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Theme session Report

Temperature impacts on fish growth and consequences for fisheries

Conveners: John Morrongiello (Australia), Asta Audzijonyte (Lithuania, Australia), Paul Spencer (USA)

Theme Session J provided an opportunity to compare different modelling approaches suitable for isolating temperature effects on fish growth, review empirical evidence about changing individual growth rates of fish in multiple marine ecosystems, consider implications of body size changes for fisheries management and coordinate international-scale research efforts in the field. The session had 29 contributed oral talks and 4 posters from delegates spanning a wide range of career levels, starting from recent Masters graduates to prominent researchers like prof. Daniel Pauly and prof. David Atkinson. The session's panel discussion attracted over 100 attendees, registered on Whova app. We grouped the Session J into four main themes, briefly presented below, which were used as the basis for panel discussions.

1) ***Assessing the temperature effects on growth and body size, as well as possible underlying mechanisms***: presentations from Max Lindmark, Daniel Pauly and Mimi Elizabeth Lam, Vytautas Rakauskas and Asta Audzijonyte, David Atkinson, Henry Wootton, Jennifer Bigman and Federico Cali.

This theme addressed questions about the physiological mechanisms behind temperature impacts on fish growth, especially focusing on the temperature-size rule (TSR) proposed by David Atkinson in 1994 and showing that ectotherms grown in warmer conditions grow faster as juveniles and mature at smaller body sizes. In this session, the generality of TSR was explored using long-term empirical fish growth data from two artificially heated ecosystems (nuclear power plant cooling systems) in Sweden (Max Lindmark) and Lithuania (Rakauskas and Audzijonyte). Both studies showed that TSR is not universal: there were species-specific growth responses to temperature, although in nearly all cases even small changes in temperature (2C in Lithuania) led to clear changes in growth. Despite the empirical evidence for species-level differences in TSR responses, David Atkinson's presentation suggests that TSR could be used as a general expectation of ectotherm responses to temperature, against which other environmental or ecological influences should be assessed. The mechanisms behind the TSR were debated by presentations from Daniel Pauly/Mimi Elizabeth Lam, Asta Audzijonyte and Henry Wootton. These presentations provided opposing theoretical and empirical perspectives on the role of maintenance costs versus life-history (growth-reproduction) trade-offs in defining fish growth trajectories across temperatures. During the live panel discussion session, David Atkinson pointed out the discrepancies between the original definition of TSR (defined largely from observations of terrestrial ectotherms with determinate growth), which described temperature impacts on juvenile growth and maturation size only, and current use of the term in fisheries related studies, which often focus on the maximum fish body size.

2) ***Presenting new analytical methods to assess temperature-dependency of growth and body size***: presentations from Christine Stawitz, Alan Baudron, Timo Rittweg, Deirdre Brophy and Leire Ibaibarriaga.

The 2nd theme included a series of talks that explored different analytical approaches to detect and then quantify TSR-like responses in wild populations, and how complex these models really need to be. Christine Stawitz and Alan Baudron both analysed the same California Current fish age-size data set using different models (state space model vs. dynamic factor analysis). Interesting differences arose from each model, leading to a discussion of the value of mechanistic versus statistical modeling frameworks. For example, can we use estimated parameters (e.g. $L\infty$) to infer TSR, or should we be using size-at-age itself? The different modelling approaches presented in this theme and also in theme 3 below highlighted the importance of considering life-stage and age-dependent thermal sensitivities. Such an approach makes intuitive sense given that the TSR theory makes different predictions for the effects of temperature on the growth of juveniles and recently matured fish. Lastly, the remaining talks explored new ways to derive age and growth information from otoliths which could have important applications in detecting seasonal (as opposed to annual) growth patterns, and estimating an individual's growth history when otolith increments are not clear.

3) ***Analysing long-term growth patterns in large marine ecosystems***: presentations from Tuan Anh Bui, Lea Simonet, Shin-ichi Ito, Zhen Lin, Sarah Willington, Aidan Long and John Morrongiello.

This theme demonstrated the value of analysing existing long-term fisheries length-age datasets to explore temperature impacts on fish growth. Key outcomes of the talks (e.g. Sarah Willington, John Morrongiello, Aidan Long) and subsequent panel discussion was that researchers needed to consider the possibility for strong interactions between fishing and temperature on growth trajectories. Fishing can affect growth in multiple ways, including a reduction in stock density that could lead to density-dependent responses, and the potential for fishery selection of the fastest-growing fish at a given age. Further, large variation in growth due to internal and external processes affecting fish populations can make it difficult to disentangle the true TSR-like effects of temperature on fish body size. Another more practical issue was that there is, outside of the major fisheries in the North Atlantic, often a lack of sufficient data across ages, sizes and time periods to perform necessary analyses. Nevertheless, given the strong evidence presented for temperature affecting fish growth (e.g. Shin-ichi Ito, Zhen Lin, Lea Simonet, Tuan Anh Bui), all speakers argued that it is important to account for warming impacts in fisheries assessment models. There was a consensus from speakers and members of the audience that we need to urgently improve our monitoring of fish growth in fisheries around the world.

4) ***Assessing the impacts of warming on commercial fisheries and forecast trends in future productivity***: Noah Khalsa, Miguel Barajas, Laurel Smith and Alan Baudron.

The fourth theme comprised a series of presentations that explored how we can incorporate temperature sensitives biological rates into stock assessment models. This is obviously a non-trivial task, but nonetheless empirical (Laurel Smith) and simulation studies (Miguel Barajas, Noah Khalsa) showed that this is something we need to consider. Panel discussion then moved on to the more general questions of how do we effectively communicate TSR to stakeholders? What information do we need in order to make good forecasts of temperature-dependent growth in the future?

Conclusions

Session J attracted a series of engaging and informative presentations that explored how temperature impacts fish growth, and the subsequent implications of fish body size changes for ecosystems are fisheries. The theme session was very popular with conference delegates, as evidenced by the high in person and virtual attendance and subsequent engagement at the panel discussion. Despite the theoretical predictions of TSR theory on how temperature affects body size, many presentations empirically proved that responses in natural populations can be more complex and that other factors such as fishing and food availability must be appropriately considered. Our session highlighted that there are still large disagreements in the underlying mechanisms of temperature impacts on fish size in natural ecosystems. It did, however, reinforce to all in attendance that temperature does have strong impacts on fish populations (directly or indirectly), that careful experimentation and analysis of fisheries data offers exciting opportunities to test new theoretical models and that concerted effort is urgently needed to appropriately consider temperature effects in fisheries models.

Contents

CM 8: Larger but younger fish when growth compensates for higher mortality in warmed ecosystem

Max Lindmark, Malin Karlsson, Anna Gårdmark

Ectotherms are often predicted to “shrink” with global warming. General growth models and the temperature-size rule (TSR) predict smaller adult sizes with warming, but they also predict faster juvenile growth rates. Hence, for it to cause a general “shrinking” of a population, mortality rates need to increase more to offset the faster juvenile growth and resulting larger size-at-age. In this study, we used data spanning two decades from an artificially heated (+8C) bay in comparison with an unheated area, to analyse how warming has affected body growth, mortality rates and population size-structure of unexploited populations of Eurasian perch (*Perca fluviatilis*). In the warm bay, body size was larger for all ages and growth faster for all sizes, resulting in larger size-spectrum slope (greater proportion of large fish) – despite higher mortality. Combining temperature effects on growth with those on mortality is necessary for understanding warming-induced changes in size-distributions. Because ecological dynamics emerge from size-dependent processes and functions, addressing how warming affects size-distributions through multiple processes is essential for predicting the effects of climate change.

Keywords: body growth, size-structure, size-spectrum, mortality, climate change

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CM 34: Resolving impacts of climate-induced life history changes of American lobster on its management

Noah Khalsa, Cameron Hodgdon, Yong Chen

American lobster (*Homarus americanus*) support the most valuable fishery in the US and have a demonstrated susceptibility to climate change. Decreasing size-at-maturity, increased molting frequency, and decreased molt increment size have been observed due to a warming environment, although the consequences of these life history changes on the population dynamics and fishery productivity are not well understood. Further, there is a paucity of work linking climate-driven life history changes and alternative regulations to understand and remedy impacts on stock dynamics and inform climate-ready management. In particular, the utility of minimum legal size conservation measures for alleviating potential impacts has not been evaluated. These knowledge gaps are concerning, as lobsters are socioeconomically vital in the Gulf of Maine. The overarching goal of this research is to assess the value of minimum legal size as a conservation measure for attenuating incipient impacts of climate-driven changes to maturity and growth on the American lobster fishery in the Gulf of Maine. An individual-based lobster simulator is used to simulate the effects of hypothesized future changes to lobster size-at-maturity and growth on the population and fishery dynamics under alternative minimum legal-size regulations. Spawning stock biomass, landings, and percentile-based indicators for stock status under alternative scenarios are evaluated. Recommendations will be made to reduce potential impacts of climate-induced changes in lobster maturation and growth on the lobster management in a changing Gulf of Maine.

Keywords: American lobster, minimum legal size, maturity, growth, climate change, individual-based models

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CM 45: Analysis of California Current groundfish growth using a state-space autoregressive length-at-age (sarla) model

Christine C. Stawitz, Sean Anderson, Melissa A. Haltuch, Paul D. Spencer, Timothy J. Miller, Timothy E. Essington, Alan Baudron

Many factors cause fish growth to vary over time, with factors affecting different segments of the population. For example, genetic factors affect the growth of individuals and close kin, the history of environment and food availability can affect growth in individuals and cohort groups, and environmental changes, such as changing temperature or salinity, can affect entire populations at a given time interval. Ideally we could track the changes in growth rates by repeated measurements of a single fish, but the most commonly available data are from fish caught in subsequent years in fishery-independent and -dependent samples. To quantify the effects of changes in the environment on growth, we need a method that can estimate environmentally-induced growth change across fish temporally while accounting for the effects of individual and sampling variability. We first introduced a state-space model to estimate annual, initial size, and cohort variability in mean length-at-age data in Stawitz et al. (2015). This state-space model for fish length-at-age was modified to improve sampling performance and allow simultaneous estimation of different types of variation in the Stan language and packaged in the R package sarla to allow for wider use. We also compared the model performance against alternative methods developed in Miller et al (2018) and Baudron et al (2014) on a dataset of California Current groundfish growth to explore the relative ability of these three models to detect growth change. Furthermore, fitting these alternative models to the same dataset allows us to determine if the modeling approach used influences the conclusion of whether or not environmental conditions affect fish growth.

Keywords: somatic growth, state-space models, environmental effects

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CM 72: Too hot or too cold: the biochemical basis of temperature-size rules for ectotherms

Daniel Pauly[a], Mimi E. Lam[b]

The temperature-size rules of fish and aquatic invertebrates describe the effect of temperature on the synthesis and denaturation of proteins that constitute, with water, the bulk of their bodies. Many adaptationist interpretations of these rules exist, compounded by misinterpretations of Bergman's Rule, but their biochemical basis lacks consensus. One fundamental component of the mechanism that leads to temperature-size rules is that (native) proteins only 'work' if their quaternary structure (or folding) is maintained. Thus, proteins have half-lives that are U-shaped functions of temperature, and higher or lower than optimal temperatures increase their rates of spontaneous denaturation in aqueous solutions, i.e., within body cells. Proteins that lose their quaternary structures, either because the surrounding water is too hot or too cold, and thus cease to function and must be resynthesized. This denaturation explains why the metabolic rates of ectotherms increase with temperature. However, frigid temperatures also promote protein denaturation, known as 'cold denaturation'. While controversial among biologists, cold denaturation clearly affects the metabolism of high-latitude fish and marine invertebrates. Only by understanding the biochemical basis of the temperature-size rules for ectotherms, especially for the growth a fish and aquatic invertebrates, can science advance to inform policies to mitigate adverse consequences of climate warming for fisheries.

Keywords: native protein, quaternary structure, Brownian motion, denaturation, enzyme activity

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CM 81: Modelling temperature impacts on fish growth using a growth model with reproductive costs: can we reproduce the temperature-size rule?

Asta Audzijonyte[1], Egle Jakubavičiūtė[1], Max Lindmark[2], Shane A. Richards[3]

The temperature size rule (TSR) is one of the universal rules in ecology and states that ectotherms growing at warmer temperatures will grow faster as juveniles, mature at a smaller size and/or younger age, and reach smaller maximum body sizes. While this phenomenon has been observed in many experimental and field studies, it is not clear which physiological processes are causing it. Many models have unsuccessfully attempted to reproduce TSR consistent life-histories using two-term (anabolism and catabolism) Pütter-type growth models (such as the von Bertalanffy). Here we present a simple mechanistic, individual growth model, which accounts for energy intake through feeding, energy use through maintenance and reproduction, and optimises energy allocation to growth, reproduction and reserves. The key aspect of the model is a size-dependent reproduction cost, which an organism must meet before maturation can occur. This cost results in growth, maturation and reproduction rates becoming emergent properties. By incorporating temperature-dependence into the physiological processes modelled, we identify conditions necessary for TSR-type growth to emerge under climate change. Specifically, we show that simple increases in metabolic or feeding rates with warming do not produce realistic TSR-type life-histories. Instead, individual growth and maturation trajectories consistent with TSR observations can only be achieved when both energy intake and reproduction investment increase with warming. Our results suggest that commonly adopted von Bertalanffy-type models, which do not explicitly include reproduction processes, may fail to accurately predict fish growth responses under climate change.

Keywords: ectotherms, temperature-size rule, reproduction cost, Von-Bertalanffy type growth model, optimal energy allocation.

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CM 95: Detecting trends in fish growth patterns using Dynamic Factor Analysis: A California Current ecosystem example

First author: Alan R. Baudron
Co-authors: Timothy J. Miller, Melissa A. Haltuch, Christine Stawitz, Paul D. Spencer

Ectotherms' growth is heavily impacted by temperature. According to the Temperature-Size Rule (TSR), warm temperatures lead to faster juvenile growth and smaller adult sizes. As seas are warming worldwide there is increasing empirical evidence of TSR in marine fish. However, in commercially exploited fish populations, size can also be impacted by size-selective fishing mortality, and other potential environmental drivers. Therefore, empirically detecting temperature-driven changes in marine fish sizes can be challenging, and attributing observed changes to temperature even more so. This is especially true when using in-situ observations such as trawl survey data that can vary greatly in quality. Nevertheless, temperature-driven changes in size are more likely to be detected across species that share the same environment compared to other species-specific drivers. Here we applied a Dynamic Factor Analysis (DFA), designed to identify common trends in a set of time series, to trawl survey data from 1977 to 2018 for seven commercial fish species of the California Current ecosystem spanning a wide range of life history traits in order to: (i) test if a common trend in size consistent with TSR can be detected across species and (ii) whether such trend can be attributed to temperature changes. Length-at-age observations were partitioned into three regions from north to south: Eureka/Columbia/Vancouver (ECV), Monterey, and Conception. The impact of two candidate explanatory variables, temperature and fishing mortality, were explored. Two different approaches were used: 1) a von Bertalanffy growth model was fitted to cohorts of each species in each region, and DFA was used to identify common trends in asymptotic length; 2) DFA was used to identify common trends in the mean length at three different life stages: juveniles, maturing, and mature individuals. Approach 1) successfully identified a declining common trend in asymptotic length supported by most species in all three regions, thereby supporting TSR. In contrast, approach 2) failed to identify a clear directional trend in mean length at all life stages in all three regions, except for mature individuals in Monterey, which showed a decline consistent with TSR. No significant impact of either temperature or fishing on the observed trends could be identified in either approach. Our findings suggest that using asymptotic length provides better chances of identifying common trends in fish sizes with DFA applied to patchy survey data across species with vastly different life history traits. Attributing trends in growth to TSR and/or fishing effort remains challenging.

Keywords: fish growth, temperature, temperature-size rule, dynamic factor analysis, von Bertalanffy

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CM 116: Fish growth changes in a large lake used for nuclear power plant cooling show that not all fish know about the temperature size rule

Vytautas Rakauskas, Andrius Steponėnas, Vytautas Kesminas, Asta Audzijonyte

It is generally expected that warmer temperatures will lead to smaller fish body sizes. Temperature size rule (TSR) states that fish, growing in warmer conditions grow faster as juveniles, but end up as smaller adults. Yet, it is unclear how commonly these patterns are observed in real ecosystems, where temperature, food availability and predation all change at the same time. It is also not clear whether these growth changes are long-term or easily reversible. Nuclear power plant cooling reservoirs offer natural laboratories to test TSR in real life conditions, and Druksiai Lake in Lithuania (area 45km^2) offers a unique case, because the lake was heated by nearly 3C and later returned to ambient temperatures, when the power plant was closed. We studied growth of five common fish species over the period of 50 years, encompassing years before, during and after the heating. We show that only one species follows TSR type growth responses. In other species either all ages get larger and in one case the opposite response was found – during heating juveniles grow slower and adults were larger. Some species returned to the original growth patterns once the lake cooled down, but this pattern was not universal. Our results suggest that warming changes many aspects of natural ecosystems, making it unlikely that most fish will follow the TSR type growth pattern in response to global heating.

Keywords: natural laboratories, temperature-size rule, long-term growth changes, multi-species analysis, temperature size rule

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CM 138: Warm and wanted: effects of climate change and fisheries on fish growth

Tuan Anh Bui, Marleen De Troch¬, Jan Jaap Poos, Adriaan Rijnsdorp, Bruno Ernande, Karen Bekaert, Kélig Mahé, Jochen Depestele

The effects of climate change and fishing pressure on fish populations have been of great concern. Temperature and fishing can additively or synergistically stimulate fish growth but only a few studies have investigated their effects simultaneously. Besides, most of the studies are conducted in a single region while it has been shown that there is inter-regional variation in the magnitude and direction of factors influencing somatic growth. In this study, we use a large archive of otoliths collected from Dutch and Belgian fisheries to develop multidecadal biochronologies (1957-2020) of average annual growth of two genetically distinct populations of sole (*Solea solea*) in the North Sea and the Irish Sea. These regions are at the cold edge of sole distribution and have experienced contrasting warming rate and fishing pressure. We then examine the relationship between the estimated growth variability and intrinsic (age, age at capture, size at the start of the growing season) and extrinsic factors (temperature, density dependence, fishing pressure, coastal nutrient loading) using a hierarchical mixed-effects modeling framework. We hypothesize that: (1) average individual annual growth of sole is positively correlated to warming conditions, which is consistent with other demersal species in the North East Atlantic and because the studied areas are at the cold edge and, thus, are not close to critical upper thermal limits of sole; (2) Temperature and fishing variables additively or synergistically affect the individual annual growth of sole; and (3) There is consistency in the direction but inter-regional variation in the magnitude of effects of temperature and fishing variables on the individual annual growth of sole.

Keywords: sole, growth, climate change, temperature size rule, fisheries-induced evolution, mixed-effects modeling

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CM 150: Biological changes in key commercially exploited fish in the light of climate & ocean change

Callum Sturrock, Deirdre Brophy, Russell Poole, Cóilín Minto, Louise Vaughan, Dave Reid

Climate change is affecting marine ecosystems worldwide with consequences for fish populations. These are manifested as changes in their distribution, phenology and growth across a wide diversity of taxonomic groups and a broad geographical range. However, many fish populations are subject to other stressors, including fisheries exploitation. Selective harvesting can gradually reduce population complexity and these stressors could then erode population resilience to environmental changes and magnify their impacts. In this context, there is a need to evaluate the past variability of fish populations to identify, quantify and contextualise the causes of observed changes and forecast their future impacts. Across many commercial fish stocks, patterns of increased growth rates of younger fish and smaller maximum body size have been observed in recent decades and has been linked to the interacting effects of climate change and fishing pressure. This study aims to identify these biological responses and their variation in time and space. This is achieved by using trawl survey data to develop time series of important life history parameters (Length/ weight-at-age, maturity at size/age) for selected commercially important fish stocks in the waters around Ireland and from the last three decades. Advanced modelling techniques are used to separate intrinsic sources of growth variability from the annual signal which captures variability due to extrinsic factors (temperature, population abundance and fishing pressure). Correlations in the annual growth signal across species and stocks, which may reflect a common response to an environmental driver, are investigated. Results will contribute to the development of adaptive management approaches within the context of climate change in Ireland.

Keywords: climate change, fish growth, fisheries, mixed effect modelling, temperature

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CM 163: Implications of climate driven changes on growth and size-at-maturity for size structured stock assessment

Cameron Hodgdon, Noah Khalsa, Mackenzie Mazur, Yong Chen

Crustaceans are socioeconomically and ecologically crucial globally. However, as ectotherms, anthropogenic climate change threatens to significantly alter key life history characteristics such as size-at-maturity and growth. Size-structured stock assessments are commonly utilized for assessing crustacean fisheries because of difficulty in aging crustaceans, but climate-induced changes in maturation and growth can greatly influence the performance of these models. We couple an individual-based model and a size-structured stock assessment model for American lobster (*Homarus americanus*) to conduct a novel sensitivity analysis by altering maturity and growth-related input parameters using bottom-up (parameters shifted independently) and top-down (parameters shifted jointly as influenced by climate change) approaches. The main objective of this research is to demonstrate the importance of evaluating the sensitivity of the size-structured stock assessment model for lobster to climate influenced shifts in maturation and growth-related inputs. We found the lobster stock assessment model to be resilient of relatively extreme shifts in biological input parameters. This research demonstrates the critical need to expand sensitivity analyses for size-structured stock assessments of crustaceans to evaluate the influence of climate-driven shifts on life history input parameters on a case-by-case basis, for time-varying life history traits in stock assessment modelling, and for research on quantifying the relationship of lobster life history parameters with the environment. The global sensitivity analysis we employ is greatly underutilized in many fisheries, but can ultimately aid in determining model resilience to climate-induced shifts in life history parameters.

Keywords: growth, size-at-maturity, crustacean fisheries, individual-based models, stock assessment, sensitivity analysis

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CM 179: Simulating the effects of warming ocean temperatures on fish growth and evaluating population outcomes

Miguel F. Barajas, Katherine E. Mills

Warming ocean temperatures have led to a number of changes to fish and their marine ecosystems. Warmer ocean temperatures can result in smaller fish body sizes which can affect fish population outcomes. Young fish may grow quicker but will reach smaller adult sizes which can potentially lead to a loss of yield in fisheries. We developed spatial population simulation models to test how life history features such as growth, survival, and fecundity between contrasting fish archetypes (Atlantic herring and Atlantic cod) may be affected differently by warming ocean temperatures and to evaluate their relative impacts on population outcomes. We found that the negative effects of warming ocean temperatures on size composition and fecundity can be balanced against the influence of warming ocean temperatures on survival when the rate of warming is moderate and when warming leads to an increase in suitable habitat. We also found that the negative impacts of warming are greater for species with a more sensitive thermal response to warming. Population outcomes depend on interactions between life history traits, rates of warming ocean temperatures, and the ability of fish to migrate to suitable habitat.

Keywords: fish growth, temperature impacts, life history, marine fisheries

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CM 185: Effects of ocean conditions on the body growth and maturity of Korea chub mackerel (Scomber japonicus) population

Saang-Yoon Hyun, Heejoong Kang, Jung Hyun Yoon

Our study was motivated by the ICES/PICES Working Group (WG) on impacts of warming on growth rates and fisheries yields (GRAFY). It is well recognized that global warming, caused by the increased amount of carbon dioxide, has changed aquatic ecosystems. For example, the temperature size rule (TSR) dictates the effect of temperatures on body growth and maturation of ectotherm organisms, where they mature at smaller body sizes under warmer temperatures, although TSR would be difficult to detect in the wild because growth and maturation are also affected by other factors such as food (prey) nutrition. We in Korea rarely identify ages of fish caught by fisheries and surveys, and even available temporal data about fish growth and maturity are not long enough for the investigation of climate effects. Given limited information about Korea chub mackerel (*Scomber japonicus*), which includes the length-at-age key from 2000's (specific years are unknown), length frequency data from 2000-2020, and sexual maturity-at -length data from 2005-2020, we would like to examine effects of the ocean conditions on the growth and maturity of the chub mackerel population and implication to the fishery yield. Our methods will include estimating biannual or yearly age compositions hidden in the length frequency data, and maturity parameter (e.g., L50%) with the maturity-at-age data, and then link ocean condition variables to those estimates. Furthermore, as in part of WG GRAFY tasks, we will check the impacts of warming on yield per recruit of the mackerel fishery.

Keywords: fishery yield; hidden age compositions; length frequencies; maturity at length; *Scomber japonicus*

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CM 202: Trends in populations growth and demersal community size structure in the Bay of Biscay and Celtic Sea

Léa Simonet, Morgane Travers-Trolet, Arthur Valance, Marie Savina-Rolland

In the Bay of Biscay and Mediterranean Sea, pelagic populations length-at-age (especially anchovies and sardines) have declined since the 2000s. More recently, it was observed that mean weight indices also decreased in the case of several demersal species throughout the Bay of Biscay ecosystem (e.g. greater weaver, red gurnard, veined squid, megrim, hake, red mullet, boarfish), and especially in its coastal part. This decrease might be due to changes in population demographics (modifications in the proportion of young individuals) or in growth (length/weight-at-age) or a combination of both. Changes in weight/length at age can be caused by environmental and biotic factors, including a change in food availability (quality and/or quantity), or density-dependent processes.

In this study, we will analyse extensive datasets (over more than 20 years) from scientific surveys and auction sampling to determine the causes of the observed trends in the demersal species listed above, and determine if these are also observed in other demersal species both in the Bay of Biscay and in the Celtic Sea. We will particularly assess if growth and maturation have changed over the past decades, through analysis of length-at-age and length/age at maturity times series for several demersal species. Spatial analysis will be carried out to check whether the trends in weight and size structure differ according to habitats and if any north/south, coast/large gradients exist, both at the species and the community levels. Finally, available spatialized environmental forcing data in the area will be used to identify the factors that may have contributed to the decrease in average weight observed in the Bay of Biscay and to the potential changes in community size structure identified in this study.

Keywords: bottom-up effect, sea surface temperature, density-dependence, demersal populations, spatial and time analysis, Bay of Biscay, Celtic Sea

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CM 232: What use is the Temperature-size Rule for fisheries?

David Atkinson, Curtis R. Horne, Andrew G. Hirst

The Temperature-size Rule (TSR) is the reduction in mature or final body size of ectotherms, including fish, after they initially grow faster at increased temperatures. A reduced size is fully expected under stressful conditions (e.g. food limitation, hypoxia, temperatures exceeding an organism's normal range). But the TSR has long been considered a puzzle because it is defined as applying to conditions that seem to be non-stressful for growth (non-limiting food supply, non-extreme temperatures). We have found that the temperature-dependence of mature body size varies systematically among diverse groups of animals, which provides an opportunity to test hypotheses proposed to explain the TSR. In this paper, we first compare physiological models that have been proposed to explain different temperature dependencies of mature or final size in fish and other water-breathers. One model is the Gill Oxygen Limitation Theory (GOLT), which has been developed for predicting body size in global fisheries; another is our new Emergent Metabolic Scaling model. GOLT overestimates temperature-dependence of mature size by at least 2-10 times. Our model predictions fit the data significantly better in strength and direction of response, when assessed against the GOLT model. We propose that some problems in prediction arise from the misuse of the von Bertalanffy growth function. We then consider how research on the TSR may be used to help quantify the combined effect of multiple stressors on fish growth and mature size in warming seas. Predicting the amount of reduction in fish body size with warming and the fate of populations is thwarted by the sheer complexity of the environment and multiplicity of stresses, including fishing mortality, predation, disease, food shortage and competition. We propose that reductions in fish growth and mature size in nature may be compared against a standardized "no-stress" response to temperature that is observed or predicted in studies of the TSR, thereby quantifying combined stress impacts in the field. By comparing a reference "maximum" response to temperature with actual responses in the field, we would adopt an approach well established in ecosystem modelling (e.g. phytoplankton population growth). The numerous potential explanations proposed for the TSR may also help us propose what body condition measures (fat content, blood health diagnostics) and relevant ecosystem information (e.g. on food abundance) may be used to help diagnose the effects of warming and other effects on growth and mature body size in fish populations.

Keywords: growth, warming, temperature, body size, fish, fisheries

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CM 268: Smaller adult fish size in warmer water is not explained by elevated metabolism: a multigenerational experimental approach

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Co-authors: Asta A, Michael K, John M

Fish and other ectotherms living in warmer waters often grow faster as juveniles, mature earlier, but become smaller adults. Known as the temperature-size rule (TSR), this pattern is commonly attributed to higher metabolism in warmer waters, leaving fewer resources for growth. An alternative explanation focuses on growth and reproduction trade-offs across temperatures. We tested these hypotheses by measuring growth, maturation, metabolism and reproductive allocation from zebrafish populations kept at 26 and 30°C across six generations. Zebrafish growth and maturation followed TSR expectations but were not explained by baseline metabolic rate, which converged between temperature treatments after a few generations. Rather, we found that females at 30°C allocated more to reproduction, especially when maturing at the smallest sizes. We show that elevated temperatures do not necessarily increase baseline metabolism if sufficient acclimation is allowed and call for an urgent revision of modelling assumptions used to predict population and ecosystem responses to warming.

Keywords: warming, metabolic rate, temperature size rule, evolution, adaption

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CM 285: Warming leads to opposite patterns in weight-at-age for young versus old age classes of Bering Sea walleye pollock

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The metabolic theory of ecology predicts that climate warming will lead to faster growth rates for juvenile fishes but lower adult body size. Testing this prediction is central to understanding the effects of climate change on population dynamics. Here, we use fisheries-independent data (1999-2019) to test predictions of age-specific climate effects on body size in eastern Bering Sea walleye pollock (*Gadus chalcogrammus*). This stock supports one of the largest food fisheries in the world and is experiencing exceptionally rapid warming. Our results support the predictions that weight-at-age increases with temperature for young age classes (ages 1-3) but decreases with temperature for older age classes (ages 8-11). Simultaneous demonstrations of larger juveniles and smaller adults with warming have thus far been rare, but pollock provide a striking example in a fish of exceptional ecological and commercial importance. The age-specific response to temperature was large enough (0.5 – 1.5 SD change in log weight-at-age) to have important implications for pollock management, which must estimate current and future weight-at-age to calculate allowable catch, and for the Bering Sea pollock fishery, which could see considerable per-fish loss of biomass in older age classes. We also quantified the impacts of ignoring temperature effects on weight-at-age when projecting future biomass to illustrate the importance of considering temperature-dependent growth dynamics when determining biological reference points.

Keywords: walleye pollock, *Gadus chalcogrammus*, growth, metabolic theory, temperature

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CM 288: Disentangling potential hypothesis for the decrease in weight of anchovy in the Bay of Biscay

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Ocean warming promotes a decline in the body size of marine ectotherm species. The temperature size rule –the earlier maturation and cessation of growth at warmer temperatures– provides a framework to understand the response of marine organisms to warming. Here, we report a 35% decrease in the body weight of Bay of Biscay anchovy (*Engraulis encrasicolus*) during the last decades, based on data from research surveys covering different life-stages (BIOMAN spring surveys since 1987 and JUVENA autumn surveys since 2003). We also considered alternative mechanisms ranging from density-dependent effects mediated by changes in food-availability and changes in size-selective mortality, to the impact of fishing on age structure and population abundance. The collapse of the stock in 2005 provides an unpairedopportunity to assess the relative contribution of intrinsic population mechanisms with respectto fishing. Our analyses suggest that the main driver of the decline in anchovy weight is relatedto density-dependent constrains, given the parallel increase in abundance since the reopening of the fishery. The increase in sea water temperature (0.10-0.25 °C per decade since 1980) mighthad amplified these effects leading to smaller sizes for both, juveniles and adult fish. The hypotheses about smaller size due to fishing or changes in food availability were rejected. Whilethis work provided some insights about the underlying mechanisms, further studies are neededto evaluate if there has been a change in the environmental conditions affecting the size- selective mortality at early life-stages that has led to a larger survival of smaller size individuals.

Keywords: anchovy, body weight, body size, temperature size rule, environmental conditions, ocean warming, density-dependence

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CM 306: Can the temperature size rule help us predict fisheries productivity in a changing climate?

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The temperature size rule, or the inverse relationship between temperature and ectothermic body size, has come to encompass both the laboratory-based response whereby individuals reared in warmer waters grow faster to a smaller maximum size, and the macroecological pattern of smaller, faster-growing individuals (and species) in warmer waters. Despite being nearly ubiquitous, the interplay among size, growth, and temperature that gives rise to such widespread patterns across species is not well understood. In particular, the effects of temperature on size and growth are likely uneven across life stages – faster growth under warmer temperatures may result in a larger size-at-age for earlier life stages but a smaller size-at-age for later life stages. Yet we lack an understanding of whether this pattern is common across species (and regions) and how these dynamics will affect the future of fisheries, which have already induced shifts in size and growth. Here, we bridge macroecological theory with fisheries science and examine how the interaction of size, growth, and temperature will affect fisheries productivity in a changing climate. To do so, we combine fisheries survey data, estimates of abundance and size from stock assessments, and time series of temperature from regionally downscaled global climate models to assess how size-at-age and abundance-at-age of commercially important fishes in Alaska's large marine ecosystems has changed with temperature in the past and will continue to change in the future. We then assess how these effects vary with oxygen (also from global climate models) to understand how both temperature and oxygen may relate to patterns of growth and size. Additionally, we use established size-fecundity relationships to predict how changes in adult size may confer changes in reproductive output. Finally, to inform how the combined effects of climate and demography may shape fisheries productivity, we incorporate these size- and environment-dependent growth patterns and fecundity into fisheries models. Observations indicate that the strength and direction of size, growth, and temperature relationships depend on size class (and thus change along the ontogenetic growth trajectory) and that these dynamics allow for predicting stage-structured population dynamics based on future environmental conditions. This work highlights the complexity in the temperature size rule and applies this complexity to predict fisheries productivity, thus connecting theory with empirical data and models to uncover the intricate dynamics between the environment and life histories.

Keywords: ecophysiology, life history theory, macroecology, fisheries modeling, temperature size rule

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CM 358: Fish body weight long-term variability around Japan. Part 1: Data mining and historical variations

Shin-ichi Ito, Zhen Lin

Ocean has been warming over the last 100 years and will continue in the next decades. Rising water temperatures are expected to reduce somatic size of aquatic organisms, an outcome known as "temperature-size rule" (TSR). The western North Pacific has a wide range of sea water temperature, many fish species habitat and Japan is one of the most data rich countries regarding fisheries data. In addition, Kuroshio is one of the hotspots of warming. Therefore, the western North Pacific is an appropriate testbed to investigate whether TSR works in the ocean and quantize its impact to the fish as a large marine ecosystem scale. We searched Fish resource assessment reports published by the Fisheries Agency and the Fisheries Research and Education Agency and found that historical year-specific weight data for 26 populations of 16 species. However, the length of data was different between the populations. We picked up 6 populations (Japanese sardine Pacific stock, Japanese sardine Tsushima Warm Current stock, Japanese anchovy Pacific stock, Japanese anchovy Tsushima Warm Current stock, round herring Tsushima Warm Current stock and chub mackerel Pacific stock) which data exist between 1978 and 2018. First we defined their life stages to juvenile, maturing and mature stages by their age. Averaged wet weight normalized anomaly for the 3 stages was used for dynamic factor analysis (DFA). The DFA derived common trends reveled strong influence of large biomass fluctuation of Japanese sardine until 1990 instead of sea surface temperature. However, the common trends showed different tendency with biomass of Japanese sardine after 1990. The results indicate the shift of main environmental drivers to control the common trends before and after 1990.

Keywords: temperature size rule, fish body weight, Northwestern Pacific

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CM 363: Fat Fish, Thin Fish: Regime Shifts in Fish Condition and Environmental Drivers

Laurel A. Smith[1], Andrew J. Beet, Michael J. Fogarty, Ryan Morse

Fish condition is an indicator of fish health, where fatter fish are generally healthier and produce more viable recruitment. Many factors may contribute to fish condition including temperature, food availability and food quality. In this study, 29 years of relative condition factors (Kn) were analyzed for 47 finfish species regularly caught on the Northeast Fisheries Science Center's autumn bottom trawl survey. Chronological clustering using multivariate regression trees were performed to evaluate significant change points in condition across species. A significant regime shift to poorer condition was seen after the year 2000 across fish species on the Northeast US Continental shelf, and a non-significant change was seen after 2008, with some species starting to improve in condition and others continuing to decline. Similar regime shifts were seen in bottom water temperature and copepod size structure, indicating that these changes in fish condition may be due to broad ecosystem regime shifts. These changes in weight can directly cause implications for stock assessments, catch quotas and management and may indirectly impact natural mortality and fish recruitment. Linking environmental drivers to regime shifts in fish condition has proven to be useful in stock assessments by providing an ecosystem context to determine stanzas of years to be used for stock recruitment projections.

Keywords: fish condition, regime shifts, temperature, fisheries

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CM 364: Negative effects of warming on fishery yields in the Chinese waters

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Chinese waters including the Yellow Sea, East China Sea and South China Sea are parts of the most productive areas in fishery yields globally. These seas are located in hotspots of global warming and significantly increasing water temperatures would alter greatly the ecosystem structures and further their functions, such as the fishery yields. To identify the effects of warming on fishery yields in the Chinese waters, I complied 34 catch time-series spanning in the three seas 1980-2019 from Chinese Fishery Statistics and then related them to fishing efforts and sea surface temperature with a linear mixed-effects model. Despite the dominant effects of fishing efforts, catch time-series were negatively affected by increasing sea surface temperature, and magnitudes of the negative effects differed by species and seas. Specifically, cold-affinity species suffer more from warming than warm-affinity species. In addition, species in the East China Seas where the warming is drastic had the most observed negative associations with warming, whereas species in the South China Seas where the warming is smooth showed relatively weak relationships with increasing sea surface temperature. Temperature size rule may be an explanation on the negative effects of warming on fishery yields in the Chinese waters. However, the similar pattern between fishing efforts and warming, make it difficult to disentangle their effects clearly.

Keywords: warming, fishery yields, Chinese waters, temperature size rule

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CM 365: Fish body weight long-term variability around Japan. Part 2: Recent variations responding to climate change

Zhen Lin, Shin-ichi Ito

Ocean has been warming over the last 100 years. Rising water temperatures are expected to reduce somatic size of aquatic organisms, an outcome known as "temperature-size rule" (TSR). Warming temperature induces a mismatch between increasing anabolic oxygen demand and decreasing oxygen solubility, where individuals reduce their mature size to provide more breeding energy for the next generations. The analysis of historical data on useful fish species in the North Sea and the Mediterranean has pointed out a decrease in maximum body length. Since many factors (e.g., fishing pressure) compound to influence the observed data, thus, separating the influence of temperature from other factors is important. State-space models have been used to quantify the effects temperature and fishing pressure on specific fish sizes. However, it remains unclear about the influence of TSR in an ecosystem-level. The western North Pacific has a wide range of sea water temperature, many fish species habitat and Japan is one of the most data rich countries regarding fisheries data. In addition, Kuroshio is one of the hotspots of warming. Therefore, the western North Pacific is an appropriate testbed to investigate whether TSR works in the ocean and quantize its impact to the fish as a large marine ecosystem scale.

Historical year-specific weight data for at least 26 populations of 16 species were found from Fish resource assessment reports published by the Fisheries Agency and the Fisheries Research and Education Agency. We selected 1993-2018 as an analysis period since all populations have data. If the TSR has a non-negligible effect on the growth of aquatic organisms, it is likely that different fish group will show a similar trend. Dynamic factor analysis (DFA) is a multivariate time series analysis that can estimate the general trends underlying short non-stationary time series, including missing values. DFA is used to estimate general trends in weight time series by age. Before applying DFA, we deleted time series of specific age which are highly positively related with younger age to exclude the co-linearity problem. For the short-term data, 28 fish groups were finally selected. Two common trends were identified by the DFA. Observed fish growth variation are caused by many reasons (fishing pressure, initial size at recruitment, density dependence, changes in maturity, etc.). We will extend the analysis to determine the drivers to generate the common trends.

Keywords: temperature size rule, fish body weight, Northwestern Pacific

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CM 374: Are fundamental thermal performance curves a good indicator of real ones? A first answer with a marine food web model approach in the North Sea ecosystem

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Understanding how temperature affects fish populations is important to predict the effects of climate change. Physiological thermal performance curves (TPC) are commonly used to project future species distributions or physiological performances. However, beyond the direct effect of temperature, physiological rates are also affected by other extrinsic factors that covary with temperature, such as food availability. The emerging realized physiological performances result from both direct and indirect effects of temperature, the latter channeled through other extrinsic factors.

Ev-Osmose is a multi-species eco-evolutionary model, notably developed to account for plastic trait variations and their impacts on food-web dynamics. A bio-energetic model describes mechanistically net energy acquisition as emerging from energy fluxes sustained by food intake through explicit predation. These fluxes depend directly on temperature, oxygen concentration and food availability. The available food biomass depends on the dynamics of explicitly modeled prey species and of low trophic level biomass forcing the model, which both vary with temperature. This model is applied to the North Sea ecosystem to compare species' fundamental physiological TPCs with their realized ones. We explore the results for sixteen species at different life stages. The small pelagic species and the 0-year stages have the most sensitive TPCs to extrinsic factors whereas the demersal higher trophic level species realized TPCs are similar to fundamental ones. These results complement previous analyses solely based on fundamental physiological thermal preferences and tolerances, and are crucial to better determine thermal vulnerability and the persistence of populations in the context of climate warming.

Keywords: thermal performance response, marine ecosystem modeling, trophic interactions, temperature directs and indirect consequences

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CM 407: Life-history traits of a cold-water species in a warming Mediterranean Sea: the case of whiting from the Northern Adriatic Sea

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Understanding the interaction between environmental factors and fish populations is crucial to address fishery management policies, especially in the context of climate change. Nowadays, one of the most striking variations is the increase in sea temperature, showing a greater magnitude in shallow regional seas. Temperature controls the metabolic processes rates because enzymatic reactions are strongly temperature-dependent, affecting directly the growth performance and the reproductive potential. Although several studies explored the warming effects on thermophilic species, little attention has been paid to cold-waters species in the Mediterranean Sea (MS). In the last decades, a decline in abundance of gadoid species has been observed and the rate of decline was notably high in semi-enclosed basins, such as the Adriatic Sea. Although whiting (*Merlangius merlangus,* Gadidae) has a quite local distribution in the MS, being commercially targeted only in the Northern Adriatic Sea (NAS), the Black Sea, and the Aegean Sea, current data in this area are scanty. The unknown biological effects of sea warming and the dramatic landings' decline of the last decades impose the need for updated biological data. In this study, we focused on growth and reproduction patterns of whiting in the NAS, to unravel the adaptive strategies of this species in the basin that presents the highest values of sea temperature increase and fishing exploitation of the MS. Fish samples were collected from commercial landings of the Veneto region, which hosts one of the most important fishing fleets in Italy, within the periods 1990-1991 (n= 1475) and 2020-2021 (n=728). The whiting population exploited by the Italian fishing fleet of the NAS is composed mostly of young individuals (<2 years) with a high growth rate, ensuring a good yearly biomass of recruits joining the adult population. Based on the macroscopic analysis of gonad maturity, sexual maturity is reached after one year at approximately 18 cm total length in both sexes. Spawning takes place from December to March, with a peak between December and January. Length-frequency distribution analyses show a simplified population structure in the 2020-2021 sampling compared to the one from 1990-1991, with the disappearance of modal classes representing older individuals. Furthermore, analyses of otolith sections are still ongoing to point out whether differences in growth rate are detectable comparing samples collected with a time-shift of 30 years and how the observed growth patterns are related to the sea temperature trend in the NAS over the last decades.

Keywords: Northern Adriatic Sea, Mediterranean Sea, commercial species, sea warming, growth, reproduction, cold-water species, gadids, whiting.

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CM 425: Fishing and warming combine to affect expressed size-at-age in commercially fished species

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Selective harvesting, like fishing, can erode size diversity in wild fish populations by truncating population size-structures and homogenising growth rates. Many important population and fishery metrics are influenced by size, including reproduction, recruitment success, stock biomass and mortality regimes. Reductions in trait variation (within the population portfolio) can lead to altered population dynamics, with stocks becoming more synchronous within a region and hence more susceptible to environmental perturbations. Understanding the capacity to which exploited populations can buffer environmental disturbances through portfolio effects is becoming increasingly important due to the impacts of climate change. To test whether fishing and climate have eroded trait variation in commercially fished stocks, we analysed time series (up to 55 years) of size-at-age data for 20 species from two large marine ecosystems (LMEs), in relation to life stage (juvenile or adult), fishing pressure and temperature. We measured three different metrics to quantify changes in size-at-age: the mean, maximum and variance in size-at-age. We found clear evidence that size-at-age changed through time in both LMEs and that these temporal changes could be attributed to both temperature and fishing. The magnitude of changes was dependent on life stage, with results suggesting that warming waters can result in a reduction in adult body size but that this effect is potentially mitigated by a fishing-induced relaxation of density-dependent controls. Our results provide novel insight into the importance of addressing the synergistic impacts of fishing and climate on body size. Such knowledge will improve predictions of population vulnerability to disturbance leading to more sustainably managed fisheries, especially in the face of rapid environmental change.

Keywords: density-dependent growth, temperature size rule, fisheries induced evolution, spatial synchrony, climate change

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CM 435: Inferring the thermo-saline niche of a freshwater top piscivore (Esox lucius) living in brackish lagoons

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Physiological preferences and tolerances of fish are typically size-dependent and, together with behavioral decisions and growth-mortality trade-offs, shape the realized niche within the environment. Besides temperature adaptation, osmoregulation is a key challenge for freshwater fish when colonizing saline habitats. In this context, eco-physiological and evolutionary theory predicts early life stages of freshwater fish seeking out conditions favoring fast growth, such as sheltered habitats with higher temperatures and low salinity, because optimal growth temperature is higher while osmoregulatory capacity is lower in early life-stages with small body size compared to later life stages at large body size. We test this hypothesis using a northern pike (Esox lucius) population sampled from brackish lagoons in the southern Baltic Sea of Germany. We inferred the realized thermo-saline niche along the life of 100 pike by employing a combined otolith microchemistry approach based on trace element analysis of Sr/Ca ratio as a marker of salinity and oxygen isotopy as a thermal marker. The small and young pike, particularly age-0 pike, generally experienced warmer and less saline environments than later life stages. The realized thermo-saline niche of pike consistently shifted towards higher salinities and lower average temperatures as the fish aged and grew in length, indicating active habitat choice moving from low saline, warm and shallow littoral zones to deeper, more saline water as the fish age and grow. However, considerable individual variation in the realized thermo-saline niches was observed, suggesting the presence of broad clusters of distinct life strategies, including freshwater residents living year-long in tributaries to the Baltic Sea, anadromous pike, high salinity specialists and flexible, intermediate phenotypes. Our results suggests that the population of Baltic pike is composed of at least three different ecotypes. The individual variability inherent in the ecotypes seems important to maintain the adaptive potential of the pike population to ongoing climate change.

Keywords: Northern pike, Bodden, growth, size-at-age, scaling, warming, secondary ion mass spectrometry, laser ablation inductively - coupled plasma mass spectrometry

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CM 448: Detecting age-related seasonal signals in otolith chemistry data; a statistical approach that incorporates biological properties of growth

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Accurate and precise age estimates are important for deriving biological reference points used in the scientific assessment of fish stocks and for understanding how temperature-dependency affects growth and body size across the life history. Age estimates are usually obtained by counting and measuring periodic growth marks in otoliths, scales or other calcified structures. However, the appearance of growth marks in calcified structures is variable and their visual interpretation can be prone to subjectivity. Otolith growth reflects fish growth, responding to both the external environmental conditions and the physiological response of the individual. As otoliths are not reabsorbed and grow continuously throughout the life of the fish, seasonal changes in temperature and physiology can produce periodic patterns in otolith chemical composition, in addition to the visual growth patterns. The analysis of these chemical signals can provide a method of age-determination, and help to resolve uncertainties in the interpretation of visual growth marks. Across several species, clearly defined minima and maxima in the concentrations of some elements and isotopes correspond to age.

A transect of otolith composition is a time series with a distinct characteristic: the temporal resolution varies within and between years. The distance between measurements decreases in times of slower growth, as well as over the lifetime and with increasing distance from the origin (due to logistic growth of the fish). Visual growth marks can provide a temporal reference point, but when interpretation of these marks is difficult, the age of the fish at any point along the transect – and thus the temporal resolution becomes more uncertain. This presents a challenge when using time series methods to analyse otolith chemistry profiles. The aim of this study was to develop a statistical tool to detect periodic signals in otolith chemistry profiles that incorporates the logistic properties of fish growth. Two approaches were used; (1) the Lomb-Scargle periodogram (Ruf, 1999), modified to incorporate the von Bertalanffy growth function and (2) a novel von Bertalanffy chirp function. The efficacy of these methods was demonstrated using data from cod (*Gadus morhua L.*), for which age was independently verified using visual inspection of otolith growth marks, and from white anglerfish, for which there is a high degree of ageing uncertainty. Both approaches provided new insights into the relationship between visual and chemical features in the otolith and represent an important advance for investigations of fish age and growth and their drivers.

Ruf, T. (1999) The Lomb-Scargle Periodogram in Biological Rhythm Research: Analysis of Incomplete and Unequally Spaced Time-Series. Biological Rhythm Research 30, 178.

Keywords: fish growth, von Bertalanffy function, spectral analysis, age validation, white anglerfish, Lophius piscatorius, cod, Gadhus morhua

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CM 450: Synchronous growth trends in wild and ranched Atlantic salmon Salmo salar over 62 years in a western European catchment

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In recent decades, growth and survival of Atlantic salmon (*Salmo salar*) at sea have declined across much of the species' range. Multiple interacting factors are implicated, including the direct and indirect effects of increasing temperature on metabolism, feeding, phenology and avoidance of predation. The release of hatchery-bred (ranched) salmon to supplement returns of adult salmon to rivers may affect resilience of salmon stocks and their ability to adapt to climate change. This study uses scales from returning adults to compare growth profiles during the marine phase between hatchery-bred (ranched) and wild salmon from the Burrishoole catchment (western Ireland) over 62 years (1956-2017). The objectives were to establish if there were differences in growth trajectories and temporal growth trends between wild and ranched fish and to identify the main environmental drivers of observed change for each population. Due to the constant food supply in the hatchery, ranched salmon grew more quickly than wild salmon during the freshwater phase, as reflected by the size of the scale on entry to the marine environment. Modelling of scale growth trajectories showed evidence of a compensatory growth response in wild fish, particularly during the first summer at sea or the post-smolt growth (PSG) period, which is a critical period for growth and survival. Although ranched fish remained larger than wild fish on the return migration, the relative difference in size was much reduced. Despite these population-specific growth patterns, long-term temporal trends in marine growth of wild and ranched fish were similar, with a marked decline in PSG and length of returning fish occurring in both populations from the early 2000s on. In linear mixed effect models, the decline in PSG was significantly related to freshwater growth and autumn sea surface temperature in the Norwegian Sea. A generalised additive mixed effects model of intercirculi spacings (ICS) in the PSG period identified temporal changes in the growth trajectories; for both wild and ranched fish, circuli deposited during the first summer at sea were narrower in the 2000s and 2010s compared to earlier decades while circuli from the first winter were wider (though a net reduction in ICS was detected overall). The results show that while wild salmon have a greater capacity for growth at sea than ranched salmon, the recent decline in growth affects both populations similarly, is primarily driven by temperature and is manifested as a change in growth pattern as well as overall growth.

Keywords: marine migration, compensatory growth, salmonid, hatchery, temperature response, climate change

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CM 528: Rapid warming, regional climate and fishing all drive fish growth variation in SE Australian waters: novel insight from 100 years of otolith-based observation

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Understanding and predicting the joint impacts of rapid warming and fisheries harvest on biological systems are key tasks facing marine researchers today. Unfortunately, long-term biological datasets are uncommon for many aquatic systems, and animals such as large-bodied fishes are unsuitable for targeted experimentation. Growth biochronologies, generated from the time-dependent information naturally recorded in fish otoliths that themselves are archived in their millions worldwide, can provide valuable long-term datasets that facilitate the development of ecological and evolutionary insights into marine and freshwater environments.

South-east Australian waters support both unique biodiversity and major commercial fisheries, but the region and its natural resources are increasingly being exposed to rapid oceanic warming. Here, I present the results of a large-scale project investigating the environmental drivers of fish growth variation using a data set of unprecedented spatial, temporal, and biological coverage. Otolith-based growth time series for over 30 species and stocks, each up to 100 years in length, from across nearly 3000km of coastal SE Australia and a range of habitats were analysed using dynamic factor analysis and generalised additive models. Long-term growth patterns for many species displayed strong temporal synchrony, pointing to universal ecosystem drivers of change. Directional trends in modes of growth variation were indicative of ubiquitous warming impacts (via direct and/or indirect pathways) that either promoted or inhibited growth depending on a species' habitat and distributional range. Quasi decadal oscillations in observed growth rates reemphasised the importance of Zonal Westerly Winds and the Southern Annular Mode in driving regional recruitment and system productivity variation. Overall, growth variation was also sensitive to regional fishing effort. This finding corroborates other work in identifying the larger-scale impacts of trawl fishing on fish assemblages. Together, this work highlights the valuable information stored within otoliths and their potential to provide unprecedented levels of spatial and temporal resolution into the drivers of productivity change in our oceans.

Keywords: otolith biochronology, density dependence, climate change, warming, growth rate, regional drivers, harvest, temperature size rule

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CM 572: Investigating thermal windows of juvenile Sockeye Salmon populations under climate change

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Climate-induced changes in population status are widely expected, but the mechanisms of climate impacts in early life stages and carry-over effects to adult life stages are poorly understood. Laboratory studies demonstrate fish growth exhibits a 'thermal window', increasing with temperature to species-specific thermal optima, beyond which additional increases in temperature lead to decreases in fish growth. Slower growth can result in lower survival, leading to reduced stock productivity. Salmon stocks have unique life history cycles that alternate between freshwater and marine environment. Similar decadal scale changes occur both in the North Atlantic and in the Pacific and this study pertains to Pacific salmon. In this study, we reconstruct stock-specific long-term time series (1970-now) of annual growth rates of juvenile Sockeye Salmon in freshwater in relation to their thermal environments and other factors. We then estimate the influence of lake surface water temperature on the growth of rearing Sockeye and subsequent effects on escapement. This represents a key area where climate change and other factors may be influencing stock outcomes (i.e. productivity), that are not currently accounted for by fisheries managers.

Keywords: juvenile salmon, growth rate, decadal changes, early life history, thermal growth window, climate change

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