:81-89.

Marsh, P. C. 1985. Secondary production of introduced Asiatic clam, *Corbicula fluminea*, in a central Arizona canal. Hydrobiologia 124(2):103-110.

Maslin, J.-L., and E. Pattee. 1989. The production of *Corbula trigona* (Bivalvia) in relation to its demographic strategies in a West African lagoon. Oikos 55:194-204.

Maslin, J., and Y. Bouvet. 1986. Population dynamics of *Corbula trigona* (Mollusca) in Lake Aheme, a west African Lagoon in Benin. Oikos 46(3):292-302.

Mason, J. 1957. The age and growth of the scallop, *Pecten maximus* (L.), in Manx waters. Journal of the Marine Biological Association of the United Kingdom 36:473-492.

Mason, J. 1983. Scallop and queen fisheries in the British Isles.

Mattei, N., and M. Pellizato. 1996. A population study on three stocks of a commercial Adriatic pectinid (*Pecten jacobaeus*). Fisheries Research 26:49-65.

Matteson, M. 1948. Life history of *Elliptio complanatus* (Dilwyn, 1817). American Midland Naturalist 40(3):690-723.

Matveeva, T. A., and N. V. Maksimovich. 1977. Peculiarities of ecology and distribution of *Hiatella arctica* (Mollusca, Bivalvia, Heterodonta) in the White Sea. Zoologicheskii zhurnal 46:199-204.

Maximovich, N. V., and A. V. Guerassimova. 2003. Life history characteristics of the clam *Mya arenaria* in the White Sea. Helgoland Marine Research 57(2):91-99.

McGrath, D., and D. O'Foighil. 1986. Population dynamics and reproduction of hermaphroditic *Lasaea rubra* (Montagu) (Bivalvia, Galeommatacea). Ophelia 25(3):209-219.

McGraw, K. A., M. Castagna, and L. L. Conquest. 2001. A study of the arkshell clams, *Noetia ponderosa* (Say 1822) and *Anadara ovalis* (Bruguiere, 1789), in the oceanside lagoons and tidal creeks of Virginia. Journal of Shellfish Research 20(1):185-195.

McGreer, E. R. 1983. Growth and reproduction of *Macoma balthica* (L.) on a mud flat in the Fraser River estuary, British Columbia. Canadian Journal of Zoology 61(4):887-894.

McLachlan, A. 1979. Growth and production of *Donax sordidus* Hanley on an open sandy beach in Algoa Bay. South African Journal of Zoology 14(2):61-66.

McLachlan, A., C. Cooper, and G. van der Horst. 1979. Growth and production of *Bullia rhodostoma* on an open sandy beach in Algoa Bay. Suid-Afrikaanse tydskrif vir Dierkunde 14:49-53.

McLachlan, A., and N. Hanekom. 1979. Aspects of the biology, ecology and seasonal fluctuations in biochemical composition of *Donax serra* in the East Cape. South African Journal of Zoology 14:183-193.

McLusky, D. S., and D. G. Allan. 1976. Aspects of the biology of *Macoma balthica* (L.) from the estuarine firth of forth. Journal of Molluscan Studies 42:31-45.

McLusky, D. S., S. A. Nair, A. Stirling, and R. Bhargava. 1975. The ecology of a central West Indian beach, with particular reference to *Donax incamatus*. Marine Biology 30:267-276.

McMillin, H. C. 1924. The life-history and growth of the razor clam.

McQuiad, C. D., and T. L. Lindsay. 2000. Effect of wave exposure on growth and mortality rates of the mussel *Perna perna:* bottom-up regulation of intertidal populations. Marine Ecology Progress Series 206:147-154.

Menesguen, A., and L. Dreves. 1987. Sea-temperature anomalies and population dynamics variations: effects on growth and density of three bivalves. Marine Ecology Progress Series 36:11-21.

Merrill, A. S., and J. A. Posgay. 1964. Estimating the natural mortality rate of the sea scallop (*Placopecten magellanicus*). International Commission for the Northwest Atlantic Fisheries Research Bulletin 1:88-106.

Merrill, A. S., J. A. Posgay, and F. E. Nichy. 1966. Annual marks on shell and ligament of sea scallop (*Placopecten magellanicus*). Fishery Bulletin 65(2):299-311.

Metaxatos, A. 2004. Population dynamics of the venerid bivalve *Callista chione* (L.) in a coastal area of the eastern Mediterranean. Journal of Sea Research 52(4):293-305.

Michaelson, D. L., and R. J. Neves. 1995. Life history and habitat of the endangered dwarf wedgemussel *Alasmidonta heterodon* (Bivalvia:Unionidae). Journal of the North American Benthological Society 14(2):324-340.

Milione, M., and P. Southgate. 2012. Growth of the winged pearl oyster,*Pteria penguin*, at dissimilar sites in northeastern Australia. Journal of Shellfish Research 31(1):13-20.

Mills, S. C., and I. M. Cote. 2003. Sex-related differences in growth and morphology of blue mussels. Journal of the Marine Biological Association of the United Kingdom 83:1053-1057.

Milne, H., and G. M. Dunnet. 1972. Standing crop, productivity and trophic relations of the fauna of the Ythan Estuary. Pp. 86-106. *In* R. S. K. Barnes, and J. Green, eds. The Estuarine Environment. Associated Scientific Publishers, Amsterdam.

Mirzaei, M. R., Z. Yasin, and A. T. Shau Hwai. 2014. Length-weight relationship, growth and mortality of *Anadara granosa* in Penang Island, Malaysia: an approach using length-frequency data sets. Journal of the Marine Biological Association of the United Kingdom 95(02):381-390.

Mistri, M., R. Rossi, and V. U. Ceccherelli. 1988. Growth and production of the ark shell *Scapharca inaequivalvis* (Bruguiere) in a lagoon of the Po River Delta. Marine Ecology 9(1):35-49.

Mohammed, S. Z., and M. H. Yassien. 2003. Population parameters of the pearl oyster *Pinctada radiata* (Leach) in Qatari waters, Arabian Gulf. Turkish Journal of Zoology 27:339-343.

Mohite, S. A., and A. S. Mohite. 2009. Age and growth of the shortneck clam, *Paphia malabarica* (Chemnitz) in estuarine regions of Ratnagiri, West coast of India. Asian Journal of Animal Science 3(2):235-240.

Moles, K. R., and J. B. Layzer. 2008. Reproductive ecology of *Actinonaias ligamentina* (Bivalvia:Unionidae) in a regulated river. Journal of the North American Benthological Society 27(1):212-222.

Monti, D., L. Frenkeil, and M. Moueza. 1991. Demography and growth of *Anomalocardia brasiliana* (Gmelin) (Bivalvia: Veneridae) in a mangrove, in Guadeloupe (French West Indies). Journal of Molluscan Studies 57:249-257.

Moore, H. B., and N. N. Lopez. 1969. The ecology of *Chione cancellata* Bulletin of Marine Science 19(1):131-148.

Moore, H. B., and N. N. Lopez. 1970. A contribution to the ecology of the Lamellibranch *Dosinia elegans*. Bulletin of Marine Science 20:980-986.

Moore, H. B., and N. N. Lopez. 1972. A contribution to the ecology of the Lamellibranch *Anodontia alba*. Bulletin of Marine Science 22(2):381-390.

Morsán, E., and N. F. Ciocco. 2004. Age and growth model for the southern geoduck, Panopea abbreviata, off Puerto Lobos (Patagonia, Argentina). Fisheries Research 69(3):343-348.

Morsan, E., P. Zaidman, M. Ocampo-Reinaldo, and N. Ciocco. 2010. Population structure, distribution and harvesting of southern geoduck, *Panopea abbreviata*, in San Matías Gulf (Patagonia, Argentina). Scientia Marina 74(4):763-772.

Morsan, E. M., and J. M. L. Orensanz. 2004. Age structure and growth in an unusual population of purple clams, *Amiantis purpuratus* (Lamarck 1818) (Bivalvia : Veneridae), from Argentine Patagonia. Journal of Shellfish Research 23(1):73-80.

Morton, B. 1974. Some aspects of the biology, population dynamics, and functional morphology of *Musculista senhausia* Benson (Bivalvia, Mytilidae). Pacific Science 28(1):19-33.

Morton, B. 1978. The population dynamics of *Anomalocardia squamosa* Lamarck (Bivalvia:Veneracea) in Hong Kong. Journal of Molluscan Studies 44:135-144.

Morton, B. 1988. The population dynamics and reproductive cycle of *Brachidontes variabilis* (Bivalvia:Mytilidae) in a Hong Kong Mangrove. Malacological Review 21:109-117.

Morton, B. 1995. The population dynamics and reproductive cycle of *Septifer virgatus* (Bivalvia : Mytilidae) on an exposed rocky shore in Hong Kong. Journal of the Zoological Society of London 235:485-500.

Morton, B. S. 1969. Studies on the biology of *Dreissena polymorpha* Pall III. Population dynamics. Journal of Molluscan Studies 38(6):471-482.

Moura, P., M. B. Gaspar, and C. C. Monteiro. 2009. Age determination and growth rate of a *Callista chione* population from the southwestern coast of Portugal. Aquatic Biology 5:97-106.

Moura, P., P. Vasconcelos, and M. B. Gaspar. 2013. Age and growth in three populations of *Dosinia exoleta* (Bivalvia: Veneridae) from the Portuguese coast. Helgoland Marine Research 67(4):639-652.

Mukai, H. 1974. Ecological studies on distribution and production of some benthic animals in the coastal waters of Central Inland Sea of Japan. Journal of Science of Hiroshima University 1:1-82.

Munch-Petersen, S. 1973. An investigation of a population of the soft clam (*Mya arenaria* L.) in a Danish estuary. Medd Dan Fisk Havunders 7(3):47-73.

Murawski, S. A., J. W. Ropes, and F. M. Serchuk. 1982. Growth of the ocean quahog, *Arctica islandica*, in the Middle Atlantic Bight. Fishery Bulletin 80(1):21-34.

Nakaoka, M., and S. Matsui. 1994. Annual variation in the growth rate of *Yoldia notabilis* (Bivalvia: Nuculanidae) in Otsuchi Bay, northeastern Japan, analyzed using shell microgrowth patterns. Marine Biology 119:397-404.

Nalepa, T. F., and J. M. Gauvin. 1988. Distribution, abundance, and biomass of freshwater mussels (Bivalvia: Unionidae) in Lake St. Clair. Journal of Great Lakes Research 14(4):411-419.

Narasimham, K. A. 1998. Biology of the blood clam *Anadara granosa* (Linnaeus) in Kakinada Bay. Journal of the Marine Biological Association of India 30(1&2):137-150.

Narayanan, K. R., and M. S. Michael. 1968. On the relation between age and linear measurements of the pearl oyster, *Pinctada rulgaris* (Schumacher), of the Gulf of Kutch. The Journal of the Bombay Natural History Society 65:444-452.

Nayar, K. N. 1955. Studies on the growth of the wedge clam, *Donax* (Latona) *cuneatus* Linnaeus. Indian Journal of Fisheries 2(2):325-348.

Negus, C. L. 1966. A quantitative study of growth and production of unionid mussels in the River Thames at Reading. The Journal of Animal Ecology 35(3):513-532.

Neves, R. J., and S. N. Moyer. 1988. Evaluation of techniques for age determination of freshwater mussels (Unionidae). American Malacological Bulletin 6(2):179-188.

Newcombe, C. L. 1935. Growth of *Mya arenaria* L. in the Bay of Fundy region. Canadian Journal of Research 13(6):97-137.

Nickerson, R. B. 1975. A critical analysis of some razor clam (*Siliqua patula*, Dixon) populations in Alaska. State of Alaska Department of Fish and Game.

Nolan, C. P. 1988. Calcification and growth rates in Antarctic molluscs.

Nolan, C. P., and A. Clarke. 1993. Growth in the bivalve *Yoldia eightsi* at Signy Island, Antarctica, determined from internal shell increments and calcium-45 incorporation. Marine Biology 117(2):243-250.

Norte-Campos, A., and K. Villarta. 2010. Use of population parameters in examining changes in the status of the short-necked clam *Paphia undulata* Born, 1778 (Mollusca, Pelecypoda: Veneridae) in coastal waters of southern Negros Occidental. Science Diliman 22(1):53-60.

O'Brien, K., and B. F. Keegan. 2006. Age-related reproductive biology of the bivalve *Mysella bidentata* (Montagu) (Bivalvia:Galeommatacea) in Kinsale Harbour (south coast of Ireland). The Irish Naturalists' Journal 28(7):284-299.

O'Foighil, D., D. McGrath, M. E. Conneely, B. F. Keegan, and M. Costelloe. 1984. Population dynamics and reproduction of *Mysella bidentata* (Bivalvia: Galeommatacea) in Galway Bay, Irish west coast. Marine Biology 81:283-291.

Ocaña, F. A. 2015. Growth and production of *Donax striatus* (Bivalvia: Donacidae) from Las Balsas beach, Gibara, Cuba. Revista de Biología Tropical Revista de Biología Tropical(3):639-646.

Ohba, S. 1959. Ecological studies in the natural population of a clam, *Tapes japonica*, with special reference to seasonal variations in the size and structure of the population and to individual growth. Biological Journal of Okayama University 5:13-42.

Okera, W. 1976. Observations on some population parameters of exploited stocks of *Senilia senilis* (= *Arca senilis*) in Sierra Leone. Marine Biology 38:217-229.

Orton, J. H. 1928. On rhythmic periods in shell-growth in *O. edulis* with a note on fattening. Journal of the Marine Biological Association of the United Kingdom 15(2):365-427.

Ostrovsky, I., M. Gophen, and I. Kalikhman. 1993. Distribution, growth, production, and ecological significance of the clam *Unio terminalis* in Lake Kinneret, Israel. Hydrobiologia 271(1):49-63.

Palacios, C., R. Cruz, and P. Urpi. 1983. Estructura poblacional y cuantificacion de *Donax dentifer* Hanley, 1843 (Pelecypoda:Donacidae) en Playa Garza, Puntarenas, Costa Rica. Revista de Biología Tropical 31(2):251-255.

Palacios, R., J. M. Orensanz, and D. A. Armstrong. 1994. Seasonal and life-long variation of Sr/Ca ratio in shells of *Mya arenaria* from Grays Harbor (Washington) - an ancillary criterion in demographic studies. Estuarine, Coastal and Shelf Science 39:313-327.

Palmer, D. W. 2004. Growth of the razor clam *Ensis directus*, an alien species in the Wash on the east coast of England. Journal of the Marine Biological Association of the United Kingdom 84:1075-1076.

Parulekar, A. H. 1984. Studies on growth and age of bivalves from temperate and tropical estuarine ecosystems. Indian Journal of Marine Sciences 13:193-195.

Patel, B., and J. T. Eapan. 1989. Physiological evaluation of naphthalene intoxication in the tropical acrid clam *Anadara granosa*. Marine Biology 103:193-202.

Paterson, C. G. 1985. Biomass and production of the unionid, *Elliptio complanata* (Lightfoot) in an old reservoir in New Brunswick, Canada. Freshwater Invertebrate Biology 4(4):201-207.

Paul, A. J., and H. M. Feder. 1973. Growth, recruitment, and distribution of the littleneck clam, *Protothaca staminea*, in Galena Bay, Prince William Sound, Alaska. Fishery Bulletin 71(3):665-677.

Paul, A. J., and H. M. Feder. 1976. Clam, mussel, and oyster resources of Alaska. Institute of Marine Science, 76.

Paul, A. J., J. M. Paul, and H. M. Feder. 1976a. Age, growth and recruitment of the butter clam, *Saxidomus gigantea*, on Porpoise Island, Southeast Alaska. Proceedings of the National Shellfisheries Association 66:26-28.

Paul, A. J., J. M. Paul, and H. M. Feder. 1976b. Growth of the littleneck clam, *Protothaca staminea,* on Porposie Island, southeast Alaska. The Veliger 19(2):163-166.

Pearson, R. G., and J. L. Munro. 1991. Growth, mortality and recruitment rates of giant clams, *Tridacna gigas* and *T. derasa*, at Michaelmas Reef, central Great Barrier Reef, Australia. Australian Journal of Marine and Freshwater Research 42:241-262.

Peck, L. S., and L. W. Bullough. 1993. Growth and population structure in the infaunal bivalve *Yoldia eightsi* in relation to iceberg activity at Signy Island, Antarctica. Marine Biology 117:235-241.

Peharda, M., J. Bolotin, N. Vrgoč, and N. Jasprica. 2003a. A study of the noah's ark shell (*Arca noae* Linnaeus 1758) in Mali Ston Bay, Adriatic Sea. Journal of Shellfish Research 22(3):705-709.

Peharda, M., M. Crnčević, I. Bušelić, C. A. Richardson, and D. Ezgeta-Balić. 2012. Growth And Longevity ofGlycymeris nummaria(Linnaeus, 1758) from the Eastern Adriatic, Croatia. Journal of Shellfish Research 31(4):947-950.

Peharda, M., C. A. Richardson, I. Mladineo, S. Šestanović, Z. Popović, J. Bolotin, and N. Vrgoč. 2007. Age, growth and population structure of *Modiolus barbatus* from the Adriatic. Marine Biology 151(2):629-638.

Peharda, M., C. A. Richardson, V. Onofri, A. Bratos, and M. Crncevic. 2002. Age and growth of the bivalve *Arca noae* L. in the Croatian Adriatic Sea. Journal of Molluscan Studies 68(4):307-310.

Peharda, M., A. Soldo, A. Pallaoro, S. Matic, and P. Cetinic. 2003b. Age and growth of the Mediterranean scallop *Pecten jacobaeus* (Linnaeus 1758) in the northern Adriatic Sea. Journal of Shellfish Research 22(3):639-642.

Penchaszadeh, P., and S. Oliver. 1975. Ecologia de una poblacion de "Berberecho" (*Donax hanleyanus*) en Villa Gesell, Argentina. Malacologia 15(1):133-146.

Penzias, L. P. 1969. *Tellina martinicensis* (Mollusca: Bivalvia): Biology and productivity. Bulletin of Marine Science 19(3):568-579.

Pérez-Valencia, S. A., and E. A. Aragón-Noriega. 2013. Age and growth of the Cortes Geoduck *Panopea globosa* (Dall, 1898) in the upper Gulf of California. Indian Journal of Geo-Marine Sciences 42(2):201-205.

Persson, L. 1976. Abundance and growth of a *Cardium glaucum* Bruguiere population in Hano Bight (Southern Baltic). Ophelia 15(2):163-174.

Petersen, G. H. 1978. Life cycles and population dynamics of marine benthic bivalves from the Disko Bugt area of West Greenland. Ophelia 17(1):95-120.

Peterson, C. H. 1986. Quantitative allometry of gamete production by *Mercenaria mercenaria* into old age. Marine Ecology Progress Series 29:93-97.

Peterson, C. H., P. B. Duncan, H. C. Summerson, and G. W. Safrit. 1983. A mark recapture test of annual periodicity of internal growth band deposition in shells of hard clams, *Mercenaria mercenaria,* from a population along the southeastern United States. Fishery Bulletin 81(4):765-779.

Philipp, E., T. Brey, O. Heilmayer, D. Abele, and H. O. Portner. 2006. Physiological ageing in a temperate and a polar swimming scallop. Marine Ecology Progress Series 307:187-198.

Philipp, E., T. Brey, H. O. Portner, and D. Abele. 2005. Chronological and physiological ageing in a polar and a temperate mud clam. Mechanisms of Ageing and Development 126:598-609.

Pinn, E. H., C. A. Richardson, R. C. Thompson, and S. J. Hawkins. 2005. Burrow morphology, biometry, age and growth of piddocks (Mollusca: Bivalvia: Pholadidae) on the south coast of England. Marine Biology 147(4):943-953.

Ponurovskii, S. K. 2008. Population structure and growth of the Japanese littleneck clam *Ruditapes philippinarum* in Amursky Bay, Sea of Japan. Russian Journal of Marine Biology 34(5):329-332.

Pozdnyakova, L. A., A. V. Silina, and G. A. Evseev. 1997. Age, size distribution and growth of native and cultured Japanese scallops in Possjet Bay, Sea of Japan, Russia. Aquaculture International 5:79-88.

Quayle, D. B. 1952. The Rate of Growth of *Venerupis pullastra* (Montagu) at Millport, Scotland. Proceedings of the Royal Society of Edinburgh. Section B. Biology 64(4):384-406.

Quayle, D. B., and N. Bourne. 1972. The clam fisheries of British Columbia. Fisheries Research Board of Canada, 179.

Rabaoui, L., S. Tlig-Zouari, S. Katsanevakis, W. Belgacem, and O. K. B. Hassine. 2011. Differences in absolute and relative growth between two shell forms of *Pinna nobilis* (Mollusca: Bivalvia) along the Tunisian coastline. Journal of Sea Research 66(2):95-103.

Rabaoui, L., S. Tlig Zouari, S. Katsanevakis, and O. K. Ben Hassine. 2007. Comparison of absolute and relative growth patterns among five *Pinna nobilis* populations along the Tunisian coastline: an information theory approach. Marine Biology 152(3):537-548.

Rainer, S. F. 1985. Population dynamics and production of the bivalve *Abra alba* and implications for fisheries production. Marine Biology 85:253-262.

Rainer, S. F., and V. A. Wadley. 1991. Abundance, growth and production of the bivalve *Solemya* sp., a food source for juvenile rock lobsters in a seagrass community in Western Australia. Journal of Experimental Marine Biology and Ecology 152:201-223.

Ralph, R., and J. G. H. Maxwell. 1977. Growth of two antarctic Lammelibranchs: *Adamussium colbecki* and *Laternula elliptica*. Marine Biology 42:171-175.

Ramon, M., P. Abello, and C. A. Richardson. 1995. Population structure and growth of *Donax trunculus* (Bivalvia: Donacidae) in the western Mediterranean. Marine Biology 121:665-671.

Ramon, M., and C. A. Richardson. 1992. Age determination and shell growth of *Chamelea gallina* (Bivalvia: Veneridae) in the western Mediterranean. Marine Ecology Progress Series 89:15-23.

Ramsay, K., M. J. Kaiser, C. A. richardson, L. O. Veale, and A. R. Brand. 2000. Can shell scars on dog cockles (*Glycymeric glycyermis* L.) be used as an indicator of fishing disturbance? Jouranl of Sea Research 43:167-176.

Rapson, A. M. 1952. The Toheroa, *Amphidesma ventricosum* Gray (Eulamellibranchiata) development and growth. Australian Journal of Marine and Freshwater Research 3(2):170-198.

Redfern, P. 1974. Biology and distribution of the toheroa *Paphies* (Mesodesma) *ventricosa* (Gray). Fisheries Research Bulletin Western Australia 11:1-51.

Reed, A. J., K. Linse, and S. Thatje. 2014. Differential adaptations between cold-stenothermal environments in the bivalve *Lissarca* cf. *miliaris* (Philobryidae) from the Scotia Sea islands and Antarctic Peninsula. Journal of Sea Research 88:11-20.

Reynolds, D. J., P. G. Butler, S. M. Williams, J. D. Scourse, C. A. Richardson, A. D. Wanamaker, W. E. N. Austin, A. G. Cage, and M. D. J. Sayer. 2013. A multiproxy reconstruction of

Hebridean (NW Scotland) spring sea surface temperatures between AD 1805 and 2010. Palaeogeography, Palaeoclimatology, Palaeoecology 386:275-285.

Riasco, J., and H. Uranb. 2002. Dinamica poblacional de *Donax dentifer* (Veneroidae:Donacidae) en Bahia Malaga, Pacifico colombiano durante el fenomeno "El Nino" 1997/1998. Revista de Biolog a Tropical 50(3):1113-1123.

Riascos, J. M., O. Heilmayer, and J. Laudien. 2008. Population dynamics of the tropical bivalve *Cardita affinis* from Málaga Bay, Colombian Pacific related to La Niña 1999–2000. Helgoland Marine Research 62(S1):63-71.

Riascos, J. M., O. Heilmayer, M. E. Oliva, and J. Laudien. 2011. Environmental stress and parasitism as drivers of population dynamics of *Mesodesma donacium* at its northern biogeographic range. ICES Journal of Marine Science 68(5):823-833.

Riascos V, J. M. 2006. Effects of El Niño-Southern oscillation on the population dynamics of the tropical bivalve *Donax dentifer* from Málaga bay, Colombian Pacific. Marine Biology 148(6):1283-1293.

Richard, G. 1981. A first evaluation of the findings of the growth and produciton of lagoon and reef molluscs in French Polynesia. Pp. 637-641. Fourther International Coral Reef Symposium. Manilia.

Richardson, C. A. 1987. Microgrowth patterns in the shell of the Malaysian cockle *Anadara granosa* (L.) and their use in age determination. Journal of Experimental Marine Biology and Ecology 111:77-98.

Richardson, C. A., S. A. Collis, K. Ekaratne, P. Dare, and D. Key. 1993a. The age determination and growth rate of the European flat oyster, *Ostrea edulis*, in British waters determined from acetate peels of umbo growth lines. ICES Journal of Marine Science 50(493-500).

Richardson, C. A., H. Kennedy, C. M. Duarte, D. P. Kennedy, and S. V. Proud. 1999. Age and growth of the fan mussel, *Pinna nobilis* from south-east Spanish Mediterranean seagrass (*Posidonia oceanica*) meadows. Marine Biology 133:205-212.

Richardson, C. A., M. Peharda, H. Kennedy, P. Kennedy, and V. Onofri. 2004. Age, growth rate and season of recruitment of *Pinna nobilis* (L) in the Croatian Adriatic determined from Mg:Ca and Sr:Ca shell profiles. Journal of Experimental Marine Biology and Ecology 299(1):1-16.

Richardson, C. A., R. Seed, E. M. H. Al-Roumaihi, and L. McDonald. 1993b. Distribution, shell growth and predation of the New Zealand oyster, *Tiostrea* (=*Ostrea*) *lutaria* Hutton, in the Menai Strait, North Wales. Journal of Shellfish Research 12(2):207-214.

Richardson, C. A., R. Seed, and E. Naylor. 1990. Use of internal growth bands for measuring individual and population growth rates in *Mytilus edulis* from offshore production platforms. Marine Ecology Progress Series 66:259-265.

Richardson, C. A., and P. Walker. 1991. The age structure of a population of the hard-shell clam, *Mercenaria mercenaria* from Southampton Water, England, derived from acetate peel replicas of shell sections. ICES Journal of Marine Science 48:229-236.

Richardson, M. G. 1979. The ecology and reproduction of the brooding Anarctic bivalve *Lissarca miliaris*. British Antarctic Survey Bulletin 49:91-115.

Ridgway, I., T. J. Bowden, A. Roman-Gonzalez, and C. A. Richardson. 2014. Resistance to oxidative stress is not associated with the exceptional longevity of the freshwater pearl mussel, Margaritifera margaritifera nor three unionid species. Aquatic Sciences 76(2):259-267.

Ridgway, I. D., C. A. Richardson, E. Enos, Z. Ungvari, S. N. Austad, E. E. R. Philipp, and A. Csiszar. 2011. New species longevity record for the Northern Quahog (=Hard Clam), *Mercenaria mercenaria*. Journal of Shellfish Research 30(1):35-38.

Ridgway, I. D., C. A. Richardson, J. D. Scourse, P. G. Butler, and D. J. Reynolds. 2012. The population structure and biology of the ocean quahog, Arctica islandica, in Belfast Lough, Northern Ireland. Journal of the Marine Biological Association of the United Kingdom 92(03):539-546.

Robinson, R. F., and C. A. Richardson. 1998. The direct and indirect effects of suction dredging on a razor clam (*Ensis arcuatus*) population. ICES Journal of Marine Science 55:970-977.

Robinson, T. B., A. Govender, C. L. Griffiths, and G. M. Branch. 2007. Experimental harvesting of *Mytilus galloprovincialis*: Can an alien mussel support a small-scale fishery? Fisheries Research 88(1-3):33-41.

Rogers, S. O., B. T. Watson, and R. J. Neves. 2001. Life history and population biology of the endangered tan riffleshell (*Epioblasma florentina walkeri*) (Bivalvia: Unionidae). Journal of the North American Benthological Society 20(4):582-594.

Roper, D. S., R. D. Pridmore, and S. F. Thrush. 1992. Recruitment to the macrobenthos of *Macomona liliana*(bivalvia: Tellinidae) in Manukau Harbour, New Zealand. New Zealand Journal of Marine and Freshwater Research 26(3-4):385-392.

Ropes, J. 1987. Age and growth, reproductive cycle, and histochemical tests for heavy metals in hard clams, *Mercenaria mercenaria*, from Raritan Bay 1974-1975. Fishery Bulletin 85(3):653-662.

Ropes, J. W. 1984. Procedures for preparing acetate peels and evidence validating the annual peridiocity of growth lines formed in the shells of ocean quahogs, *Arctica islandica*. Marine Fisheries Review 46(2):27-35.

Rowell, T. W., D. R. Chaisson, and J. T. McLane. 1990. Size and age of sexual maturity and annual gametogenic cycle in the ocean quahog, *Arctica islandica* (Linnaeus, 1767), from coastal waters in Nova Scotia, Canada. Journal of Shellfish Research 9(1):195-203.

Royer, C., J. Thebault, L. Chauvaud, and F. Olivier. 2013. Structural analysis and paleoenvironmental potential of dog cockel shells (*Glycymeris glycymeris*) in Brittany, northwest France. Palaeogeography, Palaeoclimatology, Palaeoecology 373:123-132.

Şahin, C., E. Duzgunes, C. Mutlu, M. Aydin, and H. Emiral. 1999. Determination of the growth parameters of the *Anadara cornea* R. 1844 population by the Bhattacharya method in the eastern Black Sea. Turkish Journal of Zoology 23:99-105.

Sakurai, I., T. Horii, O. Murakami, and S. Nakao. 1998. Population dynamics and stock size prediction for the sunray surfclam, *Mactra chinensis*, at Tomakomai, southwest Hokkaido, Japan. Fishery Bulletin 96:344-351.

Sakurai, I., M. Kurata, and E. Abe. 1996. Age structure and mortality of the sunray surf clam *Mactra chinensis* off Tomakomai, southwest Hokkaido. Fisheries Science 62(2):168-172.

Saloman, C. H., and J. L. Taylor. 1959. Age and growth of large southern quahogs from a Florida estuary. Proceedings of the National Shellfisheries Association 59:46-51.

Salzwedel, H. 1979. Reproduction, growth, mortality and variations in abundance and biomass of *Tellina fabula* (Bivalvia) in the German Bight in 1975/1976. Veroffentlichugen des Instituts fur Meeresforschung in Bremerhaven 18:111-202.

San-Miguel, E., S. Monserrat, C. Fernández, R. Amaro, M. Hermida, P. Ondina, and C. R. Altaba. 2004. Growth models and longevity of freshwater pearl mussels (*Margaritifera margaritifera*) in Spain. Canadian Journal of Zoology 82(8):1370-1379.

Sanchez-Salazar, M. E., C. L. Griffiths, and R. Seed. 1987. The interactive roles of predation and tidal elevation in structuring populations of the edible cockle, *Cerastoderma edule*. Estuarine, Coastal and Shelf Science 25:245-260.

Sasaki, K. 1981. Growth of the Sakhalin surf clam, *Spisula sachalinensis* (Schrenck), in Sendai Bay. The Tohoku Journal of Agricultural Research 32(4):168-180.

Sato, S. 1994. Analysis of the relationship between growth and sexual maturation in *Phacosoma japonicum* (Bivalvia: Veneridae). Marine Biology 118:663-672.

Sato, S. 1999. Temporal change of life-history traits in fossil bivalves: an example of *Phacosoma japonicum* from the Pleistocene of Japan. Palaeogeography, Palaeoclimatology, Palaeoecology 154:313-323.

Schäffer, F., and M. L. Zettler. 2007. The clam siphon as indicator for growth indices in the soft-shell clam *Mya arenaria*. Helgoland Marine Research 61(1):9-16.

Schimdt, R. R., and J. E. Warme. 1969. Population characteristics of *Protothaca staminea* (Conrad) from Magu Lagoon, California. The Veliger 12(2):193-199.

Schmidt, A., A. Wehrmann, and S. Dittmann. 2008. Population dynamics of the invasive Pacific oyster *Crassostrea gigas* during the early stages of an outbreak in the Wadden Sea (Germany). Helgoland Marine Research 62(4):367-376.

Schöne, B. R., A. D. Freyre Castro, J. Fiebig, S. D. Houk, W. Oschmann, and I. Kröncke. 2004. Sea surface water temperatures over the period 1884–1983 reconstructed from oxygen isotope ratios of a bivalve mollusk shell (Arctica islandica, southern North Sea). Palaeogeography, Palaeoclimatology, Palaeoecology 212(3-4):215-232.

Schöne, B. R., D. H. Goodwin, K. W. Flessa, D. L. Dettman, and P. D. Roopnarine. 2002. Sclerochronology and growth of the bivalve mollusks *Chione* (*Chionista*) *fluctifraga* and *C*. (*Chionista*) *cortezi* in the northern Gulf of California, Mexico. The Veliger 45(1):45-54.

Schöne, B. R., K. Tanabe, D. L. Dettman, and S. Sato. 2003. Environmental controls on shell growth rates δ18O of the shallow-marine bivalve mollusk *Phacosoma japonicum* in Japan. Marine Biology 142:473-485.

Schöne, B. R., Z. Zhang, P. Radermacher, J. Thébault, D. E. Jacob, E. V. Nunn, and A.-F. Maurer. 2011. Sr/Ca and Mg/Ca ratios of ontogenetically old, long-lived bivalve shells (Arctica islandica) and their function as paleotemperature proxies. Palaeogeography, Palaeoclimatology, Palaeoecology 302(1-2):52-64.

Schweers, T., M. Wolff, V. Koch, and F. S. Duarte. 2006. Population dynamics of *Megapitaria squalida* (Bivalvia: Veneridae) at Magdalena Bay, Baja California Sur, Mexico. Revista de Biología Tropical 54(3):1003-1017.

Scourse, J., C. Richardson, G. Forsythe, I. Harris, J. Heinemeier, N. Fraser, K. Briffa, and P. Jones. 2006. First cross-matched floating chronology from the marine fossil record: data from growth lines of the long-lived bivalve mollusc *Arctica islandica*. The Holocene 16(7):967-974.

Searcy-Bernal, R., and R. Juarez-Romero. 1991. Estructura por edades y tallas en muestras de captura comercial de la almeja pismo *Tivela stultorum* (Mawe, 1823), extraidas de playa San Ramon, B.C., Mexico. Ciencias Marinas 17(2):71-82.

Seed, R. 1968. Factors influencing shell shape in the mussel *Mytilus edulis*. Journal of the Marine Biological Association of the United Kingdom 48:561-584.

Seed, R. 1973. Absolute and allometric growth in the mussel, *Mytilus edulis* L. (Mollusca Bivalvia). Proceedings of the Malacological Society of London 40:343-357.

Seed, R., and R. A. Brown. 1978. Growth as a strategy for survival in two marine bivalves, *Cerastoderma edule* and *Modiolus modiolus*. Journal of Animal Ecology 47:283-292.

Segerstrale, S. G. 1960. Investigations on Baltic populations of the bivalve *Macoma balthica* (L.). Commentationes Biologica 23:3-72.

Sejr, M. K., M. E. Blicher, and S. Rysgaard. 2009. Sea ice cover affects inter-annual and geographic variation in growth of the Arctic cockle Clinocardium ciliatum (Bivalvia) in Greenland. Marine Ecology Progress Series 389:149-158.

Sejr, M. K., and P. B. Christensen. 2007. Growth, production and carbon demand of macrofauna in Young Sound, with special emphasis on the bivalves *Hiatella arctica* and *Mya truncata*. Pp. 122-135. *In* S. Rysgaard, and R. N. Glud, eds. Carbon cycling in Arctic marine ecosystems: Case study Young Sound, Meddr. Gronland, Biosceince.

Sejr, M. K., M. K. Sand, K. T. Jensen, J. K. Peterson, P. B. Christensen, and S. Rysgaard. 2002. Growth and production of *Hiatella arctica* (Bivalvia) in a high-Arctic fjord (Young Sound, Northeast Greenland). Marine Ecology Progress Series 244:163-169.

Selin, N. I. 1980. Size-age structure of settlements of *Crenomytilus grayanus* on differnt grounds in Pos'et Bay, Sea of Japan. Soviet Journal of Marine Biology:44-49.

Selin, N. I. 1988. Size-age structure and growth of the mussel *Mytilus coruscus* in Peter the Great Bay, Sea of Japan. Soviet Journal of Marine Biology 14:284-288.

Selin, N. I. 1993. Production and growth of the bivalve mollusk *Keenocardium californiense* in the Northwestern part of the Sea of Japan. Russian Journal of Marine Biology 19(1):26-33.

Selin, N. I. 2007. Shell form, growth and life span of Astarte arctica and A. borealis (Mollusca: Bivalvia) from the subtidal zone of northeastern Sakhalin. Russian Journal of Marine Biology 33(4):232-237.

Selin, N. I. 2008. Distribution, population structure and growth of *Protothaca euglypta* (Sowerby, 1914) (Bivalvia: Veneridae) from the northwestern part of the East Sea of Russia. Korean Journal of Malacology 24(2):81-87.

Selin, N. I. 2010. The growth and life span of bivalve mollusks at the northeastern coast of Sakhalin Island. Russian Journal of Marine Biology 36(4):258-269.

Selin, N. I., and V. N. Lysenko. 2006. Size and age composition of populations and growth of Mytilus trossulus (Bivalvia: Mytilidae) in the subtidal area of western Kamchatka. Russian Journal of Marine Biology 32(6):360-368.

Selin, N. I., and M. S. Selina. 1988. Production characteristics of the bivalve mollusk *Callista brevisiphonata* in Peter the Great Bay, Sea of Japan. Soviet Journal of Marine Biology 14:219-223.

Sellmer, G. P. 1967. Functional morphology and ecological life history of the gem clam, *Gemma gemma* (Eulamellibranchia: Veneridae). Malacologia 5(2):137-223.

Semenova. 1970. Linear growth in *Macoma balthica* in the Gulf of Kandalsksha in the White Sea. Trudy Belomorskoi Biologicheskoi Stantsii Moskovskogo Gosudarstuennogo Universiteta.

Sephton, T. W., and C. F. Bryan. 1990. Age and growth rate determinations for the Atlantic surf clam, *Spisula solidissima* (Dillwyn, 1817), in Prince Edward Island, Canada. Journal of Shellfish Research 9(1):177-185.

Sewell, R. B. 1924. Observations on growth in certain molluscs and on changes corrleated wtih growth in the radula of *Pyrazus palustris*. Records of the Indian Museum 26:529-548.

Shafee, M. S. 1979. Ecological energy requirements of the green mussel, *Perna viridis* Linnaeus from Ennore estuary, Madras. Oceanologica Acta 2(1):69-74.

Shafee, M. S. 1992. Production estimate of a mussel population *Perna picta* (Born) on the Atlantic coast of Morocco. Journal of Experimental Marine Biology and Ecology 163:183-197.

Shaul, W., and L. Goodwin. 1982. Geoduck (*Panope generosa*:Bivalvia) age as determined by internal growth lines in the shell. Canadian Journal of Fisheries and Aquatic Sciences 39:632-636.

Sheldon, R. W. 1968. The effect of high population density on the growth and mortality of oysters (*Ostrea edulis*). Journal du Conseil Permanent Internatinal pour l'Exploration de la Mer 31(3):352-363.

Shelley, C. 1988. Growth rates of *Hippopus hippopus* from Orpheus Island, Great Barrier Reef. Pp. 207-212. *In* J. W. Copland, and J. S. Lucas, eds. Giant clams in Asia and the Pacific. Australian Centre for International Agricultural Research.

Siletic, T., and M. Peharda. 2003. Population study of the fan shell *Pinna nobilis* L. in Malo and Veliko Jezero of the Mljet National Park (Adriatic Sea). Scientia Marinia 67(1):91-98.

Silina, A. V. 2006. Tumor-like formations on the shells of Japanese scallops *Patinopecten yessoensis* (Jay). Marine Biology 148(4):833-840.

Silina, A. V. 2007. Growth responses of the scallop *Patinopecten yessoensis* (Pelecypoda: Pectinidae) to shell bioerosion and bottom sediment type. Korean Journal of Malacology 23(1):9-16.

Silina, A. V. 2012. Growth of bivalve *Atrina vexillumin* the Gulf of Thailand. Journal of Shellfish Research 31(4):989-995.

Silina, A. V. 2014. Habitat preferences and growth of *Ruditapes bruguieri* (Bivalvia: Veneridae) at the northern boundary of its range. The Scientific World Journal 2014:235416.

Silina, A. V., and N. V. Zhukova. 2007. Growth variability and feeding of scallop *Patinopecten yessoensis* on different bottom sediments: Evidence from fatty acid analysis. Journal of Experimental Marine Biology and Ecology 348(1-2):46-59.

Sims, N. A. 1992. Population dynamics and stock managment of the black-lip pearl oyster, *Pinetada margaritifera* (L.), in the Cook Islands, South Pacific. Australian Journal of Marine and Freshwater Research 43:1423-1435.

Sims, N. A. 1993. Size, age and growth of the black-lip pearl oyster, *Pinctada margaritifera* (L.) (Bivalvia: Pteriidae). Journal of Shellfish Research 12(2):223-228.

Slattery, J. P., R. A. Lutz, and R. C. Vrijenhoek. 1993. Repeatability of correlations between heterozygosity, growth and survival in a natural population of the hard clam *Mercenaria mercenaria* L. Journal of Experimental Marine Biology and Ecology 165:209-224.

Slattery, J. P., R. C. Vrijenhoek, and R. A. Lutz. 1991. Heterozygosity, growth, and survival of the hard clam, *Mercenaria mercenaria*, in seagrass vs sandflat habitats. Marine Biology 111:335-342.

Sloan, N. A., and S. M. C. Robinson. 1984. Age and gonad development in the geoduck clam *Panope abrupta* (Conrad) from southern British Columbia, Canada. Journal of Shellfish Research 4(2):131-137.

Smith, E. B., K. M. Scott, E. R. Nix, C. Korte, and C. R. Fisher. 2000. Growth and condition of seep mussels (*Bathymodiolus childressi*) at a Gulf of Mexico brine pool. Ecology 81(9):2392-2403.

Sola, J. C. 1997. Reproduction, population dynamics, growth and production of *Scrobicularia plana* Da Costa (pelecypoda) in the Bidasoa estuary, Spain. Netherlands Journal of Aquatic Ecology 30(4):283-296.

Soldati, A. L., D. E. Jacob, B. R. Schone, M. M. Bianchi, and A. Hajduk. 2008. Seasonal periodicity of growth and composition in valves of *Diplodon chilensis* patagonicus (d'Orbigny, 1835). Journal of Molluscan Studies 75(1):75-85.

Somasekar, M., K. Sriraman, and R. Kasinathan. 1982. Age, growth and length-weight relationship in the backwater oyster *Crassostrea madrasensis* (Preston). Indian Journal of Marine Sciences 11:190-192.

Steffani, C. N., and G. M. Branch. 2003. Growth rate, condition, and shell shape of *Mytilus galloprovincialis*: responses to wave exposure. Marine Ecology Progress Series 246:197-209.

Stephen, A. C. 1931. Notes on the biology of certain lamellibranchs on the Scottish Coast. Journal of the Marine Biological Association of the United Kingdom 17(2):277-300.

Stern-Pirlot, A., and M. Wolff. 2006. Population dynamics and fisheries potential of *Anadara tuberculosa* (Bivalvia: Arcidae) along the Pacific coast of Costa Rica. Revista de Biología Tropical 54(Suppl. 1):87-99.

Stevenson, J., and L. Dickie. 1954. Annual growth rings and rate of growth of the giant scallop, *Placopecten magellanicus* (Gmelin) in the Digby Area of the Bay of Fundy. Journal of the Fisheries Research Board of Canada 11(5):650-671.

Stober, Q. J. 1972. Distribution and age of *Margaritifera margaritifera* (L.) in a Madison River (Montana, U.S.A.) mussel bed. Malacologia 11:343-350.

Stockton, W. L. 1984. The biology and ecology of the epifaunal scallop *Adamussium colbecki* on the west side of McMurdo Sound, Antarctica. Marine Biology 78:171-178.

Stotz, W. B., and S. A. Gonzalez. 1997. Abundance, growth, and production of the sea scallop *Argopecten purpuratus* [Lamarck 18 191: bases for sustainable exploitation of natural scallop beds in north-central Chile. Fisheries Research 32:173-183.

Strahl, J., and D. Abele. 2010. Cell turnover in tissues of the long-lived ocean quahog Arctica islandica and the short-lived scallop Aequipecten opercularis. Marine Biology 157(6):1283-1292.

Strauss, J. 2005. Oxygen and carbon isotopic profiles of recent and Cenozoic mollusks: growth rates and paleoenvironmental analysis. Florida Atlantic University.

Strayer, D. L., J. J. Cole, G. E. Likens, and D. C. Buso. 1981. Biomass and annual production of the freshwater mussel *Elliptio complanata* in an oligotrophic softwater lake. Freshwater Biology 11:435-440.

Strom, A., R. C. Francis, N. J. Mantua, and E. L. Miles. 2004. North Pacific climate recorded in growth rings of geoduck clams: A new tool for paleoenvironmental reconstruction. Geophysical Research Letters 31(6):1-4.

Sugiura, D., S. Katayama, S. Sasa, and K. Sasaki. 2014. Age and growth of the ark shell *Scapharca broughtonii* (Bivalvia, Arcidae) in Japanese Waters. Journal of Shellfish Research 33(1):315-324.

Sukhotin, A., D. Abele, and H. O. Portner. 2006. Ageing and metabolism of *Mytilus edulis*: Populations from various climate regimes. Journal of Shellfish Research 25(3):893-899.

Sukhotin, A. A., D. Abele, and H.-O. Portner. 2002. Growth, metabolism and lipid peroxidation in *Mytilus edulis*: age and size effects. Marine Ecology Progress Series 226:223-234.

Sukhotin, A. A., and N. V. Maximovich. 1994. Variability of growth rate in *Mytilus edulis* L. from the Chupa Inlet (the White Sea). Journal of Experimental Marine Biology and Ecology 176:15-26.

Sukhotin, A. A., and H.-O. Portner. 2001. Age-dependence of metabolism in mussels *Mytilus edulis* (L.) from the White Sea. Journal of Experimental Marine Biology and Ecology 257:53-72.

Surge, D., and K. J. Walker. 2006. Geochemical variation in microstructural shell layers of the southern quahog (Mercenaria campechiensis): Implications for reconstructing seasonality. Palaeogeography, Palaeoclimatology, Palaeoecology 237(2-4):182-190.

Swennen, C., M. F. Leopold, and M. Stock. 1985. Notes on growth and behaviour of the American razor clam *Ensis directus* in the Wadden Sea and the predation on it by birds. Helolander Meeresunterschuchugen 39:255-261.

Talikhedkar, P. M., U. H. Mane, and R. Nagabhushanam. 1976. Growth rate of the wedge clam *Donax cuneatus* at Miriya Bay, Ratnagiri. Indian Journal of Fisheries 23(1 & 2):183-193.

Tanabe, K. 1988. Age and growth rate determinations of an intertidal bivalve, *Phacosoma japonicum*, using internal shell increments. Lethaia 21:231-241.

Tanabe, K., and T. Oba. 1988. Latitudinal variations in shell growth patterns of *Phacosoma japonicum* (Bivalvia: Veneridae) from the Japanese coast. Marine Ecology Progress Series 47:75-82.

Tang, S. F. 1941. The breeding of the escallop (*Pecten maximus* (L.)) with a note on the growth rate. Proceedings and Transactions of the Liverpool Biological Society 54:9-28.

Taylor, A. C., and T. J. Venn. 1978. Growth of the queen scallop, *Chlamys opercularis*, from the Clyde Sea area. Journal of the Marine Biological Association of the United Kingdom 58:687-700.

Theisen, B. F. 1973. The growth of *Mytilus edulis* L. (Bivalvia) from Disko and Thule District, Greenland. Ophelia 12:59-77.

Theisen, B. F. 1975. Growth parameters of *Mytilus edulis* L. (Bivalvia) estimated from tagging data. Meddelelser fra Danmarks Fiskeri og Havundersoegelser 7:99-109.

Thippeswamy, S., and M. Joseph. 1991. Population selection strategies in the wedge clam, *Donax incarnatus* (Gmelin) from Panambur beach, Mangalore. Indian Journal of Marine Sciences 20:147-151.

Thomas, S., and M. Nasser. 2009. Growth and population dynamics of short-neck clam *Paphia malabarica* from Dharmadom estuary, North Kerala, southwest coast of India. Journal of the Marine Biological Association of India 51(1):87-92.

Thompson, I., D. S. Jones, and D. Dreibelbis. 1980. Annual internal growth banding and life history of the ocean quahog *Arctica islandica* (Mollusca: Bivalvia). Marine Biology 57:25-34.

Thorarinsdóttir, G. G., and L. D. Jacobson. 2005. Fishery biology and biological reference points for management of ocean quahogs (Arctica islandica) off Iceland. Fisheries Research 75(1-3):97-106.

Thorarinsdottir, G. G., and S. A. Steingrimmson. 2000. Size and age at sexual maturity and sex ratio in ocean quahog, *Arctica islandica* (Linnaeus, 1767), off Northwest Iceland. Journal of Shellfish Research 19(2):943-947.

Thouzeau, G., G. Robert, and S. J. Smith. 1991. Spatial variability in distribution and growth of juvenile and adult sea scallops *Placopecten magellanicus* (Gmelin) on eastern Georges Bank (Northwest Atlantic). Marine Ecology Progress Series 74:205-218.

Trevallion, A. 1971. Studies on *Tellina tenuis* Da Costa. III. Aspects of general biology and energy flow. Journal of Experimental Marine Biology and Ecology 7:95-122.

Trutschler, K., and C. Samtleben. 1988. Shell growth of *Astarte elliptica* (Bivalvia) from Kiel Bay (Western Baltic Sea). Marine Ecology Progress Series 42:155-162.

Tunberg, B. 1983a. Growth of *Dosinia exoleta* (L.) (Bivalvia) in Raunefjorden, Western Norway. Sarsia 68(1):40-45.

Tunberg, B. 1983b. Population structure, size distribution, and shell growth of *Dosinia lupinus* (L.) (Bivalvia) in Raunefjorden, Western Norway, with biometrical comparison to Dosinia exoleta (L.). Sarsia 68(1):33-40.

Tunçer, S., and C. Ç. Erdemir. 2002. A preliminary study on some properties for *Chamelea gallina* (L.,) (Bivalvia: Verenidae from Karabiga-Çanakkale. Turkish Journal of Fisheries and Aquatic Sciences 2(2):117-120.

Turekian, K., J. K. Cochran, D. Kharkar, R. Cerrato, J. Vaisnys, H. Sanders, J. Grassle, and A. Allen. 1975. Slow growth rate of a deep-sea clam determined by 228Ra chronology. Proceedings of the National Academy of Sciences 72(7):2829-2832.

Turekian, K. K., and J. K. Cochran. 1981. Growth rate of a vesicomyid clam from the Galapagos spreading center. Science 214(4523):909-911.

Turra, A., M. Petracco, A. C. Z. Amaral, and M. R. Denadai. 2014. Temporal variation in life-history traits of the clam *Tivela mactroides* (Bivalvia: Veneridae): Density-dependent processes in sandy beaches. Estuarine, Coastal and Shelf Science 150:157-164.

Turra, A., M. Petracco, A. C. Z. Amaral, and M. R. Denadai. 2015. Population biology and secondary production of the harvested clam *Tivela mactroides* (Born, 1778) (Bivalvia, Veneridae) in Southeastern Brazil. Marine Ecology 36(2):221-234.

Urban, H.-J. 1996. Population dynamics of the bivalves *Venus antiqua*, *Tagelus dombeii*, and *Ensis macha* from Chile 36° S. Journal of Shellfish Research 15(3):719-727.

Urban, H.-J. 1998. Description and management of a clam fishery (*Gari solida*, Psammobiidae) from Bahía Independencia, Peru (14° S). Fisheries Research 35:199-207.

Urban, H.-J., and G. Mercuri. 1998. Population dynamics of the bivalve *Laternula elliptica* from Potter Cove, King George Island, South Shetland Islands. 1998 10(2):153-160.

Urban, H.-J., and J. Tarazona. 1996. Effects of El Niño/Southern Oscillation on the population dynamics of a *Gari solida* population (Bivalvia: Psammobiidae) from Bahía Independencia, Perú. Marine Biology 125(4):725-734.

Urban, H. J., and B. Campos. 1994. Population dynamics of the bivavles *Gari solida, Semel solida* and *Protothaca thaca* from a small bay in Chile at 36S. Marine Ecology Progress Series 115:93-102.

Urban, H. J., and C. Tesch. 1996. Aspects of population dynamics of six bivalve species from South Chile: Results of the Victor Hensen cruise to the Magellan Strait and the Beagle Channel in October/Novemeber 1994. Archive of Fishery and Marine Research 44(3):243-256.

Urrutia, M. B., I. Ibarrola, J. I. P. Iglesias, and E. Navarro. 1999. Energetics of growth and reproduction in a high-tidal population of the clam *Ruditapes decussatus* from Urdaibai Estuary (Basque Country, N. Spain). Jouranl of Sea Research 42:34-48.

Vadopalas, B., C. Weidman, and E. K. Cronin. 2011. Validation of age estimation in geoduck clams using the bomb radiocarbon signal. Journal of Shellfish Research 30(2):303-307.

Vahl, O. 1981. Energy transformations by the Iceland scallop, *Chlamys islandica* (O.F. Müller), from 70° N. I. The age specific energy budget and net growth efficiency. Journal of Experimental Marine Biology and Ecology 53:281-296.

Vannote, R. L., and G. W. Minshall. 1982. Fluvial processes and local lithology controlling abundance, structure, and composition of mussel beds. Proceedings of the National Academy of Sciences 79(13):4103-4107.

Velarde, A., J. Flye-Sainte-Marie, J. Mendo, and F. Jean. 2015. Sclerochronological records and daily microgrowth of the Peruvian scallop (*Argopecten purpuratus*, Lamarck, 1819) related to environmental conditions in Paracas Bay, Pisco, Peru. Journal of Sea Research 99:1-8.

Velez, A., B. Venables, and L. Fitzpatrick. 1985. Growth and production of the tropical beach clam *Donax denticulatus* (Tellinidae) in eastern Venezula. Caribbean Journal of Science 21:63-73.

Veloso, V., J. Moreira, and J. Tronocoso. 2007. Annual dynamics of bivalve populations in muddy bottoms of the Ensenada de Baiona (Galicia, NW Iberian Peninsual). Iberas 25(2):1-10.

Verdelhos, T., J. M. Neto, J. C. Marques, and M. A. Pardal. 2005. The effect of eutrophication abatement on the bivalve *Scrobicularia plana*. Estuarine, Coastal and Shelf Science 63(1-2):261-268.

Verginelli, R., and A. Prieto. 1991. Produccion secundaria de *Pinctada imbricata* (Roding, 1798) (Pterioda:Pteriidae) en una poblacion del Golfo de Cariaco, Venezuela. Acta Cientifica 42:138-144.

Vincent, B., C. Brassard, and M. Harvey. 1987. Variations de la croissance de la coquille, et de la structure d'âge du bivalve *Macoma balthica* (L.) dans une population intertidale de l'estuaire du Saint-Laurent (Québec). Canadian Journal of Zoology 65(8):1906-1916.

Wade, B. 1964. Notes on the ecology of *Donax denticulatus* (Linne). Pp. 36-42. Proceedings of the Gulf and Carribbean Fisheries Institute.

Wade, B. 1969. Studies on the biology of the West Indian beach clam, *Donax denticulatus* Linne. 2. Life-history. Bulletin of Marine Science 18(4):876-901.

Walker, R. L., and P. B. Heffernan. 1994. Age, growth rate, and size of the southern surfclam, *Spisula solidissima similis* (Say, 1822). Journal of Shellfish Research 13(2):433-441.

Walker, R. L., and K. R. Tenore. 1984a. The distribution and production of the hard clam, *Mercenaria mercenaria*, in Wassaw Sound, Georgia. Estuaries 7(1):19-27.

Walker, R. L., and K. R. Tenore. 1984b. Growth and production of the dwarf surf clam *Mulinia lateralis* (Say 1822) in a Georgia estuary. Gulf Research Reports 7(4):357-363.

Walliser, E. O., B. R. Schöne, T. Tütken, J. Zirkel, K. I. Grimm, and J. Pross. 2015. The bivalve *Glycymeris planicostalis* as a high-resolution paleoclimate archive for the Rupelian (Early Oligocene) of central Europe. Climate of the past 11(4):653-668.

Wanamaker, A. D., Jr., P. G. Butler, J. D. Scourse, J. Heinemeier, J. Eiriksson, K. L. Knudsen, and C. A. Richardson. 2012. Surface changes in the North Atlantic meridional overturning circulation during the last millennium. Nat Commun 3:899.

Wanamaker, A. D., K. J. Kreutz, B. R. Schöne, K. A. Maasch, A. J. Pershing, H. W. Borns, D. S. Introne, and S. Feindel. 2009. A late Holocene paleo-productivity record in the western Gulf of Maine, USA, inferred from growth histories of the long-lived ocean quahog (Arctica islandica). International Journal of Earth Sciences 98(1):19-29.

Warwick, R. M., C. L. George, and J. R. Davies. 1978. Annual macrofauna production in a Venus community. Estuarine and Coastal Marine Science 7:215-241.

Warwick, R. M., and R. Price. 1975. Macrofauna production in an estuarine mud-flat. Journal of the Marine Biological Association of the United Kingdom 55:1-18.

Watanabe, T., A. Suzuki, H. Kawahata, H. Kan, and S. Ogawa. 2004. A 60-year isotopic record from a mid-Holocene fossil giant clam (Tridacna gigas) in the Ryukyu Islands: physiological and paleoclimatic implications. Palaeogeography, Palaeoclimatology, Palaeoecology 212(3-4):343-354.

Weinberg, J. R. 1985. Factors regulating population dynamics of the marine bivalve *Gemma gemma*: intraspecific competition and salinity. Marine Biology 86:173-182.

Weinberg, J. R., and T. E. Hesler. 1996. Growth of the Atlantic surfclam, *Spisula solidissima*, from Georges Bank to the Delmarva Peninsula, USA. Marine Biology 126:663-674.

Wendell, J., D. DeMartini, P. Dinnel, and J. Siecke. 1976. The ecology of the gaper or horse clam, *Tresus capax* (Gould 1850) (Bivalvia:Mactridae) in Humboldt Bay, California. California Fish and Game 62(1):41-64.

Westerbom, M., M. Kilpi, and O. Mustonen. 2002. Blue mussels, *Mytilus edulis*, at the edge of the range: population structure, growth and biomass along a salinity gradient in the north-eastern Baltic Sea. Marine Biology 140(5):991-999.

Weymouth, F. W. 1931. The life history and growth of the Pismo clam. State of California Fish and Game Commission 7.

Weymouth, F. W., and H. C. McMillin. 1930. Relative growth and mortality of the Pacific razor clam (*Siliqua patula*, Dixon) and their bearing on the commercial fishery. Bulletin of the Bureau of Fisheries 46:543-567.

Weymouth, F. W., H. C. McMillin, and H. B. Holmes. 1925. Growth and age at maturity of the Pacific razor clam, *Siliqua patula* (Dixon). Bulletin of the Bureau of Fisheries 47:201-236.

Weymouth, F. W., and S. H. Thompson. 1930. The age and growth of the Pacific cockle (*Cardium corbis*, Martyn). Bulletin of the Bureau of Fisheries 46:633-641.

Wijsman, J., and A. C. Smaal. 2011. Growth of cockles (*Cerastoderma edule*) in the Oosterschelde described by a Dynamic Energy Budget model. Journal of Sea Research 66(4):372-380.

Wiktor, J. 1963. Research on the ecology of *Dreissena polymorpha* Pall, in the Szczecin Lagoon (Zalew Szczecinski). Ekologia Polska 11:275-280.

Williams, M. J., and M. C. L. Dredge. 1981. Growth of the saucer scallop, *Amusium japonicum balloti* Habe, in central eastern Queensland. Marine and Freshwater Research 32(4):657-666.

Wilson, B. R., and E. P. Hodgkin. 1967. A comparative account of the reproductive cycles of five species of marine mussels (Bivalvia:Mytilidae) in the vicinity of Fremantle, western Australia. Australian Journal of Marine and Freshwater Research 18:175-203.

Wilson, D. P. 1977. *Modiolus modiolus* (L.) in small mid-tidal rock pools at Penrhyn Bay, North Wales. Estuarine and Coastal Marine Science 5(2):215-222.

Winckworth, R. 1931. On the growth of *Paphia undulata* (Veneridae). Journal of Molluscan Studies 19(4):171-174.

Winkelstern, I., D. Surge, and J. W. Hudley. 2013. Multiproxy sclerochronological evidence for Plio-Pleistocene regional warmth: United States Mid-Atlantic Coastal Plain. Palaios 28(9):649-660.

Winther, U., and J. S. Gray. 1985. The biology of *Mya arenaria* (Bivalvia) in the eutrophic inner Oslofjord. Sarsia 70(1):1-9.

Witbaard, R., G. C. A. Duineveld, M. J. N. Bergman, H. I. J. Witte, L. Groot, and M. J. C. Rozemeijer. 2015. The growth and dynamics of *Ensis directus* in the near-shore Dutch coastal zone of the North Sea. Journal of Sea Research 95:95-105.

Witbaard, R., M. I. Jenness, K. Van der Borg, and G. Ganssen. 1994. Verification of annual growth increments in *Arctica islandica* L. from the North Sea by means of oxygen and carbon isotopes. Netherlands Journal of Sea Research 33(1):91-101.

Wolf, B. M., and R. W. G. White. 1995. Age and growth of the queen scallop, *Equichlamys bifrons*, in the D'Entrecasteaux Channel and Huon River Estuary, Tasmania. Marine and Freshwater Research 46(8):1127-1135.

Wolf, W. J., and L. de Wolf. 1977. Biomass and production of zoobenthos in the Grevelingen Estuary, the Netherlands. Estuarine and Coastal Marine Science 5:1-24.

Wolfe, D. A., and E. N. Petteway. 1968. Growth of *Rangia cuneata* Gray. Chesapeake Science 9(2):99-102.

Wolff, W. J., A. Gueye, A. Meijboom, T. Piersma, and M. A. Sall. 1987. Distribution, biomass, recruitment and productivity of *Anadara senilis* (L.)(Mollusca: Bivalvia) on the Banc d'Arguin, Mauritania. Netherlands Journal of Sea Research 21(3):243-253.

Wolowicz, W. 1980. Characteristics of the *Cardium glaucum* Bivalvia population in Gdanfsk Bay growth rate, age mortality. International Council for the Exploration of the Sea 1:1-10.

Xavier, B. M., G. M. Branch, and E. Wieters. 2007. Abundance, growth and recruitment of *Mytilus galloprovincialis* on the west coast of South Africa in relation to upwelling. Marine Ecology Progress Series 346:189-201.

Yan, L., B. R. Schöne, S. Li, and Y. Yan. 2014. Shells of *Paphia undulata* (Bivalvia) from the South China Sea as potential proxy archives of the East Asian summer monsoon: a sclerochronological calibration study. Journal of Oceanography 70(1):35-44.

Yap, W. G. 1977. Population biology of the Japanese little-neck clam, *Tapes philippinarum*, in Kaneohe Bay, Oahu, Hawaiian Islands. Pacific Science 31(3):223-244.

Yavnov, S. V., and V. Ignat'ev. 1979. Shell structure and growth temperature of mollusks, family Mactridae. Biologiya Morya 44(5):409-414.

Zeichen, M. M., S. Agnesi, A. Mariani, A. Maccaroni, and G. D. Ardizzone. 2002. Biology and Population Dynamics of *Donax trunculus* L. (Bivalvia: Donacidae) in the South Adriatic Coast (Italy). Estuarine, Coastal and Shelf Science 54(6):971-982.

Zeinalipour, M., B. H. Kiabi, M. R. Shokri, and A. A. Ardalan. 2014. Population dynamic and distribution of *Barbatia decussata* (Bivalvia: Arcidae) on rocky intertidal shores in the northern Persian Gulf (Iran). Tropical Zoology 27(3):73-87.

Zettler, M. L., R. Bonsch, and F. Gosselck. 2001. Distribution, abundance and some population characteristics of the ocean quahog, *Arctica islandica* (Linnaeus, 1767), in the Mecklenburg Bight (Baltic Sea). Journal of Shellfish Research 20(1):161-169.

Ziuganov, V., E. S. Miguel, R. J. Neves, A. Longa, C. Fernández, R. Amaro, V. Beletsky, E. Popkovitch, S. Kaliuzhin, and T. Johnson. 2000. Life Span Variation of the Freshwater Pearl Shell: A Model Species for Testing Longevity Mechanisms in Animals. AMBIO: A Journal of the Human Environment 29(2):102-105.

Zolotarev, V. N. 1980. The life span of bivalves from the Sea of Japan and Sea of Okhotsk. The Soviety Journal of Marine Biology 6:3-12.

References Cited

Ahn, I., J. Surh, Y. Park, H. Kwon, K. Choi, S. Kang, H. Choi, K. Kim, and H. Chung. 2003. Growth and seasonal energetics of the Antarctic bivalve Laternuala elliptica from King George Island, Antarctica. Marine Ecology Progress Series 257:99-110.

Alroy, J. 2010. Geographical, environmental and intrinsic biotic controls on Phanerozoic marine diversification. Palaeontology 53(6):1211-1235.

Alroy, J., M. Aberhan, D. Bottjer, M. Foote, F. Fursich, P. Harries, A. Hendy, S. Holland, L. Ivany, W. Kiessling, M. Kosnik, C. R. Marshall, A. McGowan, A. Miller, P. Wagner, N. Bonuso, P. Borkow, B. Brenneis, M. Clapham, L. Fall, C. Ferguson, V. Hanson, A. Krug, K. Layou, E. Leckey, S. Nurnberg, C. Powers, J. Sessa, C. Simpson, A. Tomasovych, and C. Visaggi. 2008. Phanerozoic trends in global diversity of marine invertebrates. Science 321:97-100.

Ambrose, W. G., P. E. Renaud, W. L. Locke, F. R. Cottier, J. Berge, M. L. Carroll, B. Levin, and S. Ryan. 2011. Growth line deposition and variability in growth of two circumpolar bivalves (Serripes groenlandicus, and Clinocardium ciliatum). Polar Biology 35(3):345-354.

Ambrose, W. G. J., D. S. Jones, and I. Thompson. 1980. Distance from shore and growth rate of the suspension feeding bivalve, *Spisula solidissima*. Proceedings of the National Shellfisheries Association 70:207-215.

Aronson, R. B., D. B. Blake, and T. Oji. 1997. Retrograde community structure in the late Eocene of Antarctica. Geology 25(10):903-906.

Aronson, R. B., R. M. Moody, L. C. Ivany, D. B. Blake, J. E. Werner, and A. Glass. 2009. Climate change and trophic response of the Antarctic bottom fauna. PLOS ONE 4(2):e4385.

Aronson, R. B., S. Thatje, A. Clarke, L. S. Peck, D. B. Blake, C. D. Wilga, and B. A. Seibel. 2007. Climate change and invasibility of the Antarctic benthos. Annual Review of Ecology, Evolution, and Systematics 38(1):129-154.

Austad, S. N. 1989. Life extension by dietary restriction in the bowl and doil spider, *Frontinella pyramitela*. Exp Gerontol 24:83-92.

Bambach, R. 1993. Seafood through time: Changes in biomass, energetics, and productivity in the marine ecosystem. Paleobiology 19(3):372-397.

Bartoo, N. W., and K. R. Parker. 1983. Stochastic age-frequency estimation using the von Bertalanffy growth equation. Fishery Bulletin 81(1):91-96.

Beard, J. A., L. C. Ivany, and B. Runnegar. 2015. Gradients in seasonality and seawater oxygen isotopic composition along the early Permian Gondwanan coast, SE Australia. Earth and Planetary Science Letters 425:219-231.

Beierlein, L., G. Nehrke, T. Trofimova, and T. Brey. 2015. Bivalve Shells—Unique High-Resolution Archives of the Environmental Past.173-182.

Belding, D. 1910. The growth and habits of the sea clam (*Macta solidissima*). Report of the Department of Commercial Fish and Game Massachusetts 25.

Berke, S. K., D. Jablonski, A. Z. Krug, K. Roy, and A. Tomasovych. 2013. Beyond Bergmann's rule: size-latitude relationships in marine Bivalvia world-wide. Global Ecology and Biogeography 22(2):173-183.

Bertness, M. D., S. D. Garrity, and S. C. Levings. 1981. Predation pressure and gastropod foraging:a tropical-temperate comparison. Evolution 35:995-1007.

Bettoli, P. W., and L. E. Miranda. 2001. Cautionary Note about Estimating Mean Length at Age with Subsampled Data. North American Journal of Fisheries Management 21(2):425-428.

Beu, A. G. 2009. Before the ice: Biogeography of Antarctic Paleogene molluscan faunas. Palaeogeography, Palaeoclimatology, Palaeoecology 284(3-4):191-226.

Brandhorst, S., I. Y. Choi, M. Wei, C. W. Cheng, S. Sedrakyan, G. Navarrete, L. Dubeau, L. P. Yap, R. Park, M. Vinciguerra, S. Di Biase, H. Mirzaei, M. G. Mirisola, P. Childress, L. Ji, S. Groshen, F. Penna, P. Odetti, L. Perin, P. S. Conti, Y. Ikeno, B. K. Kennedy, P. Cohen, T. E. Morgan, T. B. Dorff, and V. D. Longo. 2015. A Periodic Diet that Mimics Fasting Promotes Multi-System Regeneration, Enhanced Cognitive Performance, and Healthspan. Cell Metab 22(1):86-99.

Brey, T., and A. Clarke. 1993. Population dynamics of marine benthic invertebrates in Antarctic and subantarctic environments: are there unique adaptations. Antarctic Science 5(3):253-266.

Brey, T., and S. Hain. 1992. Growth, reproduction and production of *Lissarca notorcadensis* (Bivalvia:Philobryidae) in the Weddell Sea, Antarctica. Marine Ecology Progress Series 82:219-226.

Brey, T., and A. Mackensen. 1997. Stable isotopes prove shell growth bands in the Antarctic bivalve *Laternual elliptica* to be formed annually. Polar Biology 17:465-468.

Brey, T., L. S. Peck, J. Gutt, S. Hain, and W. E. Arntz. 1995. Population dynamics of Magellania fragilis, a brachiopod dominating a mixed-bottom macrobenthic assemblage on the

Antarctic shelf. Journal of the Marine Biological Association of the United Kingdom 75:857-869.

Brey, T., M. Voigt, K. Jenkins, and I. Ahn. 2011. The bivalve Laternula elliptica at King George Island — A biological recorder of climate forcing in the West Antarctic Peninsula region. Journal of Marine Systems 88(4):542-552.

Brockington, S. 2001. The seasonal energetics of the Antarctic bivalve Laternaula elliptica (King and Broderip) at Rother Point, Adelaide Island. Polar Biology 24:523-530.

Brockington, S., and A. Clarke. 2001. The relative influence of temperature and food on the metabolism of a marine invertebrate. Journal of Experimental Marine Biology and Ecology 258:87-99.

Brodte, E., R. Knust, H. O. Pörtner, and W. E. Arntz. 2006. Biology of the Antarctic eelpout Pachycara brachycephalum. Deep Sea Research Part II: Topical Studies in Oceanography 53(8-10):1131-1140.

Buick, D. P., and L. C. Ivany. 2004. 100 years in the dark: Extreme longevity of Eocene bivalves from Antarctica. Geology 32(10):921-924.

Burchett, M. S., A. Devries, and A. J. Briggs. 1984. Age determination and growth of Dissostichus mawsoni (Norman, 1937) (Pisces, Nototheniidae) from McMurdo Sound (Antarctica). Cybium 8:27-31.

Butler, P. G., A. D. Wanamaker, J. D. Scourse, C. A. Richardson, and D. J. Reynolds. 2013. Variability of marine climate on the North Icelandic Shelf in a 1357-year proxy archive based on growth increments in the bivalve *Arctica islandica*. Palaeogeography, Palaeoclimatology, Palaeoecology 373:141-151.

Campana, S. 2001. Accuracy, precision and quality control in age determination, including a review of the use and abuse of age validation methods. Journal of Fish Biology 59(2):197-242.

Camus, L., B. Gulliksen, M. H. Depledge, and M. B. Jones. 2005. Polar bivalves are characterized by high antioxidant defences. Polar Research 24(1-2):111-118.

Cerrato, R., and D. Keith. 1991. Age structure, growth, and morphometric variations in the Atlantic surf clam, *Spisula solidissima,* from estuarine and inshore waters. Marine Biology 114:581-593.

Clark, G. 1974. Growth lines in invertebrate skeletons. Annual Review of Earth and Planetary Science 2:77-99.

Clarke, A., E. Prothero-Thomas, J. Beaumont, A. Chapman, and T. Brey. 2004. Growth in the limpet Nacella concinna from contrasting sites in Antarctica. Polar Biology.

Colman, R. J., T. M. Beasley, J. W. Kemnitz, S. C. Johnson, R. Weindruch, and R. M. Anderson. 2014. Caloric restriction reduces age-related and all-cause mortality in rhesus monkeys. Nat Commun 5:3557.

Comfort, A. 1957. The duration of life in molluscs. Proceedings of the Malacological Soceity of London 32(6):219-241.

Dexter, T. A., and M. Kowalewski. 2013. Jackknife-corrected parametric bootstrap estimates of growth rates in bivalve mollusks using nearest living relatives. Theor Popul Biol 90:36-48.

Douglas, P. M., H. P. Affek, L. C. Ivany, A. J. Houben, W. P. Sijp, A. Sluijs, S. Schouten, and M. Pagani. 2014. Pronounced zonal heterogeneity in Eocene southern high-latitude sea surface temperatures. Proc Natl Acad Sci U S A.

Dudley, E., and G. Vermeij. 1980. Predation in time and space: drilling in the gastropod Turritella. Paleobiology 4(4):436-441.

Dutton, A., B. T. Huber, K. C. Lohmann, and W. J. Zinsmeister. 2007. High-Resolution Stable Isotope Profiles of a Dimitobelid Belemnite: Implications for Paleodepth Habitat and Late Maastrichtian Climate Seasonality. Palaios 22(6):642-650.

Dutton, A. L., K. C. Lohmann, and W. J. Zinsmeister. 2002. Stable isotope and minor element proxies for Eocene climate of Seymour Island, Antarctica. Paleoceanography 17(2):1-13.

Fanestil, D., and C. Barrows. 1965. Aging in the rotifer. Journal of Gerontology 20(4):462-469.

Feldmann, R. M., and M. O. Woodburne. 1988. Geology and paleontology of Seymour Island, Antarctic Peninsula. Geological Society of America Memoir.

Finnegan, S., C. McClain, M. Kosnik, and J. Payne. 2011. Escargots through time: an energetic comparison of marine gastropod assemblages before and after the Mesozoic Marine Revolution. Paleobiology 37(2):252-269.

Fontana, L., L. Partridge, and V. D. Longo. 2010. Extending healthy life span-from yeast to humans. Science 328.

Francis, J. E., and I. Poole. 2002. Cretaceous and early Tertiary climates of Antarctica: evidence from fossil wood. Palaeogeography, Palaeoclimatology, Palaeoecology 182:47-64.

Freestone, A. L., R. W. Osman, G. M. Ruiz, and M. E. Torchin. 2011. Stronger predation in the tropics shapes species richness patterns in marine communitites. Ecology 92(4):983-993.

Fridriksson, A. 1934. On the calculation of age-distribution within a stock of cod by means of relatively few age-determinations as a key to measurements on a large scale. Rapports et proce s-verbaux des re unions 6:1-5.

Gillooly, J. F., J. H. Brown, G. B. West, V. M. Savage, and E. L. Charnov. 2001. Effects of size and temperature on metabolic rate. Science 293(5538):2248-51.

Goodwin, D. H., K. W. Flessa, B. R. Schone, and D. L. Dettman. 2001. Cross-calibration of daily growth increments, stable isotope variation, and temperature in teh Gulf of California bivalve mollusk Chione cortezi: Implications for paleoenvironmental analysis. Palaios 16:387-398.

Hairston, N. G. J., and N. G. S. Hairston. 1993. Cause-effect relationships in energy flow, trophic structure, and interspecific interactions. The American Naturalist 142(3):379-411.

Hallmann, N., B. R. Schöne, A. Strom, and J. Fiebig. 2008. An intractable climate archive — Sclerochronological and shell oxygen isotope analyses of the Pacific geoduck, Panopea abrupta (bivalve mollusk) from Protection Island (Washington State, USA). Palaeogeography, Palaeoclimatology, Palaeoecology 269(1-2):115-126.

Harper, E. M., and L. Peck. 2003. Predatory behaviour and metabolic costs in the Antarctic muricid gastropod *Trophon longstaffi*. Polar Biology 26:208-217.

Harper, E. M., and L. S. Peck. 2016. Latitudinal and depth gradients in marine predation pressure. Global Ecology and Biogeography 25(6):670-678.

Hart, D. R., and A. S. Chute. 2009. Estimating von Bertlanffy growth parameters from growth increment data using a linear mixed-effects model, with an application to the sea scallop *Placopecten magellanicus* ICES Journal of Marine Science 66:2165-2175.

Hastie, L. C. 2006. Determination of mortality in exploited freshwater pearl mussel (Margaritifera margaritifera) populations. Fisheries Research 80(2-3):305-311.

Haveles, A., and L. C. Ivany. 2010. Rapid growth of mollusks in the Eocene Gosport Sand, U.S. Gulf Coast. Palaios 25(9):550-564.

Hay, W. W., and S. Floegel. 2012. New thoughts about the Cretaceous climate and oceans. Earth-Science Reviews 115(4):262-272.

Heim, N., M. Knope, E. Schaal, S. Wang, and J. Payne. 2015. Cope's rule in the evolution of marine animals. Science 347(6224):867-870.

Heller, J. 1990. Longevity in molluscs. Malacologia 31:259-295.

Hillbebrand, H. 2004. On the generality of the latititudinal diversity gradient. American Society of Naturalists 163(2):192-211.

Hofmann, E. F., J. M. Klinkc, J. N. Kraeuter, E. N. Powell, R. E. Grizzle, S. C. Buckner, and V. M. Bricelj. 2006. A population dynamics model of the hard clam, *Mercenaria mercenaria*:development of hte Age- and Length-frequency structure of the population. Journal of Shellfish Research 25(2):417-444.

Huber, M., and L. C. Sloan. 2001. Heat transport, deep waters, and thermal gradients: Coupled simulation of an Eocene greenhouse climate. Geophysical Research Letters 28(18):3481-3484.

Ivany, L., ed. 2012. Reconstructing paleoseasonality from accretionary skeletal carbonates-challenges and opportunities. The Paleontological Society.

Ivany, L. C., K. C. Lohmann, F. Hasiuk, D. Blake, A. Glass, R. Aronson, and R. Moody. 2008. Eocene climate record of a high souther latitude continental shelf: Seymour Island, Antarctica. Geological Society of America Bulletin 120:659-678.

Ivany, L. C., and B. Runnegar. 2010. Early Permian seasonality from bivalve 18O and implications for the oxygen isotopic composition of seawater. Geology 38(11):1027-1030.

Jablonski, D., K. Roy, and J. W. Valentine. 2006. Out of the tropics: evolutionary dyanmics of the latitudinal diversity gradient. Science 314:102-106.

Jablonski, D., J. J. Sepkoski, D. Bottjer, and P. Sheehan. 1983. Onshore-offshore patterns in the evolution of Phanerozoic shelf communities. Science 222:1123-1125.

Jones, D. S. 1980. Annual cycle of shell growth increment formation in two continental shelf bivalves and its paleoecologic significance. Paleobiology 6(3):331-340.

Jones, D. S. 1983. Sclerochronology: Reading the Record of the Molluscan Shell: Annual growth increments in the shells of bivalve molluscs record marine climatic changes and reveal surprising longevity. American Scientist 71(4):384-391.

Jones, D. S., ed. 1988. Sclerochronology and the size versus age problem. Plenum Publishing Corporation.

Jones, D. S., M. A. Arthur, and D. J. Allard. 1989. Sclerochronological records of temperature and growth from shells of *Mercenaria mercenaria* from Narragansett Bay, Rhode Island. Marine Biology 102:225-234.

Jones, D. S., and S. J. Gould. 1999. Direct measurement of age in fossil *Gryphaea*: the solution to a classic problem in heterochrony. Paleobiology 25(2):158-187.

Jones, D. S., and I. R. Quitmyer. 1996. Marking time with bivalve shells: oxygen isotopes and season of annual increment formation. Palaios 11(4):340-346.

Jones, D. S., I. Thompson, and W. Ambrose. 1978a. Age and growth rate determinations for the Atlantic surf clam *Spisula solidissima* (Bivalvia:Mactracea), based on internal growth lines in shell cross-sections. Marine Biology 47:63-70.

Jones, D. S., I. Thompson, and W. G. J. Ambrose. 1978b. Age and growth rate determinations for the Atlantic surf clam *Spisula solidissima* (Bivalvia: Mactracea), based on interal growth lines in shell cross-sections. Marine Biology 47:63-70.

Jones, D. S., D. F. Williams, and M. A. Arthur. 1983. Growth history and ecology of the Atlantic surf clam, *Spisula solidissima* (Dillwyn), as revealed by stable isotopes and shell increments. Journal Experimental Marine Biology and Ecology 73:225-242.

Kelley, P., and T. Hansen. 2007. Latitudinal patterns in naticid gastropod predation along the east coast of the United States: a modern baseline for interpreting temporal patterns in the fossil record. Pp. 287-289. *In* B. R., L. Buatois, M. Mangano, J. Genise, and R. Melchor, eds. Sediment-Organism Interactions: A Multifaceted Ichnology. SEMP Special Publication.

Kemp, D. B., S. A. Robinson, J. A. Crame, J. E. Francis, J. Ineson, R. J. Whittle, V. Bowman, and C. O'Brien. 2014. A cool temperate climate on the Antarctic Peninsula through the latest Cretaceous to early Paleogene. Geology 42(7):583-586.

Kidwell, S., and T. Rothfus. 2010. The living, the dead, and the expected dead: variation in life span yields little bias of proportional abundances in bivalve death assemblages. Paleobiology 36(4):615-640.

Kimura, D. K. 1977. Statistical assessment of the age-length key. Journal of the Fisheries Research Board of Canada 34:317-324.

Klass, M. 1977. Aging in the nematode *Caenorhabditis elegans*: Major biological and enivronmental factors influencing life span. Mechanisms of Ageing and Development 6:413-429.

Koslow, J. 2000. Continental slope and deep-sea fisheries: implications for a fragile ecosystem. ICES Journal of Marine Science 57(3):548-557.

Krantz, D. E., D. S. Jones, and D. F. Williams. 1984. Growth rates of the sea scallop, Placopecten magellanicus, determine from the 18O/16O record in shell calcite. Biological Bulletin 167:186-199.

Lakowski, B., and S. Hekimi. 1996. Determination of life-span in *Caenorhabditis elegans* by four clock genes. Science 272(5264):1010-1013.

Lawver, L. A., L. M. Gahagan, and M. F. Coffin. 1992. The development of paleoseaways around Antarctica. Pp. 7-30. The Antarctic Paleoenvironment: A Perspective on Global Change.

Lewis, D. E., and R. M. Cerrato. 1997. Growth uncoupling and the relationship between shell growth and metabolism in the soft shell clam *Mya arenaria*. Marine Ecology Progress Series 158:177-189.

Locarnini, R. A., A. V. Mishonov, J. I. Antonov, T. P. Boyer, H. E. Garcia, O. K. Baranova, M. M. Zweng, C. R. Paver, J. R. Reagan, D. R. Johnson, M. Hamilton, and D. Seidova. 2013. World Ocean Atlas.

Lomovasky, B. J., T. Brey, E. Morriconi, and J. Calvo. 2002. Growth and reporduction of the venerid bivalve *Eurhomalea exalbida* in the Beagle Channel, Tierra del Fuego. Journal of Sea Research 48:209-216.

Lutz, R. A., and M. C. Rhoads. 1980. Growth Patterns within the Molluscan Shell: An Overview. Pp. 203-254. *In* M. C. Rhoads, and R. A. Lutz, eds. Skeletal Growth of Aquatic Organisms: Biological Records of Environmental Change. Plenum Press, New York.

MacDonald, B., and M. Thomas. 1980. Age determination of the soft-shell clam *Mya arenaria* using shell internal growth lines. Marine Biology 58:105-109.

Macellari, C. 1984. Late Cretaceous stratigraphy, sedimentology, and macropaleontology of Seymour Island, Antarctic Peninsula. The Ohio State University, Columbus.

Macellari, C. 1988. Stratigrpahy, sedimentology, and paleoecology of Upper Cretaceous/Paleocene shelf-deltaic sediments of Seymour Island. Geological Society of America Memoir 169:25-33.

Marshall, C. R. 1995. Distinguishing between sudden and gradual extinctions in the fossil record: Predicting the position of the Cretaceous-Tertiary iridium anomaly using the ammonite fossil record on Seymour Island, Antarctica. Geology 23(8):731-734.

Martinelli, J. C., S. Gordillo, and F. Archuby. 2013. Muricid drilling predation at high latitudes: Insights from the southernmost Atlantic. Palaios 28(1):33-41.

Masoro, E. J. 2000. Caloric restriction and aging: an update. Exp Gerontol 35:299-305.

McKay, C. M., M. F. Crowell, and L. A. Maynard. 1935. The effect of retarded growth upon the length of life span and upon the ultimate body size. The Journal of Nutrition 10:63-79.

Mette, M. J., A. D. Wanamaker, M. L. Carroll, W. G. Ambrose, and M. J. Retelle. 2016. Linking large-scale climate variability withArctica islandicashell growth and geochemistry in northern Norway. Limnology and Oceanography 61(2):748-764.

Moss, D. K., L. C. Ivany, E. J. Judd, P. C. Cummings, C. E. Bearden, J. Kim, E. G. Artruc, and J. R. Driscoll. 2016. Lifespan, growth rate, and body size across latitude in marine Bivalvia, with implications for Phanerozoic evolution. Proceedings of the Royal Society B 283.

Munroe, D. M., D. A. Narváez, D. Hennen, L. Jacobson, R. Mann, E. E. Hofmann, E. N. Powell, and J. M. Klinck. 2016. Fishing and bottom water temperature as drivers of change in maximum shell length in Atlantic surfclams (Spisula solidissima). Estuarine, Coastal and Shelf Science 170:112-122.

Narváez, D. A., D. M. Munroe, E. E. Hofmann, J. M. Klinck, E. N. Powell, R. Mann, and E. Curchitser. 2015. Long-term dynamics in Atlantic surfclam (Spisula solidissima) populations: The role of bottom water temperature. Journal of Marine Systems 141:136-148.

Neville, W. 1945. The Quahog Fishery of Rhode Island. Department of Agriculture and Conservation of the State of Rhode Island.

Norton, I. O., and J. G. Sclater. 1979. A model for the evolution of the Indian Ocean and the breakup of Gondwanaland. Journal of Geophysical Research: Solid Earth 84(B12):6803-6830.

Oji, T. 1996. Is predation intensity reduced with increasing depth? Evidence from the West Atlantic stalked crinoid Endoxocrinus parrae (Gervais) and implications for the Mesozoic Marine Revolution. Paleobiology 22(3):339-351.

Pannella, G. 1976. Tidal growth patterns in recent and fossil mollusc bivalve shells: a tool for the reconstruction of paleotides. Die Naturwissenschaften 63:539-543.

Pannella, G., and C. MacClintock. 1968. Biological and environmental rhythms reflected in molluscan shell growth The Paleontological Society Meomoir 42(5):64-80.

Payne, J. L., A. G. Boyer, J. H. Brown, S. Finnegan, M. Kowalewski, R. A. Krause, Jr., S. K. Lyons, C. R. McClain, D. W. McShea, P. M. Novack-Gottshall, F. A. Smith, J. A. Stempien, and S. C. Wang. 2009. Two-phase increase in the maximum size of life over 3.5 billion years reflects biological innovation and environmental opportunity. Proc Natl Acad Sci U S A 106(1):24-7.

Payne, J. L., N. A. Heim, M. L. Knope, and C. R. McClain. 2014. Metabolic dominance of bivalves predates brachiopod diversity decline by more than 150 million years. Proc Biol Sci 281(1783):20133122.

Peck, L. S., S. Brockington, and T. Brey. 1997. Growth and metabolism in the Antarctic brachiopod Liothyrella unva. Philosophical Transactions of the Royal Society of London B 352:851-858.

Peck, L. S., P. Convey, and D. K. Barnes. 2006. Environmental constraints on life histories in Antarctic ecosystems: tempos, timings and predictability. Biol Rev Camb Philos Soc 81(1):75-109.

Peck, L. S., and L. Z. Conway. 2000. The myth of metabolic cold adaptation: Oxygen consumption in stenothermal Antarctic bivalves. Pp. 441-450. *In* E. M. Harper, ed. The evolutionary biology of the bivalvia. Geological Society [London] Special Publication, London.

Peterson, C. H., P. B. Duncan, H. C. Summerson, and G. W. Safrit. 1983. A mark-recapture test of annual periodicity of internal growth band deposition in shells of hard clams, *Mercenaria mercenaria*, from a population along the southeastern United States. Fishery Bulletin 81(4):765-799.

Philipp, E., T. Brey, O. Heilmayer, D. Abele, and H. Portner. 2006. Physiological ageing in a temperatre and a polr swimming scallop. Marine Ecology Progress Series 307:187-198.

Picken, G. B. 1980. The distribution, growth, and reproduction of the Antarctic Limpet *Nacella* (*Patinigera*) *concinna* (Strebel, 1908). Journal Experimental Marine Biology and Ecology 42:71-85.

Porebski, S. 1995. Facies architecture in a tectonically-controlled incised-valley estuary: La Meseta Formation (Eocene) of Seymour Island, Antarctic Peninsula. Studia Geologica Polonica 107:7-97.

Porebski, S. 2000. Shelf-valley compound fill produced by fault subsidence and eustatic sea-level changes, Eocene La Meseta Formation, Seymour Island, Antarctica. Geology 28(2):147-150.

Powell, E., and R. J. Stanton. 1985. Estimating biomass and energy flow of molluscs in palaeo-communities. Palaeontology 28:1-34.

Quitmyer, I. R., and D. S. Jones. 1997. The sclerochronlogy of hard clams, *Mercenaria* spp., from the South-Eastern U.S.A.: A method of elucidating the zooarchaeological records of seasonal resources procurement and seasonality in prehistoric shell middens. Journal of Archaeological Science 24:825-840.

Rhoads, D. C., and R. A. Lutz. 1980. Skeletal growth of aquatic organisms. *In* F. G. Stehli, ed. Topics in Geobiology. Plenum Press, New York.

Rhoads, D. C., and G. Pannnella. 1970. The use of molluscan shell growth patterns in ecology and paleoecology. Lethaia 3(2):143-161.

Rice. 1992. The Northern Quahog. The Biology of *Mercenaria mercenaria*. Rhode Island Sea Grant.

Richardson, C. A., D. J. Crisp, N. W. Runham, and L. D. Gruffydd. 1980. The use of tidal growth bands in the shell of Cerastoderma edule to measure seasonal growth rates under cool temperatre and sub-Arctic conditions. Journal of the Marine Biological Association of the United Kingdom 60:977-989.

Ridgway, I., T. J. Bowden, A. Roman-Gonzalez, and C. A. Richardson. 2014. Resistance to oxidative stress is not associated with the exceptional longevity of the freshwater pearl mussel, Margaritifera margaritifera nor three unionid species. Aquatic Sciences 76(2):259-267.

Ridgway, I. D., C. A. Richardson, and S. N. Austad. 2011a. Maximum shell size, growth rate, and maturation age correlate with longevity in bivalve molluscs. J Gerontol A Biol Sci Med Sci 66(2):183-90.

Ridgway, I. D., C. A. Richardson, E. Enos, Z. Ungvari, S. N. Austad, E. E. R. Philipp, and A. Csiszar. 2011b. New Species Longevity Record for the Northern Quahog (=Hard Clam),Mercenaria mercenaria. Journal of Shellfish Research 30(1):35-38.

Robertson, A. 1979. The relationship between annual production: biomass ratios and lifespans for marine macrobenthos. Oecologia 38:193-202.

Ropes, J. W. 1979. Biology and distribution of surf clams (*Spisula solidissima*) and ocean quahogs (*Arctica islandica*) off the Northeast Coast of the United States. Pp. 47-66. Proceedings of Northeast Clam Industries: Management for the Future.

Roy, K., D. Jablonski, and K. Martien. 2000. Invariant size-frequency distributions along a latitudinal gradient in marine bivalves. Proceedings of the National Academy of Sciences 97(24):13150-13155.

Rubner, M. 1908. Das problem der Lebensdauer und seine Beziehungen sum Wachstum und Ernahrung., Oldenbourg, Munich.

Runnegar, B. 1985. Origin and early history of mollusks. *In* D. J. Bottjer, C. S. Hickman, and P. D. Ward, eds. Short Course on Mollusks. University of Tennessee Department of Geological Sciences Studies in Geology, Orlando, Florida.

Sadler, P. M. 1988. Geometry and stratification of uppermost Cretacous and Paleogene units on Seymour Island, northern Antarctic Peninsula. Pp. 303-320. *In* R. M. Feldmann, and M. O. Woodburne, eds. Geology and paleontology of Seymour Island, Antarctica Peninsula. Geological Society of America Memoir.

Sato-Okoshi, W., and K. Okoshi. 2007. Characteristics of shell microstructure and growth analysis of the Antarctic bivalve Laternula elliptica from Lützow-Holm Bay, Antarctica. Polar Biology 31(2):131-138.

Sato, S. 1994. Analysis of the relationship between growth and sexual maturation in *Phacosoma japonicum* (Bivalvia: Veneridae). Marine Biology 118:663-672.

Sato, S. 1995. Spawing periodicity and shell microgrowth patterns of the venerid bivalve *Phacosoma japonicum* (Reeve, 1850). The Veliger 38:61-72.

Sato, S. 1999. Temporal change of life-history traits in fossil bivalves: an example of *Phacosoma japonicum* from the Pleistocene of Japan. Palaeogeography, Palaeoclimatology, Palaeoecology 154:313-323.

Schemske, D. W., G. G. Mittelbach, H. V. Cornell, J. M. Sobel, and K. Roy. 2009. Is There a Latitudinal Gradient in the Importance of Biotic Interactions? Annual Review of Ecology, Evolution, and Systematics 40(1):245-269.

Schöne, B. R., E. Dunca, J. Fiebig, and M. Pfeiffer. 2005. Mutvei's solution: An ideal agent for resolving microgrowth structures of biogenic carbonates. Palaeogeography, Palaeoclimatology, Palaeoecology 228(1-2):149-166.

Schöne, B. R., and D. P. Gillikin. 2013. Unraveling environmental histories from skeletal diaries — Advances in sclerochronology. Palaeogeography, Palaeoclimatology, Palaeoecology 373:1-5.

Schone, B. R., S. D. Houk, A. D. Freyre Castro, J. Fiebig, W. Oschmann, I. Kroncke, W. Dreyer, and F. Gosselck. 2005. Daily Growth Rates in Shells of Arctica islandica: Assessing Sub-seasonal Environmental Controls on a Long-lived Bivalve Mollusk. Palaios 20(1):78-92.

Schöne, B. R., Z. Zhang, P. Radermacher, J. Thébault, D. E. Jacob, E. V. Nunn, and A.-F. Maurer. 2011. Sr/Ca and Mg/Ca ratios of ontogenetically old, long-lived bivalve shells (Arctica islandica) and their function as paleotemperature proxies. Palaeogeography, Palaeoclimatology, Palaeoecology 302(1-2):52-64.

Sejr, M. K., K. T. Jensen, and S. Rysgaard. 2002a. Annual growth bands in the bivalve Hiatella arctica validated by a mark-recapture study in NE Greenland. Polar Biology 25:794-796.

Sejr, M. K., M. K. Sand, K. T. Jensen, J. K. Peterson, P. B. Christensen, and S. Rysgaard. 2002b. Growth and production of *Hiatella arctica* (Bivalvia) in a high-Arctic fjord (Young Sound, Northeast Greenland). Marine Ecology Progress Series 244:163-169.

Sephton, T. W., and C. F. Bryan. 1990. Age and growth rate determination for the Atlantic surf clam, *Spisula solidissima* (Dillwyn, 1817), in Prince Edward Island, Canada. Journal of Shellfish Research 9(1):177-185.

Smith, F. A., J. L. Payne, N. A. Heim, M. A. Balk, S. Finnegan, M. Kowalewski, S. K. Lyons, C. R. McClain, D. W. McShea, P. M. Novack-Gottshall, P. S. Anich, and S. C. Wang. 2016. Body Size Evolution Across the Geozoic. Annual Review of Earth and Planetary Sciences 44(1):523-553.

Speakman, J. R. 2005. Body size, energy metabolism and lifespan. J Exp Biol 208(Pt 9):1717-30.

Stilwell, J. D., and W. J. Zinsmeister. 1992. Molluscan systematics and biostratigraphy: Lower Tertiary La Meseta Formation, Seymour Island, Antarctic Peninsula. American Geophysical Union.

Thomas, J. A., J. J. Welch, R. Lanfear, and L. Bromham. 2010. A generation time effect on the rate of molecular evolution in invertebrates. Mol Biol Evol 27(5):1173-80.

Thompson, I., D. S. Jones, and D. Dreibelbis. 1980. Annual internal growth banding and life history of the Ocean Quahog *Arctica islandica* (Mollusca: Bivalvia). Marine Biology 57:25-34.

Tobin, T. S., and P. D. Ward. 2015. Carbon isotope (δ13C) differences between Late Cretaceous ammonites and benthic mollusks from Antarctica. Palaeogeography, Palaeoclimatology, Palaeoecology 428:50-57.

Tobin, T. S., P. D. Ward, E. J. Steig, E. B. Olivero, I. A. Hilburn, R. N. Mitchell, M. R. Diamond, T. D. Raub, and J. L. Kirschvink. 2012. Extinction patterns, δ18 O trends, and magnetostratigraphy from a southern high-latitude Cretaceous–Paleogene section: Links with Deccan volcanism. Palaeogeography, Palaeoclimatology, Palaeoecology 350-352:180-188.

Torsvik, T. H., R. D. Müller, R. Van der Voo, B. Steinberger, and C. Gaina. 2008. Global plate motion frames: Toward a unified model. Reviews of Geophysics 46(3).

Van Voorhies, W. 2001. Metabolism and lifespan. Exp Gerontol 36:55-64.

Verdone-Smith, C., and H. E. Enesco. 1982. The effect of temperature and of dietary restriction on lifespan and reproduction in the rotifer *Asplanchia brightwelli*. Exp Gerontol 17:252-262.

Vermeij, G. 1977. The Mesozoic Marine Revolution: Evidence from snails, predators, and grazers. Paleobiology 3(3):245-258.

Vermeij, G. 1978. Biogeography and adaptation. Harvard University Press, Cambridge, MA.

Vermeij, G., E. Dudley, and E. Zipser. 1989. Successful and unsuccessful drilling predation in recent pelecypods. The Veliger 32(3):266-273.

Visaggi, C. C., and P. H. Kelley. 2015. Equatorward increase in naticid gastropod drilling predation on infaunal bivalves from Brazil with paleontological implications. Palaeogeography, Palaeoclimatology, Palaeoecology 438:285-299.

Vladimirova, I., S. Kleimenova, and L. Radzinskaya. 2003. The relation of energy metabolism and body weight in bivalves (Mollusca:Bivalvia). Biology Bulletin 30(4):392-399.

von Bertalanffy, L. 1938. A quanitative theory of organic growth (inquiries on growth laws II). Human Biology 10(2):181-213.

Wanamaker, A. D., J. Heinemeier, J. Scourse, C. Richardson, P. G. Butler, J. Eiriksson, and K. L. Knudsen. 2008. Very long-lived mollusks confirm 17th century AD tephra based radiocarbon reservoir ages for north Icelandic shelf waters. Radiocarbon 50(3):399-412.

Weinberg, J. R., and T. E. Helser. 1996. Growth of the Atlantic surfclam, *Spisual solidissima,* from Georges Bank to the Delmarva Peninsula, USA. Marine Biology 126(4):663-674.

Weingber, J. R. 1999. Age-structure, recruitment, and adult mortality in populations of the Atlantic surfclam, *Spisula solidissima,* from 1978 to 1997. Marine Biology 134:113-125.

Westrheim, S. J., and W. E. Ricker. 1978. Bias in using an age-length key to estimate age-frequency distributions. Journal of the Fisheries Research Board of Canada 35:184-189.

Williams, D. F., M. A. Arthur, D. S. Jones, and N. H. Williams. 1982. Seasonality and mean annual sea surface temperatures from isotopic and sclerochronlogical records. Nature 296:432-434.

Witbaard, R., M. I. Jenness, K. van der Borg, and G. Ganssen. 1994. Verification of annual growth increments in Arctica islandica L. from the North Sea by means of oxygen and carbon isotopes. Netherlands Journal of Sea Research 33(1):91-101.

Witts, J. D., V. C. Bowman, P. B. Wignall, J. Alistair Crame, J. E. Francis, and R. J. Newton. 2015. Evolution and extinction of Maastrichtian (Late Cretaceous) cephalopods from the López de Bertodano Formation, Seymour Island, Antarctica. Palaeogeography, Palaeoclimatology, Palaeoecology 418:193-212.

Witts, J. D., R. J. Whittle, P. B. Wignall, J. A. Crame, J. E. Francis, R. J. Newton, and V. C. Bowman. 2016. Macrofossil evidence for a rapid and severe Cretaceous-Paleogene mass extinction in Antarctica. Nat Commun 7:11738.

Woodhead, A. D. 1985. Feral fishes. Interdisciplinary Topics in Gerontology 21:22-50.

Zachos, J., M. Pagani, L. Sloan, E. Thomas, and K. Billups. 2001. Trends, rhythms, and aberrations in global climate 65 Ma to present. Science 292:686-692.

Zachos, J. C., G. R. Dickens, and R. E. Zeebe. 2008. An early Cenozoic perspective on greenhouse warming and carbon-cycle dynamics. Nature 451(7176):279-83.

Zinsmeister, W. J. 1982. Review of the Upper Cretaceous-Lower Tertiary sequence on Seymour Island, Antarctica. Journal of the Geological Society 139(6):779-785.

Zinsmeister, W. J. 1984. Late Eocene Bivalves (Mollusca) from the La Meseta Formation, Collected during the 1974-1975 Joint Argentine-American Expedition to Seymour Island, Antarctic Peninsula. Journal of Paleontology 58(6):1497-1527.

Zinsmeister, W. J., R. M. Feldmann, M. O. Woodburne, and D. H. Elliot. 1989. Latest Cretaceous/Earliest Tertiary transition on Seymour Island, Antarctica. Journal of Paleontology 63(6):731-738.

Zinsmeister, W. J., and C. E. Macellari. 1988. Bivalvia (Mollusca) from Seymour Island, Antarctic Peninsula. *In* R. M. Feldmann, and M. O. Woodburne, eds. Geology and paleontology of Seymour Island, Antarctica Peninsula. Geological Society of America Memoir.

DAVID MOSS

EDUCATION

Syracuse University, Syracuse, NY
Ph.D. Earth Sciences **2016**
Dissertation: The evolution of extreme longevity in modern and fossil bivalves

University of Oklahoma, Norman, OK
M.S. Geology **2012**
Thesis: Trilobite faunas and facies of the Upper Ordovician (Sandbian) Lebanon Limestone, Nashville Dome Tennessee

Centenary College of Louisiana, Shreveport, LA
B.S. Geology with Honors **2010**
Honors Thesis: Pliocene development of great white shark serrations

AWARDS

Certificate in University Teaching, Syracuse University	**2016**
3 Minute Thesis, Syracuse University, 1st place	**2016**
Outstanding Teaching Assistant Award, National Association of Geoscience Teachers	**2015**
Outstanding Teaching Assistant, Syracuse University	**2014**
Department of Earth Sciences Publication Award, Syracuse University	**2014**
Outstanding Senior Geology Major, Centenary College	**2010**

TEACHING EXPERIENCE

INSTRUCTOR

Syracuse University, Syracuse, NY **Summer 2015**
Earth Science (EAR 105)
Introductory course in physical geology intended for non-majors, summer session enrolls ≈25 students

State University of New York, Oswego, NY **Spring 2015**
Historical Geology Laboratory (GEO 201)
Laboratory for majors and non-majors (mostly education), enrolls ≈20 Students

TEACHING ASSISTANT

Syracuse University, Syracuse, NY **2012-present**

Introduction to Paleobiology (EAR 325)

Laboratory section enrolls ≈15 students commonly majors and biology majors, developed new material and taught lab, guest lectured for lecture section

Oceanography (EAR 117)*

Four recitation sections of ≈30 students, primarily non-majors, helped develop assignments

Dynamic Earth (EAR 110)*

Three labs of 20 science majors, helped develop assignments

Earth Science (EAR 105)*

Four recitation sections of ≈30 students, intended for non-majors, helped develop assignments

Volcanoes and Earthquakes (EAR 225)

Two recitation sections of ≈30 students, intended to fulfill science requirements

*Served as TA coordinator

University of Oklahoma, Norman, OK **2010-2012**

The Dynamic Earth (GEOL 1104)

Two lab sections for non-science majors of ≈20 students

Physical Geology for Science and Engineering Majors (GEOL 114)

Two lab sections for science majors of ≈20 students

The History of Earth and Life (GEOL 1024)

One lab section of ≈20 students, developed material

TEACHER DEVELOPMENT

Teaching Controversial Issues-Climate & Energy (GSA) **November 2015**
Teaching Controversial Issues-Evolution of Life & Earth (GSA)
Syracuse University Project Advance (SUPA) **April 2014**
Invited speaker to workshop for high school Earth Science teachers teaching courses for Syracuse University credit - Syracuse & New York City

UNDERGRADUATE RESEARCH SUPERVISED

Steve Harris, Syracuse University **Fall 14-Spring 15**
Lifespan and growth rate of Pliocene *Glycymeris subovata* from the Atlantic Coastal Plain

Lauren Williamson, Colorado College **Summer 2015**
Latitude and growth rate in Pliocene *Glycymeris americana*

Emily Artruc, SUNY College of Environmental Science and Forestry **Fall 14-Spring 15**
Lifespans of Eocene Antarctic bivalves. Literature search of lifespans and growth rates in modern bivalves

RESEARCH GRANTS

Paleontological Society Allison R. "Pete" Palmer Award
"The role of phylogeny in the evolution of extreme longevity in bivalves" ($800) **2014**

Graduate Student Organization Research Grant, Syracuse University
"The role of phylogeny in the evolution of extreme longevity in bivalves" ($500) **2014**

Geological Society of America Graduate Student Research Grant
"The role of phylogeny in the evolution of extreme longevity in bivalves" ($900) **2014**

"The evolution of extreme longevity in bivalves" ($2125) **2013**

TRAVEL GRANTS

Syracuse University Earth Sciences Department travel funding to Fossilworks Workshop ($1500)	**2014**
Syracuse University Graduate Student Organization Travel Grant ($900)	**2012, 2013, 2015, 2016**
Syracuse University Prucha Research Fund ($300)	**2013**
Geological Society of America Northeastern section Student Travel Grant ($100, $200, $100)	**2012, 2013, 2015**
Geological Society of America Central section Student Travel Grant ($250)	**2011**

PUBLICATIONS

Moss, David K., Ivany, Linda C., Judd, Emily J., Cummings, Partrick W., Bearden, Claire E., Kim, Woo-Jun, Artruc, Emily G., and Driscoll, Jeremy R. Latitudinal patterns in lifespan and growth rate across modern marine bivalves with implications for Phanerozoic evolution. Proceedings of the Royal Society B, 238.

Moss, David K. and Westrop, Stephen R. 2014. Systematics of some Late Ordovician encrinurid trilobites from North America. Journal of Paleontology, v. 88, p. 1095-1119.

PUBLISHED ABSTRACTS

Moss, David K., Ivany, Linda C., Judd, Emily J., Cummings, Partrick W., Bearden, Claire E., Kim, Woo-Jun, Artruc, Emily G., and Driscoll, Jeremy R. 2015. Latitudinal patterns in lifespan and growth rate across modern marine bivalves. Geological Society of American Abstracts with Programs. v. 47, p. 668.

Moss, David K. and Ivany, Linda C. 2014. Environmental controls on extreme longevity in modern and fossil bivalves. North American Paleontological Convention. The Paleontological Society Special Publications, v. 13, p.26.

Moss, David K. And Ivany, Linda, C. 2013. The role of the environment in the evolution of extreme longevity in bivalves. Geological Society of America Abstracts with Programs, Annual Meeting. Vol. 45, no. 7, p.320.

Moss, David K. and Westrop, Stephen R. 2012. Sorting through a paraphyletic garbage can: A phylogenetic analysis of Middle and Upper Ordovician "*Encrinuoides*" (Trilobita) species from Laurentian North America. Geological Society of America, Abstracts with Programs, v. 44, no. 7, p. 233.

Moss, David K. And Westrop, Stephen R. 2011. Trilobite Biofacies and Lithofacies of the Upper Ordovician (Sandbian) Lebanon Limestone, Nashville Dome, Tennessee. Geological Society of America, Abstracts with Programs, v. 43, no. 5, p.83.

PRESENTATIONS

Geological Society of America	**November 2015**
Central NY Paleo Group (*Invited*)	**October 2015**
Central NY Earth Sciences Student Symposium	**April 2015**
Rochester Academy of Science, Fossil Division (*Invited*)	**December 2014**
Paleontological Research Institution Summer Symposium	**August 2014, 2015**
Syracuse University Project Advance (*Invited*)	**April 2014**
North American Paleontological Convention	**February 2014**
Central NY Paleo Group (*Invited*)	**Feb 2014**

WORKSHOPS

Fossilworks Intensive Workshop in Analytical Paleobiology **Summer 2014**
Macqaurie University, Sydney, Australia
Analytical methods in paleoecology, diversity, morphometrics, and phylogenetics using R

OUTREACH ACTIVITIES

Syracuse University Frontiers of Science Program **Fall 2012-2015**
Instructor for Earth Sciences day, activities have included “Fossils of New York”, “Sediments of Hyde Park Mammoth Site”, “Reconstructing human ancestry”, “Evolution of great white sharks”

National Fossil Day Jamesville-Dewitt Middle School **Fall 2012-2014**
Visited four classrooms, “what can fossils tell us?”

Liverpool High School department visit day **Fall 2012, 2014**
Research topics in geosciences for 9th grade students, helped organize and presented

Little Luke’s Preschool Dewitt, NY **Spring 2014, 2015**
Visited four classrooms, “what is a fossil?”

Syracuse University Orange Scholars Summer Program **2013**

Assisted lead instructor with activities and ran evolution of great white sharks exercise

LEADERSHIP ROLES

Geology Graduate Organization (GeoGO) Chair **Spring 2014-2016**

Founding member, run meetings and set organizational goals, serve as primary graduate student-faculty liaison

PROFESSIONAL MEMBERSHIPS

National Association of Geoscience Teachers
Geological Society of America
Paleontological Society
Sigma Xi