Spatial and Temporal Variability of Walleye Pollock Fecundity Estimates for the Gulf of Alaska and eastern Bering Sea

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Background Walleye pollock (*Theragra chalcogramma*) support the largest fishery in the U.S., and account for 24% of the total U.S. fisheries landings (NMFS 2010). Walleye pollock populations are managed by applying a harvest rate toward an assessment model estimate of spawning stock biomass (SSB). Inherent in these models is the assumption that SSB is proportional to total egg production (fecundity) (Lambert, 2008; Marshall 2009). This is a key assumption because SSB is used for status determination and to implement the allowable biological catch (ABC) control rule. Furthermore, because the ABC control rule requires that fishing mortality be reduced linearly below an inflection point (B40% the biomass when fishing at F40%), yield can be highly dependent on spawning biomass. Spencer and Dorn (in review) use simulation modeling of the Gulf of Alaska (GOA) walleye pollock stock assessment to show how reproductive dynamics affect stock productivity. They found that the effect of weight-specific relative fecundity (i.e., increasing fecundity per unit body mass with weight) was to increase the estimate of F_{MSY} (fishing mortality rate at maximum sustainable yield) relative to an estimate using SSB as reproductive potential. This was caused by a higher level of stock productivity being associated with a higher level of reproductive output (relative to an unfished stock) with positive weight-specific fecundity.

Interannual variability in eastern Bering Sea (EBS) pollock maturity (Stahl and Kruse 2008) may lead to a greater contribution to the SSB by young fish than is currently modeled (Ianelli et al. 2010). Similarly, fecundity can vary in relation to fish length and condition, the quality and availability of prey resources, and environmental conditions, such as temperature, and as a response to stock density and fishing pressure (Lambert 2008). Fecundity in EBS pollock demonstrates spatiotemporal variability (Hinckley 1987). However, there has been no robust analysis of potential spatiotemporal variability in GOA walleye pollock fecundity to date, and none for the EBS since Hinckley (1987). Additionally, fecundity estimates for walleye pollock stock assessments are outdated for the GOA and EBS, having last been updated in the mid 1980s (Miller et al. 1986; Hinckley 1987).

Examinations of variations in fecundity (in lieu of SSB) of other gadoids, such as Atlantic cod (*Gadus morhua*) showed different responses to reductions in stock size (e.g. fecundity was not found to be time-invariant per unit of biomass; Marshall 2009). Stock assessments for the GOA and EBS would be markedly improved by the incorporation of contemporary fecundity estimates under current stock levels and climate regimes. Moreover, given that phenotypic plasticity in fecundity of other gadoids is related to factors, such as stock density (Rijnsdorp et al. 1991; Marshall et al. 2009) and temperature and prey availability (Kjesbu et al. 1998), pollock stock assessments would be further improved by incorporating variability in fecundity (provided that it can be robustly estimated) and incorporating functional relationships between temporal and spatial variability in fecundity and environmental factors.

Environmental factors such as temperature and indices of ocean productivity regulate most physiological processes and govern the amount of energy available for winter spawning, respectively.

Because fecundity is such an important parameter for establishing SSB and because there is uncertainty about the current fecundity rate and its associated variability, particularly for the GOA, we propose a two-year study of walleye pollock fecundity. Our proposed research is a FATE Type 1 proposal, because it is focuses on improving stock assessments by replacing outdated estimates of fecundity with recent estimates, which are apropos to current stock densities and environmental conditions. In addition, we will estimate variability in fecundity and examine functional relationships between fecundity and stock and environmental factors so that fecundity can be treated dynamically in future stock assessments. Upon project completion, we will incorporate results of this project into a management strategy evaluation (MSE) for GOA pollock (A'mar et al. 2009) to allow us to estimate the consequences of environmental- and density-driven variability in growth, maturity and fecundity on harvest strategies, including re-estimation of target and limit biological reference points. The proposed research utilizes a collection of gonad samples obtained from fishery-independent platforms with the goal of improving NMFS's assessments (page 2 of the FATE 2013 RFP). The sample collection was directed by the late Dr. Bernard Megrey (AFSC), who passed away unexpectedly in 2010, specifically for the study proposed here. The resultant samples represent a unique and valuable time series of specimens with which to examine variability and environmental correlates of fish fecundity.

Approach We propose an iterative approach that covers a two year period. During the first year archived ovary samples from NMFS research cruises will be examined to determine which fecundity assessment methodology is most efficient. Two well-established methods will be examined for estimating walleye pollock fecundity, a gravimetric method (Hunter et al. 1985; McDermott et al. 2007) and a stereological method (Emerson et al. 1990). Of the two proposed methods, the method that allows for the most rapid estimate of fecundity will be used. Once the best methodology has been determined, all viable samples will be processed to provide estimates of fecundity for binned length groups and sampling region. Circulation model output for the GOA and the EBS is currently available through 2005. During the first year, we will begin updating the GOA model to include more recent years. In combination with in situ and satellite measurements, these model runs will provide environmental information (i.e. temperature and currents) that will be used in assessing the influence of environmental conditions on fecundity. In the second year we propose to estimate variability in fecundity and analyze the demographic and environmental drivers of spatial and temporal variability observed in the fecundity estimates. The spatial scale will be represented by the sampling locations within management regions; the temporal scale will be interannual.

<u>Available Data</u> There are a total of 1,808 ovary samples collected from prespawning walleye pollock during winter NMFS research cruises, nearly every year from 1992 to 2012 from the EBS, GOA and Aleutian Islands (AI), see table below.

<u>Sample processing – Year 1</u>

In general, the fecundity estimation will involve taking subsamples of the ovaries similar to methods described in Hunter et al. (1985) and McDermott et al. (2007). Maturity stage of each sample will be determined histologically before fecundity is estimated, because fecundity estimates are ideally conducted only on gonads that are vitellogenic and not hydrated, or hydrated but have no post-ovulatory follicles. The gravimetric method involves weighing preserved ovaries, excising small cross-sections

Year	Region	Total # ovary samples
1992	GOA	32
1993	GOA	54
1994	GOA	51
1995	EBS	124
	GOA	39
1996	GOA	53
1997	EBS	36
	GOA	72
1998	AI	47
	GOA	46
2000	AI	64
	GOA	61
2001	GOA	75
2002	EBS	112
	GOA	174
2003	AI	61
	GOA	94
2004	GOA	90
2005	GOA	55
2006	AI	34
	GOA	115
2007	GOA	66
2008	GOA	62
2012	AI	67
	GOA	124
Grand Total		1808

from the ovaries, weighing the samples to the nearest 0.001, and counting the number of eggs in the sample, with a target sample size of 1,000 eggs. The associated fecundity is estimated using methods described in Cooper et al. (2003). As an alternative the stereological method (Emerson et al. 1990) will be examined to determine whether fecundity can be estimated more rapidly. This method involves measuring the number of oocytes in a unit volume for a subsample and raising the volume to the level of the whole ovary. The formula used to estimate fecundity via the gravimetric model has been documented in Cooper et al. (2003). Two co-PIs, Drs. Gordon Kruse and Susanne McDermott, have extensive experience in the analysis and interpretation of fish maturity and fecundity and will oversee the work of a contract biologist who will conduct the laboratory work on ovary samples described above. Dr. Kruse has supervised a master's student in a study on spatiotemporal variation in size at maturity of walleye pollock in the EBS. This work resulted in two co-authored publications, one of which won the W.F. Thompson Best Student Paper Award from the American Institute of Fishery Research Biologists. The other focused on the correspondence between maturity stages determined by gonadosomatic index versus histological examination, and resulted in a new descriptive guide for more accurate macroscopic staging of pollock ovaries. Dr. Kruse is co-PI on two other projects evaluating fecundity in red king crab and snow crab, including size-fecundity relationships, interannual variability in fecundity, and maternal effects of age, size, and embryo lipid and nitrogen content. Three manuscripts have been prepared on this work on crab fecundity. Dr McDermott's research has focused on understanding temporal and spatial variation in distribution, abundance, and life history parameters of Alaskan groundfish. She has studied the reproductive life history of Alaskan groundfish, such as understanding variability in reproductive output in relation to maternal contribution and environmental factors. Her work has resulted in four publications on fish reproduction in the peer-reviewed literature.

<u>Data analysis – Years 1 and 2</u> After laboratory processing of gonad samples, we will produce an estimate of fecundity, an estimate of variability in fecundity, an analysis of trends in fecundity by length and age, and an analysis of spatial and temporal trends in fecundity. Phenotypic plasticity in fecundity is often related to biological factors, such as stock density (Rijnsdorp et al. 1991; Marshall 2009), fish size (age) and other indices of individual fish condition (Horwood et al., 1986; Rijnsdorp 1991; Kjesbu et al. 1998; Blanchard et al. 2003; Murua et al. 2003), and environmental factors, such as temperature and prey availability (Kjesbu et al. 1998). Variability in environmental conditions can influence fecundity through both direct and indirect effects reflected in growth and nutritional status (Lambert et al. 2003). For instance, temperature and ocean productivity (prey availability) regulate most physiological processes and govern the amount of energy available for somatic growth and gonadal development. Each fecundity sample has associated spatial and temporal information. The spatial data will incorporate

basin (EBS or GOA), as well as regional variability. Samples were typically collected from winter pre-spawning cruises; as such the temporal component will be annual variability. Generalized linear models (GLMs) will be applied to fecundity estimates at length and age, with geographic area and year as factors following the methods of Stahl and Kruse (2008) and Cooper et al. (2010). A spatial examination of the fecundity-at-length and fecundity-at-age models will be based upon sample regions and literature values (Miller et al. 1986). Assuming that we realize similar success as did Lambert (2008) relating condition factor to fecundity, we will use condition factor to reconstruct a time series of interannual variability in fecundity. In conducting these analyses, we will take into account potential spatial and temporal autocorrelations that could bias results (Hilborn and Walters 1992; Dormann et al. 2007). Specifically, we will test several hypotheses: (1) fish density compromises body condition and hence fecundity (density-dependence); (2) temperature directly influences the metabolic rate of walleye pollock such that colder years lead to reduced fecundity (Po□rtner et al. 2001) during either the growing season (April to October) or during the final stages of maturation (November to March); and (3) increased ocean productivity during spring and summer translates into increased consumption of prey by pollock and accumulation of energy reserves for reproduction (Kjesbu et al. 1998).

To test these hypotheses, a suite of biological and environmental variables will be incorporated into the GLMs. Biological variables used to test hypothesis 1 include stock biomass (density), abundance-at-age (or length) and a condition index based on weight/predicted weight (Blanchard et al. 2003), where predicted weights are estimated as $W = aL^b$ by Dorn et al. (2011). For the Shelikof Strait (Gulf of Alaska), weight-at-age of pollock older than age 6 has more than doubled in recent years compared to 1983-1990 (Dorn et al, 2011), so we are encouraged by the likelihood of uncovering statistically significant biological effects on fecundity. Primary oceanographic variables include temperature and indices of ocean productivity. To test hypothesis 2, we will access temperature at depth (available from moorings, numerous shipboard surveys conducted by the Pacific Marine Environmental Laboratory, and the GAK1 time series off Seward, Alaska, since 1970; http://www.ims.uaf.edu/gak1/), modeled temperatures from the ocean circulation model (C. Ladd and W. Cheng), and sea surface temperature from satellite measurement (indicative of temperatures at depth during winter) for the late stages of gonad maturation (November to March). To test hypothesis 3, we will consider two indices of productivity, including a measure of the length of the growing season (duration between spring and fall transitions from both model and in situ data) and a satellite-derived measure of phytoplankton standing stock based on ocean color to the extent that it is available (extensive cloud cover in the region limits data availability). Moreover, we will conduct exploratory analyses of other variables purported to be related to ocean productivity in the Gulf of Alaska: an updated index of freshwater discharge in to the Gulf of Alaska (Royer 1982), an index of Alaska Coast Current flow from the circulation model, sea surface height variability (SSH, an indicator of ocean surface currents and eddies, as well as vertically integrated ocean temperature), and various climate indices (e.g. El Niño Southern Oscillation, Pacific Decadal Oscillation, etc.).

Objectives

1. Estimate fecundity and the variability in fecundity for the GOA and EBS (Year 1)
2. Estimate relationships between fecundity and length and age (Year 1)
3. Analyze spatiotemporal trends in fecundity, as well as functional relationships between fecundity variability and environmental and density-dependent effects (Year 1 and Year 2)

Benefits Our research will result in improved pollock stock assessments in two ways. First, the current assessment model for walleye pollock uses SSB as a proxy to monitor and assess reproductive potential. Our research will allow the current assumption to be tested and allow a direct measure of annual reproductive output to be incorporated into the assessment. The walleye pollock fishery is managed under a harvest control rule in which biological reference points for the overfishing limit (OFL) and acceptable biological catch (ABC) depend directly on spawning biomass. Use of more direct annual reproductive output estimates in the harvest control rule would be an improvement over the SSB proxy and would result in reduction in uncertainty in the stock assessment. In addition, if variability in fecundity can be robustly estimated, than that variability will be incorporated into the assessment. After review and approval of changes to the assessment model by the Groundfish Plan Teams for the GOA and Bering Sea/Aleutian Islands and the Scientific and Statistical Committee of the North Pacific Fishery Management Council (Council), the Council would use the revised stock assessments in setting annual groundfish catch specifications.

Second, our research will improve pollock stock assessments by providing an analysis of temporal trends in fecundity, and by exploring functional relationships between fecundity, stock density and environmental factors. Accounting for time trends in life history characteristics (such as fecundity) is critically important, because it would reveal how often these vital rates need to be updated for accurate assessments. This may be especially critical for walleye pollock, because there have been strong temporal trends in stock abundance and growth, particularly in the Gulf of Alaska. Changes in growth and abundance are likely to affect the length-fecundity relationship, but no information is currently available to evaluate those impacts. Environmental conditions (growth and prey availability) may influence pollock fecundity, and our research will evaluate such potential relationships. Finally, beyond using accurate reproductive parameters in the stock assessments, we will extend a MSE (A'mar et al. 2009) to evaluate the impacts of climate change (e.g., temperature) and fishing (e.g., stock density) on reproductive output and population dynamics, thus allowing a dynamical re-evaluation of harvest policy under changing conditions, as well as producing long-term forecasts of fisheries productivity and sustainability under current and alternative harvest strategies.

Deliverables This research will result in several peer-reviewed journal publications. We will estimate fecundity-size relationships and temporal variability in fecundity with respect to stock density, temperature, and indices of ocean productivity. Additionally, results will be applicable to stock assessment in the form of:

1. Time series of fecundity-length relationships and an estimate of variability in fecundity for GOA and EBS pollock for use in the assessment model (Year 1)
2. Estimated relationships between environmental variables and pollock fecundity (and their concomitant uncertainty), allowing linkages to be established between output from global climate models and pollock population dynamics (Year 2).

Results will be presented as oral presentations at various meetings, including the North Pacific Marine Science Organization (PICES), the Alaska Marine Science Symposium, the Western Groundfish Conference, and the annual meeting of the American Fisheries Society.

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