Growth: theory, estimation, and application in fishery stock assessment models

WORKSHOP AGENDA

Center for the Advancement of
Population Assessment Methodology (CAPAM)

NOAA/IATTC/SIO
8901 La Jolla Shores Dr.
La Jolla, CA 92037, USA

www.CAPAMresearch.org

3-7 November 2014

Date and Time	**Topic**	**Presenter**
***3 November* (*Monday*)**		
1:00 pm – 4:00 pm	*Stock Synthesis* session	Taylor (IS)
***4 November* (*Tuesday*)**		
8:30 am – 9:00 am	Welcome/Overview	Semmens/Crone
9:00 am – 10:00 am	A1	Lorenzen (IS)
10:00 am – 10:30 am	A2	Matthias
10:30 am – 11:00 am	Break	
11:00 am – 11:30 am	A3	Ortiz de Zárate
11:30 am – 12:30 pm	Group discussion – A	
12:30 pm – 2:00 pm	Lunch	
2:00 pm – 3:00 pm	B1	Francis (IS)
3:00 pm – 3:30 pm	B2	Lee
3:30 pm – 4:00 pm	Break	
4:00 pm – 4:30 pm	B3	Xu
4:30 pm – 5:00 pm	B4	Carvalho
5:00 pm – 5:30 pm	B5	Márquez-Farías
6:00 pm – 8:30 pm	*Template Model Builder* session	Thorson (IS)
***5 November* (*Wednesday*)**		
8:00 am – 8:30 am	B6	Francis
8:30 am – 9:00 am	B7	Fay
9:00 am – 9:30 am	B8	Minte-Vera
9:30 am – 10:00 am	B9	Valero
10:00 am – 10:30 am	Break	
10:30 am – 11:00 am	B10	Maunder
11:00 am – 11:30 am	B11	Kinzey
11:30 am – 12:00 pm	B12	He
12:00 pm – 1:30 pm	Lunch	
1:30 pm – 2:00 pm	B13	Monnahan
2:00 pm – 2:30 pm	B14	Crone
2:30 am – 3:00 pm	B15	Courtney
3:00 pm – 3:30 pm	Break	
3:30 pm – 4:30 pm	Group discussion – B	
4:30 pm – 5:30 pm	C1	Punt (IS)
6:00 pm – 9:00 pm	Party	
***6 November* (*Thursday*)**		
8:00 am – 8:30 am	C2	Chen
8:30 am – 9:00 am	C3	Siddeek
9:00 am – 9:30 am	C4	Quinn
9:30 am – 10:00 am	C5	McGarvey
10:00 am – 10:30 am	Break	
10:30 am – 11:00 am	C6	Szuwalski
11:00 am – 12:00 pm	Group discussion – C	
12:00 pm – 1:30 pm	Lunch	
1:30 pm – 2:30 pm	D1	Martell (IS)

2:30 pm – 3:00 pm	D2	Thorson
3:00 pm – 3:30 pm	Break	
3:30 pm – 4:00 pm	D3	Stawitz
4:00 pm – 4:30 pm	D4	Isely
4:30 pm – 5:00 pm	D5	Chang
5:00 pm – 5:30 pm	D6	Hart

***7 November* (*Friday*)**

8:00 am – 8:30 am	D7	Taylor
8:30 am – 9:00 am	D8	Kuriyama
9:00 am – 9:30 am	D9	Harley
9:30 am – 10:30 am	Group discussion – D	
10:30 am – 11:00 am	Break	
11:00 am – 12:00 pm	E1	Kolody (IS)
12:00 pm – 12:30 pm	E2	Fukuda
12:30 pm – 1:30 pm	Group discussion – E	
1:30 pm	Closing	Maunder

Growth workshop – General information

- Chairperson – M. Maunder
- Welcome – B. Semmens
- Overview – P. Crone
- Closing – M. Maunder
- Presentations
  - Research presentations are arranged under review topics (see below)
  - Research presentations will be 30 minutes (20-min presentation /10-min questions)
  - Review presentations by invited speakers (IS) will be 1 hour (50-min presentation/10-min questions)
  - Group discussions following each review topic will be 1 hour (led by Chairperson)
- Additionally, all workshop participants are invited to the following related sessions that will be held throughout the course of the week-long forum:
  - An afternoon session will be held on Monday (November 3rd) that will address modeling growth using the *Stock Synthesis* modeling framework
  - An evening session will be held on Tuesday (November 4th) that will address spatiotemporal methods for statistical population dynamics models using *Template Model Builder*
- An evening social will be held on Wednesday (November 5th) at the Martin Johnson House - Bldg. T-29 on SIO's campus
- Researchers are encouraged to develop formal papers from their presentations or related work for submission to a special issue in the journal *Fisheries Research* (contact M. Maunder and P. Crone for further details)
- Sponsors for this workshop are NOAA and International Seafood Sustainability Foundation (ISSF)

Growth workshop – Review topics, sessions, and invited speakers

A. Biological processes/ontogeny (K. Lorenzen)
B. Specification and estimation: age-structured models (C. Francis)
C. Specification and estimation: length-structured models (A. Punt)
D. Spatial/temporal variation (S. Martell)
E. Modeling growth in tuna assessments (D. Kolody)

❖ *Stock Synthesis* working session (I. Taylor)
❖ *Template Model Builder* session (J. Thorson)

PRESENTATION ABSTRACTS

TOPIC A: Biological processes/ontogeny

A1. Title: Modeling body growth in fisheries assessment and management: why and how
Presenter: K. Lorenzen (Invited speaker)
Authors: K. Lorenzen
Abstract: Body growth is a central but underappreciated process in the dynamics of exploited fish, crustacean and mollusk stocks. In addition to biomass production, body growth affects lifetime patterns of natural and fishing mortality, maturation and reproductive output. Phenotypic plasticity in the growth of fishes, crustaceans and mollusks is extraordinarily high and can play an important role in mediating population responses to exploitation and environmental variation. Growth is also subject to evolutionary effects of harvesting and environmental change. Finally, growth patterns correlate with other life history traits and such correlations are frequently used to estimate parameters such as the natural mortality rate or recruitment compensation which are difficult to estimate directly. The keynote reviews approaches to modeling body growth in the light of requirements arising from the above patterns, management implications and theoretical considerations of growth processes.

A2. Title: Decoupling the effects of density and environmental variability on fish growth
Presenter: B. G. Matthias
Authors: B. G. Matthias, R. N. M. Ahrens, M. S. Allen, T. Tuten, Z. A. Siders, K. L. Wilson
Abstract: Per capita productivity changes in fish populations resulting from competition for limited resources are likely expressed along a spectrum of density dependent mortality to density dependent growth. Simulations and pond/tank-based experiments have shown both increased mortality and decreased growth at high densities. However, detecting the effects of density in wild populations can be challenging due to tradeoffs between growth and mortality at high densities. Further, in highly variable systems that experience both droughts and hurricanes, environmental variability can often mask density dependent effects and make them even more difficult to detect. Our objectives were to determine the impacts of 1) cohort strength and 2) environmental variability on fish growth. We constructed a Bayesian mixed effects model to quantify changes in the mean length at age via $L\infty$, the variation around mean length via the coefficient of variation cv, and the length-weight relationship allometric growth parameter β. Akin to previous studies, cohort density had negative impacts on mean length and weight and positive effects on growth variation. However, the biggest impacts of growth arose from changes in water level. Water level during the first year of life positively influenced growth in

length and weight while negatively affecting growth variation. During subsequent years of life, increases in water level decreased growth in length and weight and increased growth variation. We suspect that increased growth during years of higher water decreased juvenile competition by increasing the amount of habitat available for juvenile fish. For older fish, concentrated prey likely caused increased adult growth during periods of lower water levels. Decoupling the effects of density and environmental variability on growth can lead to a better understanding of plasticity in naturally fluctuating populations and better management of exploited stocks.

A3. Title: Estimating individual growth variability in albacore (*Thunnus alaunga*) from the North Atlantic stock; aging for assessment purposes

Presenter: V. Ortiz de Zárate

Authors: V. Ortiz de Zárate, E. Babcock

Abstract: Length-frequency data and catch at age matrices are used in north Atlantic albacore (*Thunnus alalunga*) stock assessment conducted within ICCAT. Growth is assumed to follow the von Bertalanffy model with the assumption that growth parameters are constant over time and the same for all fish. However individual growth variability is an important factor not considered and affecting the input into the modelling of the population. A Bayesian hierarchical model was used to estimate individual variability in growth parameters asymptotic length (Linf), growth rate (K), and age at length zero (t0) of the von Bertalanffy model. The method assumes that the Linf, K and t0 values for each individual fish are drawn from a random distribution centered on the population mean values, with estimated variances. Multiple observations of length at age for individual fish were obtained using back-calculation from spine section diameter. Then measurements of annual annuli of individual aged were used to estimate the back-calculated length and rebuild the individual growth of all fish being aged. Models with and without individual growth were compared using the deviance information criterion (DIC) to find the best model. Growth was found to vary significantly between individual fish.

TOPIC B: Specification and estimation: age-structured models

B1. Title: Growth in age-structured stock assessment models

Presenter: R. I. C. C. Francis (Invited speaker)

Authors: R. I. C. C. Francis

Abstract: Growth, an important component in age-structured assessment models, has been dealt with in a variety of ways by different modellers. I will describe and discuss this variety under three headings: how growth is specified; what functions it serves in the model; and how it may be estimated. The pros and cons of different approaches will be evaluated, as will the assumption - central to the currently popular approach of integrated modelling - that analyses should be carried out within, rather than outside, the stock assessment model.

B2. Title: Comparison of traditional versus conditional fitting of von Bertalanffy growth functions

Presenter: H-H. Lee

Authors: H-H. Lee, K. R. Piner, M. N. Maunder

Abstract: Population level estimates of fish growth are a key component of population dynamic models, especially when age composition data are unavailable. Multiple types of information can be used to estimate the age-length relationship including tagging, length and age compositions, mean size, and conditional age-at-length data. When age-length samples are collected from fishery data, two estimation approaches are commonly used to estimate the growth form. A traditional methodology assumes that each length observation used in the fitting is a random sample of fish for a given age. The conditional methodology uses age conditioned on length and assumes that each age observation is a random sample of fish of a given length. The conditional method makes use of the underlying population age structure and therefore has only been used inside stock assessment models. We use an equilibrium approximation to the age structure to estimate growth using the conditional method outside the assessment model. We evaluated the performance of the traditional and approximated conditional method to estimating the von Bertalanffy growth curve using simulated data. Sampling of the fishery catch data is conducted randomly or systematically. We evaluated the importance of the correct age structure on estimates of the conditional approach. We evaluated the effectiveness of both estimation methods for the different sampling methods over a broad range of fish life-histories, population dynamics and sample sizes.

B3. Title: Maximum likelihood estimates of North Pacific albacore (*Thunnus alalunga*) von Bertalanffy growth parameters using conditional-age-at-length data

Presenter: Y. Xu

Authors: Y. Xu, S. L. H. Teo, K. R. Piner, H-H. Lee, K-S. Chen, R. J. D. Wells

Abstract: Stock assessment results of North Pacific albacore tuna (*Thunnus alalunga*) have been strongly influenced by two recently published age and growth studies (Chen et al., 2012 and Wells et al., 2013). However, the most recent stock assessment in 2014 also highlighted the drawbacks of using traditional growth model estimation methods. The underlying assumption is that each datum is a random observation of size and age, and therefore contributes equally to the growth curve estimation. Sampling programs for age and growth studies (including the two most recent studies for North Pacific albacore) typically do not randomly sample the population, and most of these observations have associated sampling bias. For example, in Wells et al. (2013), samples from the entire size range of albacore were collected, and preferentially selected to obtain the largest fish available in the Honolulu fish market in some years, which is common practice in many age and growth studies. However, by doing so, and then assuming that these were random samples likely resulted in biased results. In this study, we obtained the otolith aging data from these two recent studies and treat them as conditional-age-at-length data in order to limit the sampling bias by weighting samples. We developed a simplified length-based and age-structured model for North Pacific albacore population, assuming von Bertalanffy growth, constant recruitment and mortality. Maximum likelihood estimates of the von Bertalanffy growth parameters were obtained by fitting the observed proportion of each age class for each size bin to the expected proportions from the simplified age-structured model, using a multinomial distribution. Conditional age-at-length data are typically used within an integrated stock assessment model. In contrast, this study is a novel use of these data with a simplified population model, without the complexity of an integrated stock assessment model, but treating the aging data appropriately as conditional age-at-length data. Preliminary results show that this method is able to reduce sampling bias by giving less weight to samples near the tail of the distribution (i.e., size classes that were oversampled). Simulation studies of this method will be presented by another study in this symposium.

B4. Title: The effects of length-biased sampling in growth models: a simulation approach

Presenter: F. Carvalho

Authors: F. Carvalho, M. Maunder, A. Aires-da-Silva, Y. Chang

Abstract: Growth parameters are key components in fisheries stock assessment and are commonly estimated using three approaches: 1) modal progression in length composition data, 2) age-length data, and 3) tagging growth increment data. In the real world, sampling biases may be inevitable, including a situation where only young fish or old fish are sampled. However, it is unclear how these biased samples affect growth estimates. We used the swordfish in the western North Pacific Ocean as a case study, and evaluated whether ageing only part of the population has strong effects on mean growth and variation of length-at-age estimates. An Individual Based Model (IBM) was developed as the operating model to generate age-at-length, length composition, and tagging data. These data were used to fit two different growth models: a simple growth model using age-at-length data, and an integrated growth model using age-at-length, length composition, and tagging data. Both models were run under two scenarios. In scenario I, only young fish were aged, while in scenario II, fish from all sizes were aged. In addition, we evaluated the performance of the integrated approach under different data availability situations (e.g. absence of length composition data).

B5. Title: Suitability of the use of the Bayesian approach for the estimation of growth parameters for viviparous Chondrichthyans

Presenter: J. F. Márquez-Farías

Authors: J. F. Márquez-Farías, R. E. Lara-Mendoza

Abstract: Age and growth estimates are essential in the study population dynamics and demographic analysis, and along with reproductive and survival rates represent a key element in formal fish stock assessment. In sharks, the age is estimated by counting growth marks of the vertebrae. The growth parameters are estimated by fitting a model (i.e., von Bertalanffy, Gompertz) to age-length data. It is now conventional to test other growth functions by using multi-model approaches. There is no general rule for the use of any growth model, and the selection of one over another is frequently assessed by a statistical criterion (AIC). However, biases caused by size-selective fishing gears and migration can influence not only the representativeness (quality and contrast) of observed data but also could induce to distortions of the model's performance. This source of bias should be present for model selection and interpretation. Once the best observed data are acquired, competing models should be selected to satisfy both fit and biological pertinence avoiding nuisance parameters such as "to" in the BVGM. In this context, the Bayesian approach requires specification of the prior probability distribution of the model's parameters. While dealing with correlated parameters is inevitable, at some point, the judgment of

experts to dimension parameters may represent a gain in model fit. In the present study, we review the benefits of building priors for the estimation of growth parameters for viviparous sharks taking advantage of available information on size of the first year of life and historical maximum length. We consider that competing growth models should be selected on the basis of not only statistical quantities, but also on biological meaningful parameters.

B6. Title: Can we combine age-length and tagging-increment data?

Presenter: R. I. C. C. Francis

Authors: R. I. C. C. Francis, A. M. Aires-da-Silva, M. N. Maunder, K. M. Schaefer, D. W. Fuller

Abstract: In age-structured assessments it would be useful to be able to include all available information on growth, including age-length observations and length increments from tagging experiments. However, it was suggested in 1988 that combing the growth information from these two sources was problematic because the age- and length-based growth information they contain are not directly comparable. We evaluate some approaches that have since been made to this problem and conclude that though there has been some progress, no method has yet been found that combines logical consistency and biological plausibility, and also lies on the right side of Occam's razor.

B7. Title: Using size increment data in age-structured stock assessment models

Presenter: G. Fay

Authors: G. Fay

Abstract: Size increment data, often available from tagging studies, provide useful information for growth estimation. Such data are frequently used in size structured stock assessment models. Traditionally, this has involved estimating the size transition matrix though applications of integrated analysis can also fit to these data directly in the stock assessment model. Use of growth increment data from tagging for age structured assessment models has been less extensive. Estimation of growth curve parameters using these data is typically conducted outside of the stock assessment model, to either provide inputs or to corroborate model-based estimates of growth resulting from fits to more typical data (e.g. age-at-length). However, because of differences in model structural assumptions and that growth increment data from tag recaptures are conditioned by selectivity, the two modeling approaches (separate tagging analysis and assessment models) may be inconsistent. Age-structured assessment models that integrate tagging data in the estimation procedure (tag-integrated assessment models) have generally focused on including likelihood components for the distribution of tag-recaptures and not fitted to the size increment data (though analyses that model tag recaptures as a length-based process do alleviate

this somewhat). I will discuss challenges associated with accounting for these longitudinal data in model frameworks such as Stock Synthesis, and review methods for including size increment data from tagging studies in age structured assessment models. I will outline an example of including a likelihood component for size increment data within a simple statistical catch at age model that accounts for the effects of selectivity on the expected distribution for growth increments, and present results of a simulation study aimed to evaluate the benefits of using these data to estimate growth when compared with alternative approaches. Finally, I will discuss modifications that might be made to Stock Synthesis to better make use of different types of tagging information for estimation of both growth and stock status.

B8. Title: Guidance for modelling the variability of length-at-age: lessons from datasets with no aging error

Presenter: C. V. Minte-Vera

Authors: C. V. Minte-Vera, S. Campana, M. Maunder

Abstract: The variability of length-at-age can highly influence the interpretation of the length-frequency information in the context of integrated analysis for stock assessment. For example, the highly used Stock Synthesis 3.0 (SS) is an age-structured model that can be fit to length-frequency data, as well as age frequencies, tagging data, and abundance indices. Several stock assessments, such as those for tropical tunas, are done with no (or very limited) amount of age-frequency data and rely mainly on length frequencies. In some cases, those data so strongly affect model fit that they may drive the absolute scale of the estimated biomass. Ideally, one parameter expressing the variability of length-at-age for each age should be estimated in an integrated model. This strategy will introduce extra parameters in the model for which there is limited information in the available data. To minimize this problem, assumptions about how the variability of length-at-age changes with age are adopted. As an illustration, five options are implemented in SS, four consider that the length-at-age varies normally around the mean length-at-age and one considers that the length-at-age distribution is log-normal. When a normal distribution is assumed, the variability can be either modeled with the coefficient of variation (CV) as a function of either length-at-age or age, or with the standard deviation (SD) also as either a function of length-at-age or age. In this presentation, we will explore two rarely available data sets that provided length-at-age and age with no (or very minimal) ageing error. The first dataset consists of four groups of cod (*Gadus morua*) from Faroe, two of which were subject to fishing, and the other two were unexploited. The fish were hatched in captivity then tagged and released as young-of-year either into mesocosms, where no fishing took place, or into the wild, in two locations: Faroe Plateau and Faroe Bank. The fish released into the wild were recovered by fishers. The second dataset for Arctic trout (*Salvelinus namaycush*) from Zeta Lake. This

population was never fished. The ageing was validated with bomb-radiocarbon methods and ageing precision was excellent, thus minimal ageing error is expected. We asked the following questions: (1) what probability density function best describes the variability of length-at-age for fished and unfished populations?, (2) what is the best summary statistics of the variability of length-at-age: CV or SD?, and (3) what functional form (e.g. constant with age, increasing with length-at-age) best summarized the changes of the variability of length-at-age over ages for fished and unfished populations? We finalize by discussing a set of lessons learned from this exercise that may help to guide decisions taken by stock assessment modelers when modeling variability of length-at-age in the context of integrated analysis.

B9. Title: Evaluating the impacts of fixing or estimating growth parameters, across life histories and data availability

Presenter: J. L. Valero

Authors: J. L. Valero, K. F. Johnson, C. Stawitz, R. Licandeo, S. C. Anderson, A. Hicks, F. Hurtado-Ferro, P. Kuriyama, C. C. Monnahan, K. Ono, I. Taylor, M. Rudd

Abstract: In statistical integrated age structured population models, there are two common practices used to incorporate somatic growth into the population dynamics. First, a parametric somatic growth model is fit externally to length-at-age data and the estimates are input to the model as fixed parameters. Second, the model simultaneously estimates growth parameters with other population dynamics and fishery processes. When growth is estimated externally to the stock assessment model, the effects of population dynamics and the cumulative effects of fishing on size-at-age on growth estimates are typically not accounted for. In addition, ignoring gear selectivity when estimating growth (internally or externally) is problematic because fisheries tend to select faster-growing fish. Therefore, growth estimated from unrepresentative data may not reflect the true population growth curve, which can lead to biased stock assessment results, biological reference points and management quantities. Furthermore, the quality and quantity of length- and age-composition data can affect the accuracy of parameter estimates and thus management reference points. Growth may be estimated internally when there is length composition data, or tag-recapture data. However, incorporating age-composition data in addition to length-composition data may or may not improve stock assessment estimates. For instance, even if length- and age-composition data are both available, the quality and quantity of this information can affect the accuracy of stock assessment outputs, with larger repercussions on some life-history types than others. Thus, estimation of growth parameters within a stock assessment model is not possible for all life-history types. Therefore, it is important to quantify the importance of different data types and quantity to stock assessment estimates across life-history types. Here we used ss3sim, a simulation framework based on

Stock Synthesis, to evaluate the types and quantity of data that are needed to estimate somatic growth within an assessment model and the tradeoffs between estimating growth internally versus externally. The focus of this research is not only on the ability to estimate growth but also on the impact of potential model misspecification related to growth estimation on assessment-derived quantities of interest to management across contrasting life-history types. We used measurements of bias and precision with respect to spawning stock biomass, fishing mortality level, and management reference points to quantify the performance of stock assessment models that internally estimated somatic growth parameters compared with stock assessment models that had somatic growth fixed at externally estimated values.

B10. Title: Estimation of growth within stock assessment models: implications when using length composition data

Presenter: M. N. Maunder

Authors: J. Zhu, M. N. Maunder, A. M. Aires-da-Silva, Y. Chen

Abstract: In contemporary fisheries stock assessment, growth modeling is an important component and typically conducted outside assessment models (i.e., fixed before running the assessment model). However, direct growth estimates may be difficult for some species because of difficulty in aging old individuals using otoliths. The objectives of this study are to evaluate the influence of mean length-at-age (mean length) and variation in length-at-age (variation) in relation to length composition on management advice and to determine if mean length and variation can be estimated reliably inside stock assessment models. We conduct a sensitivity analysis regarding the parameters of mean length and variation using a full stock assessment model of bigeye tuna (BET; with Stock Synthesis (SS)) in the eastern Pacific Ocean. We then use a simplified SS model, as the simulator and estimator in the simulation analysis, to estimate mean length and variation of the von Bertalanffy growth model. Mean length is parameterized using L1 (length at minimum age), L2 (length at maximum age), and K (growth coefficient), and variation is parameterized using CVs for young and adult tunas (CVs for the young females are assumed to be equal to that for the young males). Twenty scenarios regarding L1, L2, K, CV, and selectivity assumption for the longline fishery (LL, asymptotic or dome-shaped) were considered. Median bias and CV are used to define the reliability of estimates of these parameters. Estimates of L2 are found reliable with the maximum median bias less than 7% (CV < 0.05), and robust to misspecification of LL selectivity. L1 can be estimated with maximum median bias being around10.7% (CV < 0.11). K is not considered to be estimable because of the high median biases (-20.2% ~ -16.6%). CVs for young tunas are estimated with moderate median biases (maximum =10.5%) except for one scenario, but with high cv. CVs for both female and male adults can also be reliably estimated (minimum CV =16% and 14%, respectively). Influences of

misspecification for parameters that could not be reliably estimated are also evaluated with respect to key management reference points.

B11. Title: Estimating growth of Antarctic krill (*Euphausia superba*) in an age-based assessment model

Presenter: D. Kinzey

Authors: D. Kinzey, G. Watters, C. Reiss

Abstract: An age-based assessment model for Antarctic krill has been extended to estimate von Bertalanffy growth. Estimating growth inside the model improved the fit to the length-compositions substantially over earlier models that used pre-specified growth parameters from previous studies. Model parameters that included growth were estimated in multiple trials using randomized phase sequences until a positive definite Hessian matrix was obtained. The reproducibility of model estimates for growth and other derived quantities was tested using simulated data. Multiple configurations of the models and data produced similar, robust estimates of growth. Growth estimated by the models was somewhat slower than growth rates used currently in managing the krill fishery. The two-stage approach of first randomizing the phase order and secondly verifying the reproducibility of the estimates of derived quantities through simulation-testing is recommended for the estimation of potentially confounded parameters using complex assessment models and data.

B12. Title: How many conditional age-at-length data are needed to estimate growth in stock assessment models?

Presenter: X. He

Authors: X. He, J. C. Field, D. E. Pearson, L. Lefebvre

Abstract: One of main usages of age information in stock assessments is as conditional age-at-length (CAAL) data to internally estimate growth and cohort strength(as well as inform natural mortality). Obtaining sufficient age data is not a trivial task, not only because it requires considerable sampling effort to cut fish and extract otoliths (and as such is often resisted by processors seeking to market whole fish) but also requires substantial effort to develop ageing criteria and subsequently age sufficient numbers of fish. The difficulties associated with developing reliable aging criteria (as well as validating estimated ages) vary from species to species, but can be substantial. For example, Bocaccio (*Sebastes paucispinis*) are a highly important commercial and recreational target in California, have been under a rebuilding plan since the early 2000s, and as such have been subjected to over 12 stock assessments since 1984. However, due to the difficulties with developing reliable aging criteria, as well as the rapid growth and variable recruitment that allowed resolution of growth and cohort strength in the absence of ages. In 2014, the Fisheries Ecology Division successfully developed ageing criteria for Bocaccio, and since then over

four thousand fish have been aged for an upcoming assessment. In this study, we tested utilities of CAAL data in the 2013 Bocaccio assessment model, mainly on how many CAAL data are needed to get reasonable estimates of growth of the species. The same test was also conducted on the 2013 assessment model for Pacific Sanddab (*Citharichthys sordidus*), which has much shorter life span, and less variable recruitment, than Bocaccio. The tests were done by intermittently removing annual age data at various intervals (i.e. removing data every other year, etc.). Preliminary results showed that, for the Bocaccio assessment model, the results were very comparable among the model runs with different levels of input data, and that even with only one out five years of CAAL being used, the assessment outputs and estimated growth were similar to those with all available data included. For the Pacific Sanddab assessment model, however, the assessment outputs and estimated growth rates were somewhat different, particularly with respect to estimating virgin recruitment levels. These could mainly be due to lack of CAAL data from early years of the fishery, and high variability in ageing data. Ongoing efforts are also underway to evaluate the influence of age data for a longer lived rockfish with slower growth (blackgill rockfish) as well as to simulate the effects of different levels of CAAL data availability on assessment outputs. Results will be presented at the workshop as they became available.

B13. Title: An evaluation of alternative binning approaches for composition data in integrated stock assessments

Presenter: C. Monnahan

Authors: C. Monnahan, S. Anderson, F. Hurtado-Ferro, K. Ono, M. Rudd, J. Valero, K. Johnson, R. Licandeo, C. Stawitz, A. Hicks, M. Muradian, I. Taylor

Abstract: Age and length composition data provide important information needed to estimate biological growth in integrated stock assessments. There is an extensive literature on estimating effective sample sizes and appropriately weighting compositional likelihoods relative to indices of abundance. However, there are other subjective decisions facing analysts with regard to how to incorporate length composition data in an assessment: the number and spacing of composition bins, whether to compress the tails of the distribution, and whether to add a constant to observed and expected proportions to make the likelihood calculations more robust. There has been little formal investigation of how these decisions impact the ability to estimate growth, leaving analysts to use personal preference. In this study, we investigate the implication of these options on the estimation of growth and management quantities using ss3sim, a simulation framework utilizing Stock Synthesis, a generalized, integrated stock assessment model. We performed simulations across life histories, fishery exploitation patterns, and a wide range of type, quantity, and quality of compositional and index data. We also explored model selection-based approaches

to guide these decisions. Results from this study can be used to help guide analysts in the treatment of length composition data to optimize growth estimation and performance of stock assessments for management purposes.

B14. Title: Model time step and species biology considerations for growth estimation in integrated stock assessments

Presenter: P. R. Crone

Authors: P. R. Crone, J. L. Valero

Abstract: Modeling growth in modern statistical stock assessments typically requires fitting respective models to seasonal- or annual-based time series of growth-related data, often size- and age-composition time series developed from fishery and/or survey samples collected in the field. The underlying time step (quarter, semester, annual, etc.) is an important model dimension, serving as the basis for growth estimation and accurately identifying potential changes in growth over time. The objective of the study is to evaluate the influence of intra-annual variability in composition data on estimating growth parameters and dynamics in the model. In this evaluation, stock assessments are conducted based on alternative time-step dimensions and results are compared using simulation methods. Quantitative comparisons are presented for derived growth parameter estimates (e.g., K, length-at-age$_{min}$ and -age$_{max}$, L_∞) and management quantities (e.g., $SSB_{current}$, depletion, MSY). Other practical considerations related to model development, such as model complexity (total number of estimated parameters) and speed (run time), are qualitatively contrasted. Stock assessments and associated simulations are evaluated in terms of two broad life history strategies: shorter-lived, more productive species (e.g., small pelagic spp.); and longer-lived, less productive species (e.g., groundfish spp.). Finally, inherent sample size consequences associated with finer-scale time step considerations are generally discussed.

B15. Title: Sensitivity to sexually dimorphic growth of a length-based age-structured stock assessment model (Stock Synthesis) developed for North Pacific swordfish (*Xiphias gladius*)

Presenter: D. Courtney

Authors: D. Courtney, K. Piner

Abstract: Sensitivity to sexually dimorphic growth was evaluated for a North Pacific swordfish (*Xiphias gladius*) length-based age-structured Stock Synthesis model. The swordfish model was developed for the International Scientific Committee for Tuna and Tuna-like Species in the North Pacific Ocean (ISC). The North Pacific swordfish model included options to implement sexual dimorphism and to estimate sexual dimorphic growth within the model, but neither of these options was included in the final model. Sensitivity analysis was conducted here to evaluate the effects of

implementing sexual dimorphism and then estimating sexual dimorphic growth within the North Pacific swordfish model. Model sensitivity was evaluated based on relative changes in likelihood component fits for relative abundance indices and available length composition data. Model sensitivity was also discussed relative to input and output likelihood component variances (variance adjustments) obtained from Stock Synthesis for indices of relative abundance, available length composition data, and process error in recruitment variability.

TOPIC C: Specification and estimation: length-structured models

C1. Title: Estimating growth within size-structured fishery stock assessments: What is the state of the art and what does the future look like?

Presenter: A. Punt (Invited speaker)

Authors: A. Punt, M. Haddon, R. McGarvey

Abstract: Most growth studies have considered the relationship between age and growth. Such relationships are essential to age-structured fishery stock assessments. In contrast, assessments based on stage-structured population dynamics models require information on the probability of animals moving from one stage to each of the other stages at each time step. Size-structured population dynamics models are a special case of stage-structured population dynamics models in which each class represents a unique set of sizes. These models form the basis of assessments for many valuable, hard to age, marine species, including crabs, abalone, lobsters and prawns. Growth within these models is governed by a size-transition matrix. The values for the parameters of a size-transition matrix can either be estimated externally to the assessment, generally utilizing data from tag-recapture experiments, or the estimation of growth can be integrated within the assessment model. This paper reviews the approaches used to construct size-transition matrices, including the underlying structural formulation, statistical estimation framework, and the consequences of error when specifying these matrices on the ability to estimate population size and manage populations sustainably.

C2. Title: Modeling growth for American lobster *Homarus americanus*

Presenter: Y. Chen

Authors: Y. Chen, J-H. Chang

Abstract: Growth plays a critical role in regulating fish population dynamics, and modeling growth is one of the key components in stock assessment that provides vital information for fisheries management. For crustacean species like the American lobster, *Homarus americanus*, modeling growth tends to be complicated. Growth of the American lobster is not continuous, and molting is seasonal, mainly occurring in summer and fall. Molting frequency is size-dependent and influenced by the individual's reproductive status with the maturation being likely to significantly slow down the growth of female lobster. An egg-bearing female does not molt. There are also large thermal differences in lobster habitats, which may result in large differences in growth among individuals. As a result, there are large variations among individuals and between sexes in growth. In this study, we develop an individual-based lobster simulator (IBLS) to develop growth transition matrix required for a length-structured stock assessment model. The IBLS expresses various components of lobster life history and fishery processes as random Bernoulli trials and simulates the complex biological and fishery processes including size- and

maturation-dependent seasonal molting and management regulations used in the fishery, such as minimum and maximum legal sizes, prohibition against the taking of egg-bearing lobsters, and protection of previously ovigerous females through V-notching. For each time step, a certain number of lobster of a defined size, are added to the population in the IBLS as new recruits. Each lobster has a probability of being caught in the fishery, dying of natural mortality, growing and maturing, and, for females, becoming egg-bearing, V-notched, and/or losing V-notching due to a molt. When a lobster is caught in the fishery, it is examined to see if it needs to be protected according to existing requirements. If it is legal to be kept, its sex and size are recorded to generate catch and size-frequency data. V-notched lobsters are protected from fishing for two molts. Egg-bearing lobsters are protected from harvesting and need to be V-notched. The molt frequency of mature female lobster is affected by maturation. Lobster undertake a major molting event in summer, and a small proportion of small lobster also experience a second molt in fall. Each individual lobster entering into the IBLS goes through all the processes again and again until it dies due to natural mortality or is caught in the fishery. We run the simulation for 50 years with constant recruitment. Once the simulation is completed, we calculate the average probability of a lobster of a given size staying in the same size class or growing into the other size classes, which yields growth transition matrix. Because the IBLS tracks the detailed life history and fishery processes of individual lobster and likely captures large differences among individuals in biology and fishery, the growth transition matrix derived from the IBLS can capture biological variability among individuals in the quantification of the lobster population dynamics. We also evaluate factors that may influence the estimation of the growth transition matrix. The approach developed can also be useful for other crustacean species.

C3. Title: Estimation of size-transition matrices with and without molt probability for Alaska golden king crab using tag–recapture data

Presenter: M. S. M. Siddeek

Authors: M.S.M. Siddeek, J. Zheng, D. Pengilly

Abstract: Size-structured models are used for stock assessment of hard to age invertebrate populations, such as crabs, and size transition matrices play an important role in modeling growth in those models. Crabs grow by molting and then incrementing in size. Therefore, the size transition matrix estimator should contain the molt and the growth increment sub-models. Size transition matrices are estimated using tag-recapture data in an integrated model setting. Unless tag-recaptures are delineated by molt and non-molt stages, it will be difficult to estimate the molt probability unequivocally. We have that situation with the Aleutian Islands golden king crab (*Lithodes aequispinus*) tag-recapture data from the Dutch Harbor region. We

considered a logistic molt probability and a normal growth increment models for the size transition matrix estimator. We used a number of diagnostic statistics (e.g., covariance matrix, length frequency fit, chi-square statistics) to investigate the estimator without the molt probability (scenario 1) and with the molt probability (scenario 2) sub models. Although molt probability and growth increment parameters are highly correlated, there is a very few differences in the diagnostic statistics.

C4. Title: Combining the Cohen-Fishman growth increment model with a Box-Cox transformation: flexibility and uncertainty

Presenter: T. J. Quinn II

Authors: T. Quinn II, R. B. Deriso

Abstract: Many choices are available for modeling the growth transition process. For length-based-only models, common choices include the normal, lognormal, and gamma distributions for uncertainty combined with a von Bertalanffy growth model. For length-and-age-based models, the Cohen-Fishman model has been used, which models growth increments with a von Bertalanffy growth model and two normal distributions for the initial size-at-age distribution and for the growth increments themselves. The combination of the Cohen-Fishman model and alternative error structures is a generalization of previous usages of the Cohen-Fishman model, including the von Bertalanffy model for size, the Gompertz model with logarithm of size, as well as all intermediate distributions with power function of size. The combined model can be used to estimate growth parameters with mark-recapture data and to develop a growth transition matrix for use in length-and-age-based models.

C5. Title: A flexible approach to estimating length transition matrices: growth increment and variance as polynomial functions of body length

Presenter: R. McGarvey

Authors: R. McGarvey, J. E. Feenstra

Abstract: Increasing the flexibility of growth descriptions, within a growth transition matrix framework, is important for crustacean and other length-based fishery stock assessments, because these models are sensitive to growth assumptions. We present a relatively flexible growth transition estimation model, fitting to ordinary fishery single tag-recoveries, which reduces to von Bertalanffy mean growth as a default. As in most growth transition matrix estimation methods, the growth-transition probabilities are computed as integrals under a pdf curve over fixed body size intervals. We use normal or gamma pdf's specified by two parameters. Model flexibility is achieved by writing both pdf parameters as polynomial functions of the mid-point length of the (pre-growth) length bin. For the normal pdf model, the two pdf parameters quantify the mean and variance of model-predicted growth increment.

A default von Bertalanffy growth submodel is achieved by setting the normal pdf mean parameter equal to a linear polynomial function of pre-growth body length. Adding higher polynomial terms permits more complex dependence of mean growth increment, and of variation in growth increment, on animal body length. We tested models of successively increasing polynomial parameter number, using likelihood ratios, from constant up to 4^{th} order polynomials for both pdf parameters. Female crustacean growth is known to slow at the onset of sexual maturity. This relatively abrupt change in steepness of the curve of growth rate versus body length has been observed and analysed in many studies of crustacean growth, first modelled using a broken-stick approach. The flexibility achieved by adding higher polynomial terms permitted a more accurate growth model of female *Jasus edwardsii* lobster stocks in South Australia. In particular, we found that the model using higher polynomials better fitted the relatively faster growth of smaller females, and the decelerated growth of larger ones. The range of body lengths at which female growth slows was also inferred. For male lobsters, the fit was not substantially improved with polynomials higher than linear, consistent with von Bertalanffy growth.

C6. Title: Uncertainty in growth, reference points, and selecting bin size

Presenter: C. Szuwalski

Authors: C. Szuwalski

Abstract: Fitting growth data inside an assessment method, rather than fitting outside and specifying growth parameters within an assessment method, allows uncertainty in growth parameters to be propagated to reference points. Here, posterior distributions of reference points sampled via MCMC for Pribilof Island red king crab and Galapagos Island spiny lobster are compared for scenarios in which growth is estimated within the assessment method and specified based on models fit outside of the assessment method. The specified bin size (i.e. the range of sizes that are grouped within the population dynamics model) can bias derived quantities in assessment (like mature male biomass) that influence the posterior distribution of reference points. Methods for evaluating the tradeoffs between bin sizes are presented and the impacts of different bin sizes are presented for red king crab.

TOPIC D: Spatial/temporal variation

D1. Title: Spatial and temporal variation in Pacific halibut size-at-age and the harvest policy implications

Presenter: S. Martell (Invited speaker)

Authors: S. Martell

Abstract: Since 1888, the Pacific halibut fishery has landed nearly 6 billion pounds net weight, or on average 47 million pounds per year. During this 126 year period there have been dramatic changes in halibut size-at-age. For example, in the early 1990's the average weight of an 18-year old female halibut was roughly 100 pounds net weight. Twenty years later the average weight has declined to less than 40 pounds net weight. There are a number of hypotheses regarding changes in size-at-age for Pacific halibut including, density-dependent growth, intra-specific competition, climatology and temperature effects, cumulative effects of size-selective fishing, bycatch, and potential biases in aging methods. The current harvest policy for Pacific halibut apportions estimates of coast-wide biomass into 8 regulatory areas and a fixed fraction of the biomass is harvested within each area. This paper examines the spatial and temporal variation in Pacific halibut size-at-age among regulatory areas and the harvest policy implications associated with spatial variation and continued changes in size-at-age.

D2. Title: How much does growth vary over time, space, and among individuals? Three case studies and their implications on biological reference points

Presenter: J. Thorson

Authors: J. Thorson, C. Minte-Vera, D. Webber

Abstract: Aquatic populations exhibit variation in growth over time, space, and among individuals. Variation in growth affects the values of fishing mortality and spawning biomass that will maximize sustainable yield. We summarize results from three ongoing projects, which estimate (1) temporal variation in von Bertalanffy growth parameters for 89 species worldwide, (2) spatial variation in relative condition factor for 28 species of groundfishes off the U.S. West Coast, and (3) individual variation in anabolism and catabolism parameters for Antarctic toothfish. Then we use elasticity analysis to illustrate the potential impact of temporal variation in growth on the biological reference points (BRPs) commonly used in fisheries management. We conclude by discussing a few practical steps for improving estimation and forecasting of growth and condition in stock assessment models and fisheries management strategies.

D3. Title: A state-space approach for measuring size-at-age variation and application to North Pacific groundfish

Presenter: C. C. Stawitz

Authors: C. C. Stawitz, T. E. Essington, T. A. Branch, M. A. Haltuch, A. B. Hollowed, N. J. Mantua, P. D. Spencer

Abstract: Understanding drivers and impacts of variation in demographic processes such as recruitment and somatic growth is key to improving fisheries population dynamics models. However, trends and the magnitude of growth rate variation are not quantified on broad scales for many commercially harvested fish species. This is likely related to the difficulty inherent in modeling growth from fisheries size-at-age data, which may contain multiple patterns of growth variation (i.e. cohort- or annual-scale) in addition to measurement error. Here we develop a state-space approach to modeling size-at-age patterns in marine fish to make inferences about the underlying growth dynamics. Using Bayesian estimation methods, we then apply this technique to thirty-one Pacific groundfish species across the California Current, Gulf of Alaska, and Bering Sea/Aleutian Islands marine ecosystems. We find most stocks (35/41 stocks) experience size-at-age variation consistent with annual changes in growth expressed across all age classes. This variability was expressed either as interannual fluctuation or as sustained trends over longer time periods. This method represents a novel way to use size-at-age patterns from fishery-dependent or -independent data to test hypotheses about growth dynamics while allowing for annual variation and measurement error.

D4. Title: Comparison of time-varying and non-time-varying growth in the Gulf of Mexico king mackerel stock assessment: a case study

Presenter: J. J. Isely

Authors: J. J. Isely

Abstract: In the recent Gulf of Mexico King Mackerel Stock Assessment, we compared four model configurations within Stock Synthesis. Model 1 was configured with catch per unit effort only. No length or age-at-length information was included, and sex-specific growth parameters were fixed at externally-calculated values. Model 2 added age at length, and freely estimated (no informed priors) sex-specific growth parameters. Model 4 fixed growth parameters at those estimated in in Model 3, but allowed for annual deviations in male and female $L\infty$ and k. Model fit improved with each successive model. Further investigation identified a negative trend in size at age among older age classes across years. That is, older females appeared to be getting smaller through time. As there was no biological justification for the apparent change in growth, we selected Model 3 as the preferred model for management advice.

D5. Title: Performance of a stock assessment model with misspecified time-varying growth

Presenter: Y-J. Chang

Authors: Y-J. Chang, B. Langseth, M. Maunder, F. Carvalho

Abstract: Growth in fish can change over time and between cohorts due to many biotic and abiotic factors, yet temporal variability in fish growth is rarely accounted for in fisheries stock assessment models. Rather, stock assessment models commonly assume that growth is constant through time. We conducted a simulation study to evaluate the performance of a stock assessment model under various assumptions for time-varying growth. Fish populations under scenarios of year- and cohort-varying growth were simulated using an individual-based model (IBM), and formed the basis for sampling data used to fit a statistical catch-at-age model (Stock Synthesis version 3, SS). Four different configurations of SS were used in model estimation including (1) static growth, (2) time-varying growth parameters, (2) cohort growth deviations, and (4) empirical mass-at-age data. Bias in estimates of spawning stock biomass, fishing mortality, and key management quantities was recorded, and implications of various ways of handling time-varying growth using SS were discussed.

D6. Title: Interactions between spatial heterogeneity in growth and fishing mortality

Presenter: D. R. Hart

Authors: D. R. Hart, A. S. Chute

Abstract: Both growth and fishing effort can vary spatially, even though these variations are often ignored in fishery models. Areas of faster growth can be especially attractive to fishers. Fishing can thus reduce (apparent) mean growth by selectively removing fast growers from the population. This phenomenon is demonstrated for the sea scallop (*Placopecten magellanicus*) fishery off the northeast U.S. coast. Growth is estimated in sea scallops using data from growth rings laid down on the shells and a mixed-effects model. Growth decreases with depth, likely due to reduced food supply. Scallops in shallow waters tend to fished harder than ones in deeper water at the same density and age. It is demonstrated that commercial-sized scallops in closed areas grow faster than those from areas that are moderately fished, which in turn grow faster than those that are intensively fished. This is likely due to selective fishing, since this relationship does not appear to hold for smaller scallops. This spatial pattern in fishing effort can induce reduced yield, since fast growers should optimally be fished less than slow growing scallops.

D7. Title: Empirical weight-at-age vs. model-based estimation of time-varying growth: lessons from the evolution of Pacific Hake stock assessments

Presenter: I. G. Taylor

Authors: I. G. Taylor, I. J. Stewart, A. C. Hicks

Abstract: Pacific Hake (*Merluccius productus*) is subject to a large and well-sampled fishery on the Pacific coast of the US and Canada. Since 1975, over 5 million length observations and 150,000 age readings with associated weight measurements have been amassed. The population has also been subjected to more than 20 stock assessments since early 1990s. The assessments have explored a variety of parametric treatments of growth including annual growth variations, cohort-specific growth patterns, and seasonal patterns in weight-length relationships, as well as non-parametric empirical weight-at-age measurements. This rich assessment history is drawn on to describe general issues and trade-offs associated with modeling complex growth processes using parametric relationships or empirical weight-at-age matrices. The need to explore these issues using simulation analyses is also discussed.

D8. Title: An investigation of using empirical weight-at-age instead of modeling parametric growth in statistical age-structured population models

Presenter: P. Kuriyama

Authors: P. Kuriyama, A. Hicks, K. Johnson, I. Taylor, S. Anderson, F. Hurtado-Ferro, R. Licandeo, C. Monnahan, K. Ono, M. Rudd, C. Stawitz, J. Valero

Abstract: Fisheries stock assessments typically assume fish grow according to a theoretical growth curve (e.g., von Bertalanffy, Richards, or Gompertz). In some cases, such as Pacific hake (*Merluccius productus*), growth is empirically incorporated into stock assessments with weight-at-age data from research surveys or fishery observations. Estimating growth and incorporating weight-at-age data into stock assessments may each bias fisheries reference points, provided to decision makers, but these biases have not been well studied. Monte Carlo simulations were used to identify conditions under which using empirical weight-at-age in stock assessments provide more robust estimations of stock status and management reference points than when growth is internally estimated. Results of this research will provide guidance to fisheries scientists regarding under what circumstances (i.e., fishing pattern, life-history type, and data availability) it is most beneficial to estimate growth within a stock assessment rather than empirically incorporate growth data.

D9. Title: Not the drunken sailor, but still bad: what can we do with spatially varying growth in a model that allows movement?

Presenter: S. Harley

Authors: S. Nicol, J. Hampton, S. Harley

Abstract: We present evidence of spatially varying growth of bigeye tuna within the Western and Central Pacific Ocean based on both preliminary direct ageing data and catch-at-size data. Currently this stock is assessed using a spatially structured MULTIFAN-CL model which has time invariant, but seasonal and age-based movement, and only a single growth morph. We discuss some simple hypotheses that could explain the differences in growth that we observe and consider what is the best of some bad options to overcome this in a stock assessment modelling framework.

TOPIC E: Modeling growth in tuna assessments

E1. Title: Issues in modelling tuna growth

Presenter: D. Kolody (Invited speaker)

Authors: D. Kolody, R. Hillary, P. Eveson

Abstract: We describe a number of challenges related to the use of growth curves in tuna Regional Fisheries Management Organization (tRFMO) stock assessments. The challenges are described in two broad categories: i) data and communication issues (e.g. age validation methods are still lacking for some species, biologists do not always understand how their data will be used in an assessment or the assessment analysts do not appreciate the limitations of the data that they are working with), and ii) failure of the assessment analysts to recognize and describe the uncertainty associated with violations to their modelling assumptions (this includes direct issues like temporal and spatial variation in growth, and indirect issues such as the interactions between growth and other uncertain model features like natural mortality). We argue that growth curve uncertainty should be examined in the context of management decision implications (e.g. ideally in the context of Management Strategy Evaluation, where alternative plausible growth models are admitted as possible). However, we speculate that for most tuna and tuna-like fisheries, the growth uncertainties are likely to be much less important than other fundamental problems, notably uncertainty in relative abundance indices derived from commercial CPUE and uncertain population connectivity.

E2. Title: Estimates of growth from direct ageing and mark-recapture data for Pacific bluefin tuna

Presenter: H. Fukuda

Authors: H. Fukuda, T. Kitakado, I. Yamasaki, T. Ishihara, T. Ohta, M. Watai, N. Suzuki, Y. Takeuchi

Abstract: Lengths at age and growth rate of Pacific bluefin tuna (PBF) have been estimated from direct readings of otolith annual rings which covered older than age-1. Therefore, the length at age-0 has been extrapolated before the data, and resulting estimates of smaller length than the observed length in fisheries. In the case of PBF, since the fisheries utilized from age-0 (about 2-3 months after the spawning season; ca. 20 cm in folk length [FL]) as a seedling for the aquaculture, so the estimation of accurate age at this stage is quite important for the stock assessment purpose. In this study, we challenged to integrate three different data sources, namely direct observation of otolith daily rings, annual rings, and a mark-recapture (M-R) experiment, to improve growth estimation especially in the young ages (age 0-1). The direct observation of otolith daily rings covered from 51 to 453 days after hatching (18.6-60.1 cm in FL; n = 143), and otolith annual rings data covered age 1 to 26 (70.5-260.5 cm in FL; n = 1,112). In the M-R experiment, FL of tagged fish at

released are around 20-25 cm, and the time at liberty ranged from 14 to 2,218 days. The growth curve derived from integrated analysis had a larger growth rate than that from annual rings data only. Both the daily rings observation and M-R experiment data showed obvious tendency of seasonal change in the growth rate.