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Developing a sclerochronology network in the Adriatic Sea: Growth synchrony among populations of *Callista chione*

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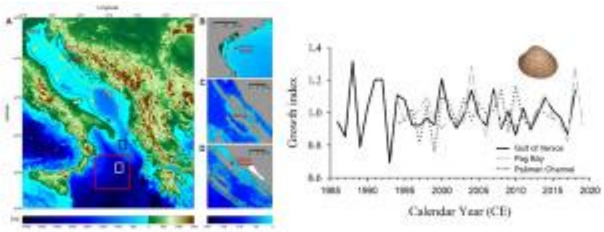
Abstract :

Callista chone samples were live collected at three localities in the Adriatic Sea: Gulf of Venice, Italy, Pag Bay and Pašman Channel, Croatia. Acetate peel replicas were prepared and the Image Pro Primer program was used to measure increment widths in samples that had clear boundaries. Visual cross-dating of the images was performed using list-year method and validated using COFECHA, while the R package dplR was used to construct the chronologies. The age of analysed shells ranged from 15 to 46 years (N=32; 29,9 ± 8,8 years) at the Gulf of Venice, from 14 to 41 years (N=63; 26,0 ± 5,1 years) at Pag Bay, and from 14 to 41 years (N=33; 26,8 ± 4,8 years) at the Pašman Channel. Final statistically robust standard master chronologies spanned from 1986 to 2018 (Gulf of Venice), from 1994 to 2019 (Pag Bay) and from 1994 to 2015 (Pašman Channel). Statistically significant correlation was obtained only between the Gulf of Venice and Pag Bay residual master chronologies (1994–2018; r = 0.607; p <0.001). Although there are some coincidences between all three localities, suggesting a common signal among populations, the growth chronology in the Pašman Channel recorded a very different signal potentially linked to differing oceanographic influences. The Pašman Channel locality is more affected by the inflow of warmer and saline waters coming from the south than the two other sites which are located in geographically and hydrographically isolated Adriatic areas. No correlation was found between any shell master chronologies and surface seawater temperature. Also, no correlations between the shell C.chione master chronologies and parameters describing the Adriatic-Ionian Bimodal Oscillating System (BiOS) were observed. Correlation maps indicate different relationships between shell master chronology and chlorophyll a concentration in the region. Significant correlations were mostly limited to March and April and showed spatial variations.

Graphical abstract



Keywords : Mediterranean Sea, dplR, Veneridae, shell growth, clams, sclerochronology

1. Introduction

Coastal and shelf areas are dynamic and complex multifunctional systems at the interface between land and sea (Salgado-Hernanz *et al*., 2022). These areas are subject to a variety of stressors that overlap, including the effects of climate change, land-based pollution, and commercial fisheries (Ramírez *et al*., 2018). Semi-enclosed seas, such as the Mediterranean Sea, are particularly vulnerable to disturbance due to high surface-to-volume ratios and strong pressures from various human activities (Halpern *et al*., 2015; Schroede *et al*., 2015; Piroddi *et al*., 2017). Anthropogenic pressures on Mediterranean marine ecosystems are predicted to increase in the future (Coll *et al*., 2010), particularly due to habitat destruction, resource exploitation, and climate change (Giorgi and Lionello, 2008; Coll *et al*., 2012; Adloff *et al*., 2015).

To understand the significance of potential future changes, knowledge of present and past environmental variability and its influence on marine organisms is critical. This requires detailed records of oceanic conditions over broad temporal and spatial scales (Grebmeier, 2012). As observational multidecadal or multicentennial records are often lacking, scientists have been exploring possibilities for reconstructing environmental conditions from growth increments in hard tissues of various marine organisms including bivalve shells, fish otoliths, coralline algae and corals (Gröcke and Gilikin, 2008; Oschmann, 2009; Butler *et al*., 2019). Bivalves are often used in sclerochronological research because they continuously deposit shell material throughout their lifetimes and populations may exhibit a common response to environmental forcing, exhibiting synchronous shell growth rates (e.g., Wanamaker *et al*., 2012; DeLong *et al*., 2014; Reynolds *et al*., 2016). Measuring of growth increment widths enables the development of absolutely dated, annually resolved, and environmentally sensitive proxy records ranging from several decades to a few millennia (e.g., Schöne, 2008; Black *et al*., 2009; Butler *et al*., 2013). By applying statistical methods adopted from the dendrochronological research, individual shell growth series data are used for constructing robust master chronologies (e.g., Wanamaker *et al*., 2012; Butler *et al*., 2013; Reynolds *et al*., 2022). These chronologies can be related to modern environmental conditions and used for the reconstruction of past climate changes (e.g. Black *et al*., 2009; Butler *et al*. 2010; Edge *et al*., 2021). Further, efforts have been devoted to the construction of shell chronology networks, based on data from multiple sites within a certain geographic region, in order to obtain more comprehensive insight into past environmental variability on a larger scale (e.g. Butler *et al*., 2009; Reynolds *et al*., 2017; Peharda *et al*., 2019).

While the majority of bivalve chronologies have been developed at relatively high latitudes and in major ocean basins, such studies are still very rare in the Mediterranean and limited to the Adriatic Sea and to species from the genus *Glycymeris*, including *G. bimaculata* (Bušelić *et al*., 2015) and *G. pilosa* (Peharda *et al*., 2016: Peharda *et al*., 2018; Peharda *et al*., 2019). Previous studies on age and growth of the commercially important venerid bivalve *Callista chione* have shown that the longevity of this species can extend up to four decades (Forster, 1981; Ezgeta-Balić *et al*., 2011), making it an interesting target species for sclerochronological studies (Purroy *et al*., 2018a). *Callista chione* is a relatively large (up to 10 cm), shallow-burrowing suspension-feeding bivalve that inhabits sandy sediments in coastal waters at depths up to 180 m and is widely distributed in the eastern Atlantic Ocean and the Mediterranean Sea, including the Adriatic Sea (Poppe and Goto, 2000). It is commercially exploited in several countries from the eastern Mediterranean to the Atlantic, including Croatia, France, Greece, Italy, Morocco, Portugal, and Spain (e.g., Gaspar *et al*., 2001, 2002; Tirado *et al*., 2002; Metaxatos, 2004; Moura *et al*., 2009; Ezgeta-Balić *et al*., 2011; Baeta *et al*., 2014; Bouzaidi *et al*., 2020). Previous studies conducted on *C.chione* include analyses of the reproductive cycle (Valli *et al*., 1984; Tirado *et al*., 2002; Moura *et al*., 2008; Purroy *et al*., 2019), population dynamics (Metaxatos, 2004), age and shell growth rate (Hall *et al*., 1974; Forster, 1981; Keller *et al*., 2002; Leontarakis and Richardson 2005; Moura *et al*., 2009; Ezgeta-Balić *et al*., 2011, Purroy *et al*., 2018b). Understanding growth synchrony within and among populations in the species *C.chione* is needed in order to obtain an insight into its growth dynamics in relation to environmental conditions.

The main objectives of this study were to: (1) determine if well-replicated, annually- resolved, shell growth chronologies can be developed from *C.chione* shells collected at three localities in the Adriatic Sea, (2) determine the potential of *C.chione* for developing a network of bivalve chronologies in the Adriatic Sea, and (3) test possible environmental influences on the shell growth of this species.

2. Materials and methods

Individuals of *Callista chione* were collected live at three localities in the Adriatic Sea: (1) the Gulf of Venice, Italy (45.344° N, 12.525° E; 17-18 m depth); (2) the Pag Bay, Croatia (44.495° N, 14.987° E; 4-6 m depth); and (3) the Pašman Channel, Croatia (43.948° N, 15.388° E; 1.5-3 m depth) (Fig. 1). Specimens were obtained from the catch of the commercial fishing vessels at the locality in the Gulf of Venice in 2018, and by SCUBA and skin-diving at the other two localities on several occasions from 2013 to 2020 (Supplementary Material; Table S1). For the laboratory analysis, we selected the largest-sized shells (>60 mm).

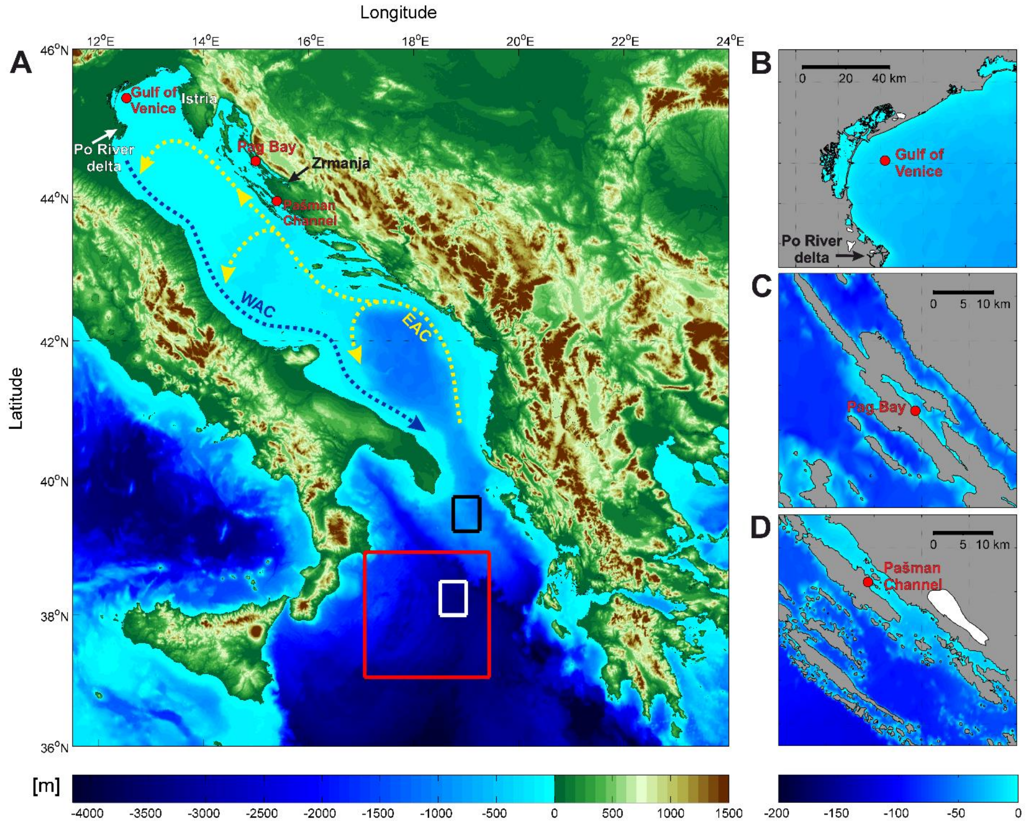


Figure 1. The study area: **A.** The bathymetry of the Northern Ionian Sea and the Adriatic Sea. The localities of *Callista chione* sampling in the Adriatic are denoted by red dots. Schematic representation of the Adriatic circulation is also depicted (the yellow line represents the Eastern Adriatic Current – EAC, while the blue line represents the Western Adriatic Current – WAC). The river mouth of the Zrmanja River (Croatia) is indicated by black arrow, while the delta of the Po River (Italy) is denoted by white arrow. Black and white rectangles in the Northern Ionian denote the areas between which the height difference of the absolute dynamic topography (ADT) was calculated. The red rectangle in the Northern Ionian represents the area used for computating vorticity. **B.** Gulf of Venice (the Po River delta is indicated by black arrow), **C.** Pag Bay and **D.** Pašman Channel.

Immediately after collection, the specimens were frozen, and in the laboratory the shells were thawed and the tissue removed. The shell length (anterior-posterior axis) of each specimen was measured with a digital caliper to the nearest 0.1 mm, and the dry weight was determined using a scientific scale with a precision of 0.01 g.

The hinge area of each shell was cut and embedded in epoxy resin. The resin blocks containing the hinge were cut along the axis of maximum growth, ground, and polished. The polished surfaces were etched in 0.1 M HCl for 2 min. After etching, samples were rinsed in tap water and left to air dry. Acetate peels were prepared by pouring ethyl acetate with a pipette on the polished and etched shell section and covering the surface with a piece of acetate sheet. Acetate peels were placed between two microscope glass slides and photographed using an Axio Lab A1 microscope equipped with a Zeiss AxioCam ERc 5s camera. Multiple photographs were taken for each sample and then stitched together into a single composite photograph using Image-Pro Plus 10 software. Due to the better visibility of annual growth lines, all measurements were done in the inner shell layer and were conducted from the ontogenetically youngest part of the shell towards the oldest part (Fig. S1).

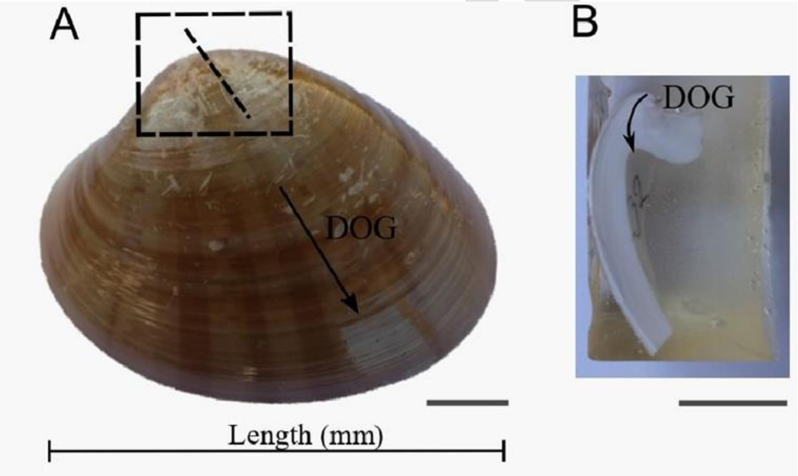


Figure 2. A. *Callista chione* shell, black rectangle represents hinge area that was cut from each sample, while dashed black line presents axis of maximum growth along which the shells were sectioned. **B.** Shell of *C. chione* embedded in epoxy resin. DOG – direction of growth. Scale bar 1 cm.

At each locality the age was estimated for all specimens that had clearly visible growth lines, but only shells that had clearly delineated growth increments boundaries were used to construct master chronologies. Counting of growth lines was performed independently by two experienced researchers and age estimates are reported only for shells for which estimates matched. Acetate peel images were visually cross-dated using the list-year method (Yamaguchi, 1991) to ensure that each increment was assigned to the correct year of formation. This technique is based on the assumption that some aspects of the environment limit growth, and as the environmental conditions vary over time, they induce a synchronous growth pattern in contemporaneous individuals sampled from the same area (Fritts, 1976; Yamaguchi, 1991). The correct calendar year of each increment was assigned by cross-dating backward from the known year of sampling. Cross-dating was also checked using the program COFECHA (Holmes, 1983). It is important to note that analysis of stable oxygen isotope composition (δ18O) in shells of *C.chione* specimens collected from Adriatic Sea showed that this species deposits an annual growth line during late summer/early autumn (Purroy *et al.*, 2018b; Uvanović, 2022) while the growth stop/cessation occurs during January and February. This means that a given annual growth increment can contain environmental data from two calendar years. For example, the annual growth increment marked as "2015" in our time series contains shell material deposited over two time periods: from September to December 2014, and from March to August 2015. This was taken into account when analysing the potential correlations with environmental data.

After visual cross-dating, individual growth increment widths were measured from the internal shell surface towards the external surface (Figure 2B) along the axis of maximum growth and perpendicular to the growth increment boundaries using the Image-Pro Plus 10 software (Supplementary Material; Figure S1). All detrending and chronology construction were performed in R (R Core Team, 2022) using dplR package (Bunn, 2008). Detrending was performed with a cubic spline with a rigidity of 10 years and a cut-off frequency of 50%. Population-level signal strength in the chronology was assessed using the Expressed Population Signal (EPS). Although arbitrary, an EPS ~0.85 is considered the threshold at which the sample set adequately reflects the theoretical population from which it was drawn (Wigley *et al.*, 1984). EPS was calculated over a window of 5 years. For each locality, two versions of the chronologies were built: a standard and a residual version. To build the residual chronology, each individual growth time series was first prewhitened by fitting an autoregressive model, in order to remove autocorrelation. Then all prewhitened time series were averaged using the Tukey's biweight robust mean, in order to minimize the effect of outliers.

In order to test possible environmental influences on the growth of *C. chione*, available data of surface seawater temperature (SST) and chlorophyll-a concentrations were correlated with the shell growth chronologies. Seawater temperature can affect growth directly, but also indirectly - through its influence on bivalve reproductive cycle and food supply (Schöne *et al.*, 2005). Bivalve shell growth is known to be strongly influenced by food quantity and quality (Ballesta - Artero *et al.*, 2018). In order to highlight possible relationships between *C.chione* master chronologies and environmental data, correlation maps (Pearson's r) were computed over a large area (36°-46°N 12°-22°E) around our three localities. The sea surface temperature data used to compute correlation maps were retrieved from the NOAA Optimum Interpolation Sea Surface Temperature (OI SST V2) dataset, provided by the NOAA PSL, Boulder, Colorado, USA (https://psl.noaa.gov). An estimation of the monthly concentration of chlorophyll-a (Chl- a) in the Adriatic, Ionian and Tyrrhenian Seas was obtained for the period 1998-2019 from GlobColour (http://globcolour.info). High-resolution (1/24°, i.e. approx. 4 km × 4 km) ocean colour data retrieved from different sensors (SeaWIFS, MERIS, MODIS Aqua, and VIIRS) were averaged using the Garver-Siegel-Maritorena (GSM) model (Maritorena and Siegel, 2005). All files were downloaded in NetCDF4 format. For each cell of the gridded environmental dataset, pairwise Pearson's correlations were computed between the annual values of the master chronology and environmental data for the months of March, April, May, June, July and August. Only correlations at a 90% significance level (or higher) are displayed on these maps. NetCDF4 files were processed using R 4.2.0 "Vigorous Calisthenics" (R Core Team, 2022), after loading of packages 'rgdal', 'raster', and 'ncdf4'. Correlations between the chronologies and environmental time series developed for the sampled locations were performed in order to detect the environmental force at each site. All additional information can be find in Supplementary material.

The regime of the Adriatic - Ionian Bimodal Oscillating System (BiOS, Gačić *et al.*, 2010) indicates the origin of waters entering the Adriatic Sea. In order to estimate the state of the BiOS, the monthly values of the height difference of the absolute dynamic topography (ADT), here termed ADT_difference, were computed for a 0.5°x0.5° area centered on the northern edge of the eddy in the northern Ionian Sea (black rectangle in Fig. 1A) in relation to an area of the same dimensions at the center of the eddy (white rectangle in Fig. 1A). Another parameter used to describe the state of the BiOS was vorticity, calculated in for the northern part of the Ionian Sea (37.0°N - 39.0°N; 17.0°E - 19.5°E; red rectangle in Fig. 1A), using the procedure described by Shabrang *et al.* (2016). When the value of the parameter ADT_difference is positive, the level in the center of the vortex is lower than the level at the edge of the vortex, which indicates cyclonic (counter-clockwise) rotation of the vortex. In the mentioned periods, the vorticity mostly has a positive value. The positive value of the

ADT_difference parameter in- dicates the inflow of ultra-oligotrophic and highly saline water from the eastern Mediterranean into the Adriatic, which is characterized by low nutrients and lower primary production (Civitarese *et al*., 2010). When the value of the parameter ADT_difference is negative, the level at the center of the vortex is higher than the level at the edge of the vortex, indicating an anticyclonic (clockwise) rotation. Then, the vorticity mostly has negative values. In anticyclonic periods, the inflow of less oligotrophic water with lower salinity goes from the western Mediterranean into the Adriatic prevails

3. Results

In the Gulf of Venice, it was possible to estimate the age of 34 out of 52 processed shells, 19 of which were used in chronology construction. In Pag Bay, a total of 85 shells were processed and it was possible to estimate age for 64 shells, 47 of which were used to construct the chronology. In the Pašman Channel it was possible to estimate the age of 33 out of 37 processed shells, 26 of which were used in chronology construction (Table 1).

Table 1. Overview of the *Callista chione* specimens analysed in this study.

		Gulf of Venice	**Pag Bay**	**Pašman Channel**
Shells used for chronology construction	N	21	48	27
	L (mm) min - max (x̄ ± sd)	66.5 - 85.5 (73.4 ± 3.3)	62.2 - 81.3 (73.4 ± 3.7)	69.3 - 87.3 (76.2 ± 4.7)
	Age (years) min - max (x̄ ± sd)	18 - 46 (29.9 ± 8.8)	18 - 41 (26.3 ± 4.9)	21 - 41 (26.8 ± 4.8)
Other shells	N	13	16	6
	L (mm) min - max (x̄ ± sd)	70.1 - 79.5 (72.9 ± 2.4)	70.0 - 76.9 (73.4 ± 2.1)	56.0 - 88.6 (76.2 ± 10.9)
	Age (years) min - max (x̄ ± sd)	15 - 39 (27.4 ± 6.9)	14 - 32 (25.4 ± 5.3)	21 - 33 (22.2 ± 7.8)

Shells used in chronology were of similar size and age compared with those for which only age was estimated. An exception was the case of several younger shells (n=5; <16 years) that were omitted from chronology development. All shells older than 40 were included in our analysis. Pronounced variation was noted in the estimated age of similar sized shells; for example, shells with length from 70 to 80 mm had an estimated age from 20 to more than 40 years (Supplementary Material; Figure S2). The mean correlation between each detrended time series and the average of others (series intercorrelation) for shells from Gulf of Venice was 0.542. The average mean sensitivity which expresses the year-to-year variability of the values in a time series was 0.256. For shells from Pag Bay, the series intercorrelation was 0.579 and mean sensitivity was 0.279, while for the Pašman Channel samples, the series intercorrelation was 0.543 and mean sensitivity was 0.263.

During the first few years of life, shell growth is very rapid and often the annual growth lines are not sufficiently clear, so it is not possible to accurately measure the distances between them. Therefore, the widths of annual growth increments during the earlier ontogeny (~first 5 years) were not measured. Similary, in samples collected in periods before late summer/early autumn when the annual growth line is formed, last year at the very edge was not measured. Also, due to very narrow growth increments, the positions of annual growth lines at the very edge (late ontogeny) were not sufficiently clear in some specimens and in such cases were not measured.

Data on the width of annual growth increments for *C. chione* specimens collected at the three localities were obtained for the periods showed in Table 2.

Table 2. Overview of the periods of measured annual growth increments for *Callista chione* specimens and constructed master chronologies per localities.

Locality	Measured annual growth increments	Master chronology period
Gulf of Venice	1997 - 2018	1986 - 2018
Pag Bay	1984 - 2019	1994 - 2019
Pašman Channel	1982 - 2015	1994 - 2015

Figure 3. Individual detrended growth time series of *Callista chione* from; **A.** The Gulf of Venice (1979-2018), **B.** Pag Bay (1984-2019), and **C.** The Pašman Channel (1982-2015). Solid black line represents standard chronology. The growth index varies around 1, with higher values indicating positive wider and lower values indicating negative narrower growth than expected by the model. Sample depth (denoting number of samples, grey shading area), 0.85 EPS threshold (straight dashed line) and calculated EPS (black line) are shown for each sampling locality below corresponding chronology data.

Comparison of the three residual master chronologies obtained for *C.chione* individuals collected from the three localities in the Adriatic Sea was made for the time periods over which each chronology was determined to be suitable for environmental comparison based on EPS~>0.85. A statistically significant correlation was obtained only between the Gulf of Venice and Pag Bay chronologies from 1994 to 2018 (r = 0.607; p <0.001). The correlation between these two localities is supported by the synchrony found in years 2004, 2007, 2014, and 2018 that were characterized by higher growth indexes (wider increments). Likewise, coincidences were also found in the years 2006, 2008, 2012, and 2017 that showed lower growth indexes (narrower increments; Fig. 5). Interestingly, the years 2002, 2006, and 2012 were characterized by low growth for all three localities (Fig. 4).

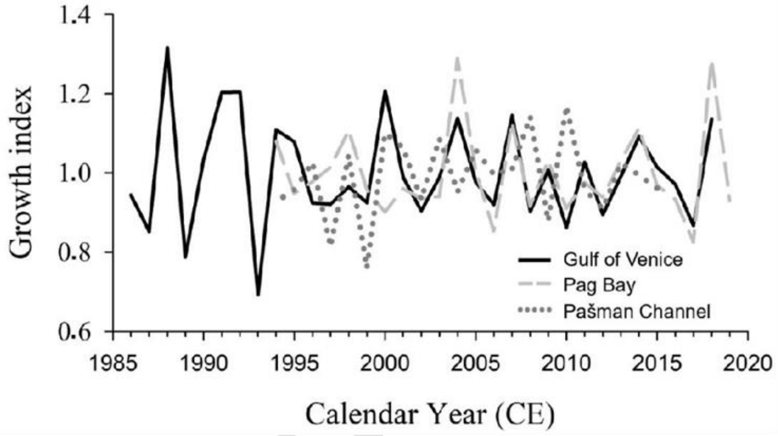


Figure 4. Comparison of *Callista chione* residual shell master chronologies from the three sampling localities. The growth index varies around 1, with higher values indicating wider growth and lower values indicating narrower growth than expected by the model.

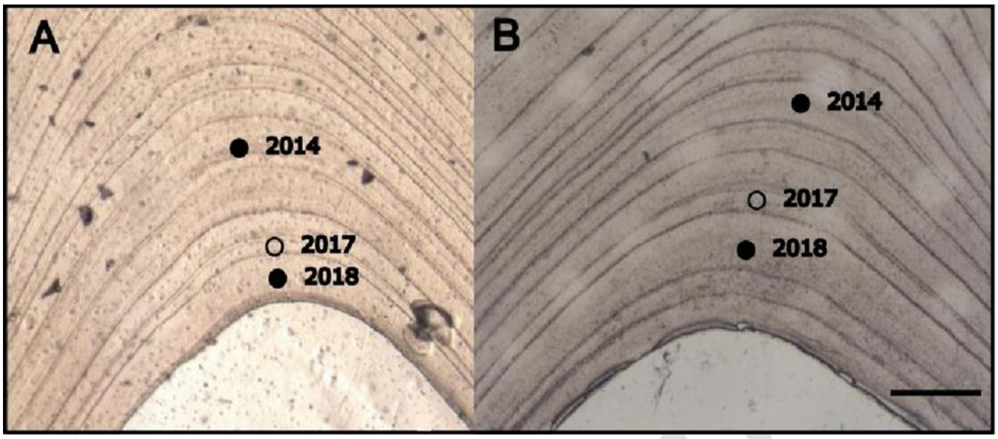


Figure 5. Acetate peels of shells collected in **A.** Gulf of Venice, (ITA2), and **B.** Pag Bay (PAG39). Full circles indicate wide growth increments, open circles indicate narrow growth increments. Scale bar 100 mm.

No significant correlations were found between the Gulf of Venice shell growth chronology and chlorophyll *a* concentrations in the nearby area of the Northern Adriatic, however, some areas of positive and negative correlation were observed further south of this locality. Pearson's r correlations at a 90% significance level (or higher) were observed between the shell master chronologies and chlorophyll concentration for March and April. Positive correlations were observed between shell data for Pag Bay and chlorophyll values at nearby sites for the same months, while for shells from the Pašman Channel significant positive correlation was only found for March (Fig. 6). Comparisons between shell growth chronologies and sea surface temperatures (not shown) showed no significant correlations in any area of the Adriatic for any of the three master chronologies.

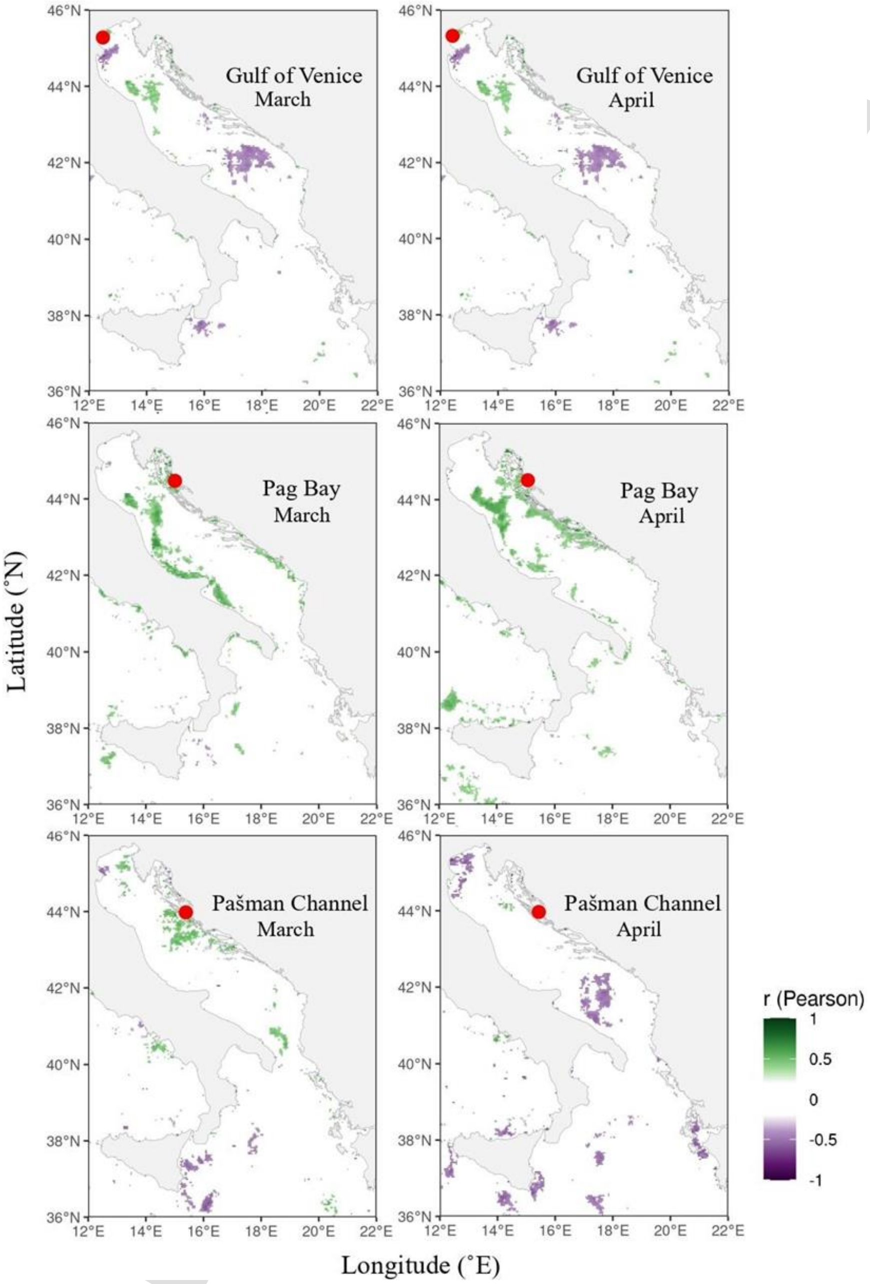


Figure 6. Correlation maps between shell master chronology and chlorophyll concentration for the Gulf of Venice (1999-2018), Pag Bay (2002-2019) and the Pašman Channel (1996-2015) in March and April. Red circle represents locality of shell collection.

4. Discussion

4.1. *Callista chione* age estimation

Growth rate and age are widely used biological parameters for the management and conservation of living marine resources. The age of a bivalve can be estimated using surface growth rings or checks that can be clearly seen on the external shell surface (Richardson 2001). They are particularly clear in *C.chione* during early ontogeny, when the rings are widely spaced and easy to identify (Forster, 1981). However, later in ontogeny (>20 years) they are deposited more closely together at the shell margin and are not always easily discernible. Results of this study show that age of individuals of in this species can pronouncedly vary with respect to length, as estimated age of specimens measuring ~ 75 mm shell length ranged from 22 to 45 years (Supplementary Material; Figure S2). Slow growth during late ontogeny and high intraspecies variation in shell growth rates were previously noted for *C.chione* (Ezgeta- Balić *et al*., 2011), as well as for a number of other bivalves species including for example *Arctica islandica* (e.g. Witbaard *et al*., 1999, Schöne, 2013), and *Lithophaga lithophaga* (Peharda *et al*., 2015). Therefore, it is more appropriate to use acetate peel replicas examined under magnification to estimate the age of larger sized *C.chione* individuals, as opposed to size-age relationships, suggested by Ezgeta-Balić *et al*. (2011).

Callista chione is a moderately long-lived bivalve that can attain an age of >40 years (Forster, 1981; Ezgeta-Balić *et al*., 2011). However, according to previous studies it is more common to find populations with individuals showing a maximum age of 16 years (Leontarakis and Richardson, 2005) or 17 years (Hall *et al*., 1974; Metaxatos, 2004; Moura *et al*., 2009) have been recorded in most of the studied populations. The population structure of *C.chione* in the Adriatic Sea has been documented by Ezgeta-Balić *et al*. (2011) at four localities along the eastern coast (Rab, Pag Bay, Kaštela Bay and the estuary of the Cetina River); individual ages ranged between 3 and 44 years, and contribution of older specimens in a given population varied pronouncedly with respect to locality. In this study, estimated age ranged from 14 to 46 years and 90% of analysed specimens were over 20 years old. It is important to note that for the purpose of chronology construction, larger individuals with >60 mm in length were chosen. Maximal longevity of 46 years estimated in this study is two years longer than previous estimates for specimens from Rab (Ezgeta-Balić *et al*. 2011). Due to the commercial importance of this species, it is highly likely that larger sized and older specimens have already been selectively removed from the Adriatic populations. Age data is a prerequisite to generate the information on population structure, longevity, mortality, recruitment and fluctuations in fishery, which could contribute to the improvement of the national management plans of the species stock (Pauly *et al*., 2002).

4.2. *Callista chione* master chronologies

In the last decade, at least 25 species of the Veneridae family have been the subject of sclerochronological studies, with most species analysed in only one or two studies, indicating the ongoing quest for suitable target species as well as the expanding interest for sclerochronological studies (Peharda *et al*., 2021). Nevertheless, there is a relatively small number of studies on venerid species that focus on the construction of master chronologies. One of the first such studies was conducted by Schöne (2003) on three short-lived species (<10 years) collected in the Gulf of California, Mexico. Multidecadal master-chronologies of long-lived venerids *Mercenaria stimpsoni* (~100 years) were built by Tanabe *et al*. (2017) and Shirai *et al*. (2018), thanks to its long lifespan, clearly visible growth lines, and synchronized growth between individuals as well as clearly visible growth lines. It should be noted that the chronology published in the work of Shirai *et al*. (2018) was made on data for only three specimens. To the best of our knowledge, there are no other published studies related to the construction of master chronology for Veneridae species, and data from our study contribute to the understanding of growth in this bivalve family.

Previous research aimed at developing master chronologies of bivalves in the Adriatic Sea, but also in the Mediterranean Sea, has been limited to species of the genus *Glycymeris* that were targeted for their longevity. The genus *Glycymeris* has been interesting for sclerochronology research in other parts of the world, including research conducted on *G. glycymeris* from the Northeast Atlantic (Brocas *et al*., 2013; Featherstone *et al*., 2017; Reynolds *et al*., 2017; Alexandrof *et al*., 2021); *G. longior* from the Southwest Atlantic (Gimenez *et al*., 2020a; 2020b) and *G. vanhengstumi* from North Atlantic (Nemeth and Kern, 2018). In the Adriatic Sea, a 16 years long master chronology of the species *G. bimaculata* was constructed based on growth increment data obtained from shells collected in Pag Bay (Bušelić *et al*., 2015). Maximal estimated longevity of *G. bimaculata* in that study was 57 years. Given the relatively small number of *G. bimaculata* individuals that were older than 20 years, research focused on master chronology construction later on targeted the species *G. pilosa*. The length of the chronologies for this species ranged from 17 years in the Pašman Channel (Peharda *et al*., 2016) to 42 years at the locality Drače (Peharda *et al*., 2019) and they were constructed using a larger number of specimens. Maximal estimated longevity of *G. pilosa* in the Adriatic

Sea was estimated at impressive 97 years (Peharda *et al*., 2019). In our study, the lengths of the constructed master chronologies of *C.chione* were 32 years for the Gulf of Venice, 25 years for Pag Bay, and 21 years for the Pašman Channel.

Collecting growth data at multiple localities allows the development of networks of chronologies and the analysis of spatial similarities and differences (Black, 2009; Butler *et al*., 2009; Brocas *et al*., 2013; Reynolds *et al*. 2017; Peharda *et al*., 2019). So far, such research has been conducted at several localities in the Pacific, Atlantic, and Mediterranean, and has included species such as *Panopea generosa* (Edge *et al*., 2021), *Arctica islandica* (Butler *et al*., 2009), *G. glycymeris* (Brocas *et al*., 2013) and *G. pilosa* (Peharda *et al*., 2019). Research conducted in open marine systems in the Pacific and Atlantic has shown that there are some statistically significant correlations between master chronologies from different localities, as well as correlations with environmental factors (Black *et al*., 2009; Butler *et al*., 2009; Brocas *et al*., 2013; Reynolds *et al*., 2017). Most of these studies have analysed the spatial coherence among populations from a single species, while a limited number of studies also focus on networks that include multiple species. Such approach was conducted by Reynolds *et al*. (2017) and included the species *A. islandica* and *G. glycymeris* collected from several localities along the western British continental shelf, and by Reynolds *et al*. (2022) which analysed the species *Astarte borealis* and *Liocyma fluctuosa* collected from the eastern Chukchi Sea in the Arctic Ocean. In the eastern Adriatic, a comparison of chronologies of *G. pilosa* growth at several localities revealed similarities between chronologies for samples collected along the western coast of Istria and the Pašman Channel, and between chronologies at Živogošće and Drače (Peharda *et al*., 2019). In this study, similarities were found between the master chronologies of *C.chione* at the Gulf of Venice and Pag Bay, while the chronology obtained for the Pašman Channel did not correlate with the two northern chronologies. The sampled localities are in the shallow coastal area of the Adriatic Sea and according to Peharda *et al*. (2019) the heterogeneity in bivalve growth can potentially reflect heterogeneous climate regimes or the influence of local limiting environmental factors on their growth.

One possible explanation as to why the Pašman Channel chronology differs from other two sites could be related to different environmental conditions affecting the Gulf of Venice and Pag Bay sites. Namely, the general Adriatic surface circulation is cyclonic (Orlić *et al*., 1992), with a north-westward flow along the eastern coast (Eastern Adriatic Current – EAC, Fig. 1A) and a south-eastward current along the western coast (Western Adriatic Current – WAC, Fig. 1A). The Pašman Channel sampling site is therefore more affected by the inflow of warmer and saline waters coming from the south than the two other sites, as Pag Bay and the Gulf of Venice sampling sites are located in somewhat geographically and hydrographically isolated Adriatic areas. Pag Bay is a part of the deeply indented north-eastern Adriatic coastline, strongly influenced by the severe wintertime outbreaks of cold and dry Bora wind (Grisogono and Belušić, 2009) and local fresh water sources (Zrmanja River and submarine fresh water springs, e.g., Novosel *et al*., 2002; Šupraha *et al*., 2011). The oceanographic properties of the northernmost part of the Adriatic are strongly dependent on the Po River discharges and characteristics of the air-sea fluxes, particularly those related to the strong Bora outbreaks, which excite the cyclonic gyres encompassing the area of the sampling site (Orlić *et al*., 1994; Kuzmić *et al*., 2006). Additionally, a persistent thermohaline front positioned to the south and southwest of the Istrian peninsula (Istrian Front), separating colder and less saline waters of the northernmost part of the northern Adriatic from the warmer and more saline southern waters, was reported during oceanographic surveys and in model simulations (e.g., Kokkini *et al*., 2017 and references therein).

4.3. Environmental influence on the growth of *Callista chione*

Growth synchrony among *C.chione* specimens collected from the same locality suggests that a common environmental parameter influences individual growth. However, relationships between shell growth and external factors can be complex, especially in shallow coastal environments in semi-enclosed seas such as the Adriatic Sea (Epple *et al*., 2006). In these areas, local processes, including precipitation, riverine input and terrestrial runoff, may be highly localised (Gillanders, 2005). Some previous sclerochronological studies have identified seawater temperature as one of the main drivers of shell growth. Positive correlations between seawater temperature and bivalve growth have been observed for several bivalve species including *Arctica islandica* (e.g., Marali and Schöne, 2015), *Glycymeris glycymeris* (Reynolds *et al*., 2013; Royer *et al*., 2013), and *Glycymeris bimaculata* (Bušelić *et al*., 2015). Negative correlation between seawater temperature and bivalve growth have also been observed in the case of master chronologies of species *Ciliatocardium ciliatum* in the northwest Barents Sea (Carroll *et al*., 2014) and species *A. islandica* in the southern Barents Sea (Mette et al., 2016). Some of the studies found very low (e.g., Butler et al., 2013) or time-unstable (e.g., Marali and Schöne, 2015) corelation between seawater temperature and shell growth thus further highlighting the complexity in growth-temperature relationships among and even within species. In the case of *C.chione* master chronologies, no correlations were observed with seawater temperature in the Adriatic Sea.

Previous studies of *G. pilosa* in the Adriatic Sea have identified the impact of decadal (5 - 10 years) oscillation of water masses referred to as the Adriatic - Ionian Bimodal Oscillating System (BiOS), on populations at the Barbariga and Pašman Channel localities (Peharda *et al*., 2019). BiOS is known to be the dominant driver of the thermohaline and biogeochemical oscillations across most of the basin, including southern and middle Adriatic and the shallow northern areas (Civitarese *et al*., 2010; Vilibić *et al*., 2012; Batistić *et al*., 2014; Dautović *et al*., 2017). However, in the same study, at two southern localities Živogošće and Drače, growth of *G. pilosa* was influenced more by the local factors. In this study, no correlations of *C. chione* master chronologies and parameters describing BiOS were observed.

In this study, positive and negative correlations between shell growth chronologies and nearby chl a values were observed for the three different locations. Although satellite chlorophyll a data provide insights into state of phytoplankton communities in an area, this does not monitor sudden changes of conditions in enclosed bays or straight channels between islands (Kirk, 2011). A previous study of trophic ecology of the *C.chione* conducted in Pag Bay and the Cetina River estuary showed that the diet differs between localities (Purroy *et al*., 2018a). According to Purroy *et al*. (2018a), for the bivalves in Pag Bay the most important food source are particles deposited on sediment, while in the estuary of the Cetina River the most important food source is suspended particulate matter. Correlation maps obtained in our study indicate different relationships between the shell master chronology and chlorophyll a concentration in the region. Significant correlations were mostly limited to March and April and showed spatial variations. However, the environmental variables that influence bivalve growth can vary over fine spatial scales, especially in coastal environments in semi enclosed seas where local processes can be highly localized (Gillanders, 2005). While no direct influence of enviormental data on the growth of bivalve *C. chione* were observed, results in this study highlight the need to combine sclerochronological analyses with ecological studies and *in situ* measurements of parameters such as food availability and quality to understand life history traits of bivalves as archives of environmental variables.

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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