Evaluation of Stock Structure for Gulf of Alaska Walleye Pollock

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1.0 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 that identifies various scientific data from which we may infer stock structure (Table 1). The joint Plan Team at its September 2011 meeting recommended application of the template consistently to all stocks, and identified Gulf of Alaska walleye pollock as a candidate for initial application of the template.

This document considers evidence of pollock spatial structure in the Gulf of Alaska, and does not consider larger-scale issues such as connectivity between pollock in the Gulf of Alaska and the eastern Bering Sea or the Aleutian Islands. The template developed by the stock structure committee is used to summarize scientific information on walleye pollock in the Gulf of Alaska. The document evaluates whether the current spatial management measures for Gulf of Alaska walleye pollock are consistent with the scientific information and with the Council's broad objectives for fisheries management.

Walleye pollock (*Theragra chalcogramma*) is a semi-pelagic schooling fish widely distributed in the North Pacific Ocean and adjoining waters such as the Sea of Okhotsk and Bering Sea (Fig. 1). Pollock in the Gulf of Alaska are managed as a single stock independently of pollock in the Bering Sea and Aleutian Islands. Currently pollock in the Gulf of Alaska are managed using seasonal openings by management area. ABCs are set by management area, while OFLs are set for Central/Western and Eastern stocks. This system was developed as a protection measure for Steller sea lions, listed as endangered under the ESA, but also serves to maintain historical participation in the fishery by different communities in the Gulf of Alaska.

2. Application of stock structure template to Gulf of Alaska walleye pollock.

2.1 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)
The estimates of fishing mortality for the ten-year period 2002-2011, obtained from the 2011 assessment (Dorn et al. 2011), ranged from 0.07 to 0.17 with a mean of 0.12. The ratio of catch to the ABC during this period ranged from 0.83 to 1.02 with mean of 0.96, indicating that pollock are fully exploited in the Gulf of Alaska.

Spatial concentration of harvest relative to abundance
The Steller Sea Lion Protection Measures implemented in 2001 established four seasons in the Central and Western GOA 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. There is no independent way to evaluate how well the goal of harvesting pollock proportional to biomass has been achieved. Comparisons of the ratio of the catch to survey biomass will not be informative because allocation is itself based on survey biomass.

Population trends
The NMFS bottom trawl surveys beginning in 1990 are the most useful for studying spatial aspects of the pollock stock in the GOA because they cover the entire Gulf of Alaska (except in 2000 when the eastern Gulf of Alaska was not surveyed). The CPUE of pollock is the highest on average in the Shumagin area, declines to a minimum in the Yakutat INPFC, and then increases in the Southeast INPFC area (Fig. 2). Estimates of biomass by area depend on both CPUE and the area surveyed. The continental shelf is very narrow along Southeast Alaska, but becomes much more extensive near Kodiak Island and along the Alaska Peninsula. Mean biomass is greater 100,000 t in Shumagin, Chirikof, and Kodiak INPFC area, but is less than 50,000 t in Yakutat and Southeast INPFC areas (Fig. 3). Trends in relative biomass were broadly similar between INPFC areas, showing a decline followed by an increase over the period 1990-2011 (Figure 4). A possible exception is the Southeast area, where biomass was not high initially, but this may be due to sparse sampling of this area in the early years of the survey.

2.2 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 GOA pollock is 7.9 years. This is probably on the low side of the range for groundfish in the North Pacific, and is much lower than rockfish. For example, the generation time of BSAI rougheye rockfish is 53 years. A low generation time implies that the GOA pollock population should show fairly rapid response to changes in environment and fisheries management measures.

Physical limitations (clear physical inhibitors to movement)

The Gulf of Alaska is a highly advective system, with strong currents that follow the arc of the coastline northwards then westwards (Fig 5). The Alaska Coast Current, which reaches speeds of 25-100 cm s^{-1}, flows along the continental shelf and through Shelikof Strait, while the Alaska Stream flows offshore of the continental shelf (Stabeno et al. 2004). Oceanographic barriers that would limit mixing of populations are not evident. Since pollock have pelagic eggs and larvae, transport would tend to be "downstream" of spawning locations in the prevailing currents. To avoid being transported out of the system, pelagic offspring will need to be retained in the nearshore areas long enough to develop locomotory capacity, and spawning sites may be situated to enhance retention of offspring. The primary spawning grounds of pollock in the Gulf of Alaska, Shelikof Strait, may be one such area. If these sites are scarce and widely-spaced, this would provide a potential mechanism to structure populations. A number of spawning areas in the central and western Gulf of Alaska have been identified (Fig. 6), but all are relatively small in comparison to the Shelikof Strait spawning grounds (Fig. 7). Less is known about pollock spawning locations in eastern Gulf of Alaska, but there appears to be gap between the spawning areas near Prince William Sound and those areas in Dixon Entrance and northern British Columbia (Fig. 8). Natal homing has not been demonstrated for walleye pollock.

Growth differences

Spatial differences in growth were evaluated use length and age data from the NMFS bottom trawl survey in 2005-2009. A total of 4331 samples were selected randomly from the survey catch. Five spatial strata were defined according to INPFC areas: Shumagin—Area 610, Chirikof—Area 620, Kodiak—Area 630, West Yakutat—Area 640 (west of 140°W long.), 650—Southeast (remainder of the Yakutat and Southeast Alaska)—Area 650. von Bertalanffy growth curves were fit by sex using NLS routine in R, which assumes deviations from the curve are distributed normally. In the years used in this analysis the NMFS bottom trawl survey extended from late May to the beginning of August, and worked from west to east, finishing up in each year in Southeast Alaska. Pollock are grow rapidly during this time of the year, particularly the younger fish. Consequently spatial differences in growth are potentially confounded with seasonal differences. To take this into account, I assumed that the growth year extended from 1-April to 31-October, and adjusted the age of the fish according to the proportion of growth year before the sample was collected. This affected mainly the estimate of t_{zero}, and made this parameter much more similar across areas.

Length at age was similar in all areas for fish ages 1-4, but for the older fish there were differences between areas (Figs. 9 and 10). The West Yakutat and Southeast areas showed progressively lower L_{inf} and higher k, while the other three areas showed little differences in growth (Table 2). To evaluate similarities between areas a little more rigorously, I used an iterative procedure to evaluate which combinations of areas produced the smallest increase in mean square error. First, all possible pair-wise comparisons were evaluated, and the pair of areas with the smallest increase in mean squared error was combined. This new combination was included in second round of pair-wise comparisons, and so on.

The combinations proceeded as follows (bolded areas indicate areas that were combined at each step):

Pairwise combinations	Areas	Δ MSE
1st step	**630&640**, 610, 620, 650	0.27
2nd step	**610&630&640**, 620, 650	0.45
3rd step	**610&620&630&640**, 650	0.56
Final step	**610&620&630&640&650**	1.15

The sequence of combinations generates a group that includes the western and central Gulf of Alaska together, and lastly adds Southeast Alaska. These results suggest that pollock growth in Southeast Alaska is strongly dissimilar to growth in the other areas, and that growth in the western Yakutat area is closer to growth in the Kodiak area than Southeast Alaska.

Age composition data

The estimated age compositions of walleye were obtained from data from NMFS trawl surveys conducted from 2005 to 2009. To facilitate comparisons, the cumulative age distribution was plotted for each area using the same areas as the length at age analysis (Figure 11). There is consistent pattern of decreasing age from west to east. Southeast Alaska has the youngest fish, while the Shumagin area consistently contains the oldest fish. Age-1 and age-2 pollock are present in all areas, so it would be incorrect to conclude from this analysis that any area is preferred juvenile habitat. An example showing the widespread distribution of age-1 pollock is given in Figure 12.

Spawning time differences

The time of peak spawning occurs at different times at different major spawning areas in the Gulf of Alaska. In the Shumagin area, including Sanak Trough and Shumagin Gully, spawning occurs in mid to late February. In the central Gulf of Alaska (including Shelikof Strait, and Prince William Sound), spawning occurs in late March to early April. It is unclear whether the difference in timing is due to the older fish in this area, which may tend to spawn earlier, or whether it reflects genetic differences between spawners, or a response to differing environmental conditions in the two areas.

2.3 Genetics

Genetic studies of pollock have tended to focus on larger scales, such as distinguishing Asiatic from North American stocks, or distinguishing eastern Bering Sea and Gulf of Alaska stocks. The studies have generally found that pollock lack strong genetic structure, which is not unusual for many marine species. However these results may reflect the choice of sampling locations and times and the types of genetic material studied. 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).

Pairwise genetic differences (significant differences between geographically distinct collections)
Olsen et al. (2002) specifically examined evidence of stock structure within the Gulf of Alaska, although their Gulf of Alaska samples came from only Shelikof Strait, Prince William Sound and Middleton Island, and did not include other spawning sites in Gulf of Alaska. Olsen et al. (2002) found evidence from allozyme frequency and mtDNA that spawning populations in the northern part of the Gulf of Alaska (Prince William Sound and Middleton Island) are genetically distinct from the Shelikof Strait spawning population. Shelikof Strait and Prince William Sound were found to be significantly different based on allozyme data but not based on mtDNA data, while in contrast Shelikof Strait and Middleton Island were found to be significantly different based on mtDNA but not based on allozyme data. In addition, significant variation in allozyme frequency was found between Prince William Sound samples in 1997 and 1998, indicating a lack of stability in genetic structure for this spawning population. Olsen et al. (2002) suggest that interannual genetic variation may be due to variable reproductive success (i.e., the “sweepstakes” hypothesis), adult philopatry, source-sink population structure, or utilization of the same spawning areas by genetically distinct stocks with different spawning timing.

2.4 Interpretation of the information regarding stock structure

A summary of the information in the template for Gulf of Alaska pollock 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.

The available information on pollock for areas 610-630 (Shumagin to Kodiak) supports considering pollock in these areas as a single stock, albeit with some spatial heterogeneity. Growth is similar among areas, and differences in age composition may be due to ontogenetic movement and to interannual variation in juvenile settlement. The role of different spawning areas in contributing to pollock recruitment is not well resolved, but clearly Shelikof Strait is important. In addition, spawning areas that are “upstream” in the prevailing currents such as the spawning that occurs in Prince William Sound and in Kenai Peninsula Bays may also be important.

From Prince William Sound to Southeast Alaska, there is stronger evidence of stock structure. Growth is very different in Southeast Alaska and age composition is shifted towards younger fish. Spawning from Prince William Sound and further west would not be expected to lead to settlement of juveniles in Southeast Alaska given current flow patterns. In addition, there is evidence of genetic distinctness of pollock near Prince William Sound, though the evidence is a little ambiguous. The available data supports consideration of Southeast Alaska as a separate pollock stock, but precise determination of where the split should be located is not possible. There is weaker support for identifying a stock in area 640 that may or may not include Prince William Sound. This area may be more usefully regarded as a transitional region with some affinities with both southeast Alaska and Central/Western stocks. A genetic study that is explicitly designed to address issues of pollock stock structure in the Gulf of Alaska would be very valuable. Sampling should be done on spawning aggregations with the objective of collecting samples from all known spawning areas in the Gulf of Alaska.

3.0 Management implications

History of spatial and seasonal management units for GOA walleye pollock
Spatial management has been used for pollock since the development of the domestic fishery in the late 1980s. Since at least 1988, separate ABCs were set for a Central/Western stock and an Eastern stock. In 1989-1991, a separate allocation was set for Shelikof Strait to reduce fishing pressure on the pollock that were spawning in this area. In 1992, Amendment 25 provided for the spatial allocation by Shumagin, Chirikof and Kodiak regulatory areas for the Central/Western stock based on biomass distribution to reduce potential impacts on Steller Sea Lions. Overfishing levels were set at the stock level, i.e., for the Central/Western stock and Eastern stock, but ABCs were set for the regulatory subareas.

Seasonal apportionment began in 1995 with four quarterly allocations beginning January 1, June 1, July 1, and October 1, again to reduce potential impacts on Steller sea lions. The details of the seasonal allocation scheme were tweaked over time by changing the number of seasonal allocations, the dates of openings, and percentage that can be taken during each season. However the general objective was to allocate the TAC to management areas based on the distribution of surveyed biomass, and to establish three or four seasons between mid-January and autumn during which some fraction of the TAC can be taken. The Steller Sea Lion Protection Measures implemented in 2001 established four seasons in the Central and Western GOA 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.

Although not pertaining to the Gulf of Alaska pollock, there was petition in 1999 to declare walleye pollock (among other species) in Puget Sound as endangered under the ESA. A biological review team (BRT) was convened and charged with establishing distinct population segment (DPS) for walleye pollock. The DPS concept developed under the ESA does not exactly correspond to a unit stock under the MSFCMA, and can consist of a number of demographically independent stocks. The BRT noted that most

studies of genetic population structure in walleye pollock have revealed low levels of differentiation where physical barriers to migration are lacking, and identified a Lower boreal Eastern Pacific DPS for walleye pollock extending from Puget Sound to a provisional northern boundary of 140°W longitude, which corresponds to the current break between Eastern stock and the Central/Western stock.

Implications for stock sustainability and risks/costs to the fishery and regulatory system
The SSWG report (Spencer et al. 2010) suggests that an "evaluation of the risks (biological and fishery) under alternative hypotheses concerning stock structure" be considered in the stock structure evaluation report. In particular, the risk evaluation would involve consideration of alternative management approaches for dealing with stock structure, such as setting separate ABCs and OFLs by area, or separate stock assessments and status determination criteria by area.

With the possible exception of the split between the Eastern GOA and the Central/Western GOA, the current spatial and seasonal apportionment procedure for pollock in the GOA was not developed to account for stock structure. Overfishing levels are set at the stock level, and ABCs are used to manage harvest for regional subareas to reduce impacts on Steller sea lions. Harvesting proportionate to biomass is considered to provide the least impact on Steller sea lions, but at the same time it provides protection against unequal harvest of any unrecognized component of stock structure. For example, the current treatment of area 640 and Prince William Sound in the management system produces catch/biomass ratios that are similar to those that would result if they were managed separately using a Tier 5 assessment.

This evaluation of stock structure did not reveal any major concerns about the present management system for Gulf of Alaska pollock with respect to stock structure, and if anything may be overly precautionary. The current split between the Central/Western stock and an Eastern stock is well supported. Although there is evidence of additional structure in the population, it does not seem sufficiently resolved into a clear pattern that would warrant defining additional stocks for management. One risk when managing for multiple spatial and seasonal quotas is that biomass estimates for small areas have considerable uncertainty, so that an apportioning procedure could result in mistakenly allocating a large quota in an area where there is little biomass. The seasonal and spatial management system is perhaps one of the most complicated developed for any fishery, and likely requires substantial efforts from in-season managers to implement.

Acknowledgements

I thank Paul Spencer for well-considered contributions to engaging discussions.

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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. von Bertalanffy growth parameters by area for walleye pollock in the Gulf of Alaska.

Area	Sex	Number aged	t_{izero}	K	L_{inf}
610	Male	474	0.43	0.298	61.6
620	Male	472	0.61	0.312	63.3
630	Male	478	0.46	0.332	60.8
640W	Male	144	0.47	0.391	55.9
650	Male	377	0.45	0.449	51.7
610	Female	487	0.38	0.256	67.9
620	Female	560	0.58	0.267	70.6
630	Female	580	0.49	0.288	67.9
640W	Female	212	0.46	0.353	61.3
650	Female	547	0.44	0.414	55.0

Table 3. Summary of available data on stock identification for GOA walleye pollock.

Harvest and trends	
Factor and criterion	Available information
Fishing mortality (5-year average percent of F_{abc} or F_{ofl})	Recent catches are very close the ABC.
Spatial concentration of fishery relative to abundance (Fishing is focused in areas << management areas)	Catches are apportioned according to the seasonal distribution of biomass as estimated by running averages of assessment surveys. Catches are not allocated at a smaller scale than regional management areas.
Population trends (Different areas show different trend directions)	Population trends based on survey data show a decline followed by an increase over the period 1990-2011. Different areas in the GOA have roughly concordant trends given the uncertainties in the data.
Barriers and phenotypic characters	
Generation time (e.g., >10 years)	The generation time is approximately 7.9 years
Physical limitations (Clear physical inhibitors to movement)	The northernmost point of GOA is considered biogeographic boundary. GOA is a strongly mixing and strongly advective system.
Growth differences (Significantly different LAA, WAA, or LW parameters)	Differences growth curves and length-at-age relationships between between INPFC area. The strongest differences are between eastern GOA and the other areas combined.
Age/size-structure (Significantly different size/age compositions)	Differences in age composition between areas in the GOA.
Spawning time differences (Significantly different mean time of spawning)	Spawning occurs earlier in the Western GOA.
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)	Unknown
Genetics	
Isolation by distance (Significant regression)	IBD in the entire geographic range of pollock, but genetic structure is not strong. No suitable studies within the GOA to estimate IBD.
Dispersal distance (<<Management areas)	No dispersal distances estimated as no IBD pattern observed.
Pairwise genetic differences (Significant differences between geographically distinct collections)	Pairwise differences have been found between Shelikof Strait and Middleton Island (mtDNA data), and between Shelikof Strait and Prince William Sound (allozyme data).

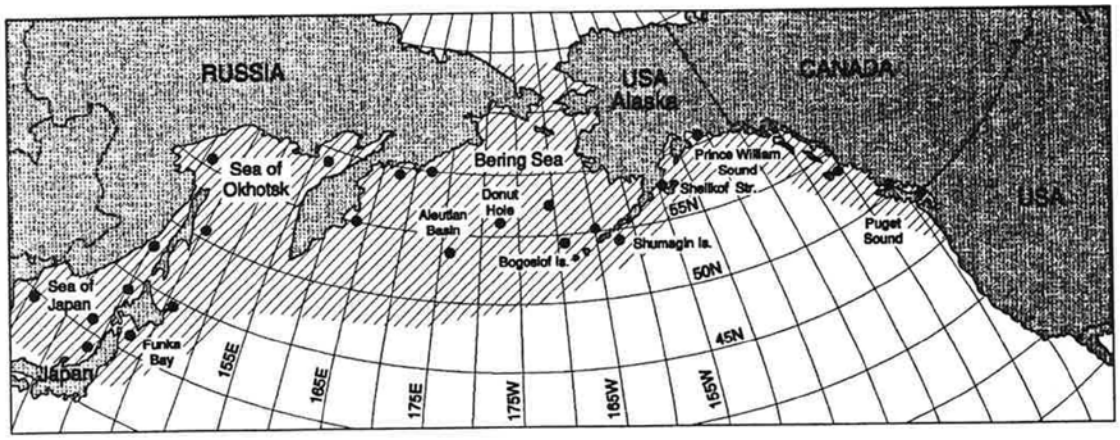

Figure 1. Distribution of walleye pollock in the North Pacific. From Bailey et al. (1999).

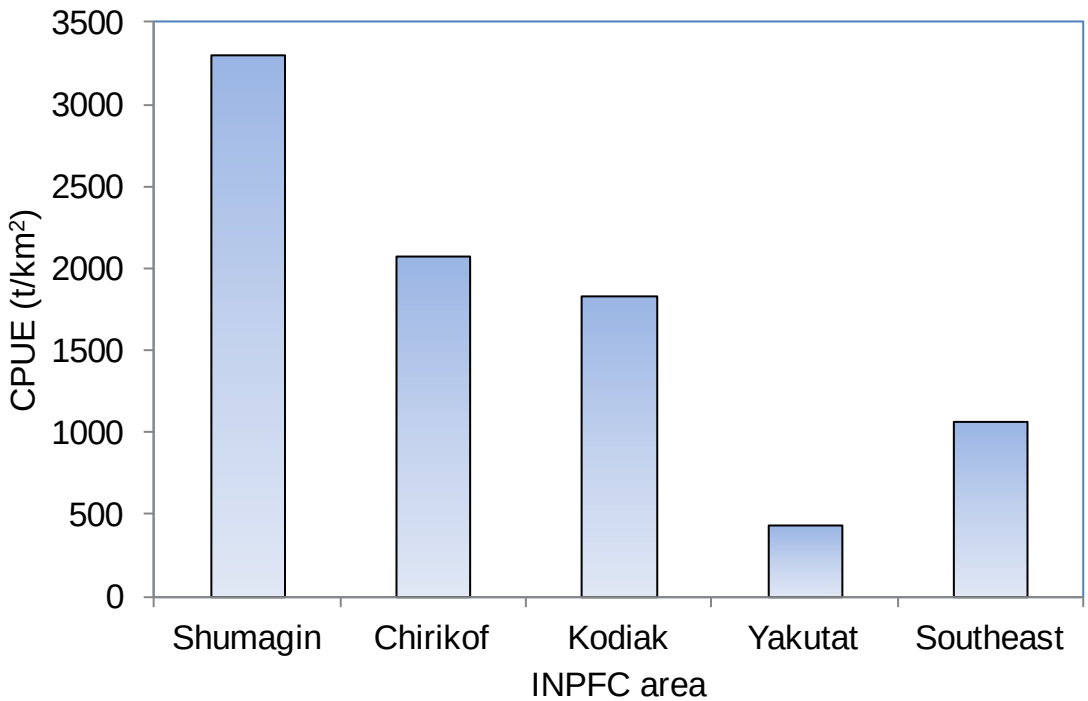

Figure 2. Weighted mean CPUE (t/km^2) for walleye pollock by INMPFC area for the NMFS bottom trawl survey in 1990-2011.

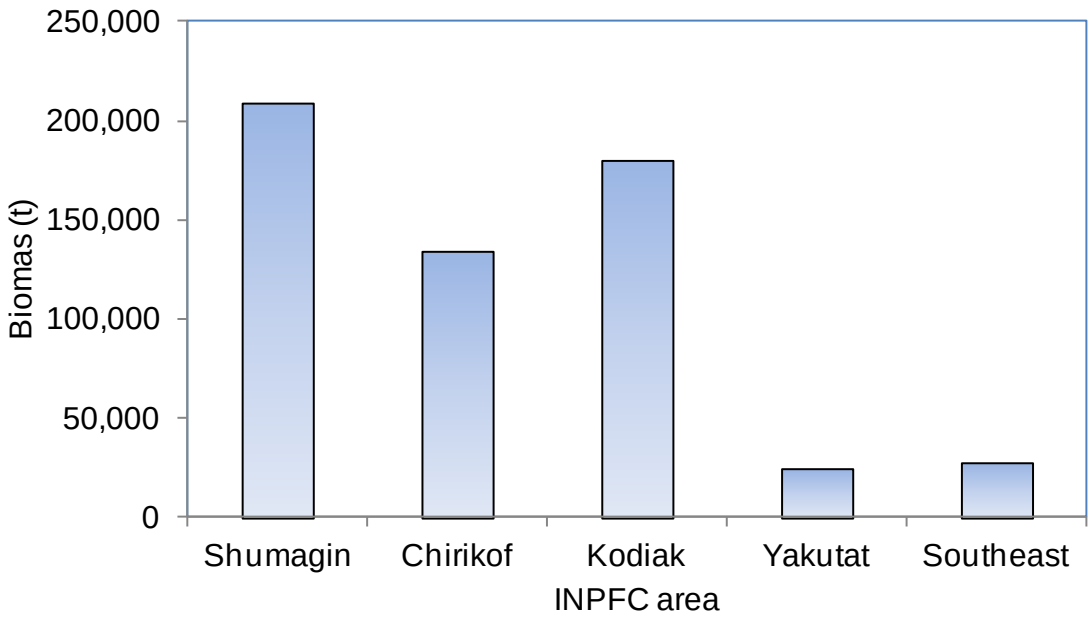

Figure 3. Mean biomass of walleye pollock by INPFC area for the NMFS bottom trawl survey in 1990-2011.

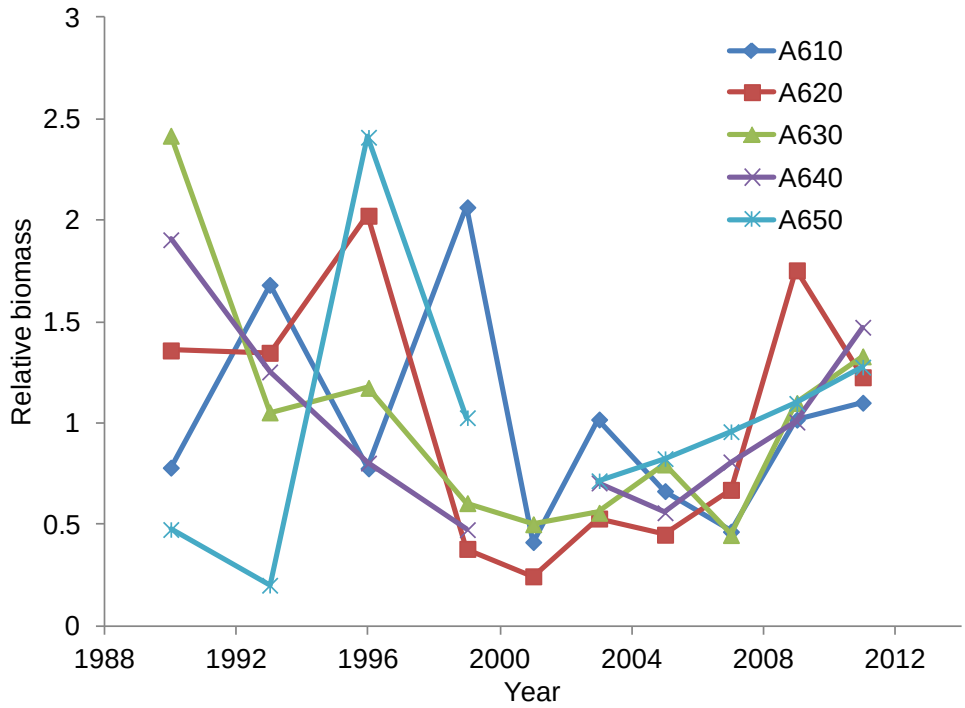

Figure 4. Relative biomass trends by INPFC area for the NMFS bottom trawl survey in 1990-2011.

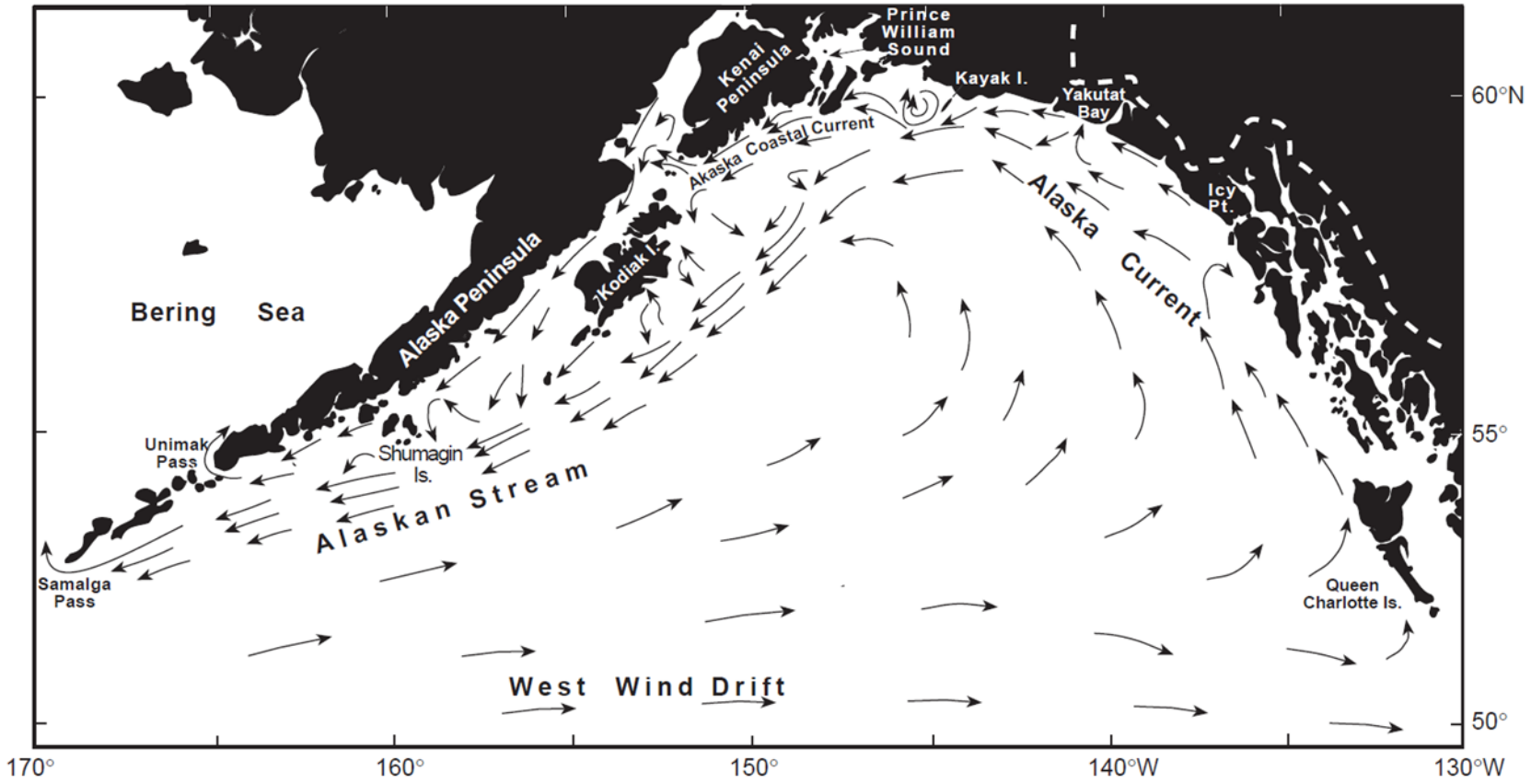

Figure 5. Schematic of ocean currents in the Gulf of Alaska, showing the Alaska Current, the Alaska Coastal Current (ACC), and the Alaskan Stream (AS) (from Stabeno et al. 2005).

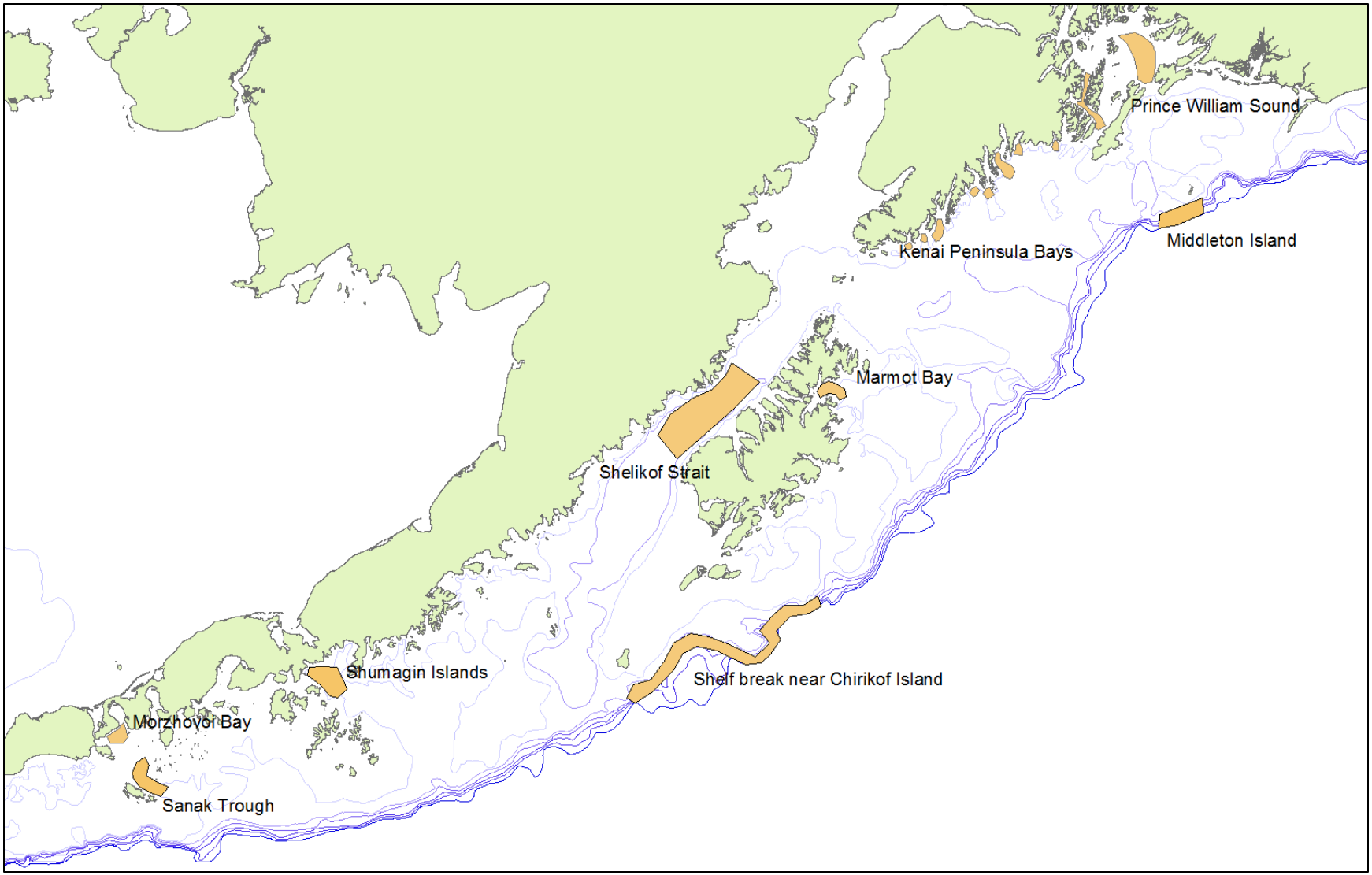

Figure 6. Spawning areas of pollock in the Gulf of Alaska.

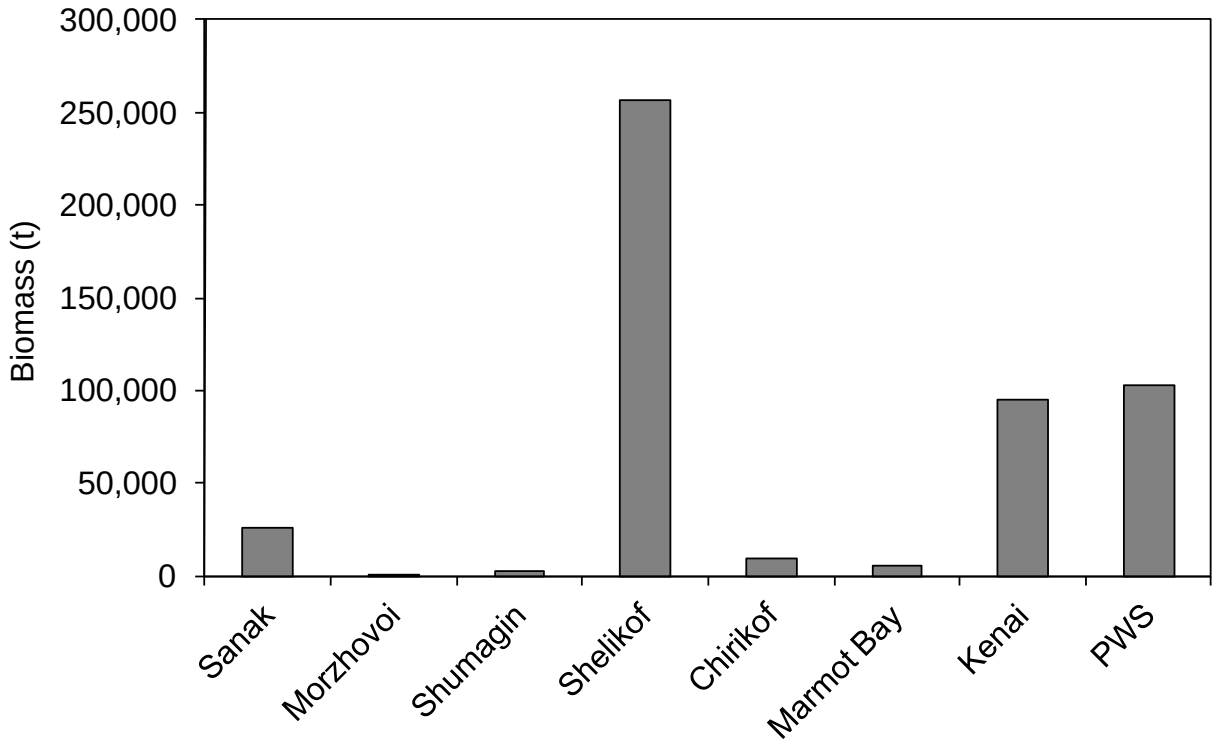

Figure 7. Total spawning biomass by area in winter 2010. Spawning biomass in Shelikof Strait is 52% of the total estimated for all areas.

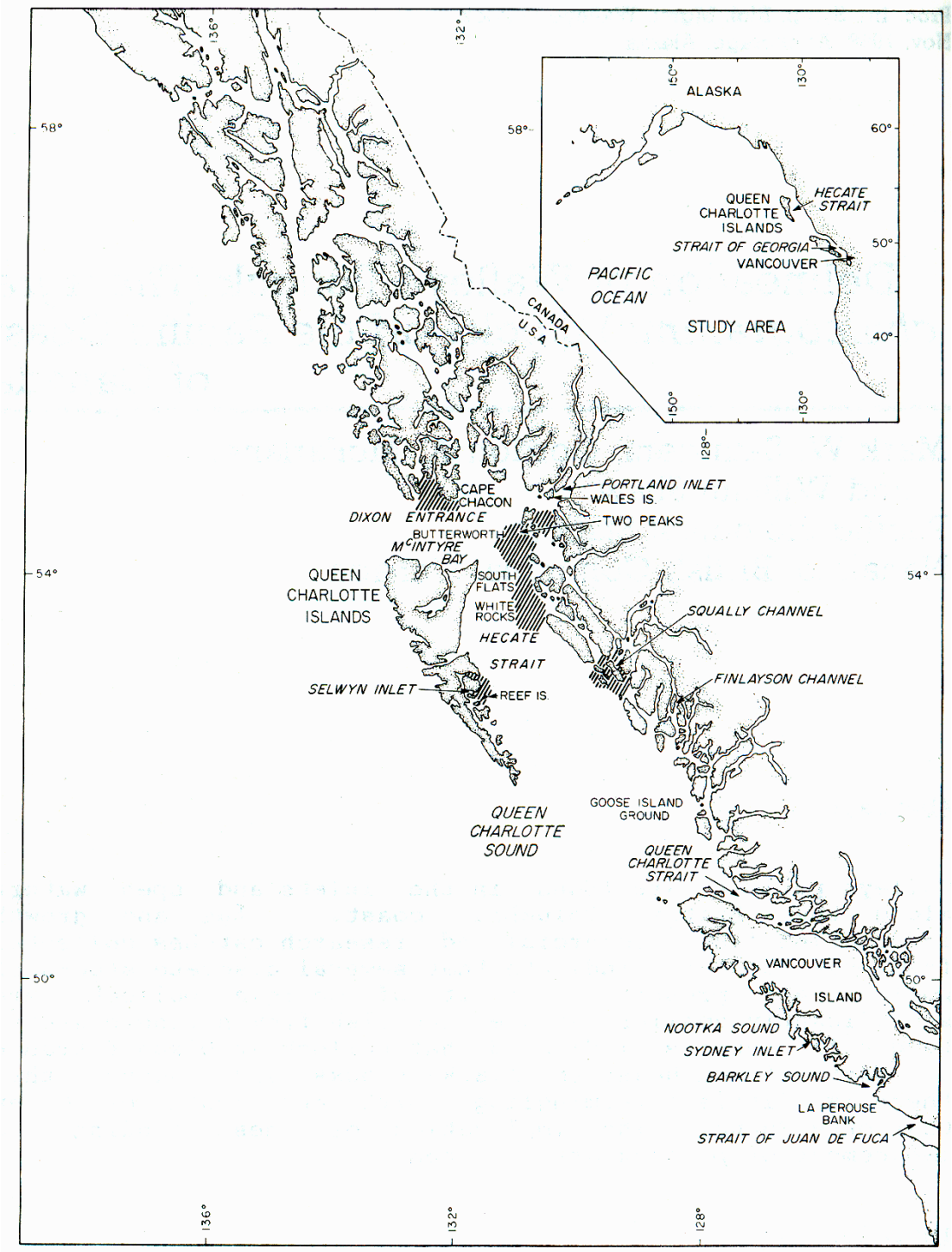

Figure 8. Reported spawning areas of pollock the eastern Gulf of Alaska (from Saunders et al. 1989).

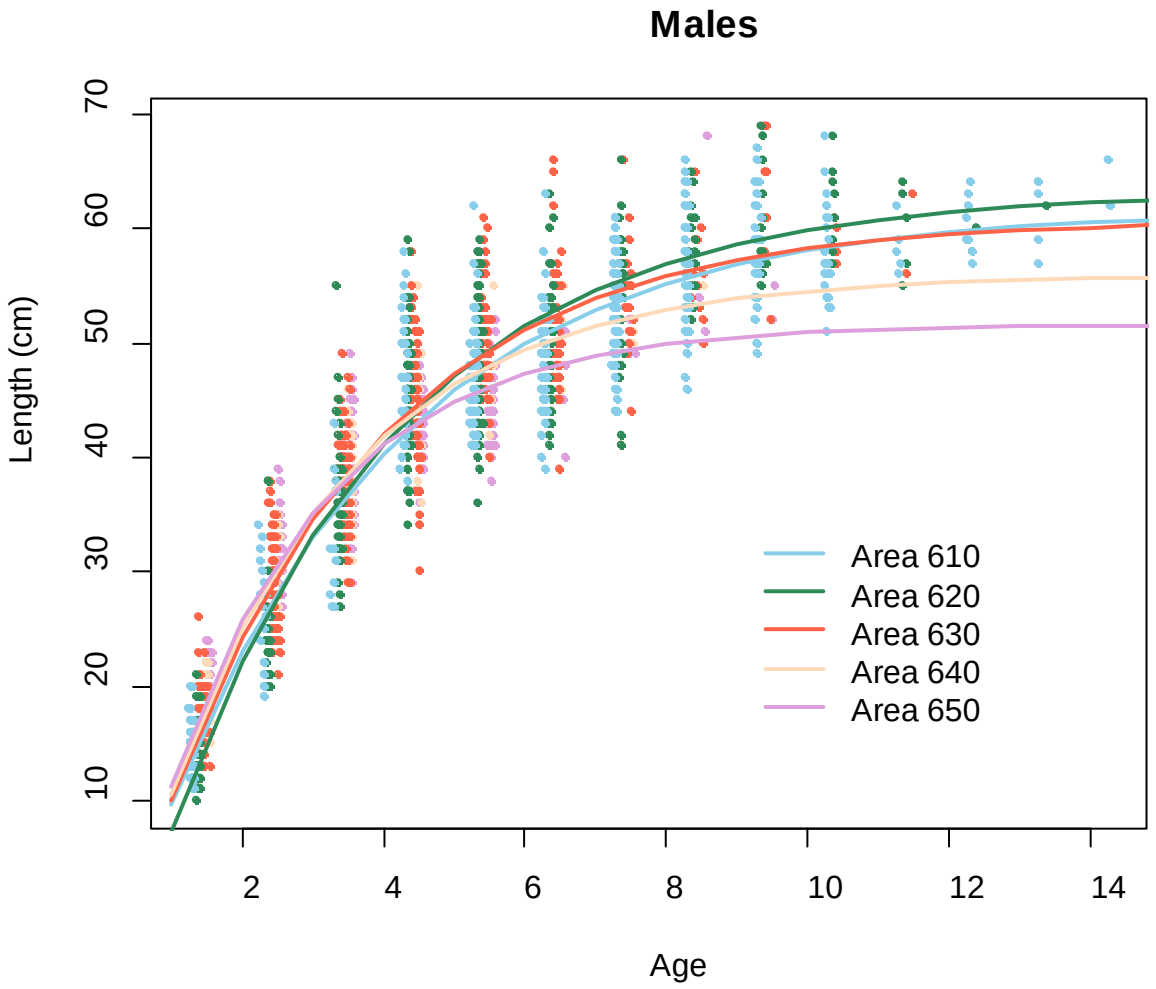

Figure 9. Male length at age and estimated von Bertalanffy growth curves by INPFC area in the Gulf of Alaska from 2005-2009.

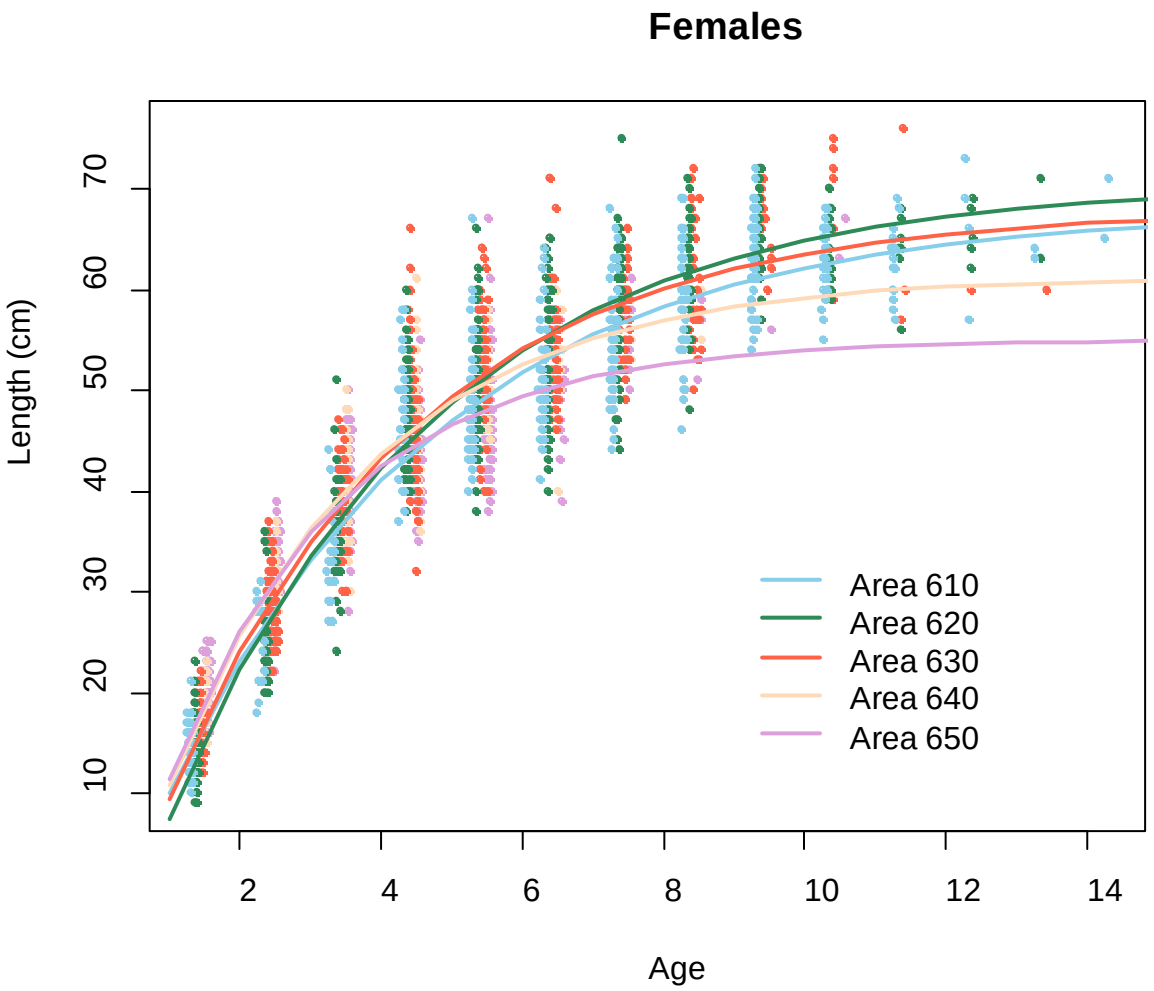

Figure 10. Female length at age and estimated von Bertalanffy growth curves by INPFC area in the Gulf of Alaska from 2005-2009.

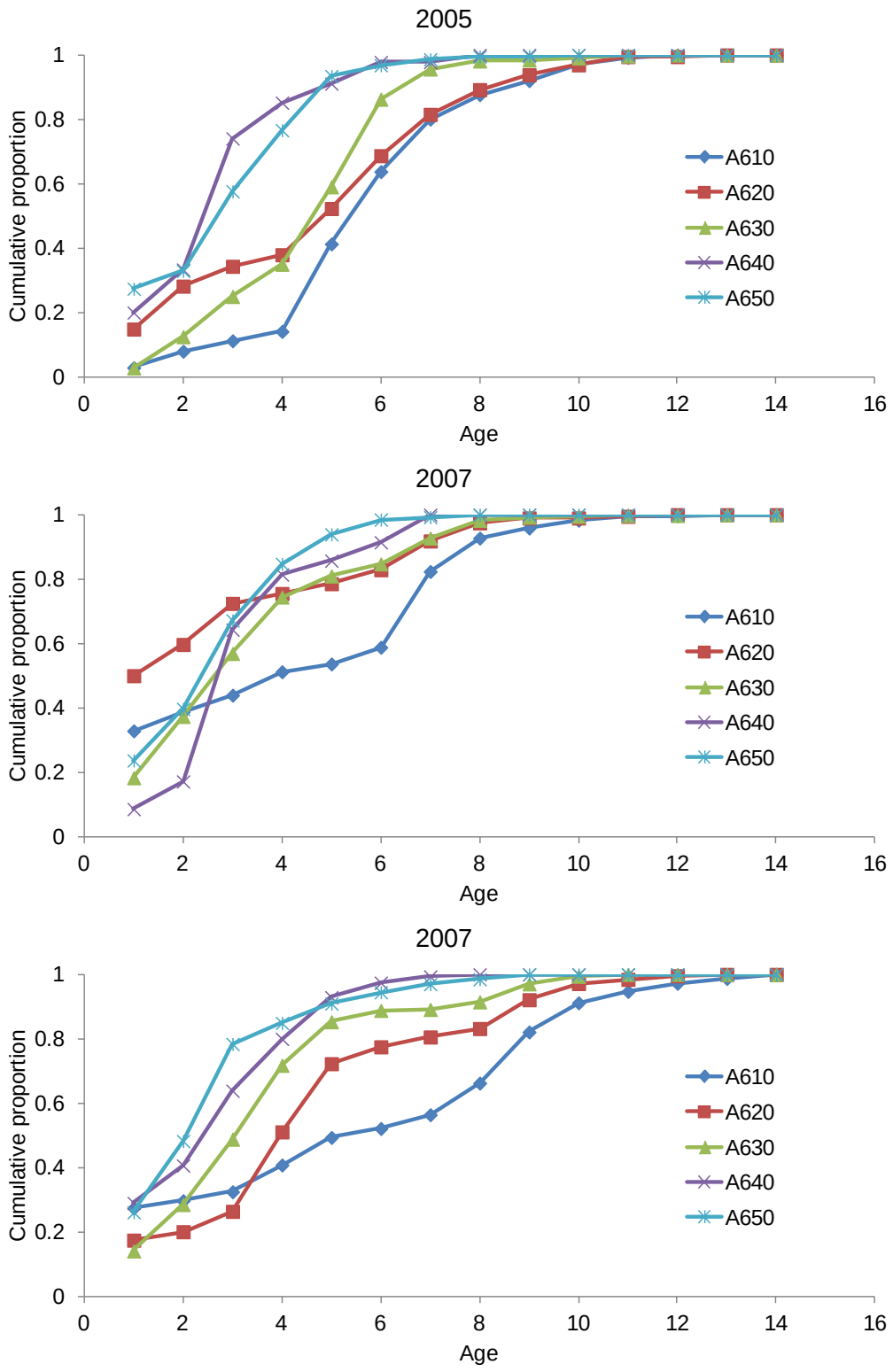

Figure 11. Cumulative age composition of walleye pollock by area for NMFS bottom trawl surveys in 2007-2009.

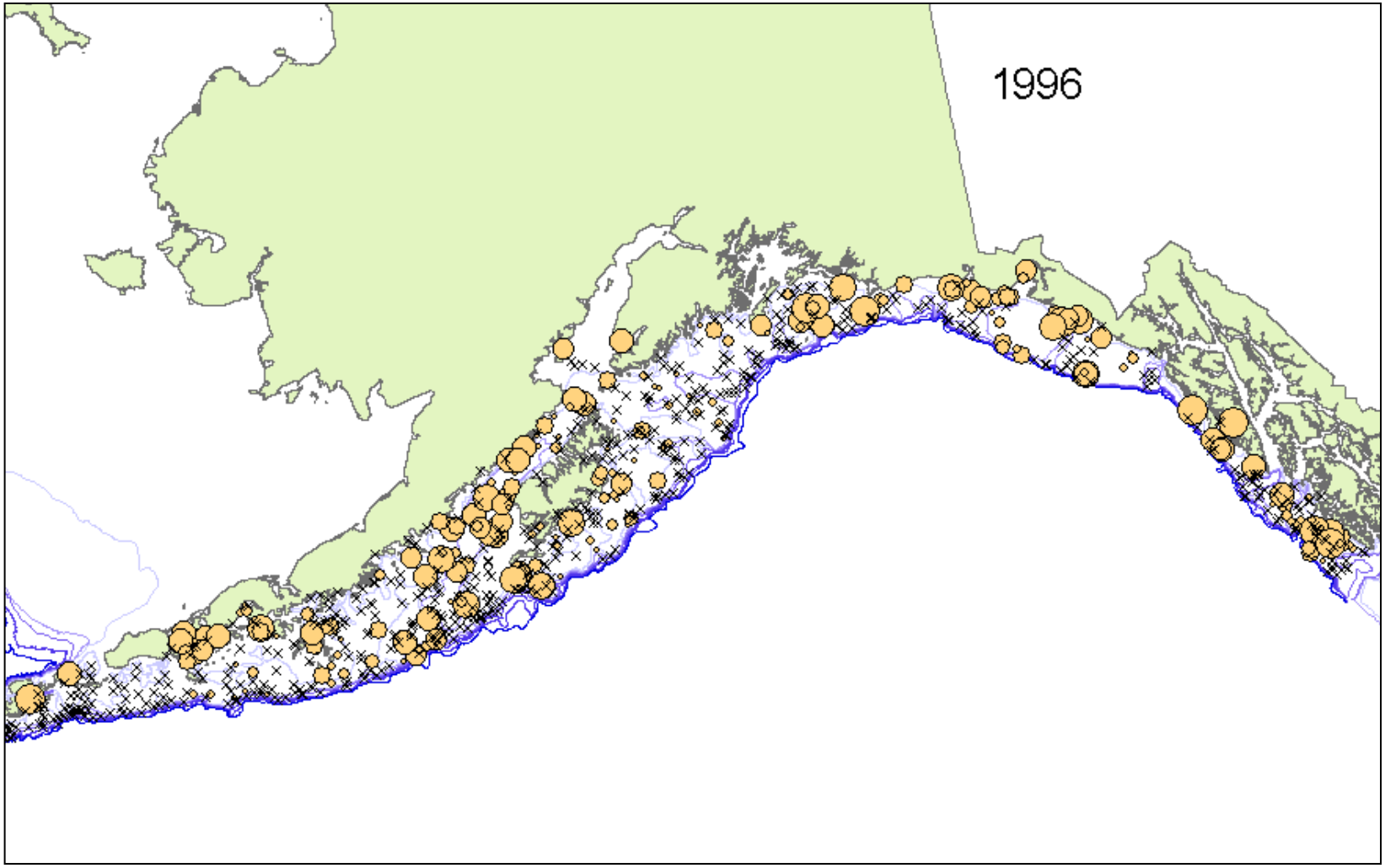

Figure 12. Distribution of age-1 pollock in the 1996 NMFS bottom trawl survey.