Evaluation of stock structure for the Bering Sea/Aleutian Islands northern rockfish

Paul D. Spencer

NMFS-Alaska Fisheries Science Center, Seattle, WA

Executive summary

In this document, various types of information pertaining to stock structure for the BSAI northern rockfish are considered, following the template recommended by the Stock Structure Working Group (SSWG). Evaluation of spatial harvest indicated that estimated exploitation rates for the eastern AI have been consistently at or above natural mortality in recent years, which in part have motivated the evaluation of stock structure.

Tests for genetic homogeneity indicated that genetic differences occurred between samples of northern rockfish collected at six locations within the BSAI, and a significant isolation by distance (IBD) pattern also occurred within the BSAI area. Two estimates of the dispersal distance between parents and offspring were estimated from the IBD relationship (one of which considers the migration rate between populations). The maximum estimate of dispersal distance was ~ 200 km, much shorter that the linear distance of the BSAI management area.

Differences in size at age and were also detected, with smaller northern rockfish in the western AI and larger northern rockfish in the eastern AI and southern Bering Sea (SBS) area.

Given the long generation time of northern rockfish (estimated here as 36 years), the genetic structure observed for northern rockfish, and the spatial differences in growth patterns, subarea ABCs are recommended. The subarea ABCs would allow improved, in-season, monitoring of spatial harvest patterns, and could potentially allow actions to avoid exceeding the area-specific ABC levels. Additionally, sub-areas ABC would be consistent with the spatial structure of the stock, and the current management for many Alaska groundfish stocks (and most Alaska rockfish species).

Introduction

In 2009 a Stock Structure Working Group (SSWG), consisting of members of the North Pacific Fisheries Management Council's (NPFMC) Scientific and Statistical Committee (SSC), Groundfish Plan Teams, geneticists, and assessment scientists, was formed to develop a set of guidelines that will help promote a rigorous and consistent procedure for making management decisions on stock structure for Alaska stocks. The committee produced a report, originally presented at the September 2009 meeting of the joint Groundfish Plan Team and updated for the September 2010 meeting (Spencer et al. 2010), which contains a template (Table 1) that identifies various scientific data from

This information is distributed solely for the purpose of pre-dissemination peer review under applicable information quality guidelines. It has not been formally disseminated by the National Marine Fisheries Service and should not be construed to represent any agency determination or policy.

which we may infer stock structure. At the September, 2011, meeting of the joint Groundfish Plan Team recommended application of the template to several stocks, including BSAI northern rockfish.

The purpose of this document is to use the template produced the stock structure committee to evaluate scientific information on stock structure, and consider the management implications of potential area-specific ABCs and OFLs. The SSWG template has a number of broad categories of information relevant to BSAI northern rockfish, including spatial harvest patterns, oceanographic characteristics, differences in growth and age/size structure, and genetic information.

Harvest and Trends

The purpose of examination of harvest data and survey population trends is twofold: 1) to evaluate whether fishing mortality is large enough that spatially disproportionate harvesting represents a potential conservation concern; and 2) to identify any differences in populations trends that may indicate demographic independence.

Fishing mortality (relative to target reference point)

Values of fishing mortality much less than the target reference point may indicate an absence of conservation concern with respect to spatially disproportionate harvesting. The estimates of fishing mortality for the ten-year period 2001-2010 ranged from 0.021 to 0.053 with a mean of 0.031. The ratio of F to the estimated F_{abc} of 0.058 from the 2010 assessment ranged from 0.35 to 0.92 during this period, with a mean of 0.54. Although overall fishing rates are below current estimates of reference fishing rates, they are not sufficiently low that conservation concerns regarding spatially disproportionate harvesting patterns could be ruled out without further analysis.

Spatial concentration of harvest relative to abundance

The spatial concentration of harvest relative to abundance was evaluated by calculating area specific exploitation rates from 2004 to 2011. For each of the Aleutian Island subareas, an exploitation rate for a given year was obtained by dividing the yearly catch by the estimate of biomass for the subarea. The subarea biomass for each year was obtained by partitioning the estimated biomass at the beginning of the year (obtained from the age-structured stock assessment and/or projection models applied in the fall prior to a given year) into the subareas. A weighted average of the three most recent surveys was applied to each subarea (weights of 4,6, and 9, with recent surveys higher weights), and the proportions from these averages were used to partition the projected biomass.

The survey biomass estimates of northern rockfish follows a gradient, with the highest abundance in the western AI (average of 119,000 t from 1991-2010) and lowest abundance in the southern Bering Sea (SBS) portion of the AI survey (average of 3,880 t from 1991-2010) (Figure 1). Northern rockfish are rarely found in the EBS slope survey. No distinct trends in biomass are observed over time. The survey coefficients of

variation (CV) are lowest in the western AI (average of 0.35 from 1991-2010) and highest in the SBS (0.68 from 1991-2010) (Figure 2). Using the weighted averages of the most recent three surveys produces relatively stable estimates of area proportions, which ranged from 0.61 to 0.75 in the WAI and from 0.17 to 0.25 in the CAI (Figure 3).

Catches of northern rockfish from 2004-2011 are highest in the western and central AI, although the 2011 catch in the western AI was unusually low (311 t, compared to a 2004-2010 average of 1,501 t for this area), which likely reflects the closure of the WAI to directed fishing for Atka mackerel beginning in 2011 (Figure 4). Catches in the eastern AI averaged 262 t from 2004 to 2006, but the average from 2007 to 2011 increased to 800 t. Exploitation rates for the western AI have been below M for all years between 2004-2011, but have exceeded $0.75*M$ (i.e., the level associated with F_{abc} for a Tier 5 stock) in the central AI from 2004-2006 (Figure 5). Exploitation rates in the EAI have been above $0.75*M$ from 2007-2011.

Because northern rockfish are taken as bycatch, high estimates of area-specific exploitation rates could suggest that the association between northern rockfish and the target species (Atka mackerel) could differ between areas. The bycatch rate of northern rockfish in tows targeting Atka mackerel (i.e., the tons of northern rockfish caught per ton on Atka mackerel caught) was calculated for AI subareas from hauls sampled by fishery observers from 2001 to 2011. From 2008 to 2011, the bycatch rates were lower in the EAI than in other AI subareas (Figure 6a), whereas in earlier years (i.e., 2005-2007, 2001-2002) the bycatch rates in the EAI met or exceeded the bycatch rate in the central AI. Given that approximately 9% of the survey biomass (based on surveys from 2004-2010) occurs in the eastern AI, one would expected the bycatch rates to be even lower than their current level (Figure 6b). For example, the average 2008-2011 bycatch rates for the CAI is 1.88 times that in the WAI, but the ratio of survey biomass proportion in the CAI from 2004-2010 is approximately 2.65 times that in the EAI.

Population trends

Differential changes in population trends between subareas could reflect stock structure and a lack of connectivity between areas. The available information does not suggest differential trends between the subareas. However, given the high survey CVs in some subareas, any potential trend in the true area biomass may be relatively difficult to observe.

Barriers and phenotypic characters

Generation time

Generation time is a characteristic of a species that reflects longevity and reproductive output, with long generation times indicating increased time required to rebuild overfished stocks. The mean generation time (G) was computed as

$$G = \frac{\sum_{a=1}^{A} aE_a N_a}{\sum_{a=1}^{A} E_a N_a} \qquad \text{Eq. 1}$$

where *a* is age, *A* is expected maximum age for an unfished stock, *N* is females per recruit in the absence of fishing, and *E* is fecundity at age (Restrepo et al. 1998). Because fecundity is unknown, *E* was replaced by the product of proportion mature and body weight, thus using spawning stock biomass rather than egg production (Restrepo et al. 1998).

The estimated mean generation time for BSAI northern rockfish was 36 years. In general, rockfish species would be expected to have large mean generation times due to their longevity; for example, the estimated generation times for BSAI POP and blackspotted/rougheye were 28 years and 53 years, respectively.

Physical limitations (clear physical inhibitors to movement)

The Aleutian Islands is characterized by deep passes, typically exceeding 500 m, that may limit the movement of northern rockfish between Aleutian Islands subareas (Figure 7). Northern rockfish are a demersal species captured during the AI trawl survey at depths between 100 m and 200 m, so traversing the much deeper AI passes would require greater utilization of pelagic habitats or deeper depths than currently observed in the AI trawl surveys.

Field data on ocean currents can be used to infer the degree of water flow between subareas within the Aleutian Islands. On the north side of archipelago, the connection between the east and west Aleutians is limited due to the break associated with Petral Bank and Bowers Ridge, which results in water flowing away from the Aleutian Islands archipelago (Figure 7, Stabeno et al 2005). On the south side of the Aleutian Islands, the Alaska Stream provides much of the source of the Alaska North Slope Current (ANSC) via flow through Amutka Pass and Amchitka Pass. However, The Alaska Stream separates from the slope west of the Amchitka Pass and forms meanders and eddies, perhaps limiting the connection between the east and west Aleutians.

Although a full discussion of ecological differences between the Aleutian Islands and neighboring areas is beyond the scope of this document, a number of biological and physical measurements suggest that a “biophysical transition zone” (Logerwell et al. 2005) occurs at Samaga Pass. Field observations in 2001-2002 indicate that water west of Samaga Pass was colder, saltier, and more nutrient rich relative to water east of Samaga Pass (Ladd et al. 2005). The passes from Samaga Pass eastward are generally shallow and well mixed by tidal currents, whereas the central and western passes are generally deeper and wider. Hunt and Stabeno (2005) summarize a series of changes that occur west of Samalga Pass, including higher chlorophyll concentrations (Mordy et al 2005), relatively more neritic zooplankton (Coyle 2005), and reduced frequency and abundance of coral (Heifetz et al. 2005). In addition, Logerwell et al. (2005) found a

large percentage decline in demersal fish species between Unimak/Samalga and Amutka Passes.

Unfortunately, data on northern rockfish spatial movements (i.e., from tagging or larval drift studies) that would reveal connectivity and physical barriers do not exist. However, information on the movement of reproductively active northern rockfish can be obtained from genetic research, which is discussed elsewhere in this document.

Growth differences

Age data from northern rockfish in the Aleutian Island surveys from 1986 – 2006 provide information on size at age within Aleutian Island subarea. Otoliths were obtained by length-stratified sampling, and unbiased estimates of mean length were obtained by multiplying the estimated size composition of the population by the age-length key for that area and year (Kimura and Chikuni 1987; Dorn 1992). No trends were observed over time, so the data from all years were grouped together in the analysis. von Bertalanffy growth curves were fit to the mean lengths by assuming the deviations between the model prediction and the observed data follow a normal distribution, and Akaike's Information Criterion (AIC) was used to evaluate whether growth patterns differ significantly between the AI subareas.

The data indicate increasing size at age from the western AI to the eastern AI (Figure 8). The largest difference in the growth curves was in the rate parameter *K*, which varied by a factor of two between the areas and reflects that fish in the WAI approached their asymptotic size more slowly than fish in the EAI and SBS. The estimated length at infinity (L_{inf}) from the von Bertalannfy relationship was approximately 5% larger in the southern Bering Sea (35.46) than in the western AI (33.63), which corresponds to a 17% difference in weight at infinity (W_{inf}) between these areas.

The resulting von-Bertalanffy growth parameters are as follows:

Area	Fish aged	t_{izero}	K	L_{inf} (cm)	W_{inf} (g)
SBS	300	0.63	0.24	35.46	651
EAI	351	0.66	0.23	35.48	652
CAI	354	-0.78	0.17	34.17	583
WAI	353	-2.15	0.12	33.63	555

Age/size structure

The estimated age compositions of northern rockfish were obtained from data from trawl surveys conducted from 2002, 2004, and 2006 (Figure 9). An ANOVA was used to test for significant differences in the mean age between areas. For each haul with aged fish, a mean age was obtained by multiplying the length composition of the haul by the age-length key. The mean age for each haul was then weighted by the relative contribution of each haul (indicted by numerical CPUE) to the estimated population size for the stratum

in which the haul occurred. The year of sampling was a significant factor, so separate analyses were applied for each year.

For each year, significant differences were observed in the mean age between subareas, but a consistent pattern did not emerge (Table 2). For example, in 2002 the mean age in the eastern AI was significantly different from the mean age in the western AI and the SBS, and marginally different from the mean age in the central AI ($P < 0.10$), but this pattern did not hold for 2004 and 2006. The mean age was significantly different between the eastern AI and the western AI for each year, but the mean age was not significantly different between the SBS and western AI for any year.

Genetics

Several genetic tests were conducted on northern rockfish samples obtained in the 2004 Aleutian Islands trawl survey (Gharrett et al. 2012). A total of 499 samples were collected at six locations ranging from the EBS slope to the western Aleutian Islands, and analyses were applied to 11 microsatellite loci.

Pairwise genetic differences (significant differences between geographically distinct collections)

Evaluation of the null hypothesis of homogeneity of allele frequency distributions between the collections were analyzed with GENEPOP 4.0 (Rousset 2008). The results were highly significant in aggregate for the 11 loci ($P < 0.001$) and for 2 of the 11 individual loci ($P < 0.01$), indicating lack of homogeneity. Information on the spatial population structure was obtained from the spatial analysis of molecular variance (SAMOVA; Dupanloup et al. 2002), which identified sets of collections that showed maximum differentiation. Three groups were identified: 1) the eastern Bering Sea; 2) two collections west of Amchitka Pass; and 3) three collections between Amchitka Pass and Unimak Pass (Figure 10). Genetic structure was not observed for samples on either side of Samaga Pass and Amutka Pass, although the structure observed with the westernmost collections may be associated with Amchitka Pass.

Isolation by distance

The fixation index F_{st} (a measure of the allele diversity between subpopulations relative to the entire population) was calculated for each pair of collections. Isolation by distance was evaluated by relating *Fst* to geographic distance (d) between each pair of collections with the following regression:

$$\frac{F_{st}}{1-F_{st}} = a + bd$$

The slope b is defined as $1/(4D_e\sigma^2)$, where D_e is the effective linear population density (i.e., effective spawners per km) and σ is the mean dispersal distance between parents and

offspring. Calculation of F_{st} between pairs of collections, as opposed to between individuals, is recommended when samples are obtained from relatively few sites rather than uniformly throughout the range (Rousset 2000).

The relationship between F_{st} and distance was statistically significant ($P < 0.007$; Figure 11), indicating genetic structure being produced from the dispersal of individuals being smaller than the spatial extent of the sampling locations.

Dispersal distance << management areas

Given a significant IBD relationship obtained from Eq. 2, an estimate of the dispersal distance between parents and offspring over one generation can be obtained from the slope of the IBD relationship $(4\sigma^2 D_e)^{-1}$. Assuming that the dispersal distance is normally distributed, approximately 95% of offspring would be contained within a distance of 4σ from their parent. Estimation of the slope of the IBD relationship, and assumptions regarding the effective density, allow estimates of the dispersal distance.

Estimates of effective linear density were obtained by estimating the linear density of mature fish, and applying a ratio of effective population size to census populations size. The linear distance from the Bering Sea slope to the western end of the Aleutian Islands is approximately 2500 km, and an estimate population size of mature (ages 13 and older) AI northern rockfish in 2010 (from the 2010 stock assessment) is 331.9 million fish, resulting in a linear density of ~ 133,000 fish per km. The width of rockfish habitat along the Aleutian Islands is probably 1/2 degree latitude (56 km), much smaller than the length and meeting the criteria for a linear distribution.

For fecund, long-lived marine species, the ratio of effective population size to census size may even be below 0.01. A sensitivity analysis conducted based upon five values of D_e/D_{census} that range from 0.1 to 0.001 produces estimates of dispersal distance (4σ) between 12 and 120 km.

An alternative estimate of dispersal distance can be obtained from relating the quantity $F_{st}/(1-F_{st})$ to the effective number of migrants, and using the regression parameters in Eq. 2 to solve for dispersal distance d (see Gharrett et al 2012 for derivation). Migration rates of approximately 10% would be expected to produce independent populations (Hastings 1993); thus, rates of 10% and 20% were evaluated in producing the alternative values of dispersal distance. The estimates of dispersal distance were 190 km and 229 km for rates of 10% and 20%, respectively.

Clearly, the spatial scale of genetic divergence for each estimation method is much smaller than the distance along the continental shelf break that extends around the eastern Bering Sea to the western Aleutian Islands. Further, the scale of the dispersal distances are also comparable to other *Sebastes* species in the north Pacific, which have ranged from 4 to 40 for near shore species such as grass rockfish (Buonaccorsi et al. 2004), brown rockfish ((Buonaccorsi et al. 2005), and vermilion rockfish (Hyde and Vetter 2009), and up to 111 km for deeper species such as POP (Palof et al. 2011) and darkblotched rockfish (Gomez-Uchida and Banks 2005). The demographic implication is

that movement of fish from birth to reproduction is at a much smaller scale than the geographic scale of the BSAI area. Finally, it is important to recall that the time unit for the estimated dispersal is not years, but generations, and the generation time for northern rockfish is more than 36 years.

Interpretation of the information regarding stock structure

A summary of the information in the template for BSAI northern rockfish is shown in Table 3. For any given data type, there may be multiple explanations consistent with the observed pattern; thus, an advantage of considering several types of data is more information on the potential differences between areas.

Spatial structure could be revealed by differences in age composition between areas, as the recruitment strengths could differ spatially between areas that are not well-mixed. However, the trawl survey age composition data for northern rockfish is characterized by high levels of variability both between areas and between years, resulting in an inability to observed a consistent and informative pattern of statistical significance.

Differences in size at age between subareas in the AI trawl survey indicate a gradient, with fish in the eastern AI and SBS being similar in size and relatively large, and smaller fish in the western AI. Differences in size at age between areas can be considered a type of "tag" reflecting fish movement, as one would expect little area differences if fish were moving between areas.

Finally, evaluation of the genetic test identified in the stock structure template indicate spatial structure, including: 1) genetic differences between geographically distinct collections; 2) isolation by distance; and 3) dispersal distances much smaller than management areas. Given the genetic information and differences in growth patterns, the most parsimonious in interpretation of the data is that there is some spatial structuring for BSAI northern rockfish.

Management Implications

History of spatial management of BSAI rockfish

After passage of the Fishery Conservation and Management Act of 1976, POP were managed as two stocks in the BSAI -- an EBS slope stock and an AI stock. At that point, other "red" rockfish species, including northern rockfish, rougheye rockfish, shortraker rockfish, and sharchin rockfish, were managed along with POP in a "POP complex" group. The recognition of separate rockfish stocks within the BSAI area was continued from INPFC management, and likely reflects the analyses of Chikuni (1975), who recognized three POP stocks in Alaskan waters based on investigation of length composition, growth characteristics, fecundity, recruitment strengths, and oceanographic characteristics: 1) a Gulf of Alaska stock; 2) an "eastern slope" stock (corresponding to the eastern slope of Bering Sea); and a Aleutian stock. The Other Red Rockfish species were separated from POP in 1991 (with the complexes varying between the AI and EBS),

and separate harvest specifications between the AI and EBS were still maintained. In 2000, the BSAI Plan Team recommended that the species comprising the Other Red Rockfish category (northern rockfish, rougheye rockfish, and shortraker rockfish; sharpchin rockfish were moved to the "Other rockfish" category) be managed as separate species, but managed with a BSAI-wide OFL and ABC (BSAI Groundfish Plan Team 2000). A concern to the Plan Team was that a low OFL for the EBS slope could result in an "immediate economic and management issue" and prove "constraining to the fleet" in their pursuit of target fisheries.

The Plan Team did note in 2000 that "there is some risk associated with establishing area-wide ABCs if there are truly separate stocks of shortraker and rougheye rockfish in the AI and EBS" (BSAI Groundfish Plan Team 2000). To address this, the BS and AI areas were allocated separate TACs, which continued from 2001 to 2003. Beginning in 2004, rougheye rockfish, shortraker rockfish, and northern rockfish were managed with BSAI-wide OFLs, ABCs, and TACs.

Considerations for BSAI northern rockfish spatial management

A concern for stock sustainability is that if disproportionate harvesting occurs within any BSAI subarea, fish may not be replenished quickly from other BSAI subareas. The long generation time for northern rockfish, and the nature of sporadic recruitment for rockfishes, further heightens the concern for stock sustainability. An additional concern regarding stock sustainability is that the productivity and fishing rate reference points could differ between areas, which may result from differences in growth and reproduction between areas.

The current management approach is to have the ABC and OFL apply to the BSAI area, and placing northern rockfish on bycatch status. Although this has resulted in relatively low levels of bycatch in recent years, there are some risks associated with this approach. First, the area-wide harvest quotas would not necessarily prevent disproportionate bycatch with BSAI subareas, as indicated by recent exploitation rates in the eastern AI consistently exceeding the natural mortality.

Given the information on spatial stock structure and the current practice of BSAI OFLs and ABCs, defining subarea ABCs might be viewed as a logical next step, and would have the following advantages:

1) *More effective monitoring*. A pattern of disproportionate harvest rates may motivate more monitoring of spatially harvest patterns in the future. Currently, this monitoring is contained within the biennual stock assessments and is thus not prominently communicated to many people. Adoption of sub-area ABCs would enhance the visibility of spatial harvest patterns and thus allow more effective communication of this information. Most importantly, it would allow the fishing industry and managers to evaluate spatial harvest patterns in real-time, perhaps leading to solutions to address disproportionate harvesting.

2) *Consistency with spatial structure*. Sub-area ABCs are often interpreted as pertaining to spatial units that have biological meaning for the stock. Continuation of BSAI-wide ABC levels suggests that relevant spatial scale is entire BSAI management area, which is not consistent with current scientific data on stock structure.

3) *Consistency with current and proposed management practices*. Adopting sub-area ABCs is a commonly used management practice intended to prevent disproportionate harvesting, and it often applied in a precautionary manner to cases with uncertain or unknown stock structure. This practice was recommended by the SSWG (Spencer et al. 2010) and at the 2010 meeting of the Joint Groundfish Plan Team. Given that the information on stock structure does exist for northern rockfish and indicates spatial scales smaller than our current management areas, it seems especially fitting to apply this recommendation in this case.

4) *Proactive management*. BSAI northern rockfish are not currently targeted, but were targeted during the 1990s. Should a target fishery develop in the future, a system of sub-area ABCs would be in place to prevent disproportionate targeting, reflecting the NPFMC goal of proactive management.

Risks/costs to the fishery and regulatory system

A necessary first step to evaluate the risks/costs of area-specific harvest quotas to the fishing fleet is to identify the extent to which current fishing practices would be affected. Because BSAI northern rockfish are taken as bycatch and not targeted, adoption of sub-area ABCs (which would prevent targeting) would be expected to have little impact on current fishing practices. Under the new ACL harvest regulations, there are implications of exceeding ABC levels at a frequency of > 25%. However, these regulations appear to pertain to the stock-wide ABC (in this case, the BSAI ABC) and not to the subarea allocation of ABC.

There is also a regulatory cost of area-specific ABC levels. However, given that subarea ABCs are commonly used in the BSAI and a management framework exists by which subarea ABCs can be implemented, one might expect that regulatory costs would be relatively minor.

Adoption of subarea OFLs could potentially impact target fisheries that harvest northern rockfish, and thus adoption of this management approach would require careful consideration of the costs and benefits. Given the current practice of BSAI-wide ABC levels, a useful next step is to adopt subarea ABCs to better monitor spatially harvest patterns, and consider the costs and benefits of subarea OFLs only if the monitoring indicates a continued pattern of spatially disproportionate harvesting.

References

BSAI Groundfish Plan Team. 2000. Summary section. In Stock Assessment and Fishery Evaluation Report for the Groundfish Resources of the Bering Sea/Aleutian Islands Regions, pp. 1-39. North Pacific Fishery Management Council, 605 W. 4th Ave, suite 306. Anchorage, AK 99501.

Buonaccorsi, V. P., C. A. Kimbrell, E. A. Lynn, and R. D. Vetter. 2005. Limited realized dispersal and introgressive hybridization influence genetic structure and conservation strategies for brown rockfish, *Sebastes auriculatus*. Conservation Genetics 6:697–713.

Buonaccorsi, V. P.,M.Westerman, J. Stannard, C. Kimbrell, E. Lynn, and R. D. Vetter. 2004. Molecular genetic structure suggests limited larval dispersal in grass rockfish, *Sebastes rastrelliger*. Marine Biology 145:779–788.

Chikuni, S. 1975. Biological study on the population of Pacific ocean perch in the north Pacific. Bull. Far Seas Fish. Res. Lab. (Shimizu) 12:1-119.

Coyle, K.O. 2005. Zooplankton distribution, abundance and biomass relative to water masses in eastern and central Aleutian Island passes. Fish. Oceanogr. 14 (Suppl. 1), 77–92.

Dorn, M.W. 1992. Detecting environmental covariates of Pacific whiting *Merluccius productus* growth using a growth-increment model. Fish. Bull. 90:260:275.

Dupanloup, I., S. Schneider, and L. Excoffier. 2002. A simulated annealing approach to define the genetic structure of populations. Molecular Ecology 11:2571–2581.

Gharrett, A.J., R.J. Riley, and P.D. Spencer. 2012. Genetic analysis reveals restricted dispersal of northern rockfish along the continental margin of the Bering Sea and Aleutian Islands. Trans. Am. Fish. Soc. 141:370-382.

Gomez-Uchida, D., and M. A. Banks. 2005. Microsatellite analyses of spatial genetic structure in darkblotched rockfish (*Sebastes crameri*): is pooling samples safe? Canadian Journal of Fisheries and Aquatic Sciences 62:1874–1886.

Hastings, A. 1993. Complex interactions between dispersal and dynamics: lessons from coupled logistic equations. Ecology 74:1362–1372.

Heifetz, J, B.L. Wing, R.P. Stone, P.W. Malecha, and D.L. Courtney 2005 Corals of the Aleutian Islands Fish. Oceanogr. 14 (Suppl. 1), 131–138, 2005

Hunt, Jr, G.L. and P.J.Stabeno. 2005. Oceanography and ecology of the Aleutian Archipelago: spatial and temporal variation. Fish. Oceanogr. 14 (Suppl. 1), 292–306.

Hyde, J. R., and R. D. Vetter. 2009. Population genetic structure in the redefined vermilion rockfish (*Sebastes miniatus*) indicates limited larval dispersal and reveals natural management units. Canadian Journal of Fisheries and Aquatic Sciences 66:1569–1581.

Kimura, D.K., and S. Chikuni. 1987. Mixtures of empirical distributions: an iterative application of the age-length key. Biometrics 43:23-34.

Ladd, C, G.L. Hunt, Jr, C.W. Mordy, S.A. Salo, and P.J. Stabeno. 2005. Marine environment of the eastern and central Aleutian Islands. Fish. Oceanogr. 14 (Suppl. 1), 22–38.

Logerwell, E.A., K. Aydin, S. Barbeaux, E. Brown, M. E. Conners, S. Lowe, J. W. Orr, I. Ortiz, R. Reuter, and P. Spencer. 2005. Geographic patterns in the demersal ichthyofauna of the Aleutian Islands. Fish. Oceanogr. 14 (Suppl. 1), 93–112.

C.W. Mordy, P.J. Stabeno, C. Ladd, S. Zeeman, D.P.Wisegarver, S.A. Salo, and G.L. Hunt, Jr. 2005. Nutrients and primary production along the eastern Aleutian Island Archipelago Fish. Oceanogr. 14 (Suppl. 1), 55–76.

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

Restrepo, V.R., Thompson, G.G., Mace, P.M., Gabriel, W.L., Low, L.L., MacCall, A.D., Methot, R.D., Powers, J.E., Taylor, B.L., Wade, P.R., Witzig, J.F. 1998. Technical Guidance on the Use of Precautionary Approaches to Implementing National Standard 1 of the Magnuson-Stevens Fishery Conservation and Management Act. NOAA Technical Memorandum NMFS-F/SPO **31**, 54 pp.

Rousset, F. 2008. GENEPOP'007: a complete re-implementation of the genepop software for Windows and Linux. Molecular Ecology Notes 8:103–106.

Rousset, F. 2000. Genetic differentiation between individuals. J. Evol. Biol. 13:58-62.

Spencer, P., M. Canino, J. DiCosimo, M. Dorn, A.J. Gharrett, D. Hanselman, K. Palof, and M. Sigler. 2010. Guidelines for determination of spatial management units for exploited populations in Alaskan fishery groundfish management plans. Paper prepared for the September 2010 NPFMC Plan Team meeting.

Stabeno,P.J., D.G. Kachel, N. B. Kachel, And M. E. Sullivan. 2005. Observations from moorings in the Aleutian Passes: temperature, salinity and transport. Fish. Oceanogr. 14 (Suppl. 1), 39–54.

Table 1. Framework of types of information to consider when defining spatial management units (from Spencer et al. 2010).

HARVEST AND TRENDS	
Factor and criterion	Justification
Fishing mortality (5-year average percent of F_{abc} or F_{ofl})	If this value is low, then conservation concern is low
Spatial concentration of fishery relative to abundance (Fishing is focused in areas << management areas)	If fishing is focused on very small areas due to patchiness or convenience, localized depletion could be a problem.
Population trends (Different areas show different trend directions)	Differing population trends reflect demographic independence that could be caused by different productivities, adaptive selection, differing fishing pressure, or better recruitment conditions
Barriers and phenotypic characters	
Generation time (e.g., >10 years)	If generation time is long, the population recovery from overharvest will be increased.
Physical limitations (Clear physical inhibitors to movement)	Sessile organism; physical barriers to dispersal such as strong oceanographic currents or fjord stocks
Growth differences (Significantly different LAA, WAA, or LW parameters)	Temporally stable differences in growth could be a result of either short term genetic selection from fishing, local environmental influences, or longer-term adaptive genetic change.
Age/size-structure (Significantly different size/age compositions)	Differing recruitment by area could manifest in different age/size compositions. This could be caused by different spawning times, local conditions, or a phenotypic response to genetic adaptation.
Spawning time differences (Significantly different mean time of spawning)	Differences in spawning time could be a result of local environmental conditions, but indicate isolated spawning stocks.
Maturity-at-age/length differences (Significantly different mean maturity-at-age/ length)	Temporally stable differences in maturity-at-age could be a result of fishing mortality, environmental conditions, or adaptive genetic change.
Morphometrics (Field identifiable characters)	Identifiable physical attributes may indicate underlying genotypic variation or adaptive selection. Mixed stocks w/ different reproductive timing would need to be field identified to quantify abundance and catch
Meristics (Minimally overlapping differences in counts)	Differences in counts such as gillrakers suggest different environments during early life stages.
Behavior & movement	
Spawning site fidelity (Spawning individuals occur in same location consistently)	Primary indicator of limited dispersal or homing
Mark-recapture data (Tagging data may show limited movement)	If tag returns indicate large movements and spawning of fish among spawning grounds, this would suggest panmixia
Natural tags (Acquired tags may show movement smaller than management areas)	Otolith microchemistry and parasites can indicate natal origins, showing amount of dispersal
Genetics	
Isolation by distance (Significant regression)	Indicator of limited dispersal within a continuous population
Dispersal distance (<<Management areas)	Genetic data can be used to corroborate or refute movement from tagging data. If conflicting, resolution between sources is needed.
Pairwise genetic differences (Significant differences between geographically distinct collections)	Indicates reproductive isolation.

Table 2. *P*-values from an ANOVA comparing mean age of northern rockfish from subareas from the Aleutian Islands survey.

Year: 2002

Area	Central AI	Eastern AI	Western AI
SBS	0.22	<0.01	0.91
Central AI		0.07	0.27
Eastern AI			<0.01

Year: 2004

Area	Central AI	Eastern AI	Western AI
SBS	0.99	0.64	0.11
Central AI		0.14	<0.01
Eastern AI			<0.01

Year: 2006

Area	Central AI	Eastern AI	Western AI
SBS	0.98	0.71	0.85
Central AI		0.54	0.10
Eastern AI			<0.01

Table 3. Summary of available data on stock identification for BSAI northern rockfish.

HARVEST AND TRENDS	
Factor and criterion	Available information
Fishing mortality (5-year average percent of F_{abc} or F_{ofl})	Recent catch in the BSAI are approximately ½ the ABC level
Spatial concentration of fishery relative to abundance (Fishing is focused in areas << management areas)	Estimated exploitation rates in the eastern AI have exceeded the 0.75**M* in recent years.
Population trends (Different areas show different trend directions)	Population trends do not appear to be different between areas, although the uncertainty of the survey data in the subareas increases with smaller sample sizes.
Barriers and phenotypic characters	
Generation time (e.g., >10 years)	The generation time is approximately 36 years
Physical limitations (Clear physical inhibitors to movement)	The Aleutian North Slope Current does not extend west of the central AI, limiting the connections within the AI. Also, studies of the AI ecosystem indicate a "biophysical transition zone" at Samalga Pass (Logerwell et al. 2005)
Growth differences (Significantly different LAA, WAA, or LW parameters)	Significantly different growth curves were observed between the AI subareas.
Age/size-structure (Significantly different size/age compositions)	Significant differences were found between subareas within individual years, but a consistent pattern was not observed.
Spawning time differences (Significantly different mean time of spawning)	Unknown
Maturity-at-age/length differences (Significantly different mean maturity-at-age/ length)	Unknown
Morphometrics (Field identifiable characters)	Unknown
Meristics (Minimally overlapping differences in counts)	Unknown
Behavior & movement	
Spawning site fidelity (Spawning individuals occur in same location consistently)	Unknown
Mark-recapture data (Tagging data may show limited movement)	Mark-recapture data not available
Natural tags (Acquired tags may show movement smaller than management areas)	Unkown
Genetics	
Isolation by distance (Significant regression)	Significant pattern of isolation by distance.
Dispersal distance (<<Management areas)	Single generation dispersal scale of <= ~ 200 km, which is << the combined BSAI management area
Pairwise genetic differences (Significant differences between geographically distinct collections)	Significant pairwise differences between sets of genetic samples in the BSAI.

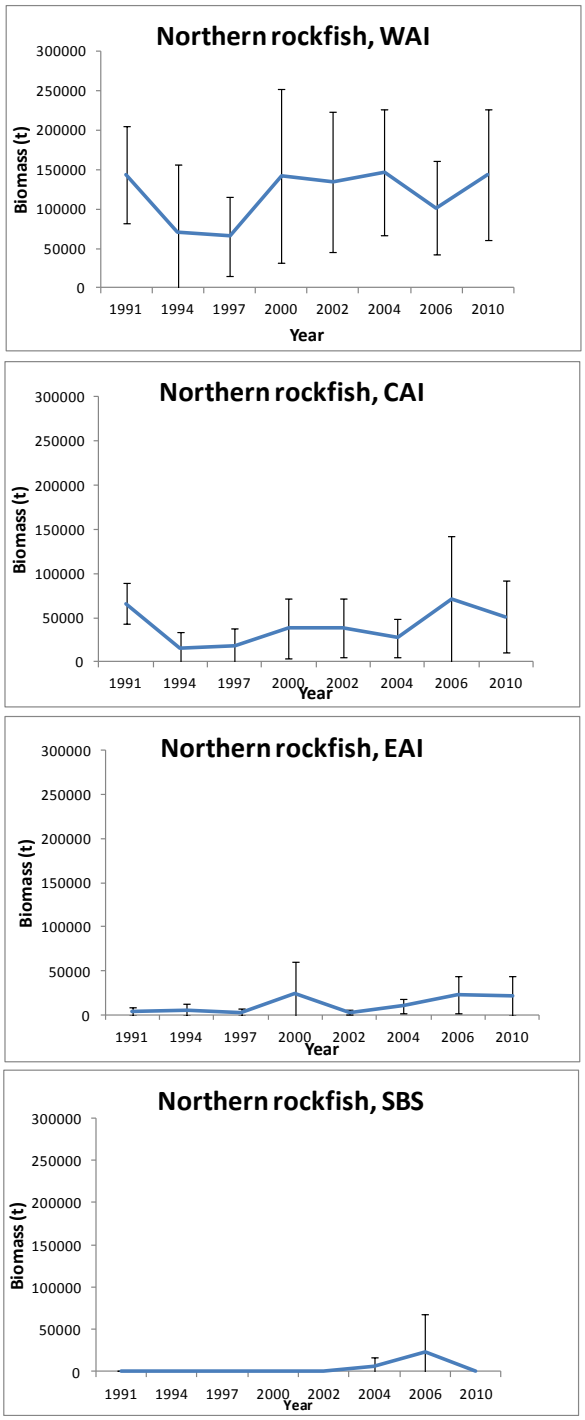

Figure 1. Northern rockfish biomass estimates from the Aleutian Islands survey.

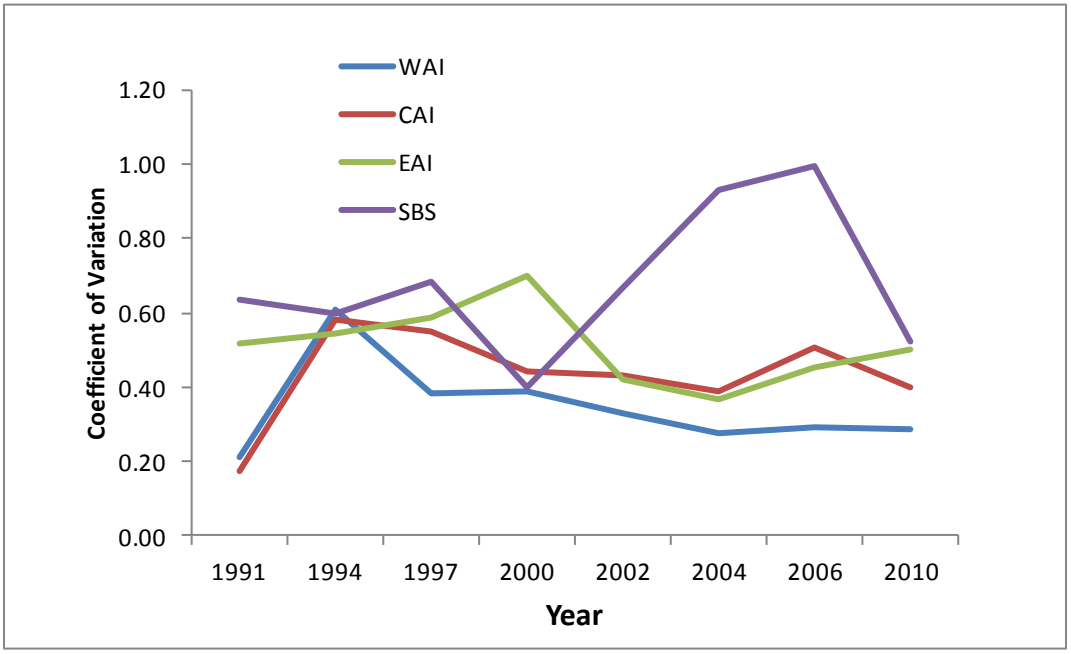

Figure 2. Coefficients of variation (CV) for northern rockfish biomass estimates from the Aleutian Islands survey.

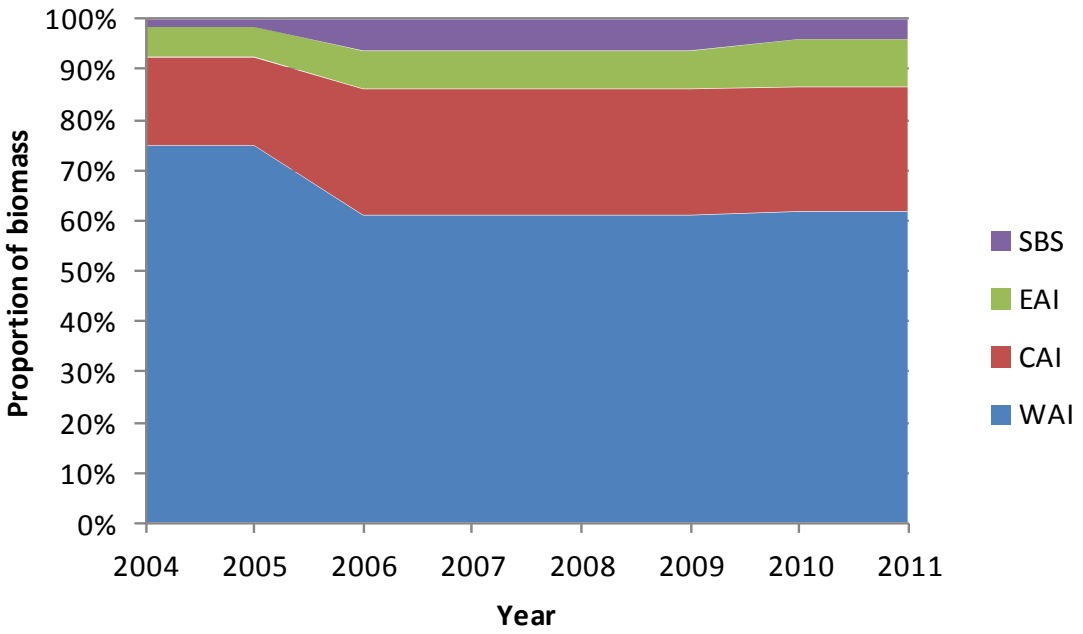

Figure 3. Estimated proportions of northern rockfish biomass for Aleutian Islands survey subareas, 2004-2011. For each year, the proportions were computed from weighted averages of the three most recent surveys.

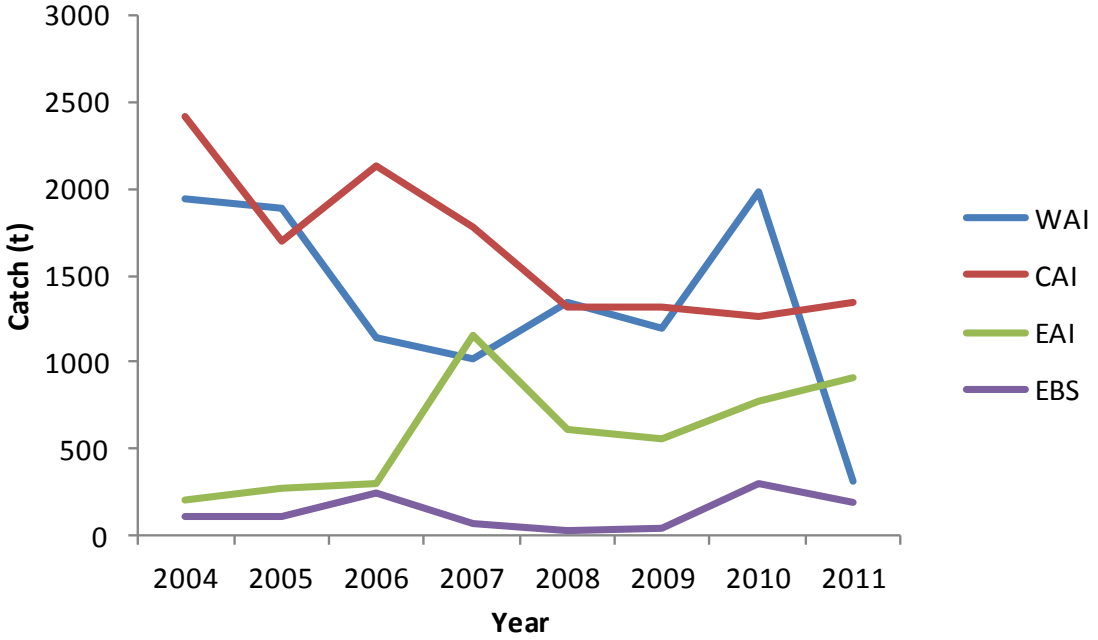

Figure 4. Catch (t) of northern rockfish by BSAI subarea, 2004-2011.

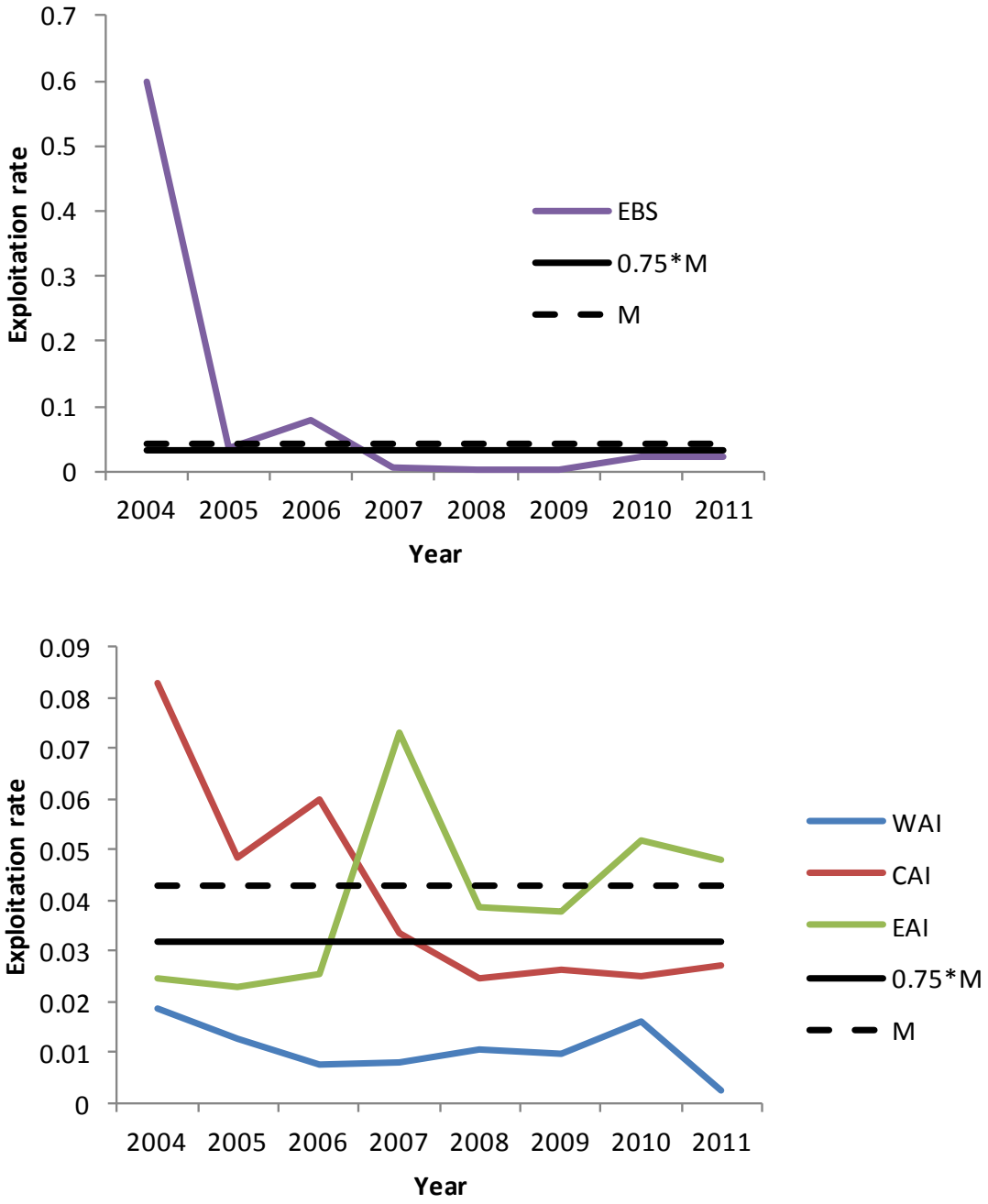

Figure 5. Estimated northern rockfish exploitation rates by area from 2004-2011.

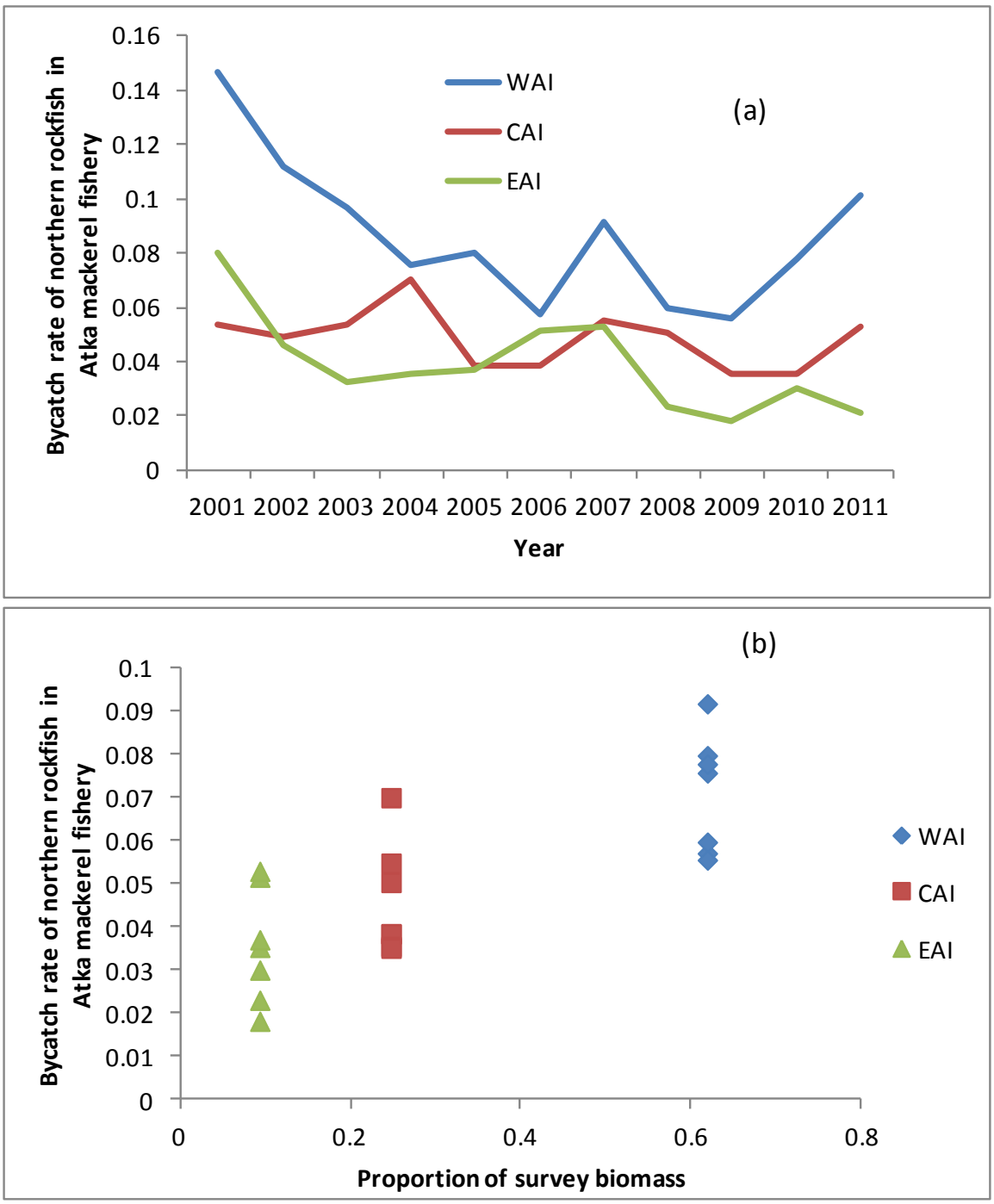

Figure 6. Northern rockfish bycatch rates from 2001-2011 (a), and from 2004-2010 as function of average proportion of Aleutian Islands survey biomass. Bycatch rates were computed as the tons of northern rockfish caught per ton of Akta mackerel caught in hauls sampled by fishery observers.

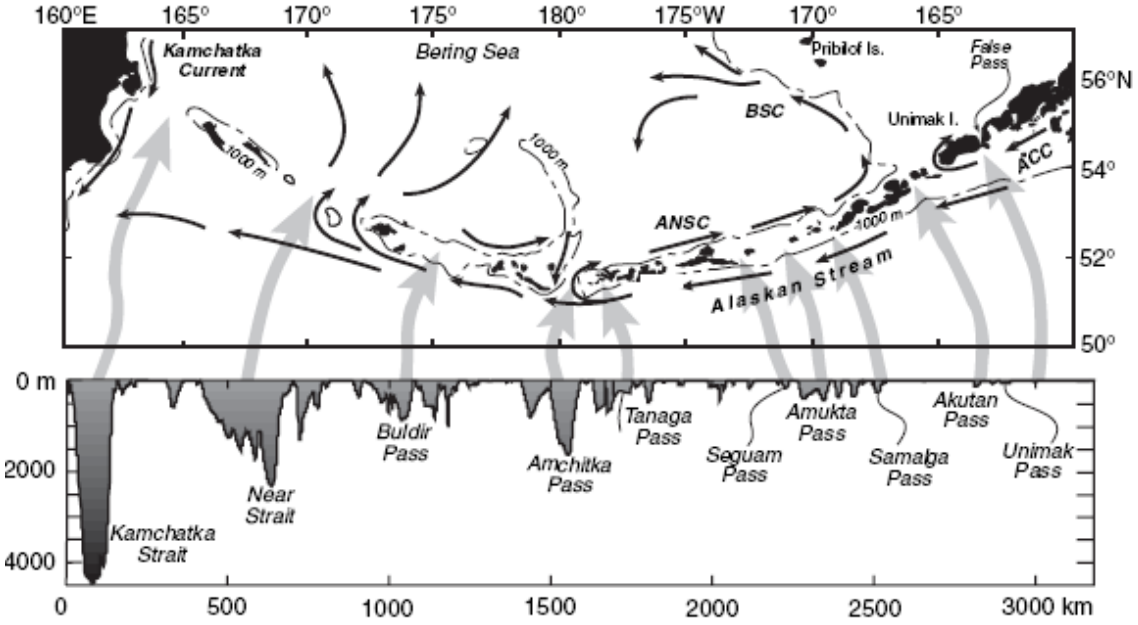

Figure 7. Schematic of ocean currents in the Aleutian Islands, showing the Alaska Steam, the Alaska Coastal Current (ACC), and the Aleutian North Slope Current (ANSC) (from Stabeno et al. 2005). The lower panel shows the location and depth of ocean passes in the Aleutian Islands archipelago.

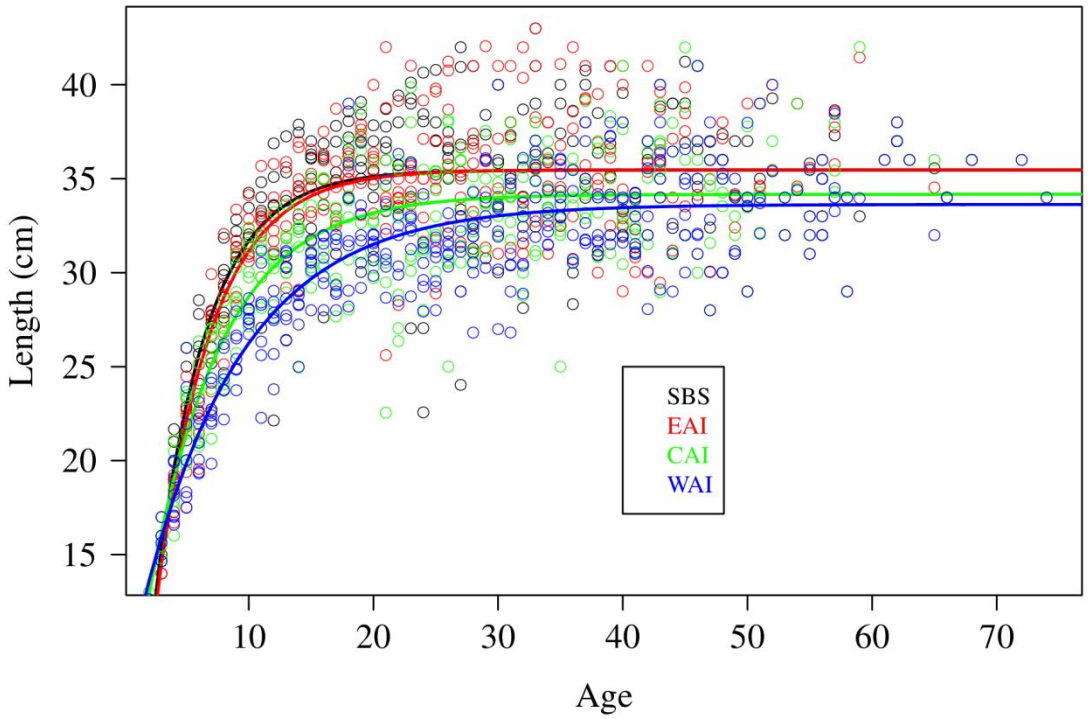

Figure 8. Estimated area-specific growth curves for northern rockfish, based Aleutian Islands survey data from 1986-2006.

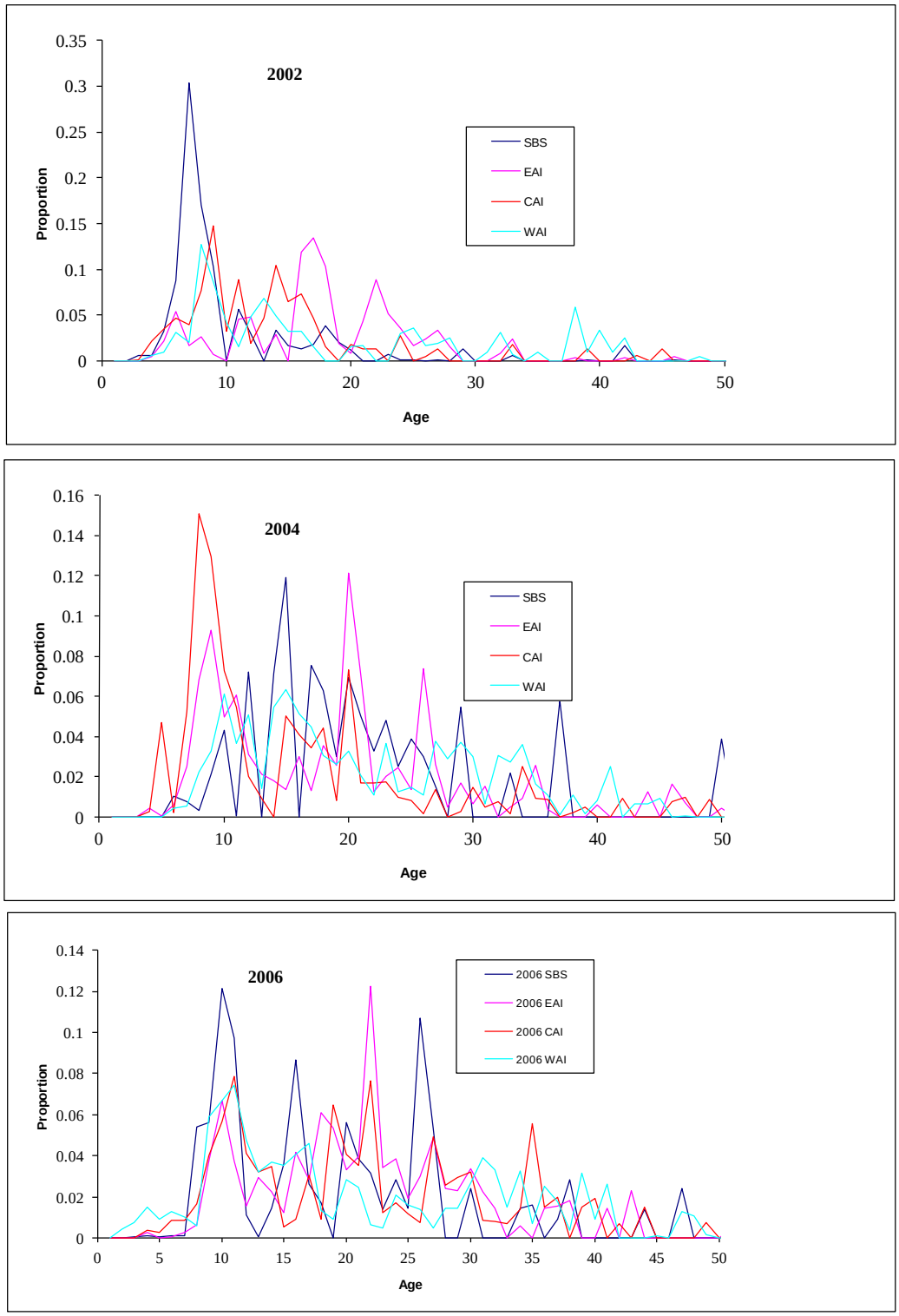

Figure 9. Survey age compositions for northern rockfish from the Aleutian Islands survey, 2002-2006.

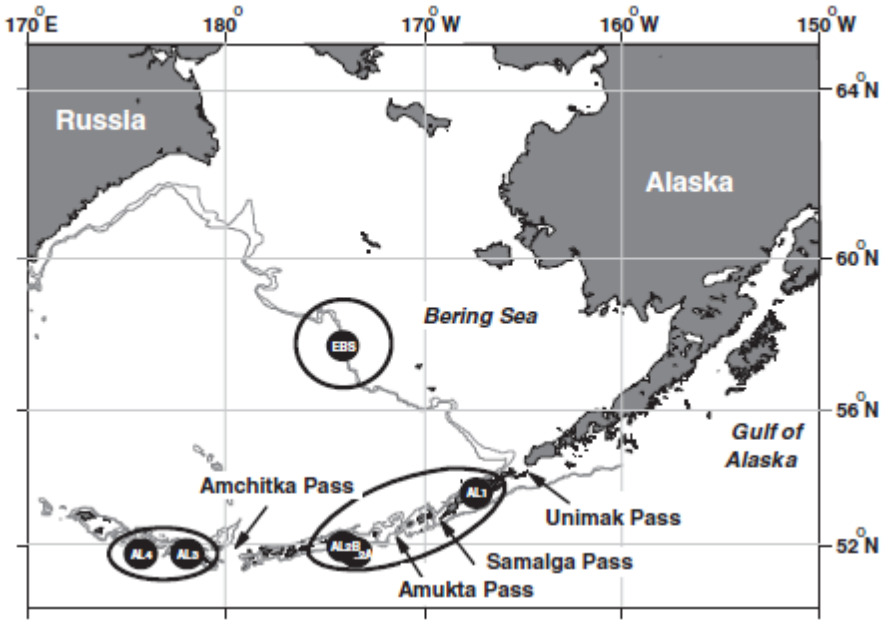

Figure 10. Locations of northern rockfish genetic samples obtained from the 2004 Aleutian Islands survey. The circles enclose sets of locations that were found to be genetically distinct based on spatial analysis of molecular variance (from Gharrett et al. 2012).

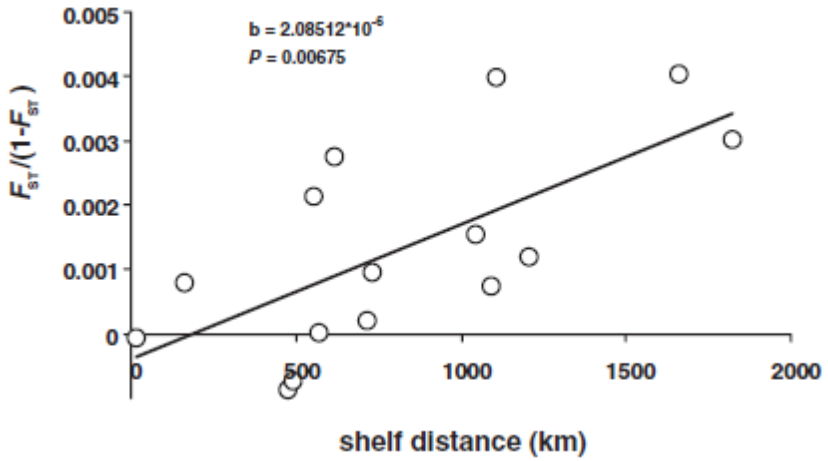

Figure 11. Relative F_{st} as function of geographical distance for six collections of northern rockfish genetics samples from the BSAI (from Gharrett et al. 2012).