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**Report on a Workshop on Spatial Structure and Dynamics
of Walleye Pollock in the Bering Sea**

Seattle WA, July 2009

by

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EXECUTIVE SUMMARY

A 4-day workshop, funded by the Pollock Conservation Cooperative Research Center (PCCRC), was held at the Alaska Fisheries Science Center in Seattle, Washington, on 7-10 July 2009. Over 35 scientists from around the world met to synthesize relevant information about the spatial structure and dynamics of the walleye pollock (*Theragra chalcogramma*) population in the Bering Sea and to examine spatial models of fish dynamics and their use in stock assessment and management internationally. The synthesis was needed to address issues related to ecosystem effects of one of the world's largest fisheries on a finer temporal and spatial scale than is currently available.

The workshop sessions reviewed empirical information from research surveys and the commercial fleet and reviewed knowledge about which factors influence the spatial distribution of pollock seasonally and annually. Reviews included spawning, feeding, day/night behavior, oceanographic and environmental variables, distribution of pollock food and predators, regime shifts, and fisheries. A dedicated session on alternative modeling approaches was held with a number of presentations from outside experts. The presentations and background documents are posted at ftp.afsc.noaa.gov/afsc/public/pollock/spatial_ws.htm.

Presentation topics included mechanisms to explain pollock spatial distribution, spatial modeling and uncertainty, the importance of tagging data, the use of fishery data to define seasonal spatial distributions, the tradeoffs of different spatial model approaches, the proper design of a tagging study on pollock, and whether current evidence of pollock movement could be used to modify management approaches. One major finding from the workshop was that innovative and useful spatial models have recently been developed that have great potential in aiding the understanding of spatial and temporal fish distributions.

Some of the key recommendations made during discussions at the meeting were

- The development of seasonally and spatially disaggregated models for pollock and other species should continue. As new technologies are applied to fishery resources (e.g., geographic information systems, genetic analyses, electronic tags, otolith chemistry and microstructure, ocean modeling) fine-scale spatial structure and connectivity patterns are being revealed. National and international workshops on spatial modeling should continue to be offered in the future to explore the incorporation of spatial complexities.
- A comprehensive synthesis of available information on the population structure of pollock and the development of a conceptual model of its population structure should be conducted. Implication of movement and fishery patterns on underlying population dynamics (e.g., stock-recruitment patterns) should be evaluated.
- Tagging information would be useful for evaluating movement and spatial structure for Bering Sea pollock. Funding and personnel are needed to develop the feasibility, design, and logistics of a tagging study.
- For stocks that are relatively mobile, adding spatially explicit recommendations for catch levels should be pursued with caution, because the uncertainty for spatially-disaggregated estimates is likely to increase and many rate parameters (e.g., fishing mortality, natural mortality, selectivity, tag loss, movement) may be strongly correlated or confounded.
- Existing arrays of acoustic data loggers should be extended to cover additional directed transects to help fill in gaps of seasonal distributions.

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Introduction

This collaborative project between University of Alaska Fairbanks (UAF), Alaska Fisheries Science Center (AFSC), University of Massachusetts Dartmouth and the pollock industry had as its goal to synthesize information about the spatial distribution and dynamics of walleye pollock (*Theragra chalcogramma*) in the Bering Sea by having a workshop. The agenda of the workshop is given in Appendix 1. Experts from a wide variety of disciplines and the fishing industry were invited to attend the workshop and offer their insights. Workshop participants are listed in Appendix 2, followed by a picture of participants in Appendix 3.

After 3 days of presentations and discussions, workshop participants made recommendations about future research and modeling. The applicability of recently developed modeling approaches that combine stock assessment information with data from a mark-recapture or tagging experiment to the Eastern Bering Sea (EBS) walleye pollock resource and fishery was examined. Participants discussed whether such an experiment is feasible and what the critical elements in its design are.

The workshop met its objectives and should lead to further research proposals (not only on pollock) and collaborations with scientists around the world.

Background

Tagging has been a useful tool in fisheries science for over a century, but rapid advances in tag technology and improved statistical methods for population modeling are expanding its role. Tagging data have been extensively applied to population modeling (e.g., Seber 1982), but most model developments have focused on estimating survival or abundance of relatively small terrestrial populations, rather than movement of abundant marine fish stocks like walleye pollock. Many early attempts to model marine fish populations based solely on tagging data were unsuccessful, and ancillary information from fisheries or research surveys are usually needed for reliable movement estimates (Schwarz 2005). A recent symposium on “Tagging and Its Use in Stock Assessments” at the 2008 annual meeting of the American Fisheries Society in Ottawa had over 20 presentations over 2 days. Thus, tagging studies are re-emerging as valuable quantitative approaches for stock assessment and fishery management. The most promising developments in the application of tagging data to fishery resources are the integration of mark-recapture patterns into catch-at-age models and the development of spatially explicit stock assessment models (e.g., Butterworth et al. 2003; Porch 2003; Maunder 2001, 2005, 2007, 2008; and Cadrin and Secor 2009).

The EBS walleye pollock stock is evaluated with a standard age-structured stock assessment model (Ianelli et al. 2007) that accounts for spatial structure externally (i.e., in compiling the data). The groundfish fishery for walleye pollock in the EBS is one of the world’s largest, and catch limits are managed by seasons and to some extent regions (40%-60% split between winter and summer-fall seasons and summer restrictions on where some fishing sectors are allowed to operate). Movement into and out of the area has been hypothesized as a cause for some of the retrospective patterns observed in the assessments over the years and more explicit accounting for spatial variability may help resolve such issues.

It has been inferred from spatial patterns of fishery and survey data that during the spring and summer EBS walleye pollock migrate to feeding areas northwestward and over the shelf. During the winter, they migrate to spawning areas in more southern parts. However, some spawning grounds appear to have changed over time. For example Hinckley (1987) found spawning aggregations over deep water based on 1984 fishery data compared to aggregations that occur primarily on the slope and shelf regions. Currently movement information from a large-scale EBS walleye pollock mark-recapture study is unavailable, but feasibility studies have shown the potential for sufficient sample size and survival rates of a tagging study

(Natural Resources Consultants 1996, Miller 2007, Winter et al. 2007). The need for genetics and tagging studies to better understand pollock stock structure has long been recognized (Bailey et al. 1999).

Knowledge of spatial structure can affect fish stock assessment conclusions and subsequent estimates of potential fishery yields and mortality, but incorporation of fish movement in stock assessment analysis is rare due to insufficient data and the added complexity (Quinn and Deriso 1999). The primary technique for determining movement rates of a fish population is a mark-recapture study (Seber 1982).

To better understand the walleye pollock population dynamics on finer spatial and temporal scales, an age-specific movement (ASM) model has been developed (Miller et al. 2008, see presentation abstract). Using available EBS disaggregated survey and fishery catch data, age-specific movement between the northwest (NW) and southeast (SE) EBS was estimated without any mark-recapture information. Under moderate assumptions, this study showed that reasonable estimates of most population and movement parameters could be obtained from existing disaggregated assessment survey and fishery data. Yet some population parameters were uncertain and high correlation existed between some parameters. Thus, with available spatially disaggregated data, the walleye pollock ASM assessment model provides an excellent candidate for integration of tagging information to supplement movement parameter estimation. Simulations showed that additional information from a mark-recapture study helped stabilize the ASM model and allowed some assumptions to be relaxed (Hulson et al., in prep., see presentation abstract). These simulations also showed that with known population structure, bias occurred in estimates under scenarios when movement information was unavailable. The bias was reduced when mark-recapture information was incorporated into the ASM model.

Topics/Outline

The workshop was structured around the following topics:

1) **Spatial Information**

Extensive data are available for the eastern Bering Sea with annual summer bottom trawl surveys that began in 1982 and are available online at www.afsc.noaa.gov/race. These data provide spatial information on the distribution of 1-year old pollock and adults with movements apparent by the evolution of temperature between years (Kotwicki et al. 2005). More recently, available light has also been shown to affect pollock vertical distribution (and hence availability to bottom-trawl surveys; Kotwicki et al. 2009). Acoustic-trawl surveys have been operated regularly through the entire Eastern Bering Sea shelf region since 1979, every 3 years initially and more regularly in the past 10 years. The summer acoustic-trawl surveys extended into the Russian zone in six different years: 1994, 2002, 2004, and 2007-2009. These surveys indicate that in some years the distribution of pollock is continuous into the Russian zone whereas in other years relatively few pollock have been observed on the Russian side (Taina Honkalehto, AFSC, pers. comm.). Surveys in the Russian Navarin region (the area immediately across the U.S.-Russia boundary line) are conducted by Russian scientists typically in mid-late autumn and consist of acoustic surveys interspersed with regular bottom and midwater trawl stations. Data from the U.S. fishery provides considerable insight on the distribution patterns and movement of pollock throughout the year (with peak targeted fishing occurring in January-March and then from mid-June to October). In wintertime, pollock appear to be constrained by ice and are concentrated in the southeast area of the EBS. The timing and regularity of the pollock distribution patterns seems to be quite consistent from year to year with concentrations most common just north of Unimak Island followed by densities towards the east and gradually to the north and then west towards the Pribilof Islands. During the summer-fall fishery, the interannual distribution of the pollock fishery varies and is most likely a function of the temperature pattern and the age composition of the population (Janelli et al. 2008). Pollock generally prefer water above 2°C and hence the extent of

the “cold pool” (water less than 2°C) affects their spatial distribution. If the pollock population is skewed towards younger fish (say when a large year-class appears) then in a relative sense the population distribution will generally shift towards the northwest region since younger pollock apparently prefer that area (Ianelli 2005). A promising source of information on distribution and movement patterns of pollock is from vessels equipped with echosounders that record fish sign. These data can be evaluated using an approach similar to that used for scientific hydro-acoustic systems to provide insights on pollock movement and distribution (Shen et al. 2008). Regarding commercial fisheries in the western Bering Sea (Russian side), the extent and availability of spatially resolved data is unknown.

2) **Review of pollock stock structure**

Bailey et al. (1999) provide a comprehensive review of information on population structure of walleye pollock through the late 1990s. Recent information supports their earlier conclusions that there are significant genetic differences between pollock in the Bering Sea and the Gulf of Alaska. Some population structure is evident within the Bering Sea, suggesting three distinct groups of pollock in 1) the Aleutian Basin, 2) the southeast shelf, and 3) the northwest shelf. These areas are distinguished by minor genetic differences (Mulligan et al. 1992, Shields and Gust 1995), and differences in spawning times (Hinckley 1987), fecundity (Hinckley 1987), growth rates (Lynde et al. 1986, Hinckley 1987), morphometrics (Mulligan et al. 1989) and otolith chemistry (Nakano et al. 1991). This information suggests that some gene flow exists among three subpopulations in the Bering Sea, but mixing is limited enough so that phenotypic differences are maintained among groups.

3) **Models**

There have been a variety of spatial population dynamics and assessment models developed over the years (Goethel et al., in prep.). The first major effort was by Beverton and Holt (1957), who incorporated movement into population dynamics equations and showed how to determine migration rates from tagging data. They created two types of models, the dispersion model and the box-transfer model. In the former, movement is treated as a continuous, random process, whereas in the box-transfer model, movement is a discrete process across different spatial compartments. These two types of models have continued to evolve to this day.

The dispersion model has evolved into advection-diffusion- reaction models (e.g., Sibert et al. 1999). This approach allows for random diffusive movements, directed movements, and mortality. Box-transfer models have had several applications in stock assessment (e.g., Butterworth and Punt 1994). Overall, models can be classified in different ways: estimation versus simulation, stochastic versus deterministic, and continuous versus discrete (Goethel et al., in prep.). A review of many approaches is provided by Quinn and Deriso (1999, chapter 10). Similarly, a variety of methods has evolved to estimate movement from tagging data (e.g., Hilborn 1990, Quinn et al. 1999, program MARK: <http://warnercnr.colostate.edu/~gwhite/mark/mark.htm>).

A major advance in the last decade is the development of tag-integrated assessment models, in which tagging data is integrated with other data sources such as fishery and survey biomass and age composition data (e.g., ITCAAN, Maunder 2001). The tagged population is modeled with the same dynamics equations as the total population but can have additional parameters to deal with tag shedding, tag non-reporting, tag mortality, and other such factors. Various software products have been developed to analyze tagging data and to perform integrated analyses: ITCAAN, MAST, MULTIFAN-CL, VPA 2-box: Porch 2003, Stock Synthesis 3, see Goethel et al., in prep.) The diversity of available models was well illustrated by the model presentations at the workshop (see presentation abstracts by Punt, Cadrin, Loerke, Goethel, Maunder, N. Taylor, T. Miller,

Valero, Murphy, Cheng, Miller, Hulson, and Sepulveda). One of the main findings of the workshop was that the modeling of spatial populations has developed into a mature discipline within fisheries population dynamics modeling.

4) **Synthesis**

Spatial distribution and movement has long been recognized as a major factor in fisheries management. In fact, the first organized international scientific investigations were initiated to examine if fluctuations in fish abundance was due to changes in numbers of fish or from movement between grounds (Cadrin and Secor 2009). Over the course of the 20th century it became apparent that fishing and variation in the production of young were the primary cause of fluctuations in abundance, and fishery science moved on to development of mathematical methods to account for change, and to predict future abundance trends (Beverton and Holt 1957, Ricker 1975). In more recent years it has also become evident that there are strong interactions between fish abundance and the ocean physical environment that are altering relationships that were thought to be immutable.

This workshop was directed toward exploring the distributional aspects of fisheries and how to incorporate these into stock assessment in order to better manage sustainable yield. The tools and mathematics to describe and predict abundance trends are well developed; however, fish population dynamics are complex, and incorporation of this complexity involves information from new sampling tools to census the fish and their surroundings. At the dawn of the 21st Century we are faced with a broader array of management issues, but scientists have an increasing array of tools that can be used to examine the interaction of fish with the environment and physical responses to fishing.

The presentations and discussions suggested that spatial dynamics are beneficial to include in stock assessments. This is especially true for the Bering Sea pollock resource where existing data suggest possible complex spatial components. As previously noted, spatial modeling is coming into use in the pollock stock assessment. However, existing data is inadequate to provide more than gross relationships. To improve the data available for this analysis new data collection methods need to be developed.

5) **Recommendations for future assessment and field work**

Over the course of the workshop a number of studies that modeled practical or theoretical aspects of spatial structure and their effect on fish dynamics were presented and discussed. In general the recommendations focused on

- a. the need for a field study to determine movement;
- b. tagging methodology, types of tags, recovery efforts;
- c. short-term studies versus long-term programs;
- d. other design issues (sample sizes, locations, cost, logistics).

For Bering Sea pollock a single population model with fisheries spatially and seasonally defined was determined to be a valuable next step toward development of spatially specific management advice and serve as a conceptual model of population structure. Spatial analysis should also be utilized to examine movement and fishery patterns on the underlying stock-recruitment patterns.

Summary of Presentations

The presentations generally fell into three categories: (1) spatial modeling, (2) pollock distribution and biology, and (3) tagging studies. The abstracts are presented here in the same order of presentation as at the workshop, as presented in Appendix 1.

Questions Raised

From these presentations, discussions throughout the week resulted in a number of questions including the following:

- What mechanisms best explain pollock spatial distribution?
- Has spatial modeling resolved retrospective patterns?
- Will spatial modeling reduce uncertainty (particularly in stock assessment recommendations)?
- How have simulation studies shown the importance of tagging data?
- Can directed fishing where data are missing improve seasonal spawning distribution information?
- Can acoustic data collected aboard commercial vessels improve understanding of winter pollock distribution (Shen et al. 2008)?
- How would conventional tagging improve understanding of spatial processes?
- How can one use spatial modeling for operating model development to test alternative harvest strategies with respect pollock and fishery spatial distributions?
- Are technological issues (pollock survival) for tagging studies prohibitive?
- What are the tradeoffs of different movement model approaches (i.e., estimation features, scalability, data requirements)?
- What is the ideal field study to determine movement (i.e., what type of tag, what type of recovery effort, sample sizes, locations, cost, logistics)?
- How should current evidence of pollock movement be used to modify management approaches?
- How well can movement estimates be improved upon from biological processes (e.g., swim speed, fish condition)?
- Are fish consistently spawning in the same aggregations and in the same area year after year? Can micro-constituents or other methods be used to identify a signature for these fish? For example, do Bogoslof spawning fish reside on the shelf during other times of the year?

Draft Conceptual Model

After discussions with the group, a conceptual model of pollock distribution, seasonal and ontogenetic movement patterns, and core spawning areas was developed (Fig. 1). These

highlighted main spawning areas and noted that over the years, locales and concentrations have varied considerably. Surface currents indicate that advection of eggs and larvae (generally over a 90-day period from peak spawning that occurs during mid-late winter) are likely to contribute to the spatial distribution of one year old pollock. The conceptual model includes the three ‘spawning stocks’ defined by Hinckley (1987) in 1) the Aleutian Basin, 2) the southeast shelf, and 3) the northwest shelf. The conceptual model allows for mixing, but the degree of mixing is unknown. The conceptual model is also generally consistent with the spatial population model developed by Miller et al. (2008) and Hulson et al. (in press) that quantifies movement between northwest and southeast areas of the Bering Sea. The present model omits the contribution from the Basin (central Bering Sea) area because it appears that deep-water high seas spawning has not occurred in recent decades.

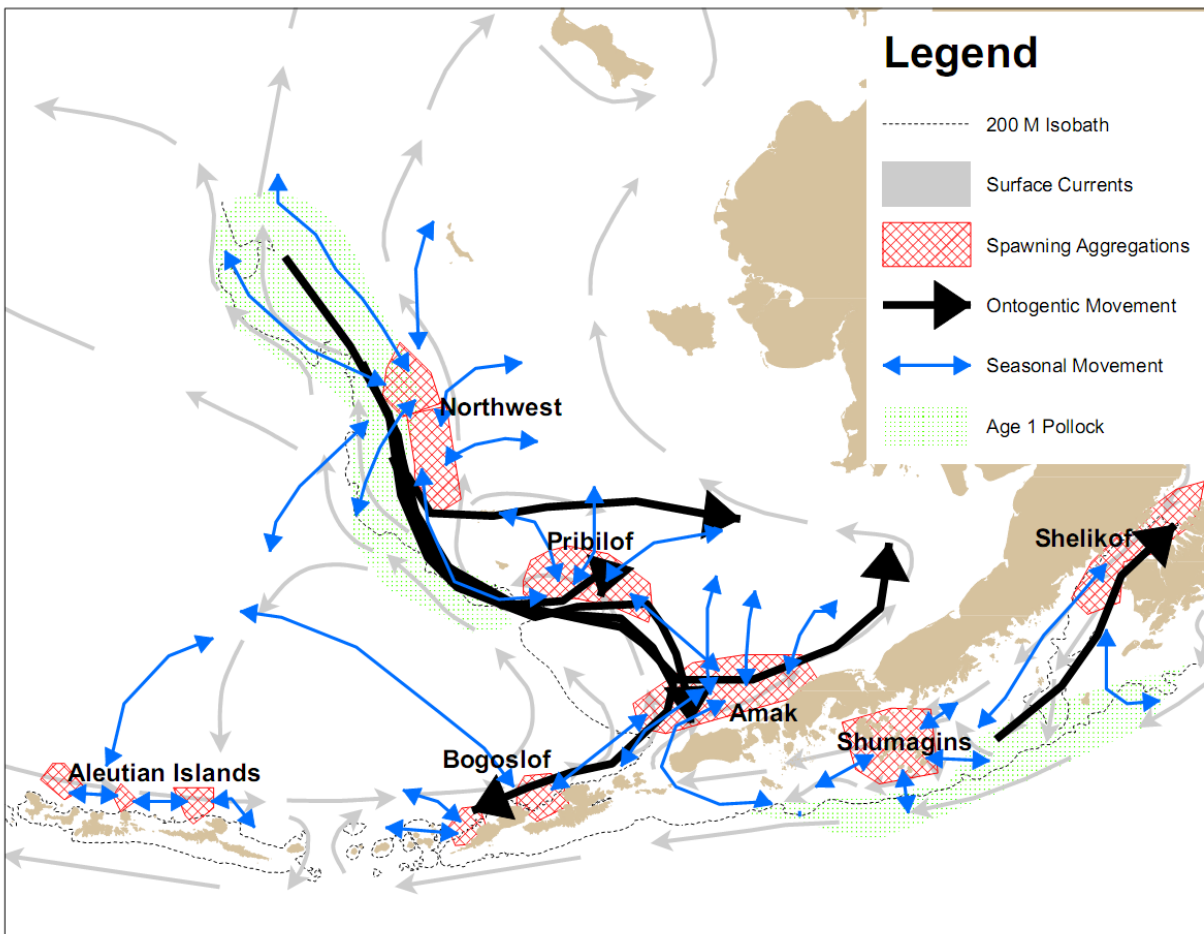


Figure 1.-- Draft conceptual model of walleye pollock seasonal and ontogenetic movements with shaded areas representing recent spawning locations.

Recommendations

The following recommendations were made during discussions at the meeting:

- Continue evaluating the effects of spatially disaggregating the present assessment model. A seasonally and spatially disaggregated model where movement between areas may be included and the available survey data applied. This could form the basis of an operating model to test the simpler model that is presently used for management. One specification might be to have a single area-model but with fisheries spatially and seasonally defined.
- Synthesize and publish available information on population structure of pollock and develop a conceptual model of population structure (e.g., Kotenev and Glubokov 2007). The formation of a conceptual model can help to refine the operating models used in the presentations Miller et al. (2008) and Hulson et al (in press).
- Evaluate the implications of movement and fishery patterns on underlying population dynamics (e.g., stock-recruitment patterns).
- Make spatially explicit recommendations for catch levels for stocks that are relatively mobile, should be pursued with caution because the greater uncertainty of spatially-disaggregated estimates.
- Examine spawning throughout the year, including the fall when roe is less of a target fishery.
- Develop an *in situ* tagging method for evaluating movement and spatial structure for EBS pollock. Due to high pollock mortality when bringing them to the surface to be tagged, development of an *in situ* tagging method would increase the chances of success greatly (Sigurdsson et al. 2006, see Bailey presentation abstract).
- Design a feasibility study for conventional tagging of pollock. Such a pilot project should be designed to begin testing hypotheses on movement.
- If tagging is pursued, consider the use of temperature recorders with the tag (technology has made them cheap, and about the size of a dime).
- Extend acoustic data logging to additional directed transects to help fill in gaps of seasonal distributions (Shen et al. 2008).
- Examine papers from the International Whaling Commission where spatial modeling and management procedures have been extensively tested.
- Constrain or simplify movement patterns if necessary to avoid problems over convergence. Several presentations involved estimation of movement parameters that needed to be constrained or simplified (e.g., Punt's analysis of school shark, Loehrke's analysis of Atlantic cod, Taylor's analysis of Atlantic bluefin).
- Use conceptual understanding of pollock movement patterns to help constrain seasonal movement to achieve realistic patterns. Simulation presentations (Miller, Hulson, Methot, Cadrin) demonstrated that the determination of the form of movement (e.g., diffusion or overlap) is critical to population modeling.

Study Products

There are three primary products from this workshop.

1. The first product is this final report describing the workshop, key findings, and recommendations for further development of spatial research and modeling of pollock. The final report will be sent to workshop participants, the Alaska Fisheries Science Center, and the North Pacific Fishery Management Council. It will also be available on the Pollock Conservation Cooperative Research Center's (PCCRC's) website.

2. The second product is the workshop presentations and materials. Scientific literature, reports, and miscellaneous information are stored on an AFSC website (<http://tinyurl.com/6hgtuon>) for general use.
3. The third and final product is new stimulation for research into spatial processes of fish species. By bringing together researchers from across the nation, synergies have been created that should lead to further collaborations. The lead investigators are planning to collaborate on a review paper in the primary literature that presents a synthesis of spatial models of fish population dynamics presented at the workshop and from other literature.

Acknowledgments

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EXTENDED ABSTRACTS

NOTE: Affiliations and e-mail addresses are given in Appendix 2 for the presenters, and in the presentations at the website for other authors.

Spatial Stock Assessments: The Example of School Shark in Australia

Andre Punt

The impetus for the development of a spatially-structured stock assessment method for school shark (*Galeorhinus galeus*) arose primarily because trends in standardized catch-rates (Punt *et al.*, 2000a) suggested that there were different trends in relative abundance in different regions around southern Australia and also because of anecdotal comments that the population was much more depleted in the east than in the west of its range. Furthermore, a spatially structured stock assessment provided a means to use data sources (tagging and length-frequency information) not included in the stock assessment which was current when the spatially-structured stock assessment was developed (Punt and Walker, 1998).

The spatially-structured stock assessment (Punt *et al.*, 2000b) was based on eight “regions” and an age- and sex-structured population dynamics model with a monthly time-step. It considered five “fleets” (catches by four sizes of gill-net, and by longlines), each of which was associated with a selectivity pattern which was time-invariant and based on data from experimental fishing. The movement dynamics (by month) were computed using a monthly transition probability matrix. This matrix included many parameters (in principle), which would have been computationally prohibitive to estimate individually, so the transition matrix was parameterized by using a small number of parameters which modified a transition matrix from a simpler (conceptual) model of movement dynamics (developed by stakeholders).

The data included in the assessment were (a) catch-rates (assumed to be log-normal), (b) mean length (assumed to be normal), and (c) tag-recapture data. The number of tags recaptured each year was assumed to be Poisson distributed while the recaptures by region conditional on year (those recaptures for which region of recapture was known) were assumed to be multinomial. The dynamics of the tags accounted for tag-loss (quantified using a double-tagging experiment), time-dependence in the tag-reporting rate, and the impact of tags which were recaptured “soon” after release.

Although the method of assessment addressed the need to account for spatial structure, and is still in use, it proved computationally impossible to quantify parameter uncertainty and hence to evaluate using simulation testing.

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Incorporating Tagging in Stock Assessments: Hard-Learned Lessons from New England Groundfish

Steve Cadrin, Jon Loehrke, Dan Goethel, Tony Wood,
Larry Alade, Tim Miller and Shelly Tallack

Spatial aspects for modeling population dynamics and stock assessment recognizes patterns of heterogeneity and connectivity. Stock identification involves determining spatial population structure, and assessing self-sustaining components separately or as a sympatric complex. Heterogeneity in vital rates among areas can be addressed by stratifying process equations, and movement rates can be quantified among areas or subpopulations. The co-evolution of stock assessment and stock identification progressed from an early stage of dynamic pool modeling for phenotypic stocks, followed by stock composition analysis of genetic stocks, and the current stage in which we recognize more complex spatial population structure and attempt to incorporate heterogeneity and movement in assessment models (Cadrin & Secor 2009). The degree of reproductive isolation and pattern of movement are critical determinations for modeling heterogeneity and movement in stock assessment models.

Several questions were posed for the prospect of modeling spatial structure and dynamics of walleye pollock in the Bering Sea:

Is the management unit a single, self-sustaining stock?

- Is there heterogeneity within the stock?
- Is heterogeneity allopatric or sympatric?
- What is the connectivity among stock components?

What is the movement pattern among fishing grounds (or stock components)?

- Seasonal movement of entire population?
- Ontogenetic patterns?
- Mixing (overlap or diffusion?)

What is the motivation for movement (e.g., spawning, feeding)

A review of information on population structure and movement to answer these questions will help to form a conceptual model that is based on the best available science. Simulating an operating model that conforms to the conceptual model will help to determine if a tagging study is cost-effective for meeting fishery management objectives; and if so, to evaluate optimal tagging design (e.g., optimal sample sizes, release locations and seasonality, tag recovery system).

Design elements for a variety of tagging programs in New England were described by Tallack et al. (2005). In summary, several design steps are needed in the strategic planning of a tagging program:

1. Define objectives
2. Choose an appropriate analytical design
3. Choose an appropriate tag or mark
4. Develop a protocol to capture, handle and release fish
5. Develop a recapture and reporting system
6. Plan a sampling design that supports the analytical design and is commensurate with the anticipated program budget.
7. Identify and conduct 'secondary studies:'
 - a. Tag retention (e.g., double tagging)
 - b. Tagging-induced mortality (e.g., holding studies)
 - c. Reporting rate (e.g., high-value tags, 'gold standards' with 100% reporting)

Applications of tagging data for stock assessment and fishery management in New England were summarized by Cadrin et al. (2009). Successes and failures of New England tagging analyses were

reviewed to be considered in strategic planning for tagging walleye pollock in the Bering Sea. Disaggregated population estimates (e.g., survival, abundance or movement rates by time or area) from tagging analyses generally require ancillary data from fisheries or surveys to allow independent estimates of correlated parameters. Information on tagging-induced mortality, tag retention and reporting rate are essential for estimation of movement or mortality rates.

Spatial and temporal design of tag releases should support the analytical design. The temporal design should include tag releases in each time step for which parameters are estimated, as close to beginning of each time step as possible. The spatial design should involve releases in each area, proportional to abundance, with an adequate number of releases in each time-area cell. Most importantly, the optimal design should be evaluated by simulating an operating model of the system of inference.

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Historical Development of Quantifying Movement Processes: Application to Atlantic cod

Jon L. Loehrke, Daniel Goethel and Steven X. Cadrin

The spatiotemporal distribution of a population is the integration of all individuals' lifetime trajectories. At the individual level, movement is dictated by internal processes (e.g., energetic needs, locomotive ability, sensory range) and external stimuli (e.g., environmental fields). An individual's lifetime trajectory can be Markovian or non-Markovian, and dependent on a multi-state process that consists of transitions among vital states (e.g. growth, maturity, mortality) and physical states (e.g. 3-dimensional positions). These have been termed advection-diffusion-reaction (ADR) processes (Okubo and Levin 2001).

An unbiased random walk provides a suitable null model for individual movement. The random walk model can be derived from logical probability arguments and recursive statements by defining a step size in time and space. The recursion equations can be solved by direct integration and Taylor expansion. The first moment of the integration or expansion coefficient represents a change in position, termed advection. The second moment of the integration or expansion coefficient represents a change in inter-step variability, termed diffusion. All approaches converge on the normal distribution model when the temporal and spatial scales of observation are reduced toward zero and the probability of moving in each direction is equal.

Atlantic cod (*Gadus morhua*) in New England exhibit a complex spatial structure with several spawning aggregations that are genetically distinct. An ADR model was developed for Pacific Skipjack Tuna (*Katsuwonus pelamis*; Sibert and Hampton 1999) and was applied to conventional tagging data from New England cod. The model had poor performance in resolving spatial structure, even when mortality was assumed to be zero. Simulations revealed that the advective and diffusive terms are highly correlated. Other investigators have applied a habitat suitability index to inform and constrain the movement

parameters. General conclusions from movement studies indicate that it is critical to identify the appropriate spatiotemporal scale of the movement process to apply movement models to population levels studies, and to understand that parametric estimation of movement rates may be confounded and may require prior or ancillary information.

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A Brief History of Integrated Stock Assessment Models with Tagging-informed Movement and Application of a Spatially Explicit Assessment to Yellowtail Flounder

Daniel Goethel, Steve Cadrin and Jon Loehrke

Although it has been known since the early 1900s that movement in marine populations plays a key role in determining population structure and size, it has only been addressed within stock assessments in the last few decades. Most stock assessments treat all fish within a given geographic zone as a closed population resulting in the key assumption of all single stock models that the population in the region is an isolated unit and no movement into or out of the area occurs. Beverton and Holt (1957) were the first to address the issue of movement and the effect it had on the distribution and availability of fish through the development of the box-transfer movement model. Their model evaluated the change in abundance between stocks of fish due to movement between connected geographic zones. Even though including movement in stock assessment was shown to be relatively straightforward, the ability to accurately estimate movement rates was the main hindrance to applying such models. Hence, most modeling focus was put on the development of tagging models to estimate movement rates.

It was not until computing power increased substantially that tagging began to be incorporated into assessment models so that tagged and untagged populations could be modeled simultaneously. Such integrated models allowed movement between multiple geographic zones and stocks of fish and included a tagging component of the objective function by comparing observed and predicted tag recaptures. Modeling tagged and untagged populations simultaneously with process equations that share estimated parameters avoids many of the technical problems associated with using tagging model outputs as stock assessment inputs. The main problems that are averted include: inconsistencies between model assumptions, loss of information, difficulties in determining error structure and including uncertainty, and reduced diagnostic ability (Maunder 2001). Furthermore, integrated models explicitly account for fishery exploitation patterns in the analysis of tag recaptures, which are often challenges for tag-recovery models. In recent years, a number of flexible integrated models have been developed that accommodate a range of different biological and movement scenarios. Examples of these models include: VPA 2-Box, Integrated Tagging Catch-Age Analysis (ITCAAN), Multifan-CL, Multi-Stock Age-Structured Tag-Integrated Assessment Model (MAST), and Stock Synthesis 3 (SS3).

Although the original box-transfer model was developed for demersal species that demonstrated relatively low and apparently random movement rates, most integrated models are applied and developed for pelagic species, such as large tunas, with relatively high movement rates. The affect of movement for species such as small flatfish that are thought to be relatively sedentary is often overlooked, when

movement rates are usually large enough to detrimentally impact single stock assessment models. For this reason a forward projecting, multi-stock statistical catch-at-age model that analyzes a variety of data sources, including tagging data to inform movement estimates between stocks was developed for yellowtail flounder off the northeastern United States. The impetus for this work was a recent tagging study which demonstrated that mixing rates between stocks was large enough to violate closed population assumptions of current assessments and could possibly explain the large retrospective patterns seen in these models. The spatially explicit assessment simultaneously models the three distinct stocks (each with its own catch at age, surveys, and vital rate data) with movement between them and incorporates four years of mark-recapture information. Initial results demonstrate the importance of a robust experimental design for tagging studies, accurate stock boundary delineation and a representative time series of tag releases and returns that correspond with the other data sources. In addition, the ability to accurately measure tag reporting rate and to determine whether it is time- or area-dependent is highlighted, because inaccurate assumptions about reporting rate can cause bias in other parameter estimates and otherwise hinder model performance.

Recommendations were provided for consideration in the development of a tagging study of walleye pollock in the Bering Sea, particularly for the goal of estimating movement rates within an integrated model framework. A primary decision is to determine how the population should be modeled with respect to the parameterization of movement. One of the main issues is whether the data available is on a fine enough spatial scale to use an advection-diffusion-reaction (ADR) framework or if a coarser box-transfer model is more appropriate. In addition, the optimal number of 'boxes' and time step needs to be considered in regards to what types of population information the assessment should provide for management of the species (e.g. are the two large zones and bi-annual movement modeled by Miller et al. 2008 optimal?). The experimental design of the tagging study should be carefully developed with thought given to the best configuration to help inform movement rate estimates within the chosen integrated model. Consideration needs to be given to how tag releases should be apportioned by area. If tags are released according to biomass by area, then determination of the minimum number of tag releases that is needed in the area with the lowest abundance should be made. This ensures that the necessary amount of tag recaptures is accomplished, thereby giving a truly representative sample of how fish are moving between zones. Finally, it is important to attempt to accurately estimate reporting rate of tags. Due to consolidation and the general characteristics of the Pollock fishery, reporting rate might be relatively high and easily calculated, especially if coded wire or PIT tags are used.

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Spatial Analysis of Tuna in the Pacific Ocean

Mark N. Maunder, Alex Aires-da-Silva, Simon D. Hoyle, Kevin Piner and Jesus Jurado-Molina

Tunas have a diverse range of spatial structures and movement patterns. Tuna are considered highly migratory species, but tagging data indicates that only a few tuna species make regular long distance migrations. Skipjack, yellowfin, and bigeye appear to have limited diffusive movement while bluefin and albacore have ontogenic and/or spawning migrations. Initial analyses indicate that restricted movement creates spatial structure in the population dynamics of some species leading to the possibility of local depletion patterns. To further complicate the analysis of tuna data, tuna fisheries also show spatial structure. The area fished increased over time as the longline and purse seine fisheries expanded during the 1950s and 1960s. Therefore, spatial analysis of tuna data is an important component of assessing tuna stocks and designing appropriate management actions.

Stock assessments of tunas in the Pacific Ocean are carried out by three main organizations: the Inter-American Tropical Tuna Commission, the Secretariat of the Pacific Community, and the International Scientific Committee for Tuna and Tuna-Like Species. Spatial structure in stock assessments has been addressed using two main approaches. The first approach is to treat catch from each area as a separate fishery so that the selectivity curves can represent the differences in age of fish in each area. This approach has generally been used for tunas in the Eastern Pacific Ocean (EPO) and north Pacific for which there is little tagging data. The second approach is to explicitly model sub-populations, and estimate movement rates among them. Tagging data are integrated into the analysis to provide information on the movement rates. Other methods to address the spatial structure have also been investigated. For example, the EPO bigeye tuna stock has been divided into four independent populations and each area assessed separately. This analysis showed that local depletion may be occurring in this stock.

Many issues must be considered when determining how to model spatial structure in stock assessments. In general, two rules of thumb are used to determine if spatial structure is treated as different selectivities or different sub-populations: 1) If the size distributions differ among areas, treat the areas as different fisheries; and 2) If indices of abundance differ among areas, treat the areas as sub-populations. However, many other factors should be taken into consideration when determining the spatial structure of the assessment model. These include keeping things simple, biogeography, having enough data for each area to reliably index abundance and size, matching areas with the statistical areas used to collect data or to implement management, specific spatial management issues (i.e. closed areas), consistency between assessments of multiple species, and home ranges of species. The spatial areas may differ in size and more numerous and smaller areas may be required where fish and effort are concentrated.

Spatial structure has been an important component of research on Pacific Ocean tunas.

- Regression trees have been applied to length frequency data to determine the spatial structure. The regression tree analysis has been developed to accommodate the possibility of skewed or multimodal length frequency distributions.
- Generalized linear models have been designed to allow catchability to be shared among areas. Essentially, the latitude and longitude interaction is included in the GLM and the estimated effects are summed up within each area to determine the relative abundance among areas.
- Comparisons of a pacific wide bigeye tuna assessment with the EPO assessment showed that the assumed/estimated growth parameters differed among the assessments and this was the main cause of differences in the results.
- A meta-population model was developed for yellowfin tuna to account for the expansion of fisheries in the Pacific Ocean. Each 5x5° square was treated as a separate population and

parameters of the population model were treated as random effects to share information among areas.

- Advection diffusion models have been created to analyze tagging data and estimate movement rates.
- SEAPODYM models the fine spatial structure of tunas from larvae to spawning. It integrates the bio-physical-geochemical environment with individual behavior in a multi-species context to model the spatial structure. SEAPODYM is fitted to fishery and tagging data to estimate model parameters.

MAST, a Multi-Stock Integrated Age-Structured Assessment Model of Atlantic Bluefin Tuna

Nathan Taylor and Murdoch McAllister

We present a spatial, **Multistock Age Structured Tag-integrated** stock assessment model (MAST) of Atlantic bluefin tuna. MAST models two populations (Eastern and Western) of Atlantic bluefin tuna simultaneously in 5 areas, with quarterly time steps. The model estimates F_{msy} and MSY as leading parameters. Each stock has specific growth, maturity and natural mortality parameters. The Western stock is assumed to spawn only in the Gulf of Mexico (GOM, ICCAT area 1) and the Eastern stock in the Mediterranean (MED, ICCAT area 6). Currently, the rest of the Atlantic is divided into three areas. In the model the range of possible movements can be constrained. In this case, fish are not permitted to move to the other stock's spawning areas but are otherwise allowed to move between any of the other areas according to estimated movement transition matrices. In non-spawning periods, each model age-group has square movement transition matrices with row indices corresponding to the 'from area' and column indices the 'to area'. During spawning periods we assume that movement transition from all areas to the spawning area of a given stock are given by that stock's maturity-at-age ogive. Non-spawning fish during that period move according to movement transition probabilities estimated for non-spawning fish but are not permitted in spawning areas during this period. We divided each electronic and conventional tag mark-recapture dataset into three groups according to whether or not the marked animal's stock of origin could be designated as Western (1), Eastern (2) or unknown (0). All mark recapture cohorts require an age, or age group designation. Conventional mark-recapture data were modeled using negative binomial likelihoods whereas electronic mark-recapture data were fit to discreet state-space likelihoods. When making a stock designation was not possible, the situation was more complicated since observations may be of either a Western or Eastern origin fish. In those cases, twice the number of state combinations is possible. Here the tag might remain on a live Western or Eastern stock fish in areas 1-4, or be returned from a Western or Eastern fish caught by fishing gear in areas 1-4, or be shed, or leave the tagged fish due to death from other causes (e.g., natural mortality). In this case, the initial probability of the state given the observation at the first time step is given by proportion of fish vulnerable to the gear and area it was initially marked in. Currently we make designation of length at marking into ages outside the model. In addition, the model is fit to as many as 29 CPUE indices.

The model shows historical patterns of exploitation similar to existing single stock VPA models but differs dramatically in terms of policy predictions and data requirements. In the mixed stock case, policy performance in any given stock is linked to policies in effect in the other stock. We illustrate this case using MAST showing that Western stock recovery depends on quotas effectively imposed in the East. The model shows that if eastern overfishing continues, catch restrictions in the West are necessary to insure the Western stock does not decline at any given quota. While existing electronic tagging data suggest that a spatially explicit mixed stock model is needed, additional data are needed to support its

implementation. In particular, stock identification of marked fish is needed and CPUE's currently used in model fitting need finer spatial and temporal resolution.

A Finite-State Continuous-Time Approach to Tagging and Population Dynamics

Timothy J. Miller

Spatially-structured population dynamics models are important tools for assessing harvested fish species that move between stock regions. Many models have been developed to estimate mortality rates and movement rates between regions from tagging experiments. The stochastic process underlying these tag models is also a natural framework for untagged animals that are captured in either commercial fisheries or independent surveys where the cohort identity and region of capture is known. I present probability models that derive from treating the regional location and fate of individuals as a stochastic finite-state continuous-time process. The probability models use both recoveries from tagging experiments and raw age measurements from surveys and landings to estimate (1) numbers of individuals recruiting by cohort and stock area, (2) instantaneous migration, fishing and natural mortality rates and (3) nuisance parameters induced by tagging such as reporting rates, shedding rates and adjustments for non-mixing. Analyses of Atlantic cod tagging data and yellowtail flounder tagging and age data illustrate the potential utility of the approach to making inferences about mixing stocks.

Exploring the Effects of Migration, Fishing and Spatial Structure on the Distribution and Dynamics of Pacific Halibut

Juan Valero, Steven Hare and Ray Webster

Stock assessments for Pacific halibut have evolved in terms of methods, models and spatial structure thru time. While coastwide, closed-area and migratory age-structured models coexisted during the 1980s, closed-area assessments were used during the 1990s and until 2006 under the assumption that adult halibut movement between areas was negligible. Analysis of results of a large scale passive integrated tagging (PIT) program provided evidence of continuing halibut migration beyond the age of recruitment to the fishery, challenging the applicability of closed-area stock assessments. A coast-wide assessment currently in use has resulted in an estimated coast-wide harvest rate near the target. However, area-specific harvest rates are estimated to have been more than twice the target in eastern areas and less than the target in western areas.

In order to illustrate the effects of migration and fishing on the distribution and population structure of Pacific Halibut we developed a simulation model with a user-friendly graphical user interface (GUI). The GUI allows the user to specify different migration patterns, area specific fishing levels, recruitment distributions, run scenarios and visualize results of the simulations. The underlying model of the GUI is an age and size structured migratory model. Scenarios using migratory and fishing patterns close to those observed for Pacific halibut suggest that the current spatial distribution of halibut differs from that expected under no fishing conditions or under a spatially uniform harvest rate, with higher levels of depletion in eastern areas relative to western areas. Preliminary results are consistent with recent and historical fishing patterns, recent coast-wide assessment estimates of realized harvest rates, and historical estimates of halibut distribution. Further work is needed to evaluate the effects of uncertainty levels and alternative spatial processes in both population and fishery dynamics on the performance of alternative assessment approaches and harvest strategies for Pacific halibut.

Spatial Model of Eastern Bering Sea Snow Crab

James Murphy

The snow crab (*Chionoecetes opilio*) population of the Eastern Bering Sea shelf has a well documented spatial structure. Younger crabs occur mainly in the more shallow northern and eastern portions of the shelf and older crabs occur in the deeper southern and western areas as a result of ontogenetic movement. Growth rates appear to vary by latitude with size-at-maturity decreasing with increasing latitude, presumably due to colder water temperatures resulting in decreased growth increments. Additionally, the male-only snow crab fishery harvests are concentrated in the southwest portion of the shelf.

To estimate spatial abundances and exploitation rates, a six area statistical spatial population model is under development. This model will complement the current non-spatial stock assessment model for the EBS snow crab. Simple annual movement rules connect subpopulations in adjacent areas. Movement is parameterized based on fishery independent survey data and fishery harvest data. Preliminary results indicate that insufficient data exists to adequately parameterize a six area model and subsequent model versions will require smaller number of spatial strata for adequate parameter estimation.

An Alternative Sampling Approach for Spatial Fishery Survey Based on Stereology

Yuk W. Cheng

Stereology is a spatial version of sampling theory. It was initially developed in biology and materials science as a quick way of analyzing three-dimensional solid materials from information visible on a two-dimensional plane section through the material. Stereological methods are almost “assumption free”. This means we do not need know the spatial distribution of habitats within the target survey area. In addition, it may be not bias or change with time. Examples from Monte Carlo integration of a surface with points generated by random and systematic sampling are given. Extension to high dimensions, e.g., the spatial and diurnal scale in fisheries and salmon redd survey, are provided. Comparison of the assumptions and restrictions of fishery and stereological survey samplings are discussed. Edge effect and bias correction are illustrated with fishery examples, IPHC longline rockfish survey and groundfish bottom travel survey. With the combination of stereology and other existing survey methods, e.g., stratified sampling or adaptive sampling, it can provide extra unbiased spatial survey designs that can help fishery managers and scientists reduce transportation costs and staff time.

Many fishery surveys employ a spatial sampling survey design over time with different types of treatments. Normally scientists will need to understand the different types of possible habitats in order to define survey stratification. It is highly likely that the habitat mapping is not be reliable and/or changes with time. For example, it is not uncommon to find an untrawlable area within a trawlable zone in a groundfish bottom trawl survey. This causes significant difficulties in planning the survey and dealing with the bias in the estimation. Stereological (Underwood, 1970; Baddeley and Jensen, 2005) survey methods provide a solution to this problem and requires far fewer assumptions than the traditional survey.

There are pros and cons of using stereology in fisheries survey. On the positive side, we do not need to create strata boundaries from habitat data as done in the traditional fishery survey. This information may not be true or change with time. So, it is better to use nearly assumption free stereological survey concept. Further, there are several bias correction methods, e.g., border and dissector methods, in stereology that can help to improve the validity of fishery survey. Advances in stochastic geometry make several alternative systematic surveys possible. These ideas can be incorporated into other sampling concepts to expand the number of possible survey designs. They can also reduce transportation and staff costs.

The main obstacle from employing these ideas is the lack of fishery statisticians with a stereology background. We recommend fisheries industries, statistics and fish modeling departments work together to advance this research topic in the future.

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Spatial Aspects of Walleye Pollock Spawning in the Gulf of Alaska and Eastern Bering Sea

Kevin Bailey

Knowledge of where and when fish spawn is important to prevent overharvesting and extirpation of local spawning populations. The current state of genetic identification of population structure of walleye pollock indicates a consistent signal of genetic isolation-by-distance that is significant over broad geographic scales. This pattern is generally consistent with ‘stepping-stone’ gene flow along continental margins (O’Reilly et al. 2004). Finer-scale information on distinct spawning areas is found in egg and larval surveys. In the central Gulf of Alaska (GOA) local spawning populations have been identified from egg distributions in Shelikof Strait, the Shumagin Islands and Unimak Bight (Ciannelli et al. 2007), in addition to previously known spawning in Prince William Sound and Resurrection Bay (Bailey et al. 1999). Spawning also occurs in offshore locations that appear to vary from year to year. In the eastern Bering Sea distinct spawning aggregations are separated in both space and time (Bacheler et al., unpubl ms.). Offshore spawning in the Aleutian Basin occurs in late winter. There is also some spatially separated late winter spawning over the southeastern continental shelf. In spring, spawning occurs in the near coastal region of the Aleutian Islands, southeastern shelf, and near the Pribilof Islands.

Understanding connectivity among these local spawning populations can be improved by: 1) finer scale sampling of spawning aggregations for genetic analysis of population structure, using state of the art technology and larger sample sizes than have been employed in the past. 2) behavioral studies of the mechanisms of natal homing (social facilitation, local genetic adaptation, imprinting), and 3) migration research using tags that are applied *in situ* rather than bringing fish to the surface, emphasizing quality of data rather than quantity.

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Eastern Bering Sea Bottom Trawl Survey

Dave Somerton, Bob Lauth and Dan Nichol

The twenty-seventh annual bottom trawl survey of the eastern Bering Sea (EBS) continental shelf was conducted between 30 May and 28 July 2008 aboard the chartered fishing vessels *Arcturus* and *Aldebaran*. Standardized biological sampling of crab and groundfish resources was completed at 375 stations covering an area of 144,493 square nautical miles and bottom depths ranging from 20 to 200 m. Since 1982, 356 stations have been systematically sampled during the May-August time period using the same standardized set of survey trawl gear (Fig. 1). An additional 20 stations in the northwest were added to the standard area in 1987 to investigate the northern distribution and abundance of snow crab (*Chionoecetes opilio*) and commercial groundfish in response to the changing climate (Fig. 1). Samples were collected at each station by trawling an 83-112 Eastern otter trawl for a target fishing time of 30 minutes at a speed of 1.54 m/sec (3 knots).

Sea bottom temperatures ranged from -1.7° to 4.4°C (Fig. 2) with warmer bottom temperatures ($> 3.0^{\circ}\text{C}$) occurring along the inner shelf from the northern portion of Bristol Bay to Nunivak Island, and on the outer shelf south of latitude 58° N. A cold pool, usually defined as an area with temperatures $< 2^{\circ}\text{C}$, occupied most of the mid-shelf at depths between 50 and 100 m, and extended south to the Alaska Peninsula and into Bristol Bay. Average bottom (1.1°C) water temperatures were lower than in 2007 (Fig. 3), but well below the long-term means from 1982 to 2007 for the bottom (2.4°C).

Walleye pollock were sorted from trawl catches, weighed in aggregate, and counted. Trawl catches exceeding 1,150 kg (2,500 lb) were randomly subsampled, in which case weights and numbers of walleye pollock were expanded to the total catch. Length measurements for pollock were taken in every haul that pollock were present. Otolith sampling on the shelf was divided into low- and high-density strata based on historical density data and a depth contour of approximately 70 m. Length measurements were taken on 20,475 walleye pollock, and sagittal otoliths were taken from a total of 1,259 walleye pollock.

Trawl survey catch data were used to estimate 1) relative abundance; 2) population biomass; 3) population numbers, and 4) population abundance by size class. Walleye pollock were captured at 89% of the standard survey stations (Fig. 4). Catch rates were lower on the inner and middle shelf compared to the outer shelf. The highest densities were north of the Alaska Peninsula, around the Pribilof Islands, and along the northwest outer shelf west of St. Matthew Island. The total biomass and abundance of walleye pollock for the entire survey area was 3.03 million t and 3.97 billion fish with an average weight per walleye pollock of 0.76 kg and average length of 44.7 cm. The 2008 biomass estimate was lower than the 2007 estimate of 4.3 million t (Fig. 5). Besides general year-class variability, relatively lower estimates may in part be due to a shift of the population to the shelf edge or a change in the vertical distribution pattern of pollock caused by the colder than average water temperatures on the Bering Sea shelf. One-year-olds, represented by the modal length of 10-15 cm, had the highest relative abundance on the inner and middle shelf compared to the outer shelf, where larger pollock had higher relative abundance (Fig. 6). The mode for the population of 1-year-olds peaked at about 100 million in 2008, compared to over 400 million in 2007 (Fig. 7). Age-2 and age-3 pollock (length range of 15-35 cm) are generally underrepresented in survey trawl catches; however, modes for both year classes can be seen in the plot of population abundance at length (Fig. 6 and Fig. 7).

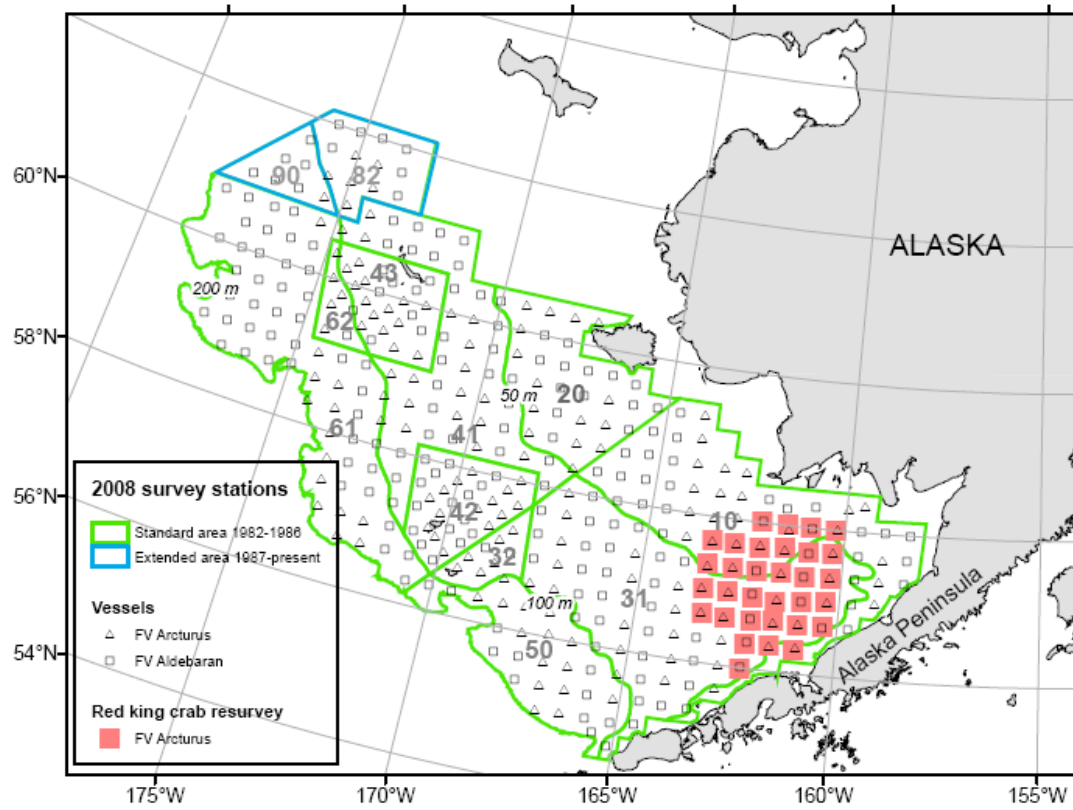


Figure 1. -- Sampled survey stations by vessel and the stratification scheme used for data analysis of the 2008 eastern Bering Sea bottom trawl survey.

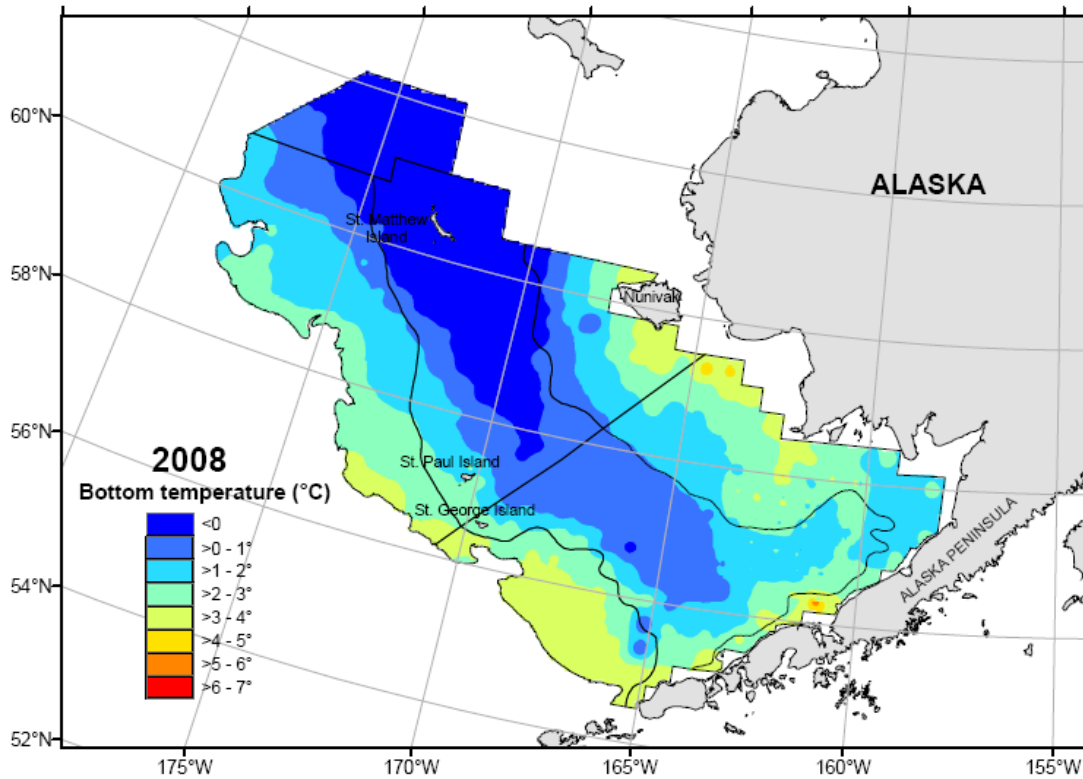


Figure 2. -- Distribution of bottom water temperatures ($^{\circ}\text{C}$) observed during the 2008 eastern Bering Sea bottom trawl survey.

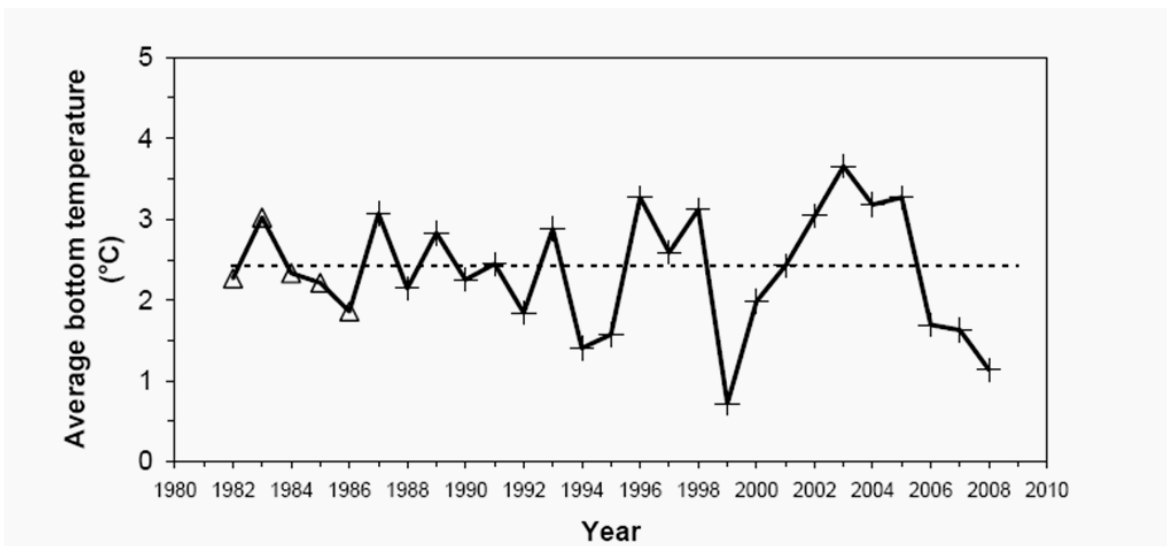


Figure 3. -- Mean bottom temperatures weighted by stratum (see Fig. 1). The 1982-1986 means (triangles) are based on the standard survey area whereas the other years represent the means from the expanded survey area. The dashed line represents the grand mean bottom temperature (1982-2008).

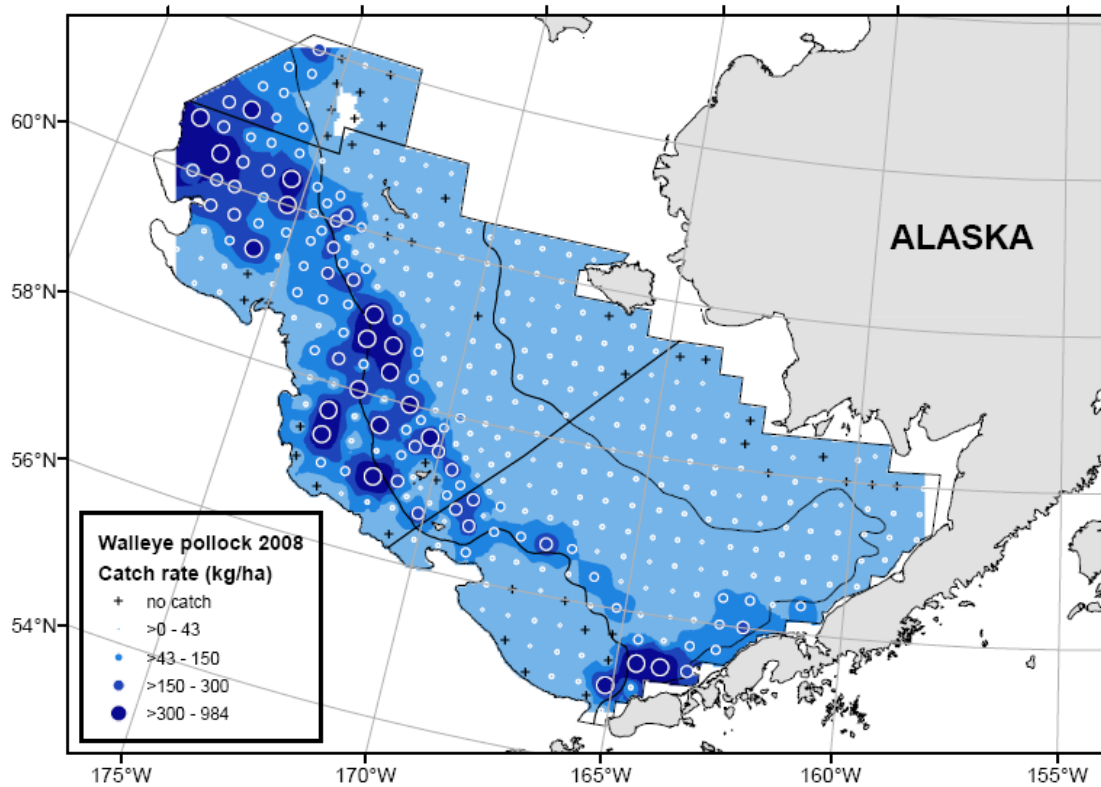


Figure 4. -- Distribution and relative abundance (kg/ha) of walleye pollock (*Theragra chalcogramma*) for the 2008 eastern Bering Sea bottom trawl survey.

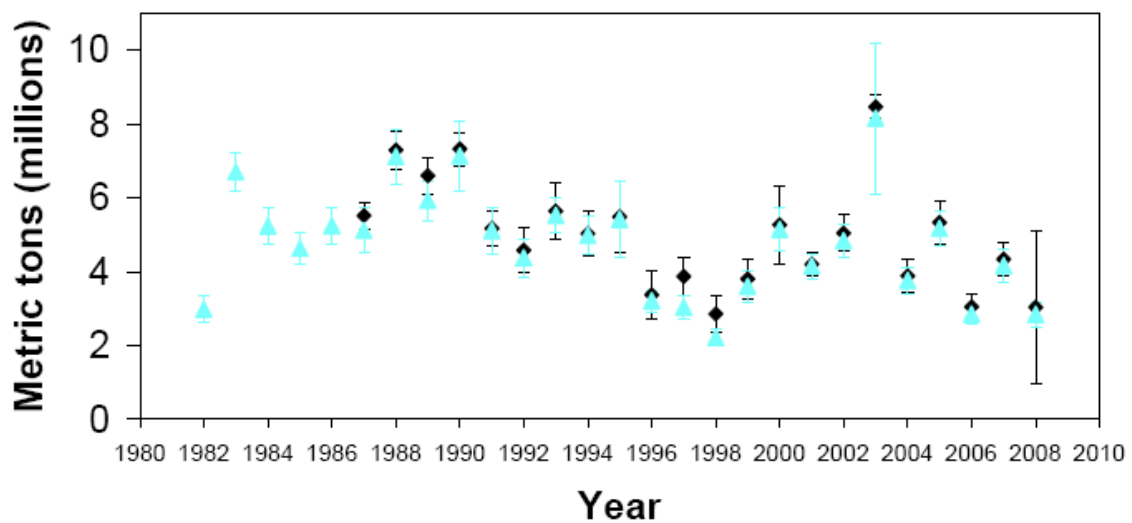


Figure 5.--Biomass of walleye pollock by year for the standard survey area (blue triangles;1982-2008) and the extended survey area (black diamonds;1987-2008).

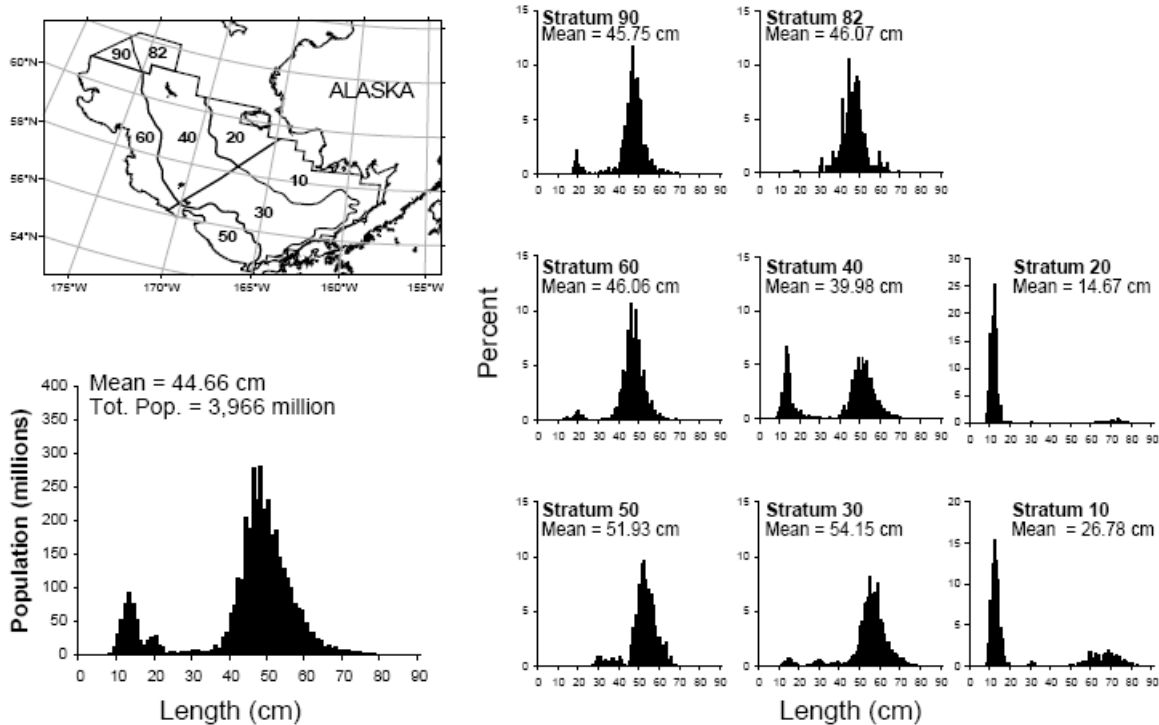


Figure 6. -- Estimated relative size distributions (sexes combined) of walleye pollock (*Theragra chalcogramma*) in terms of population numbers and percent by stratum for the 2008 eastern Bering Sea bottom trawl survey.

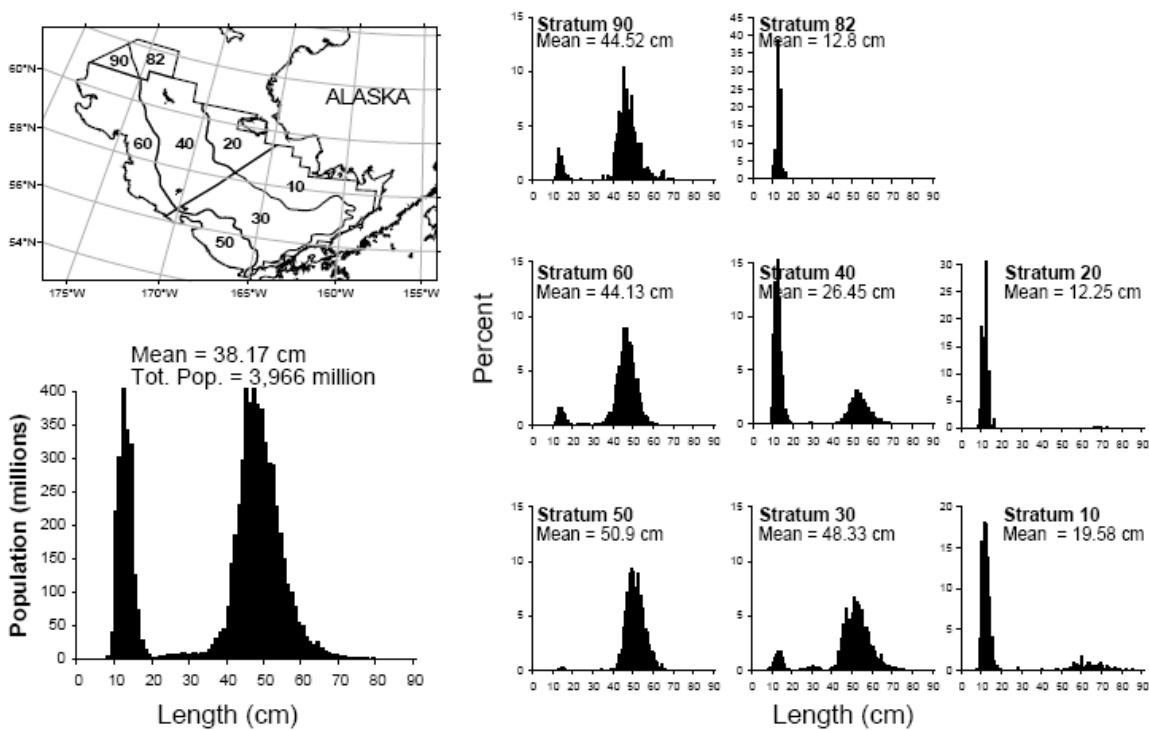


Figure 7. -- Estimated relative size distributions (sexes combined) of walleye pollock (*Theragra chalcogramma*) in terms of population numbers and percent by stratum for the 2007 eastern Bering Sea bottom trawl survey.

Overview of NOAA Acoustic-Trawl Surveys to Estimate Walleye Pollock Abundance in the Eastern Bering Sea

Christopher Wilson, Taina Honkalehto and Neal Williamson

Acoustic-trawl (hereafter acoustic) surveys to estimate the distribution and abundance of walleye pollock have been regularly conducted in the eastern Bering Sea (EBS) for several decades by Alaska Fisheries Science Center researchers with the acoustics program (Fig 1). The summer EBS acoustic survey has been conducted since 1979 on a triennial basis, and since 1994 on either a biennial or annual basis. It is conducted during June-July during daylight hours. Other survey-related research activities occur at night. A much smaller-scale survey to assess pre-spawning walleye pollock has been conducted annually in the vicinity of Bogoslof Island since 1988 and biennially since 2007. This survey occurs during the first two weeks in March and is conducted 24 hours per day. Both survey time series are largely based on data collected with the NOAA ship *Miller Freeman* and more recently with the new, noise-reduced vessel, *Oscar Dyson*.

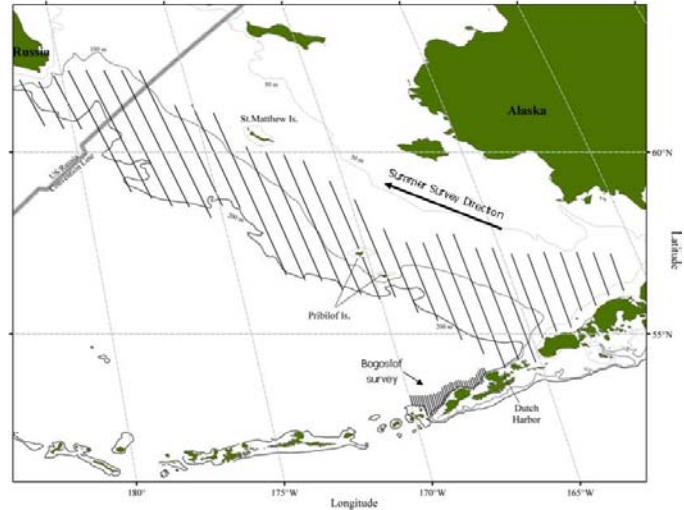


Figure 1. --Typical walleye pollock acoustic-trawl survey transect design for eastern Bering Sea summer survey over continental shelf (20 nmi transect spacing) and smaller-scale Bogoslof pre-spawning winter survey near Aleutian Islands (3 nmi spacing).

Methods are similar for both the summer and winter acoustic surveys. Currently, acoustic data are collected at five frequencies (18, 38, 70, 120, 200 kHz) using calibrated Simrad EK60 echosounders as the vessel travels along uniformly spaced transects (20 nmi EBS, 3 nmi Bogoslof) at ship speeds of around 11-12 knots. At the beginning of each survey, a randomized start location is chosen for the first transect within a pre-defined sample stratum and the following transects are then systematically offset from this new transect location. This approach generally provides the most precise unbiased estimate of abundance for spatially autocorrelated data. When substantial backscatter is detected along

transects, hauls are conducted using a large midwater or bottom trawl, or less frequently with other smaller nets, to confirm the species composition of the backscatter and to collect other biological information (e.g., individual fish lengths, weights, sex, gonad maturity, otoliths) needed to scale the acoustic data into estimates of fish number and biomass as a function of length and age. Walleye pollock estimates are based on data collected at 38 kHz.

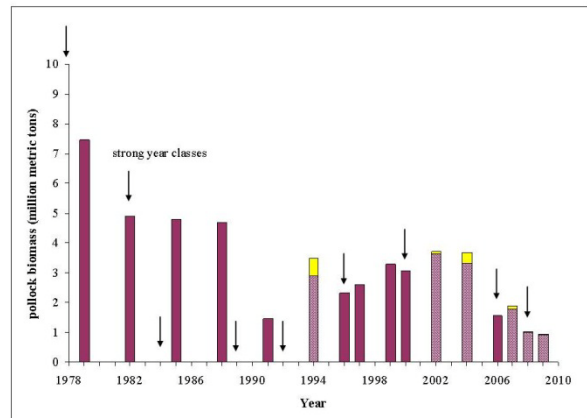


Figure 2.--Walleye pollock abundance estimates from eastern Bering Sea summer acoustic-trawl surveys. Arrows denote strong year classes and hatched bars represent years when estimates (yellow bar) exist for Russian zone.

Slight differences exist in the distributional patterns for the semi-demersal component of juvenile and adult pollock in the EBS even though the patterns broadly overlap. Thus, greater numbers of juvenile fish typically occur in the northwest region of the survey area, and juveniles are generally found shallower in the water column and farther above the sea floor than the adults.

Walleye pollock abundance estimates based on the summer acoustic survey data illustrate a declining trend over the last few decades to current levels of around a million metric tons (Fig 2). The proportion of the biomass in Russian waters was 15% in 1994 (first year permission granted to survey Russian zone) and values have declined to less than a few percent in recent years. Abundance of walleye pollock in the EBS relies on the occurrence of strong year classes, which generally occur at a 2-6 year frequency (Fig 2). Results from the Bogoslof survey of pre-spawning walleye pollock also document a decline in abundance from nearly 2.5 million tons in 1988 to about 0.5 million tons by 1999. Since 1999, Bogoslof area estimates have remained low and stable

around 0.2 – 0.3 million tons.

Warmer water temperatures may result in a generally northward expansion of walleye pollock towards shallower bottom depths. For example, the pollock distribution extended northward of the 100 m isobath in 1996, which was characterized as a warm year, whereas relatively few fish were found this far north in 2007, a relatively cold year (Fig 3). Research is currently underway to better characterize this association for the semi-demersal component of the stock as well as to determine how it may be influenced by other bio-physical factors.

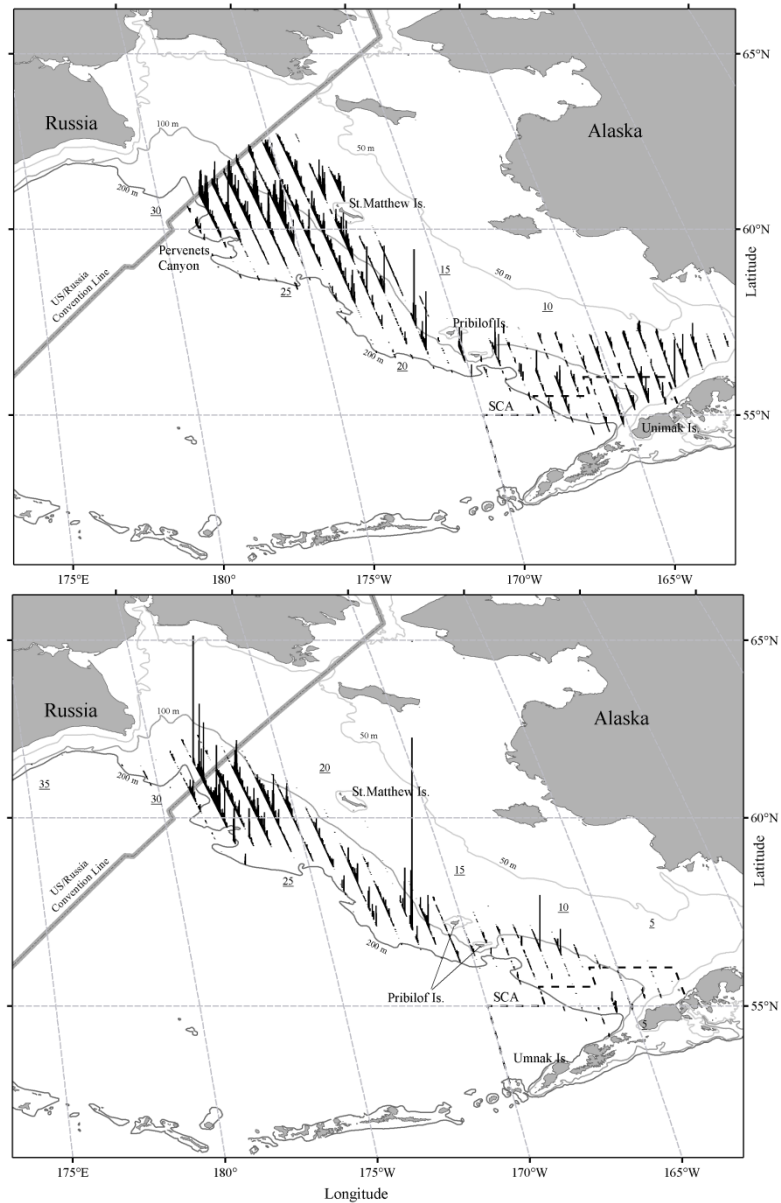


Figure 3. -- Summer acoustic-trawl survey backscatter estimates attributed to walleye pollock for a relatively warm year (upper panel, 1996) and cold year (lower panel, 2007).

Movement of pollock in the EBS Based on Observed Abundance Distributions Over Multiple Years

Stan Kotwicki, Taina Honkalehto (presenter) and Troy Buckley

Aspects of the feeding migration of walleye pollock (*Theragra chalcogramma*) in the eastern Bering Sea (EBS) were investigated by examining the relationship between temperatures and densities of fish encountered during acoustic and bottom trawl surveys conducted in spring and summer between 1982 and 2001. Bottom temperature was used as an indicator of spring and summer warming of the EBS. Clusters of survey stations were identified where the density of walleye pollock generally increased or decreased with increasing water temperature. Inferences about the direction and magnitude of the spring and summer feeding migration were made for five length categories of walleye pollock. Generally, feeding migrations appeared to be northward and shoreward, and the magnitude of this migration appeared to increase with walleye pollock size up to 50 cm. Pollock larger than 50 cm showed limited migratory behavior. Pollock may benefit from northward feeding migrations because of the changes in temperature, zooplankton production, and light conditions. Ongoing climate changes may affect pollock distribution and create new challenges for pollock management in the EBS.

Using Opportunistic Acoustic Data to Examine Distributional Dynamics of Walleye Pollock (*Theragra chalcogramma*)

Steven J. Barbeaux

From 2002 through 2009 acoustic density data were collected opportunistically from commercial fishing vessels participating in the eastern Bering Sea walleye pollock (*Theragra chalcogramma*) fishery through a project funded by the Pollock Conservation Cooperative Research Council (PCCRC). These data provide unique challenges including handling the immense number of data points (greater than 300,000 points per season), and lack of survey design resulting in an unbalanced data collection and a high degree of autocorrelation. The opportunistic acoustic data were joined with environmental and fisheries data by time and location into a relational geo-temporal database. We present inverse density biased sampling as an intelligent data reduction technique for subsampling the dataset and addressing unbalanced data collection, while retaining the spatial and temporal attributes of the pollock distribution within the data. As a case study we assess spatial and temporal structure of pollock and develop a general additive mixed model (GAMM) with an internal correlation structure and heterogeneous variance for the 2003 data set. The GAMM was used to inter-calibrate the data and to evaluate spatial and temporal distribution of pollock density among regions on the eastern Bering Sea shelf. A modified k-fold cross-validation technique is presented as a means to counter over-parametrization of smoothing splines where a GAMM was not initially optimized over the full range of data. This study introduces a new data source and presents analytic methods to quantify factors influencing fish distributions and dynamics at spatial and temporal scales that were not previously possible.

Russian/U.S. pollock fisheries and plans for spatial modeling

Keith Criddle

The absolute abundance and spatial distribution of Eastern Bering Sea (EBS) pollock have varied considerably over the past three decades, with warmer conditions being associated with a shift of the center of abundance to the north and west, where a portion of the stock is subject to harvest by vessels licensed to operate in the Russian Federation EEZ. While US EEZ pollock fisheries have operated under conservative harvest exploitation rates and tight enforcement of catch limits, Russian Federation EEZ pollock fisheries have been prosecuted at higher official exploitation rates and it is widely believed that actual harvests have exceeded official catch limits by 10-20%.

In this project, we will focus on the instability created by shifts in the geographic distribution of an exploited fish population and the consequent exposure of that population to potentially discordant management regimes. Management of transboundary fish stocks can be characterized as a two-party game. Solutions to two-party games depend on conjectures about the extent to which each party engages in strategic behavior. The current approach to management of the EBS pollock resource is quasi-competitive strategy under which the US and Russian Federation each ignore the other's harvest management strategy: we do our thing, the Russians do their thing, and we each pretend that we are harvesting stocks that do not migrate or diffuse across the Maritime Boundary line. Under a collusive management strategy, the US and Russian Federation would manage the stock to maximize the total net benefits of harvests without concern about the distribution of benefits between nations. While a collusive solution is unrealistic, it sets an upper-bound on the potential value that could be generated from joint management of a shared stock. Cournot-Nash equilibria, Stackleberg equilibria, and Stackleberg disequilibria represent alternative conjectures under which the US and Russian Federation recognize that their individual benefits are conditional on each other's choices. These conjectural variations represent recognition that there are externalities associated with harvest management strategies independently adopted by the US and the Russian Federation and that the optimal choice of a management strategy for the US EEZ pollock fishery will depend on the management strategy adopted by the Russian Federation, and vice versa.

We will use stochastic simulations to identify optimal cooperative and non-cooperative harvest management strategies from the perspective of US and Russian pollock fisheries under variations in: the abundance and distribution of EBS pollock; the relative value of pollock products, product recovery rates, and differences in the magnitude of harvesting and processing costs; the enforceability of catch limits at fishery and individual participant levels; the character of governance regimes; etc. The stochastic simulations will characterize a likelihood surface for each strategy across the range of combinations of exploitation rates, abundance, and distribution.

Predicting Recruitment for Flatfish in the EBS: Can we Improve on OSCURS?

Buck Stockhausen

Over the past decade, a relatively simple model for ocean surface currents based on long-term mean geostrophic currents and daily surface pressure fields (OSCURS, the Ocean Surface Current Simulator) has been used to make qualitative predictions of annual recruitment (age-0 fish) strength for several winter-spawning flatfish species in the Eastern Bering Sea. The model is used each year to track a single simulated surface drifter that is released from the same location each year on April 1 and followed for 90 days. Based on the ending location of the simulated drifter, recruitment of age-0 fish to several winter-spawning flatfish populations for that year is qualitatively categorized according to three levels: potentially good, mediocre-at-best, or poor. In an effort to develop a more quantitative prediction of

recruitment, as well as to improve upon the OSCURS model by incorporating more oceanographic and biological realism, we have developed DisMELS, the Dispersal Model for Early Life Stages. DisMELS couples a state-of-the-art 3-dimensional oceanographic model (ROMS) with individual-based models for adult spawning and survival, growth, and behavioral characteristics of early life stages (e.g., eggs, larvae, and settlement-stage juveniles). Preliminary results using DisMELS illustrate the maxim that bigger is not always better.

Arrowtooth Flounder in the Eastern Bering Sea

Stephani G. Zador and Kerim Y. Aydim

Multiple lines of evidence suggest that changes in the marine climate in the Bering Sea are leading to numerical and distributional shifts in fish populations. Arrowtooth flounder (*Atheresthes stomias*) have quadrupled since the early 1980s in the eastern Bering Sea, in contrast to other important groundfish species. Recently, recommended catches for Bering Sea walleye pollock (*Theragra chalcogramma*) have been reduced, in part due to concerns about the growing threat of arrowtooth flounder predation of juvenile pollock as has been witnessed in the Gulf of Alaska. Thus, the overarching goal of our study was to improve our understanding of the impact of arrowtooth flounder to commercial fisheries in the changing climate of the Bering Sea, with a specific focus on potential distributional shifts in overlap between the two species. In addition, we investigated (1) whether pollock cohorts, especially strong year classes, can be tracked in arrowtooth flounder diets across space and time; and (2) how the functional response between arrowtooth flounder as predators and pollock as prey change over space and time and with environmental/climate influences. Accordingly, for this presentation we reviewed arrowtooth flounder abundance trends, their spatial overlap with pollock, and functional responses of arrowtooth flounder to pollock.

We identified physical and biological habitat characteristics that are correlated with arrowtooth flounder biomass trends sampled at individual bottom trawl survey stations from 1983 to 2007. We found that small-scale regions within the eastern Bering Sea shelf have contributed unequally to the overall rapid increase in abundance of arrowtooth flounder. Hierarchical k-medoids clustering of arrowtooth catch-per-unit-effort revealed four distinct spatial groups showing stable, increasing, and variable trends. Catch rates in high-density areas near the shelf break have remained stable since the early 1990s while catch rates have increased to the northwest and east since the early 2000s. Annual changes in range expansion and contraction are negatively correlated with the extent of the cold water pool on the Bering Sea shelf. Both increasing temperature and depth explained higher proportions of trawls containing arrowtooth in all but one cluster and higher catch rates of arrowtooth flounder when present. Age-1 and -2 pollock comprised the majority of arrowtooth flounder diets in all areas.

The number and percent of survey trawls that contained both 40+ cm arrowtooth and age-1 and -2 pollock has generally increased over time. Some of these patterns could be explained by the increase over time and annual fluctuations in the number of survey trawls containing 40+ cm arrowtooth. Notably, after 1996, there were fewer empty 40+ cm arrowtooth stomachs sampled in the north outer domain compared to the south outer domain. The probability of a 40+ cm arrowtooth stomach being empty was significantly influenced by local bottom temperature, latitude, longitude and catch rates of age 1-2 pollock. Separate univariate GAMs confirmed the relationship between the probability of a 20+ cm arrowtooth stomach being empty in relation to local catch rates of age-1 and -2, age-1 only, or age-2 only pollock, following the expectation of a Type II or III functional response. The higher rates of non-empty stomachs in the northwest region indicate that predatory impacts on pollock may be higher there.

Most arrowtooth stomachs with >1 pollock contain similar-sized pollock, indicating that arrowtooth may be sampling from the single-aged pollock schools. Over two-thirds (69-100%) of arrowtooth stomachs

with multiple pollock contained pollock of the same age class. Only 2 stomachs contained pollock that were >1 age-class apart (e.g., an age-0 and an age-3+). The ratio of the length of pollock found in arrowtooth stomachs in relation to arrowtooth length significantly increased with predator size, indicating that overall, larger arrowtooth eat increasingly larger prey. However, the masses of points with declining trends contained within the overall increasing trend suggest that a range of arrowtooth were preying on the same-sized pollock. Some years show this declining pattern more than others, which we propose may be evidence of strong pollock year classes appearing in arrowtooth diets. We also found that the mean length of pollock prey to arrowtooth predator varied among years. The increasing mean from 2000-2003 and 2006-2007 suggests that arrowtooth are following year classes of pollock (assuming mean predator length remained constant over the same sampling period). In arrowtooth stomachs containing pollock, we found that the presence of age-1 pollock in 20+ cm arrowtooth stomachs increased in relation to catch rates of age-1 pollock using GAMs with trawl station treated as a random effect. These relationships most closely resembled Type II functional responses. We also found the presence of age-2 pollock in 20+ cm arrowtooth stomachs increased similarly in relation to catch rates of age-2 pollock.

Further analysis is planned to confirm whether strong pollock year classes can be tracked in arrowtooth flounder diets as indicated by the work presented. In addition, we plan refinements of the analysis of functional response to include spatial and temporal components. We believe that this analysis will provide information about the potential for arrowtooth flounder to further increase their distribution and abundance in the Bering Sea and help to predict future responses to climate and fisheries management actions.

The Eastern Bering Sea Pollock Stock Assessment and Fishery Patterns

James N. Ianelli

The data and current methods used for the Eastern Bering Sea (EBS) pollock include survey and fishery data on fine-scale spatial and temporal resolutions. Fishery patterns are monitored extensively and play a key role in compiling area, season, and sex-stratified data. For example, contrasting survey estimates of pollock densities with fishery locations shows apparent movement of fish towards the north onto the shelf (in 2008). Recently, salmon bycatch has played a large role in limiting where pollock fishing is allowed. Environmental conditions coupled with relative large quotas for pollock resulted in an unusually large bycatch of Chinook salmon by the pollock fishery (~121,000 Chinook). The implementation of hotspot closure areas reduced the total, but incentive programs (at the individual vessel level) were lacking. Consequently, the Council and NMFS developed new regulations that will further limit bycatch and provide appropriate incentives. The development of these proposed rule depended extensively on the spatial and temporal aspects of the fishery data that were available.

Even though data are available on fine temporal and spatial scales, the assessment model uses spatially and seasonally aggregated data. The biennial echo-integration trawl (EIT) survey provides insight on the younger, mid-water component of the pollock population whereas the annual bottom trawl survey (BTS) provides information on pollock generally older than age 4. The fishery generally catches pollock from age 3-15 but ideal sizes generally occur from age 4-8. The model accounts for spatial and temporal differences as components of “process errors” (e.g., by adding variability in selectivities over time). Results from this integrated model indicate a decline due to relatively poor recruitment during 2001-2005 based on the available data. This has resulted in relatively rapid declines in allowable catch levels.

Similar to the Gulf of Alaska pollock (Dorn, this volume), management measures on spatial patterns have mainly been designed to promote population rebuilding of Steller sea lions. These measures are intended to reduce the interaction of fisheries on prey availability to Steller sea lions during winter time in the region identified as critical habitat. Spatial allocation occurs to some degree due to the regulation that

limits the winter-season fishery to only 40% of the annual TAC (since winter ice conditions limit fishing in the northwest part of the U.S. EEZ of the Bering Sea). Further spatial management measures in the EBS are limited due to the variability in region-specific abundances by season. The consequence of further spatial TAC allocations indicate that the potential for mis-specifying apportionments—i.e., allocating a disproportionate amount of TAC to an area and season—likely outweigh the potential benefits of reducing the incidence of localized depletion.

Estimation of Age-Specific Migration in an Age-Structured Model

Sara E. Miller, Terrance J. Quinn II and James N. Ianelli

The standard Eastern Bering Sea (EBS) walleye pollock (*Theragra chalcogramma*) age-structured stock assessment model accounts for spatial structure externally (in compiling the data). To better understand its dynamics on finer spatial and temporal scales, an age-specific movement (ASM) model was developed. The ASM model stratifies the assessment data into two regions (northwest [NW] and southeast [SE] EBS), includes movement, and allows population parameters to be region-specific. The ASM model was used to evaluate hypotheses on age specific movement between the NW and SE and covered years 1977 to 2005 and ages-3 to 10+. Estimates of biomass and population parameters from the ASM model were similar to those of the standard stock assessment model. The ASM model fitted the yearly observed catch numbers and yield, and catch-age composition data well, but some population parameters were highly uncertain or highly correlated. More in-depth information on finer spatial and temporal scales is needed from spatially explicit studies of EBS walleye pollock. Having additional information from a mark-recapture study would help to stabilize the ASM model and allow some assumptions to be relaxed.

Improvement of a Spatial Age-Structured Model with Mark-Recapture Data: Walleye Pollock in The Eastern Bering Sea

Peter-John F. Hulson, Sara E. Miller, James E. Ianelli, and Terrance J. Quinn II

The Eastern Bering Sea (EBS) walleye pollock (*Theragra chalcogramma*) stock is evaluated with a standard age-structured stock assessment model (Ianelli et al. 2004) that does not take into account spatial considerations. Currently there is no movement information from a large-scale EBS walleye pollock mark-recapture study, but feasibility studies have shown the potential for sufficient sample size and survival rates of a tagging study (NRC 1996, Miller 2007, Winter et al. 2007). To better understand the walleye pollock population dynamics on finer spatial and temporal scales, an age-specific movement (ASM) model has been developed (Miller et al. 2008). In the current study, we test the ASM model's robustness and the desirability of estimating movement of a fish stock with Monte Carlo simulation, using population dynamics based on the EBS stock of walleye pollock. The ASM model is further tested by incorporating tagging data with differing protocol in the release of tags in surveys, culminating in an integrated tagging and catch-at-age analysis model (ITCAAN). The fundamental goals of this study are to determine: (1) the effectiveness of incorporating tagging data into an ASM model, (2) the most effective method to release tags into a spatially disaggregated population, and (3) the magnitude of bias in population parameter estimates if tagging data is not utilized.

In this study, simulation analysis was performed to evaluate the consequences of modeling spatially disaggregated data with and without tagging information. The simulations were performed by generating random variability in the expected values and fitting the generated data with either the ASM or ITCAAN model structures. The expected values came from parameters estimated by the ASM model that were fit to the observed EBS spatially disaggregated datasets (e.g. Miller et al. 2008). Results from the simulation analyses were compared with bias ratios for the movement parameters and biomass estimates. Three

alternative operating model configurations were developed to test against different estimation models scenarios. The operating model configurations included one model in which no tagging data were available (ASM), and two others with tags distributed evenly over space and the other with tags distributed proportional to biomass (ITCAAN). The effectiveness of movement estimation with tagging data was further evaluated by considering three levels in the proportion of catch delivered to shoreside processors that was examined for the presence of tags (25%, 50%, and 100%). Finally, we examined the accuracy of movement estimation with respect to the variability in the datasets modeled for EBS walleye pollock. In our simulation the three variance cases are determined by; (1) reducing the variance in the datasets by a factor of 4, (2) holding variability to be the same as in the ASM model, or (3) increasing the variance in the datasets by a factor of 4.

Results of the simulation analysis indicate a decrease in variability of estimates in the ITCAAN compared to the ASM model structure. This result was replicated across the variability scenarios, showing that including tagging data into a stock assessment model could decrease the variance in resulting parameter estimates and management quantities regardless of the error in the data sources. We also show that bias is not affected by reducing the proportion of catch examined for tags. Further, parameter confounding and correlation was reduced when tagging data was included, and there was less confounding when tags were distributed proportionally to abundance, rather than evenly distributed across the regions.

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Spatial Structure and Movement in Stock Synthesis

Richard Methot and Ian Taylor

Stock Synthesis (SS) is an integrated analysis model designed for the assessment of harvested fish stocks. It has been used in the assessment of dozens of stocks around the globe ranging in life history from sardines to rockfish to tuna. SS's flexibility to adapt to such diverse assessment situations is derived from its separation of the population dynamics module from the module that derives expected values for a large number of types of data. It is coded in ADMB to achieve fast execution and robust variance estimation. SS links the forecasting of management quantities (e.g., MSY and future target catch levels) with the parameters estimated within the model to propagate the model variance onto these management

quantities. SS allows for creation of multiple areas, movement of fish between areas, and tag-recapture data to help estimate movement rates.

A case study was presented where the spatial options in Stock Synthesis were used to model an ontogenetic shift toward deeper water across three depth-specific areas. Bootstrap data were generated within Stock Synthesis, matching a sablefish-like life history. Population parameters were estimated from each set of simulated data under different estimation scenarios, including a three-area model with movement and simplified single-area models which used selectivity as a proxy for age-specific availability at different depths. Single-area models with selectivity as a function of either length or age alone performed poorly. A single-area model which included selectivity as a function of both length and age captured the dynamics of the ontogenetic shift reasonably well on average, but the variability across simulations was higher than for the three-area estimation model that matched the structure of the data. This demonstration, plus some actual SS applications to spatially explicit assessments, indicate that SS has the features necessary to model the seasonal and spatial patterns in Bering Sea pollock and its fishery.

Gulf of Alaska Walleye Pollock: Spatial Structure and Management Approaches

Martin Dorn

The fishery for walleye pollock in the Gulf of Alaska developed in a complex and highly dynamic ecosystem of which pollock is an important component. This evolution also occurred in a social and economic setting characterized by strong participation by local fishing communities. Spatial management procedures have developed within this broader context to address specific management concerns. Pollock in the Gulf of Alaska are managed independently of pollock in the Bering Sea and Aleutian Islands. The separation of pollock in Alaskan waters into eastern Bering Sea and Gulf of Alaska stocks is supported by analysis of larval drift patterns from spawning locations (Bailey et al. 1997), genetic studies of allozyme frequencies (Grant and Utter 1980), mtDNA variability (Mulligan et al. 1992), and microsatellite allele variability (Bailey et al. 1997).

The results of studies of stock structure within the Gulf of Alaska are equivocal. There is evidence from allozyme frequency and mtDNA that spawning populations in the northern part of the Gulf of Alaska (Prince William Sound and Middleton Island) may be genetically distinct from the Shelikof Strait spawning population (Olsen et al. 2002). However significant variation in allozyme frequency was found between Prince William Sound samples in 1997 and 1998, indicating a lack of stability in genetic structure in this area. Olsen et al. (2002) suggest that interannual genetic variation may be due to variable reproductive success, adult philopatry, source-sink population structure, or utilization of the same spawning areas by genetically distinct stocks with different spawn timing.

Within the Gulf of Alaska, several important spawning areas have been identified and surveyed using acoustic methods repeatedly prior to peak spawning in late winter. The most important of these is the spawning aggregation in Shelikof Strait, but other areas include Sanak Trough, Morzhovoi Bay, the Shumagin Islands, along the shelf break near Chirikof Island, Marmot Bay, Middleton Island and Prince William Sound (Fig. 1). In aggregate, these other spawning areas are roughly comparable to the Shelikof Strait spawning aggregation in magnitude. The stability of these subsidiary spawning locations, and their importance in the overall population dynamics

of GOA pollock are not clear. Peak spawning at the two major spawning areas in the Gulf of Alaska occurs at different times. In the Shumagin Island area, peak spawning apparently occurs between February 15- March 1, while in Shelikof Strait peak spawning occurs later, typically between March 15 and April 1. It is unclear whether this difference in timing is genetic, or a response to differing environmental conditions in the two areas.

For management purposes, pollock are separated into separate stocks at 140° W long., at the head of the Gulf of Alaska. Bottom trawl surveys indicate a substantial reduction in pollock abundance east of 140° W long. Stock structure in this area is poorly understood. Bailey et al. (1999) suggest that pollock metapopulation structure in southeast Alaska is characterized by numerous fiord populations. Pollock in this area is assessed using a North Pacific Fishery Management Council Tier 5 calculation (recent survey biomass multiplied by natural mortality). A management restriction on trawling in Southeast Alaska precludes the development of a pollock fishery in this area.

West of 140° W long., a much larger pollock stock inhabits the broad continental shelf from Prince William Sound to the Aleutian Islands. This stock is assessed annually using an age-structured statistical assessment model fit to fishery age composition data and acoustic and bottom trawl survey information. The Total Allowable Catch (TAC) for Gulf of Alaska pollock is apportioned seasonally and spatially to mitigate potential impacts on Steller sea lion, listed as endangered under the terms of the Endangered Species Act. Steller Sea Lion Protection Measures implemented in 2001 establish four seasons in the Central and Western Gulf of Alaska beginning January 20, March 10, August 25, and October 1, with 25% of the total TAC allocated to each season. Allocations to management areas 610, 620 and 630 are based on the seasonal biomass distribution as estimated by groundfish surveys. These management areas were established historically for reporting salmon catches, and thus are not necessarily well-suited to managing walleye pollock or other groundfish, but probably are adequate for managing major substock units.

For spatial allocation of TACs in the winter, a “composite” approach is used to estimate the percent of the total stock in each management area. The estimated biomass for different acoustic surveys (which cover different regions in some years) is divided by the total biomass of pollock estimated by the assessment model in that year. These values are then allocated to relevant management areas. The percent for each survey was then added together to form a composite biomass distribution (considered to cover the entire region), which was then rescaled so that it summed to 100%. Model estimates of biomass at spawning took into account the total mortality between the start of the year and spawning, and used mean weight at age from Shelikof Strait surveys.

For summer seasons, the NMFS bottom trawl is used since it typically extends from mid-May to mid-August. However, large shifts in pollock distribution by management areas occur from one survey to the next and management area-specific biomass estimates have high sampling errors. Consequently, Dorn et al. (1999) recommended apportioning pollock TAC based on the four most recent NMFS summer surveys.

The primary goal of the current spatial and seasonal management system is to disperse fishing activity to reduce the potential for local depletion of Steller sea lion prey. However, spatial

allocation serves other purposes not directly related to Steller sea lions. Spatial allocation would tend to give greater protection to pollock stock substructure that is not presently well understood. Furthermore, participants in pollock fishery in the Gulf of Alaska have strong historical association with local areas. For example, vessels in the area 610 pollock fishery are mostly based in Sand Point or King Cove, while vessels in area 620 and 630 fishery are mostly based in Kodiak. By distributing TAC according to stock biomass, the Council takes into account social objectives as required under National Standard 4 that allocation shall be fair and equitable to all fishermen, and under National Standard 8 that conservation and management measures shall provide for the sustained participation of fishing communities. Nevertheless, successfully managing 12 separate openings (three areas × four seasons) presents challenges to in-season fisheries managers. Although the Gulf of Alaska pollock fishery is one of the most tightly regulated U.S. fisheries, there remains concern whether adequate protection is being afforded to Steller sea lions. Since effort is not limited in the pollock fishery, many seasonal openings are of short duration (< 1 week), leading to intense pulses of fishing, rather than a steady seasonal pattern considered to have the least impact on Steller sea lions.

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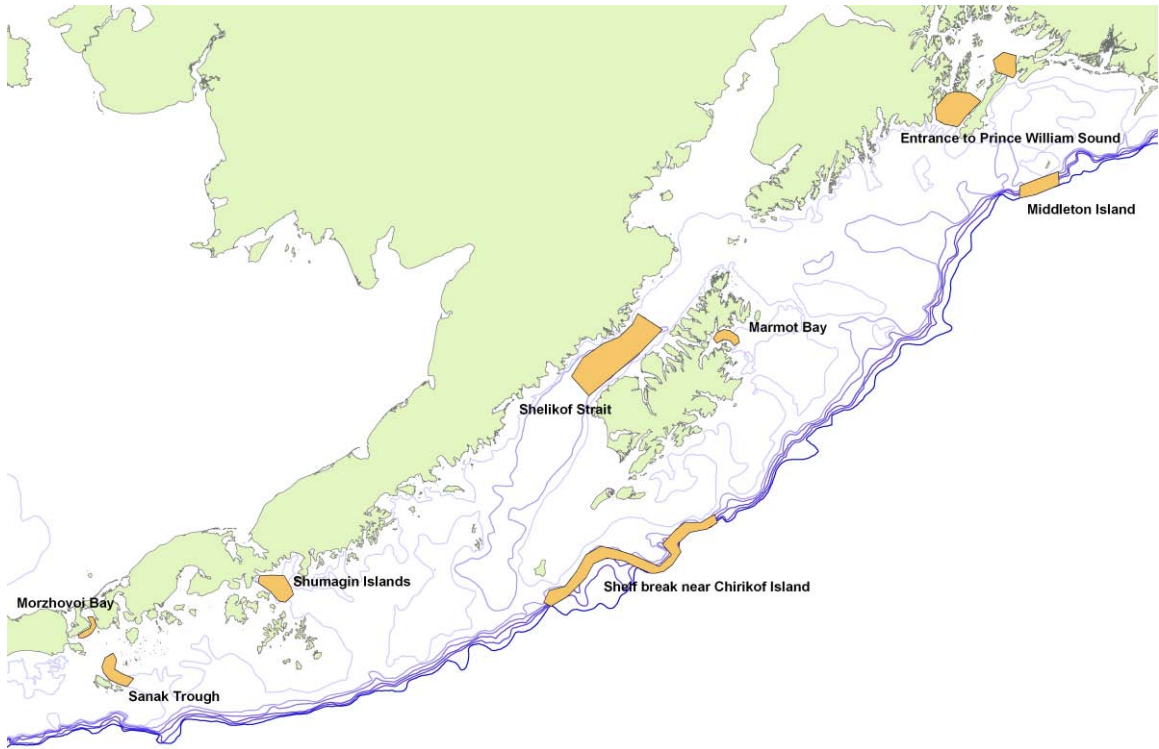


Figure 1.-- Spawning areas of walleye pollock in the Gulf of Alaska.

Factors Influencing the Mortality of Tagged Walleye Pollock Captured Using a Trawl Net

Andreas Winter, Robert J. Foy and Michael Trussell (Martin Dorn, presenter)

This project evaluated the feasibility of capturing live walleye pollock with a closed-codend trawl net, anticipated to be used for large-scale tagging surveys of pollock in the Bering Sea and Gulf of Alaska. A closed-codend trawl net is designed so that fish are pooled in calm water as the net is brought on deck. Three one-day fishing trips were conducted in March 2006, January 2007, and April 2007, collecting a total of 10 experimental trawl samples. Live pollock from the trawls were placed in laboratory holding tanks for 30 day observation periods, to analyze survival rates as a function of trawl depth, fish length, and catch density. From nine of these samples, survival after 30 days was low, with pollock having suffered significant scale loss during capture. But from one sample, the survival rate was nearly 50% after the codend unexpectedly overfilled with fish, plugging the codend pool. This outcome suggested that pollock, if caught, can benefit from being within dense aggregations of fish, which prevents them from harmful contact with the sides of the net or swimming to exhaustion. Fish length was also positively correlated with survival rates. The effects of depth resulted in some pollock displaying persistent symptoms of barotrauma. Overall survival rates of the ten trawl samples were not sufficiently strong to endorse a full-scale tagging survey without further testing. However, information gained from this study indicated that satisfactory survival may be achievable by targeting dense aggregations of large fish, and carefully de-gassing any individuals with symptoms of disorientation or swim bladder distension.

Winter, A., R. J. Foy, and M. Trussell. 2007. Factors influencing the mortality of tagged walleye pollock captured using a trawl net. North Pacific Research Board, Final Report 506, 23 p.

Statistical Feasibility of Estimating Walleye Pollock (*Theragra chalcogramma*) Movement Between the Northwest and Southeast Eastern Bering Sea

Sara E. Miller and Terrance J. Quinn II

We investigated the statistical feasibility of estimating walleye pollock (*Theragra chalcogramma*) movement between the northwest (NW) and southeast (SE) Eastern Bering Sea (EBS) based on Petersen mark-recapture sample sizes. We used standard sample size formulae assuming a single release of tagged fish (from a research operation) and a single recapture event (from commercial catch samples). Less than 5% of the commercial harvest would need to be examined for tags at an abundance estimation precision and accuracy level of $1-\alpha=0.95$ and $A=10\%$, and use of a single tagging vessel for two months (240,000 tagged fish) to attain the necessary recovery percentage of tags. For a smaller population of ages-3 and older walleye pollock, less than 2% of the harvest would need to be examined for tags. Based on a commercial harvest recovery by all sectors or just the catcher-vessel sector, the minimum number of tagged fish (n_1) needed ranged from 4,360 to 20,900. Given these mark-recapture sample size requirements, the Darroch method was used to estimate movement parameters between two regions, the NW and SE EBS, in a simple compartment model. Using simulations, directed movement could be reasonably estimated. This statistical study shows that a moderate tagging program can provide acceptable estimation of walleye pollock movement in the EBS.

PIT Tags: Useful for Tagging Alaskan Pollock?

Trevor A. Branch

Alaskan pollock are highly numerous (billions of fish) and fragile (low survival when handled), posing particular problems for tagging. However, there are only a small number (15–20) of processing lines, and therefore automated tag detectors could relatively easily scan all caught fish before they are processed, shunting detected fish off the processing lines for analysis. PIT tags (passive integrated transponders) lend themselves naturally to this kind of system. They are minute (rice-grain sized), long-lasting they do not contain batteries, fairly cheap, costing around \$2–4 each, and can be rapidly deployed using syringes. When deployed in Alaskan halibut, experiments revealed that tag shedding rates were low (2%) and detection rates high (97%). If PIT tag detectors were installed in the processing lines could achieve near-100% detection rates if fish pass within 10–30 cm of the detectors. The chief advantage of PIT tags over coded wire tags is that the detectors automatically read the information from the tags, whereas coded wire tags require laborious dissection and microscope work to obtain the tag code.

The biggest problem with PIT tags for Alaskan pollock is the extremely high mortality rates when these fish are caught and handled, sometimes near 100%. Minor additional issues to be solved would be to ensure that no PIT tags enter the human consumption chain, and to design the detectors so that the high speed processing lines do not impair detection. If these problems were solved, PIT tagging studies could in theory provide good estimates of fishing mortality, natural mortality, movements, and growth rates given the near-100% coverage of catches.

Overview of Chilean Jack Mackerel: Similarities with Pollock

Aquiles Sepulveda and James Ianelli

Chilean jack mackerel (*Trachurus murphii*) has many of the same population characteristics as walleye pollock (*Theragra chalcogramma*). Both species are highly productive, have similar longevities, grow to similar body sizes, are distributed over broad trans-boundary regions of oceans, exhibit high levels of inter-annual recruitment variability, spend time in the pelagic zone, and have supported large fisheries of over 1 million t per annum. Chilean jack mackerel can be distinguished as being distributed more expansively in deep water regions far from shelf regions. Strategies for Chilean jack mackerel stock assessments are complicated by coastal zones which tend to have variable size and age compositions and apparent ontogenetic movements. Nonetheless, survey efforts are intensive and provide excellent synoptic estimates of abundances. Acoustic survey methods are used extensively (typically conducted with 30 vessels operating simultaneously) along with surveys from research vessels and ichthyoplankton sampling which has been used to provide spawning biomass estimates based on egg-production methods.

Chilean jack mackerel, like pollock, are highly plastic and able to take advantage of favorable conditions and increase populations rapidly. The conceptual model of the main Chilean jack mackerel indicates most spawning occurring off-shore centered on about 35°S latitude during October–December. The nursery area is considered in the more northern regions nearer the coast at 20–25°S. As the juveniles grow movement appears to be southward along the coast to feeding grounds between 30°S and 43°S during March–July. Statistical methods investigating biophysical coupling indicate that wind levels and SST may define successful habitat for eggs and larvae. While there appears to be autocorrelation in the recruitment time series, SST during spawning season seems to affect subsequent year class strengths with a critical value at around 16°C.

Fishery management is complicated by international components of the fishery which have been historically substantial. Together with the South Pacific Regional Fishery Management Organization

(SPRFMO; a newly formed international body designed to assist in managing international fisheries), procedures have been developed with the following procedure:

1. Determine the appropriate fishing mortality according to biological reference points
 - a. Estimate the risk levels of exceeding reference points
 - b. To be based on the latest internationally accept assessment and scientific recommendations.
2. Specify a Total Allowable Catch based on the best information available,
 - a. Submit recommendations to the Undersecretariat of Fisheries which are then submitted to the National Fisheries Council for approval
3. Adopt TAC as passed
 - a. TAC disbursed by per ship or quota owner

APPENDIX 1. AGENDA

Building 4, Room 1055 (Observer Training) first floor

Tuesday July 7th Approaches for spatially explicit modeling		Presenter
9:00	Welcome, introductions, workshop plan, background	Quinn
9:30	Spatial stock assessments: The example of school shark in Australia	Punt
10:00	Incorporation of spatial structure and movement in stock assessment models	Cadrin
11:00	Historical development of quantifying movement processes: application to cod	Loerke
11:30	Incorporating tagging data into an assessment model, application to flounder	Goethel
12:00	<i>Lunch</i>	
1:00	Spatial modeling of tunas in the Pacific Ocean	Maunder
1:30	MAST, a multistock age structured tag integrated assessment model of Atlantic bluefin	N. Taylor
2:00	Finite-time, continuous-state approach to estimating migration, using tags	T. Miller
3:00	Spatial considerations for Pacific halibut	Valero
3:30	Spatial dynamics of snow crab in the EBS	Murphy
4:00	A new concept on fishery survey method	Cheng
4:30	Discussion	All
Wednesday July 8th Pollock data and environs		
9:00	Biology and stock structure	Bailey
9:30	Bottom trawl survey	Somerton
10:00	Acoustic trawl survey	Wilson
11:00	Evidence for pollock movement and a supplemental abundance index for EBS pollock	Honkalehto
11:30	Small scale movements of pollock during A-season fishery using opportunistic data	Barbeaux
12:00	<i>Lunch</i>	
1:00	Russian/U.S. pollock fisheries and plans for spatial modeling	Criddle
1:30	Predicting recruitment for flatfish in the EBS: Can we improve on OSCURS?	Stockhausen
2:00	Biological and physical dynamics of the EBS: BSIERP modeling	Aydin
2:15	Pollock predation patterns—arrowtooth	Zador
2:30	<i>Break</i>	
3:00	EBS pollock stock assessment and fishery patterns	Ianelli
3:30	A spatial and temporal age-structured model for EBS walleye pollock	S. Miller
4:00	Simulations of performance of a spatial age-structured model	Hulson
Thursday July 9th Software, management, and tagging issues		
9:00	Spatial structure and movement in stock synthesis	Methot
10:00	Simulation testing: selectivity versus space	Taylor
11:00	Spatial aspects of pollock management in the Gulf of Alaska	Dorn
11:30	Discussions for management considerations	All
12:00	<i>Lunch</i>	
1:00	Sample size considerations for a mark-recapture study for EBS walleye pollock	S. Miller
1:30	Experience pollock tagging	Dorn
2:00	Practical tagging issues	
3:00	Presentation on pit tags, useful for pollock tagging?	Branch
3:30	Discussion and planning	All
Friday July 10th		
9:00	Overview of Chilean jack mackerel: similarities with pollock	Sepulveda
10:00	Discussions, recommendations, report writing, and wrap up	All
12:00	<i>Lunch</i>	
3:00	<i>Adjourn</i>	

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Abbreviation	Full Name
AFSC	Alaska Fisheries Science Center, NOAA
AM SEA	American Seafoods
APA	At-sea Processors Association
IATTC	Inter-American Tropical Tuna Commission
INPESCA Chile	Instituto de Investigación pesquera, Chile
IPHC	International Pacific Halibut Commission
GFC	Glacier Fish Company
NEFSC	Northeast Fisheries Science Center, NOAA
NFRDI Korea	The National Fisheries Research and Development Institute, Korea
NMFS/OST	National Marine Fisheries Service Office of Science and Technology
NPFMC	North Pacific Fisheries Management Council
NWFSC	Northwest Fisheries Science Center, NOAA
RAI	Resource Analysts International
UAF	University of Alaska, Fairbanks
UBC	University of British Columbia
UdeC	Universidad de Concepción
UMass	University of Massachusetts
UW	University of Washington
WDFW	Washington Department of Fish and Wildlife

APPENDIX 3. MEETING PHOTO



1st row: Nathan Taylor, Sang Chul Yoon, Richard Methot Terry Quinn, Tim Miller
2nd row: Jim Ianelli, Jon Loerke, Trevor Branch, Mark Maunder, Taina Honkalehto
3rd row: Chris Wilson, Dan Goethal, Cody Szuwalski, Claudio Gatica, Martin Dorn
4th row: Susanne McDermott, Tom Wilderbuer, Aquiles Sepulveda, Andre Punt
5th row: Vidar Weststad, Sara Miller, Steve Barbeaux, Keith Criddle, Juan Valero
6th row: Buck Stockhausen, Steve Cadrin, Paul Spencer, Farron Wallace, Henry Cheng
Last row: Kray van Kirk, James Murphy, Ian Taylor, Tommy Garrison, Dave Somerton