An individual-based model for evaluation of maternal effects and spatio-temporal environmental variability on dynamics and management of Pacific ocean perch, *Sebastes alutus*

Principle Investigators
Selina Heppell[1], Paul Spencer[2], Nathan Schumaker[1], Andi Stephens[3]

Associated Staff
Linsey Arnold[1] (PhD student)

[1]Department of Fisheries and Wildlife, Oregon State University; [2]NOAA Alaska Fisheries Science Center, Resource Ecology and Fisheries Management Division; [3]NOAA Northwest Fisheries Science Center, Fisheries Resource Analysis and Monitoring Division

Background

In commercially exploited, long-lived fish species, age structure plays an important role in determining population stability and resilience to human and environmental impacts (Hsieh et al., 2010). Consequences of the reduced abundance in older age classes include increased population variability caused by increases in recruitment variability (Brunel, 2010; Marteinsdottir and Thorarinsson, 1998), as well as changes in demographic parameters (Secor, 2000) that lead to unstable, non-linear, population dynamics (Anderson et al., 2008). The often observed increase in energy allocation per offspring by older females can improve larval survival through an increased time to starvation and higher likelihood of encountering favorable environmental conditions once released (Berkeley et al., 2004; Sogard et al. 2008). Females of different age and size may also spawn earlier or over a more protracted season (Bobko and Berkeley 2004). These processes are generally referred to as maternal effects, and indicate non-genetic contributions of female spawners to the condition of their offspring. Thus, populations with broader age structure can contribute to population stability through an increase in both the quantity and quality of larvae, and by increasing the range of spawn timing and locations.

The implications of the reduced abundance of older age groups for the assessment and management of fished stocks are evident in a variety of species. O'Farrell and Botsford (2006) found that large errors in the estimate of lifetime reproductive potential in rockfish, *Sebastes* spp., can result if the relationship between larval survival and maternal age is not properly characterized. Accounting for uncertainty in the relationship between maternal age and reproductive potential in two Alaskan stocks of Pacific ocean perch, *Sebastes alutus*, Spencer et al. (2007) found an increase in the relative level of equilibrium spawning per recruit that corresponds to maximum sustainable yield (MSY) and a reduction in the fishing mortality rate producing MSY (F_{msy}) from 3% to 9%. Murawski et al. (2001) showed fishing mortality rates based on the spawning stock biomass overestimated the resiliency of the Georges Bank stock of Atlantic cod (*Gadus morhua*), specifically when estimating the maximum fishing mortality rate. Simulation analyses using Pacific ocean perch and Pacific cod (*Gadus macrocephalus*) life-history patterns also indicated that when maternal effects exist but are not recognized, stock productivity is generally overestimated, and the degree of overestimation is stronger at low stock sizes (Spencer et al., in press). More generally, a meta-analysis of 25 long-lived species in the

north temperate and Arctic latitudes found that exploited populations with an extended age structure had higher reproductive rates than truncated populations, independent of absolute spawning stock biomass (Venturelli et al., 2009).

Preserving the age structure of fished populations can enhance resilience to both human exploitation and environmental change (Scott et al., 1999; Vallin and Nissling, 2000; Hsieh et al. 2006; Berkeley, 2006; Longhurst, 2006). Variance dampening, or the portfolio effect, was investigated by Schindler et al. (2010) at the species level in salmon. They found that a diversity of population age structures within the stock resulted in weakly synchronous population dynamics, reducing the probability that an entire cohort would encounter suboptimal environmental conditions, and thus reducing recruitment variability at the level of the stock. We extend this concept to diversity within a population, specifically the diversity of reproductive traits and tactics between age classes of a long-lived rockfish. For Pacific ocean perch (POP) in the Gulf of Alaska, the diversity of traits and tactics between age classes includes age-specific reproductive biology and spawn timing. The data collected for NPRB Project 629 (Heppell et al. 2010) suggest that older POP females spawn earlier than younger females, and that older females provision their larvae with larger oil globules. In addition, Palof et al. (2011) have found genetic evidence for stock structure in POP, indicating "neighborhoods" of adult POP at scales from 400km down to 70km. We propose to investigate the potential effects of environmental variability in space and time on recruitment and reproductive success for POP when age-specific maternal effects on spawn timing, larval growth, and time to starvation are considered explicitly. Suboptimal environmental conditions encountered by Pacific ocean perch include a difference in prey patchiness or quality between warm and cool years, as quantified by the Bering Sea Integrated Ecosystem Research Program (Heintz, 2012). We plan to evaluate the consequences of a variety of "match-mismatch" (Cushing, 1990) scenarios, where larval quality is linked to the timing and location of spawning to affect the likelihood of successful recruitment.

For a long-lived fish in a highly variable environment, the combination of age-specific reproductive traits and stock structure may play a role in population stability and resilience that will impact optimal yield strategies. Investigation of the interaction between age-specific reproductive traits and the environment may improve our knowledge of population dynamic processes important to assessment and management while identifying potential mechanisms that drive population productivity and stock structure. In this study we propose to explore the effects of stock structure, age structure and spatio-temporal variability in environmental conditions on POP dynamics in the Gulf of Alaska. We will build a spatially-explicit individual based model (IBM) that will be applied as the operating model in a management strategy evaluation (MSE) for POP stocks in the Gulf of Alaska.

The objectives of this study are to:

- Characterize the interaction of maternal effects, environmental variability and oceanographic conditions, including regime shifts and climate change-induced increase in environmental variability, on the following emergent properties of the IBM:
    - Stock structure
    - Population productivity
    - Recruitment variability
- Utilize the IBM as an operating model in an MSE to test:

- Stock assessment estimates of population productivity and other management reference points when age-specific reproductive biology and environmental variability are not accounted for in the assessment.
- Management performance (i.e., yield, variability of yield, and avoidance of stock depletion) when age-specific reproductive biology and environmental variability are either accounted for or not accounted for in the assessment.
- The utility of simplified estimation methods as the operating model to evaluate the trade-off of computational efficiency and realism in estimated parameters

Approach

We will use the HexSim model (Schumaker, 2013) to construct a spatially-explicit IBM for Gulf of Alaska Pacific ocean perch that will incorporate differences in individuals based on their current and past states (size at age based on individual growth, maturity, age-specific spawning location and timing), thereby modeling the interaction of individuals with the environment (Grimm and Railsback, 2005). We will simulate population-level dynamics and structure as emergent properties resulting from variation in the vital rates applied to individuals occupying different environments A precedent for our approach was set by Hinckley et al. (1996) for Gulf of Alaska walleye pollock. They tested the effects of spatial variability in circulation and environmental conditions on recruitment and found that assumptions about temperature and depth of larval release significantly changed model outputs, and that their IBM could hindcast larval distributions with a relative degree of precision. Our project will similarly combine physical oceanographic features and environmental variability on different temporal scales, with the addition of age-specific reproductive biology of POP.

HexSim is a simulation framework utilized in diverse ecological studies (Marcot et al., 2013; Heinrichs et al., 2010; McRae et al., 2008) including an extensive recent analysis for the U.S. Fish and Wildlife Service's recovery strategy for the Northern Spotted Owl (USFWS, 2011). Key HexSim features include the ability to incorporate detailed spatial data, and an extensive use of individual traits. HexSim traits allow individuals to vary probabilistically, or based on age, exposure, resource acquisition, and myriad other ecologically-meaningful drivers, including genotype. Our HexSim model will simulate the POP life cycle within a realistic landscape built within HexSim based upon oceanographic and environmental data. We will project the simulated population forward under different environmental scenarios, including an increasingly variable environment as predicted by climate change models, a regime shift scenario, and a combination of increasing variability with a regime shift. Individual POP will move as a function of ocean currents (larvae) or individual behaviors (adult stage classes). Survival and reproductive rates of the adult stage classes will be a function of natural mortality rates, and fecundity relationships as utilized in the most recent stock assessment (Hanselman et al., 2012). The natural mortality rate will be converted to a survival probability applied at the individual level, and will vary through time. Fishing mortality will be built into the HexSim model to simulate current management methods for distributing catch in the GOA. The resulting impact of catch distribution policies on productivity will be an emergent property of the model with direct application to Pacific ocean perch assessment and management (Dana Hanselman, personal communication). Our model will also include age-specific reproductive traits and tactics. HexSim will model larval survival to settlement as an interaction between the oceanographic features encountered, including currents

and mesoscale eddies, the environmental conditions, age-specific maternal effects, and spawn timing. The emergent properties of the IBM will illustrate our model's ability to integrate population processes. In particular, we will compare HexSim's projections of genetic and demographic stock structure to values that have been observed in the Gulf of Alaska.

Previous individual-based models built to investigate larval dispersion patterns in the Gulf of Alaska utilized a linked hydrodynamic and individual-based model (Stockhausen and Hermann, 2007), or a linked hydrodynamic, individual-based, nutrient-phytoplankton-zooplankton (NPZ) model (Hinckley et al., 2001). Linking a hydrodynamic model such as ROMS (Regional Ocean Modeling System) to an NPZ and IBM can be computationally intensive but feasible approach for obtaining information on larval dispersal and spatial distributions. The ROMS-NPZ-IBM framework is also being applied to POP as part of the Gulf of Alaska Integrated Ecosystem Research Program (GOA IERP) that is focused on recruitment variability of five groundfish species. Our proposed study would complement this ongoing work in two important ways: 1) we incorporate specific consideration of rockfish reproductive biology and maternal effects in larval survival; and 2) we make use of an IBM as the operating model in a management strategy evaluation (MSE). MSEs are the evaluation of management strategies through simulation testing, typically with feedback between the estimation of stock size and productivity from an estimation model, and the underlying stock dynamics as represented by the operating model (Smith, 1994). Developing an MSE that includes an IBM operating model linked to a ROMS and NPZ model, and an estimation model based on an age-structured stock assessment is a time- and computation-intensive endeavor. As such, oceanographic and environmental features in our IBM will initially be modeled in the HexSim framework as simplified velocity fields, and spatial productivity patterns will be parameterized from existing data on the general timing, size, persistence and patchiness of primary productivity. We will work with AFSC scientists currently involved in the GOA IERP project to obtain available oceanographic and environmental data. A simplified IBM operating model for the MSE will allow initial analyses that address our research questions while we explore the availability of increasingly detailed oceanographic and environmental data, and the computational feasibility of its incorporation into the IBM.

The IBM-MSE framework will allow us to test the extent to which management performance could be affected if estimates of stock productivity were biased because interactions between an age-specific maternal effect, a variable environment, and larval dispersal, as dictated by oceanographic conditions, were not considered. The MSE will simulate multiple environmental scenarios, including an increase in variability through time to determine the impact on projected stock status. Existing age-structured assessment models are often used for the estimation models in an MSE, in which estimated values of stock size, recruitment, and key productivity parameters are obtained from application of an age-structured stock assessment model to simulated observed data. This approach provides realism for a particular stock but at a cost of computational complexity. A simpler technique is to simulate estimated values of stock size, recruitment, and key productivity parameters as the random deviations from the simulated "true" values produced by the operating model (Punt et al., 2012). Because our proposed IBM is more complex than typical MSE operating models, a simplified estimation model may enhance computational efficiency while still evaluating management performance. We propose to investigate both levels of complexity in the MSE estimation model, with the final model specification reflecting the trade-off between computational efficiency and realism in estimated quantities.

Benefits

This research meets the goals of a FATE Type 1 proposal to improve stock assessment by building an IBM-MSE modeling framework that will project stock status forward under different environmental conditions, investigate the interaction of environmental variability and age-specific reproductive biology on stock productivity and recruitment variability, and assess the possible consequences of ignoring this interaction in more traditional stock assessment approaches. The emergent properties of the IBM reflect not only the impact of environment and biology on population productivity, but also those of management through the distribution of catch. The MSE will allow us to test current and proposed management strategies, directly contributing to the understanding of the complex interactions between environment, biology, and management.

In addition, this project directly addresses the recommendations from the Center of Independent Experts (CIE) review of Alaska rockfish stock assessments held in 2013, which recommended that MSEs should be conducted for Alaskan rockfish, and further work on oceanography and the "mixing dynamics" should be conducted. The results of this study will benefit resource managers by providing an evaluation of current management procedures in the context of environmental change and reproductive biology of a managed stock. The results will be communicated to resource managers via incorporation within the stock assessment reports and/or presentations to the Plan Teams and Scientific and Statistical Committee of the North Pacific Fishery Management Council.

Deliverables

- Final report containing results of the IBM and MSE, with specific consideration of how the results can be used in stock assessment and management of Pacific ocean perch.
- Code for an individual based model of a commercially important groundfish in the Gulf of Alaska, capable of incorporating environmental and oceanographic information
- Manuscript(s) detailing the construction of the IBM and MSE, including further research suggestions on the applicability of HexSim to other stocks and systems
- Manuscript(s) addressing the role of reproductive biology and the environment on key assessment reference points
- A graduate student dissertation

Statement of Work

In year 1 we will construct the IBM, starting with a simple model that can serve as the operating model in the MSE. The goal for the first year will be a functional, simplified IBM-MSE capable of producing preliminary results that will be presented at one national meeting and the FATE meeting. In year 2, we will continue to build complexity into the IBM-MSE with detailed oceanographic and environmental data, as available. The preliminary model runs in year 1, together with input from the POP stock assessment scientists, will inform the management strategies for further evaluation in year 2. In year 2 we will also analyze the simple, alternative operating model for the MSE for comparison to the IBM-MSE.

References

Anderson, C.N.K., C. Hsieh, S.A. Sandin, R. Hewitt, A. Hollowed, J. Beddington, R.M. May, and G. Sugihara. 2008. Why fishing magnifies fluctuations in fish abundance. Nature 452:835-839.

Berkeley, S.A., C. Chapman, and S.M. Sogard. 2004. Maternal age as a determinant of larval growth and survival in a marine fish, *Sebastes melanops*. Ecology 85:1258-1264.

Bobko, S.J., and S.A. Berkeley. 2004. Maturity, ovarian cycle, fecundity, and age-specific parturition of black rockfish (*Sebastes melanops*). Fisheries Bulletin 102:418-429.

Brunel, T. 2010. Age-structure-dependent recruitment: a meta-analysis applied to Northeast Atlantic fish stocks. ICES Journal of Marine Science 67:1921–1930.

Cushing, D.H. 1990. Plankton production and year-class strength in fish populations: an update of the match/mismatch hypothesis. Advances in Marine Biology 26:249-293.

Grimm, V., and S.F. Railsback. 2005. Why individual-based modeling and ecology? *In* Individual-based Modeling and Ecology. Princeton University Press, Princeton New Jersey.

Hanselman, D.H., S.K. Shotwell, P.J.F. Hulson, J. Heifetz, and J.N. Ianelli. 2012. Assessment of the Pacific ocean perch stock in the Gulf of Alaska. *In* Stock assessment and fishery evaluation report for the groundfish resources of the Bering Sea/Aleutian Islands region, pp 563-592. North Pacific Fishery Management Council, 605 W. 4th Ave, suite 306. Anchorage, AK 99501.

Heinrichs J.A., D.J. Bender, D.L. Gummer, and N.H. Schumaker. 2010. Assessing critical habitat: Evaluating the relative contribution of habitats to population persistence. Biological Conservation 143:2229-2237.

Heintz, R. 2012. Hjort's match/mismatch hypothesis revisited—prey quality can mismatch consumer needs. Alaska Fisheries Science Center Quarterly Report, April-June, p14 (http://www.afsc.noaa.gov/Quarterly/amj2012/divrptsABL4.htm)

Hinckley, S., A.J. Hermann, and B.A. Megrey. 1996. Development of a spatially explicit, individual-based model of marine fish early life history. Marine Ecology Progress Series 139:47-68.

Hinckley, S., A.J. Hermann, K.L. Mier, and B.A. Megrey. 2001. Importance of spawning location and timing to successful transport to nursery areas: a simulation study of Gulf of Alaska walleye pollock. ICES Journal of Marine Science 58: 1042-1052.

Hsieh, C., A. Yamauchi, T. Nakazawa, and W.F. Wang. 2010. Fishing effects on age and spatial structures undermine population stability of fishes. Aquatic Sciences 72:165-178.

Marcot B.G., M.G. Raphael, N.H. Schumaker, and B. Galleher. 2013. How big and how close? Habitat patch size and spacing to conserve a threatened species. Natural Resources Modeling 26(2):194-214.

Marteinsdottier, G. and K. Thorarinsson. 1998. Improving the stock-recruitment relationship in Icelandic cod (*Gadus morhua*) by including age diversity of spawners. Canadian Journal of Fisheries and Aquatic Sciences 55:1372-1377.

McRae B, N.H. Schumaker, R.B. McKane, R.T Busing, A.M. Solomon, and C.A. Burdick. 2008. A multi-model framework for simulating wildlife population response to land use and climate change. Ecological Modelling 219:77-91.

Murawski, S.A., P.J. Rago, E.A. Trippel. 2001. Impacts of demographic variation in spawning characteristics on reference points for fishery management. ICES Journal of Marine Science 58: 1002-1014.

O'Farrell, M.R., and L.W. Botsford. 2006. The fisheries management implications of maternal-age-dependent larval survival. Canadian Journal of Fisheries and Aquatic Sciences 63:2249-2258.

Palof, K.J., J. Heifetz, and A.J. Gharrett. 2011. Geographic structure in Alaskan Pacific ocean perch (*Sebastes alutus*) indicates limited life-time dispersal. Marine Biology 158(4):779-792.

Punt, A.E., M.S.M. Siddeek, B. Garber-Yonts, M. Dalton, L. Rugolo,D. Stram, B.J. Turnock, and J. Zheng. 2012. Evaluating the impact of buffers to account for scientific uncertainty when setting TACs: application to red king crab in Bristol Bay, Alaska . ICES Journal of Marine Science 69:624-634..

Secor, D.H. 2000. Longevity and resilience of Chesapeake Bay striped bass. ICES Journal of Marine Science 57:808-815.

Schumaker, N.H. 2013. HexSim (Version 2.4). U.S. Environmental Protection Agency, Environmental Research Laboratory, Corvallis, Oregon, USA. www.hexsim.net

Smith, A.D.M. 1994. Management strategy evaluation: the light on the hill. *In* Population dynamics for fisheries management. *Edited by* D.A. Hancock. Australian Society for Fish Biology, Perth, Australia. pp. 249-253.

Sogard, S.M., S.A. Berkeley, and R. Fisher. 2008. Maternal effects in rockfishes *Sebastes* spp.: a comparison among species. Marine Ecology Progress Series 360:227-236.

Spencer, P., D. Hanselman, and M. Dorn. 2007. The effect of maternal age of spawning on estimation of F_{MSY} for Alaskan Pacific ocean perch. *In* Biology, Assessment, and Management of North Pacific Rockfishes. Proceedings of the 2005 Wakefield Symposium, Anchorage, Alaska. *Edited by* J. Heifetz, J. DeCosimo, A.J. Gharrett, M.S. Love, T.O'Connell, and R. Stanley. Alaska Sea Grant College Program, University of Alaska Fairbanks.

Spencer, P.D., S.B.M. Kraak, and E.A. Trippel. In press. The influence of maternal effects in larval survival on fishery harvest reference points for two life-history patterns. Canadian Journal of Fisheries and Aquatic Sciences.

Stockhausen, W.T. and A.J. Hermann. 2007. Modeling larval dispersion of rockfish: A tool for marine reserve design? *In* Biology, Assessment, and Management of North Pacific Rockfishes. Proceedings of the 2005 Wakefield Symposium, Anchorage, Alaska. *Edited by* J. Heifetz, J. DeCosimo, A.J. Gharrett, M.S. Love, T.O'Connell, and R. Stanley. Alaska Sea Grant College Program, University of Alaska Fairbanks.

USFWS. 2011. Revised recovery plan for the northern spotted owl (*Strix occidentalis caurina*). U.S. Fish and Wildlife Service, Portland, Oregon.

Vallin, L. and A. Nissling. 2000. Maternal effects on egg size and egg buoyancy of Baltic cod, *Gadus morhua*: Implications for stock structure effects on recruitment. Fisheries Research 49: 21-37.

Venturelli, P.A., B.J. Shuter, and C.A. Murphy. 2009. Evidence for harvest-induced maternal influences on the reproductive rates of fish populations. Proceedings of the Royal Society B 276: 919-924.