**Supplementary Material 2:** *Complete list of questions.*

The following tables provide the results from the question curation during Step 3: Processing (see Supplementary Material 1), and presented in the distributed survey of Step 4: Prioritization. A total of 130 questions are listed with their associated rankings following analysis of survey responses.

Table SM3.1: Initial list of questions in Section I – Foundations. Questions marked with an asterisk are discussed in the main body of this paper. The questions are sorted after top ratings, i.e. the percentage of participants that rated them as top or high priority. For additional insight, the percentage of zero or low priority ratings are given as well.

|  |  |  |  |
| --- | --- | --- | --- |
|  | **Questions – Section I: Foundations** | **Top or high priority (%)** | **Zero or low priority (%)** |
| 1\* | What determines the timing of the growth season and does it vary throughout ontogeny? | 74.51 | 7.84 |
| 2\* | Why do we often observe an offset between seawater temperature reconstructed from oxygen isotope ratios (using widely applied paleotemperature equations) and those measured in situ? | 71.43 | 10.20 |
| 3\* | What drives the formation of annual growth increments in fish otoliths? | 71.43 | 10.71 |
| 4\* | How can we improve estimates of past water isotopic composition to increase accuracy of temperature reconstructions? | 70.83 | 12.50 |
| 5\* | How, and to what extent, do vital effects influence biomineral stable isotope composition, elemental distribution, and elemental concentration? | 70.00 | 8.00 |
| 6\* | What are the specific processes by which climate signals are translated into growth of calcified structures? | 69.23 | 7.69 |
| 7\* | What environmental parameters can be constructed from trace element concentrations and ratios within mollusk shells, and why are some trace element proxies unreliable? | 68.42 | 13.16 |
| 8\* | Are the growth/chemical responses to specific environmental drivers consistent/stationary over geologic time? | 68.00 | 10.00 |
| 9\* | What methods can we use to better assess the leads, lags, and synchronicities in sclerochronological records across large spatial regions? | 67.35 | 14.29 |
| 10\* | What not-yet-identified long-term sclerochronological archives exist, especially outside of the North Atlantic region? | 67.35 | 14.29 |
| 11\* | To what extent do variations in multiannual to multicentennial growth patterns represent a community/ecosystem response to changing environmental conditions? | 66.67 | 10.42 |
| 12\* | What common data standards should be adopted to improve our ability to compare sclerochronological datasets with each other and with other datasets? | 65.96 | 6.38 |
| 13\* | What controls the incorporation of trace and minor elements into biogenic carbonates and how do these processes affect distribution of different trace elements between crystal lattice and organic phases? | 65.96 | 12.77 |
| 14\* | How do we discern fish movement pathways from analyses across individual life history? | 65.38 | 11.54 |
| 15\* | How can we disentangle the separate and combined effects of multiple causal factors in sclerochronological records? | 64.71 | 11.76 |
| 16\* | Why is it that within the same population of bivalves, not all of the individual growth patterns from live-collected specimens crossmatch and how should we deal with such inter-individual variability? | 64.10 | 12.82 |
| 17\* | How can we disentangle multiscale spatial and temporal variability within sclerochronological records? | 64.00 | 10.00 |
| 18\* | Through which pathways are trace and minor elements transported into mollusk’s extrapallial fluid, and from where are they sourced (e.g. digested food, directly from water)? | 63.89 | 13.89 |
| 19\* | How might climate and environmental change (e.g. ocean acidification) be altering processes of biomineralization? | 62.75 | 9.80 |
| 20\* | How can common environmental signals be identified in multiple records which have different spatial and temporal scales and resolutions? | 61.54 | 19.23 |
| 21\* | Are there differences in biomineralization processes between species and/or populations that affect skeletal isotopic composition and elemental concentrations? | 61.22 | 10.20 |
| 22\* | How does inter-individual variation in growth patterns in fish affect long-term growth time series? | 59.26 | 14.81 |
| 23\* | How can we determine if species-specific paleotemperature equations are a valid and necessary approach to increase the accuracy of paleotemperature reconstructions? | 59.18 | 16.33 |
| 24\* | What are the limitations of using clumped-isotope palaeothermometry to better constrain isotopic palaeotemperature estimates from fossil organisms? | 58.14 | 16.28 |
| 25\* | What level of sample replication is required for geochemical records for sound estimation of uncertainty associated with inter-individual variability and ensuring comparability between records? | 58.00 | 14.00 |
| 26 | How can we predict the sclerochronological patterns (growth and/or chemical records) expected under differing combinations of movement, physiology and environmental change? | 57.45 | 8.51 |
| 27 | Could long-lived deep-sea bivalve shells provide useful information on environmental conditions prevailing in abyssal plains? | 55.26 | 18.42 |
| 28 | Can trace element ratios within fish scales provide reliable habitat proxies? | 53.85 | 19.23 |
| 29 | What are the optimal spatial and temporal sampling methods for targeting climate reconstructions at different scales (e.g., microclimatic, regional, global)? | 52.00 | 18.00 |
| 30 | Do the drivers of growth rate of calcified structures vary between years and/or throughout ontogeny? | 51.92 | 17.31 |
| 31 | What environmental and/or biological factors determine interspecific differences in the growth rate and longevity of bivalves? | 51.28 | 15.38 |
| 32 | How heterogeneous is the elemental and stable isotope composition of contemporaneously precipitated biogenic carbonates with the same crystal habit and mineralogy? | 51.11 | 15.56 |
| 33 | What are the most appropriate approaches for validating physiological and environmental information obtained from proxies, especially for mobile organisms? | 51.06 | 8.51 |
| 34 | Can we quantify crossdating errors in sclerochronological records? | 50.00 | 18.00 |
| 35 | How can we develop robust, quantitative estimates of metabolic rate (expressed in oxygen consumption units) from sclerochronological proxies? | 50.00 | 20.45 |
| 36\* | What approaches can we use to identify coeval shells for deep-time geological settings that will enable us to construct multicentennial crossmatched chronologies? | 50.00 | 27.78 |
| 37 | What reliable, objective, high throughput, non-destructive method of automatic increment counting and measuring can we develop, if any? | 49.02 | 29.41 |
| 38 | How does structural organization of biominerals interact with their geochemical composition, and to what extent does it affect the comparability of geochemical records and interpretation of the inferred environmental signal? | 48.89 | 13.33 |
| 39 | Do processes of biomineralization and associated vital effects that influence stable isotope composition and concentration of trace and minor elements in calcified structures differ between freshwater and marine species? | 48.89 | 24.44 |
| 40 | What are the differences in the chemical and physical structure of opaque versus translucent growth bands apparent in some calcified structures (e.g., otoliths)? | 48.28 | 17.24 |
| 41 | What processes result in equilibrium isotopic fractionation in some isotopic systems versus others? | 47.83 | 19.57 |
| 42 | What criteria should be used when choosing detrending techniques for building growth chronologies with bivalve shells? | 47.06 | 17.65 |
| 43 | Does diagenesis differentially affect the organic and inorganic parts within the matrix of biogenic carbonates? | 46.51 | 23.26 |
| 44 | What is the potential for development of unknown or little-used proxies: e.g. skeletal density, colour, crystal structure, or skeletal organic fraction? | 45.83 | 18.75 |
| 45 | Why do some geochemical proxies in biogenic carbonates work well on a bulk scale, even though they are heterogeneous at ultrastructural level? | 45.45 | 22.73 |
| 46 | What should the standards be for calling a sclerochronological record a reconstruction and what metrics should we be developing to better quantify the uncertainties in the reconstruction? | 44.90 | 36.73 |
| 47 | How can we improve our ability to identify and quantify the effect of diagenetic and taphonomic processes on the sclerochronological record? | 44.44 | 17.78 |
| 48 | Do any chemical markers within calcified structures indicate when an individual undertook reproduction? | 42.86 | 18.37 |
| 49\* | What proportion of the whole ecosystem extent does the environmental DNA in bivalve shells capture and how can the eDNA be used to reconstruct ecosystem change? | 42.42 | 30.30 |
| 50 | How does the application of various statistical detrending techniques for long-lived species (e.g. adaptive power transform, signal-free) affect mixed effects models targeting low-frequency variability? | 41.46 | 24.39 |
| 51 | To what extent can the incorporation of different concentrations of trace elements induce oxygen isotopic fractionation and influence carbon isotope composition? | 40.91 | 27.27 |
| 52 | What controls crystal fabrics in mollusk shells and why are there so many different types in bivalves? | 40.54 | 27.03 |
| 53 | How can we measure or quantify the onset of sexual maturity as observed in calcified structures? | 39.58 | 29.17 |
| 54 | Is there a difference in nitrogen isotope ratios between different components of the organic matrix of biogenic carbonates? | 38.64 | 20.45 |
| 55 | To what extent are geochemical findings from experiments in abiogenic mineralization applicable to biominerals? | 38.64 | 34.09 |
| 56 | How can we quantify the effect of aging error on records from species that are too short-lived for crossdating? | 38.00 | 24.00 |
| 57 | How can we improve physical sampling techniques (e.g., micromilling) to increase temporal resolution of geochemical proxy-based reconstructions that require analysis of powdered samples? | 36.73 | 24.49 |
| 58 | At what geographic or taxonomic level should calibrations of sclerochronological proxies be carried out? | 36.73 | 26.53 |
| 59 | How can we determine the age of an individual organism if the usual sclerochronological structure stops forming growth increments after a certain age (e.g. interrupted growth patterns of sharks)? | 36.67 | 30.00 |
| 60 | What is the influence of amorphous calcium carbonate in the recorded biomineral geochemical signal and its relationship to environmental parameters? | 36.11 | 30.56 |
| 61 | Do the relationships between somatic, gonad and shell growth vary between years? | 33.33 | 25.00 |
| 62\* | Can we use material within the growth line to infer conditions outside the main growing season? | 33.33 | 33.33 |
| 63 | How and to what extent can variations in sampling by micro-milling (drill speed and applied pressure) influence geochemical proxy data obtained from biogenic carbonates? | 32.65 | 28.57 |
| 64 | How does sampling resolution influence precision and accuracy of season of capture estimates among various taxa? | 32.00 | 26.00 |
| 65 | Is there a component of fish vertebrae, bones or scales (those lacking calcium carbonate) that can be used to reconstruct past temperature? | 28.00 | 24.00 |
| 66 | Why are annual growth increments poorly defined in juvenile stages of some sclerochronological archives (e.g., shark vertebrae)? | 25.93 | 29.63 |
| 67 | What are the taphonomic characteristics of ancient eDNA in sclero archives, in particular under different climatic contexts? | 17.14 | 31.43 |

Table SM1.2: Initial list of questions in Section II – Applications. Questions marked with an asterisk are discussed in the main body of this paper. The questions are sorted after top ratings, i.e. the percentage of participants that rated them as top or high priority. For additional information, the percentage of zero or low priority ratings are given as well.

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| --- | --- | --- | --- |
|  | **Questions – Section II: Applications** | **Top or high priority (%)** | **Zero or low priority (%)** |
| 1\* | To what extent do sclerochronologies covary with tree-ring data, and what does that tell us about the coherence of climate variability over hemispheric scales through time? | 79.55 | 2.27 |
| 2\* | How can we use sclerochronological archives to monitor the lag in the ecosystem response to climate change and other environmental change in the oceans? | 73.47 | 8.16 |
| 3\* | How can sclerochronological proxies be used to study historical changes in the extent of Arctic sea ice? | 73.33 | 8.89 |
| 4\* | How can sclerochronology be used to assess the anthropogenic impacts on overall ecosystem process and structure throughout the Holocene? | 73.33 | 8.89 |
| 5\* | How can sclerochronological tools help us to decide which time period/condition provides an appropriate baseline for studies which require “natural”, “pristine” or pre-human-impact data on the environment? | 70.00 | 6.00 |
| 6\* | How did major climate changes affect the intrinsic variability of El Nino/ Southern Oscillation (ENSO) in the past? | 69.77 | 6.98 |
| 7\* | Can we detect changes in variability in sclerochronological records that indicate an approach to a climate or environmental tipping point? | 69.39 | 14.29 |
| 8\* | How spatially heterogeneous were climate and environmental conditions under “normal” past conditions (i.e. as opposed to extreme climate scenarios, such as MCA/LIA, LGM, YD, LIG)? | 69.05 | 9.52 |
| 9\* | How can we use sclerochronology to distinguish variations in the effects of climate change on marine ecosystems at various spatial scales (e.g., local, regional and global)? | 68.63 | 11.76 |
| 10\* | How can we utilise both high resolution sclerochronological records and traditional palaeoceanographic data (e.g. sediment core records) to produce spatial reconstructions of broad scale climate variability? | 68.09 | 6.38 |
| 11\* | How are different classes of chemical pollutants presented in the sclerochronological record and can their temporal distribution be inferred? | 68.09 | 6.38 |
| 12\* | How has the 14C reservoir effect varied over time and at different temporal scales (e.g., subannual, annual, decadal, etc.)? | 67.50 | 15.00 |
| 13\* | Which sclerochronological data are most suited for climate model assimilation? | 67.35 | 12.24 |
| 14\* | How can sclerochronological records be used to assess changes in fish and shellfish populations due to harvesting? | 66.67 | 6.67 |
| 15\* | How can we use sclerochronology to quantify the rate of recovery of marine ecological systems from natural or anthropogenic disturbances? | 66.00 | 8.00 |
| 16\* | How can we integrate tropical growth-increment data with mid- and upper-latitude sclerochronologies to explore tropical-extratropical teleconnections? | 65.12 | 11.63 |
| 17\* | How can we use sclerochronological archives to monitor changes in the role of the oceans as a buffer for carbon emissions and heat? | 61.70 | 12.77 |
| 18\* | What can sclerochronological records tell us about the links between the marine carbon and nitrogen cycles in the past, especially during times of abrupt climate change? | 60.87 | 10.87 |
| 19\* | How can we use sclerochronological archives to detect high resolution variability in AMOC strength? | 60.47 | 13.95 |
| 20\* | How can we use sclerochronological data to detectthe first signs of human impact on the marine system through fishing and climate change? | 60.47 | 18.60 |
| 21\* | How can sclerochronological records be used to infer the frequency and intensity of hypoxia and anoxia events in the past? | 60.00 | 8.00 |
| 22\* | What are the temporal and spatial limitations of sclerochronological records from shelf seas as proxies for open-ocean conditions? | 59.57 | 19.15 |
| 23\* | In the context of global climate change, which aquatic ecosystems/environments experience ecological change first or to the greatest degree (e.g., open ocean, upwelling, subtidal, intertidal, estuarine, riverine, lacustrine)? | 59.57 | 23.40 |
| 24\* | How did seasonality vary in the past in the temperate climate zone? | 59.18 | 8.16 |
| 25\* | How can sclerochronological records be used to study eutrophication dynamics in coastal ecosystems? | 58.00 | 6.00 |
| 26 | How can we use sclerochronological archives to estimate changes over time in the historic rate of advance or retreat of Antarctic ice shelves? | 57.78 | 8.89 |
| 27 | How can sclerochronological data from continental shelf areas help characterize the history of anthropogenic impacts on geochemical fluxes (e.g. Si, C, N and P) from terrestrial to shallow marine ecosystems? | 56.52 | 17.39 |
| 28 | How can sclerochronology be used to investigate changes in carbon sequestration over time? | 56.10 | 19.51 |
| 29 | What changes in growth rate and longevity are associated with mass extinctions? | 55.10 | 20.41 |
| 30\* | Can fisheries management advice be improved by combining traditional stock assessment techniques (e.g. otolith aging) with machine learning? | 54.55 | 24.24 |
| 31 | How can we increase temporal resolution of ecosystem change reconstructions based on the stable nitrogen isotopes in the organic fraction of shells? | 54.05 | 13.51 |
| 32 | What do multi-centennial sclerochronologies reveal about covariability across ocean basins, and how have these relationships changed over time? | 53.33 | 4.44 |
| 33 | Can we determine the impact of known events (e.g. volcanic eruptions, climatic changes) on ecosystem services using sclerochronological records? | 53.19 | 10.64 |
| 34 | How can sclerochronological data be incorporated in conservation plans for endangered species? | 52.08 | 18.75 |
| 35 | How can we assess the connectivity between populations of a given species using geochemistry of calcified structures? | 51.11 | 20.00 |
| 36 | How can we use sclerochronological data to identify the role of past climate and environmental variability in recruitment of fish and shellfish, and can we use this relationship to reconstruct past climatic/environmental conditions? | 48.89 | 17.78 |
| 37 | How can sclerochronological techniques be used to monitor the environmental impact/disturbance associated with the installation, operation and decommissioning of offshore infrastructure? | 48.89 | 24.44 |
| 38 | What do sclerochronological records tell us about which season(s) are represented by non-sclerochronological estimates of palaeo-seawater temperature – e.g. from sediment core proxies (e.g., assemblage composition, alkenone undersaturation, TEX86)? | 48.57 | 22.86 |
| 39 | How can sclerochronology help us to define "target" states (species abundance, taxonomic diversity, etc) for ecosystems within marine protected areas? | 47.83 | 28.26 |
| 40 | How accurate are the high temperature estimates for Palaeozoic oceans? | 47.73 | 27.27 |
| 41\* | How can we use sclerochronology to investigate potential latitudinal gradients in the response of marine biota to climate change, in terms of species die-off or range shifts? | 46.94 | 16.33 |
| 42 | How can sclerochronological archives provide reliable information on the past variability of food-web structure and trophic interaction as the environment changes? | 46.81 | 21.28 |
| 43 | How can sclerochronology be used to understand how people made use of particular species in historical periods, and can we use this knowledge to infer responses to food security issues? | 43.59 | 35.90 |
| 44 | How can we use sclerochronological techniques to assess the restorative effects of ecosystem seeding on artificial platforms (e.g., artificial coral reefs)? | 43.48 | 21.74 |
| 45 | How do rates of ecological change (in time and in space) differ between marine and terrestrial environments? | 42.55 | 10.64 |
| 46 | How can we use sclerochronology to determine how metabolic rates of calcifying organisms have varied through time? | 42.55 | 14.89 |
| 47 | How can we implement knowledge within local and lay communities into our understanding and interpretation of sclerochronological data? | 42.50 | 37.50 |
| 48 | How can we use sclerochronology to monitor past and present spatial expansion and contraction of a species range and determine the environmental factors that are driving it? | 40.82 | 14.29 |
| 49 | How can the presence of plastics in the environment be detected in calcified structures (directly, or through proxies)? | 38.30 | 36.17 |
| 50 | How can we broadly apply emerging sclerochronological tools to trace the origin of commercial shellfish products? | 37.21 | 25.58 |
| 51\* | How can possible effects of early human harvesting be separated from natural variability in marine fauna to better assess how changes in resources affected hunter-fisher-gatherers? | 36.84 | 28.95 |
| 52 | How can we investigate historical changes in season of shell collection using tropical mollusk shells? | 36.59 | 26.83 |
| 53 | What triggered biomineralization across nearly all phyla in the Upper Ediacaran and Early Cambrian? | 34.21 | 26.32 |
| 54 | Can we detect a geochemical signature of volcanic eruptions in any sclerochronological archive? | 34.04 | 40.43 |
| 55\* | How can data from sclerochronology be used to inform us about land claims by indigenous people? | 33.33 | 33.33 |
| 56 | Can we accurately assess ontogenetic age for extinct organisms such as ammonoids or rugose and tabulate corals? | 32.56 | 25.58 |
| 57 | How can we use sclerochronology to assess the role of sea‐level change in community and diversity dynamics through time and across marine and terrestrial environments? | 30.61 | 32.65 |
| 58 | Why did some fossil bivalves form thicker and larger shells than modern representatives of the same taxa? | 30.23 | 27.91 |
| 59 | How can sclerochronological archives be used to detect the incidence of marine pathogens? | 28.57 | 38.10 |
| 60 | Can we detect past pyrotechnologies by examining burned and charred shells? | 25.00 | 62.50 |
| 61 | Does crystal fabric variability contribute to the evolutionary success of mollusks? | 23.26 | 46.51 |
| 62 | How can data from sclerochronology be used to investigate past societal dynamics (including gender relations)? | 21.88 | 56.25 |
| 63 | What is the role of changes in developmental timing (heterochrony) in evolution? | 15.15 | 48.48 |