Summary of biological information regarding differences between Pacific cod in the eastern Bering Sea and Aleutian Islands

September 2008

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Executive summary

The NPFMC is considering action that would treat the eastern Bering Sea and Aleutian Islands separately for the purposes of Pacific cod management. This report is intended to summarize existing biological information on Pacific cod that may be useful in evaluating this action. The following conclusions may be useful and are described in greater detail in the report:

1) There is highly significant genetic isolation by distance in the Pacific cod stocks of North America (i.e. genetic differences among individuals increase with geographic distance; Fig. 1-2).This result, as well as several different genetic comparisons among regional groupings, suggest that Pacific cod stocks in the Aleutian Islands archipelago are distinct from those along the contiguous Alaska Peninsula.
2) In 2005, length at age was significantly higher in the AI than in the EBS for both female and male cod (Table 2-1, Figs. 2-2 & 2-3). This difference is present at all ages.
3) Commercial trawls in the AI catch bigger female and male cod than do trawls in the EBS (Figs. 3-1, 3-2 & 3-3). From 2004 to 2006, the mode for cod in the EBS occurred at 65-70 cm, while the mode for females in the AI occurred at 80-85 cm. Fish smaller than 50 cm were evident in EBS trawls, but were rare in the AI.
4) Estimates of age composition suggest that commercial trawls in the AI also catch older fish (Fig. 4-1). In particular, cod older than age 8 are largely absent from EBS trawls, while 8-11 year old fish were common in AI trawls. Age estimates were obtained by applying the growth models used in (2) above to the size composition in (3) above.
5) Length-weight relationships did not differ between the AI and EBS in 2005 (Figs. 5-1 & 5-2).
6) Length-specific gonad weight, a proxy for reproductive potential, was equal between the EBS and AI in 2005 (Fig. 6-1A). Length-specific fecundity (Fig. 6-1B) and egg size were significantly different between the EBS and AI in 2005, but the differences were small and may not be biologically relevant.
7) The fatty acid composition of egg polar lipids differed between the EBS and AI (Figs. 7-1 &7-2). Similar differences in other fish species have been used as an indicator of genetic differentiation and stock structure.
8) Cod appear to spawn in several locations in the AI and throughout the EBS (Fig. 8-1).
9) Tagged cod have moved between the EBS and AI, but such movements are limited relative to observed cod movement within the EBS and between the EBS and the western GOA.
10) Fishery exploitation rates in the AI are higher than in the EBS (22% and 17%, respectively). A recently-developed AI-specific assessment model for Pacific cod suggests that cod in the AI have a different population trajectory than cod in the EBS (Figs. 10-1 & 10-2).

11) The density (t/km2) of Pacific cod is higher in the AI than in the EBS (Fig. 11-1). The diet composition of cod is different between the AI and EBS (Fig. 5-1), based on summer survey data from the early 1990s. Simulations of Pacific cod ecological relationships suggest that fishing impacts to the ecosystem mediated by Pacific cod are higher in the AI (Fig. 11-4).
12) Several research projects that will study Pacific cod genetics and movement have recently been funded and these data will be available over the next 2-3 years.

Introduction

Pacific cod (*Gadus macrocephalus*) in Alaska are currently managed as two stocks: a Gulf of Alaska (GOA) stock and a Bering Sea/ Aleutian Islands (BSAI) stock. The North Pacific Fisheries Management Council (NPFMC) assigns a total allowable catch (TAC) of Pacific cod for the entire BSAI stock that is subsequently assigned to various gear and vessel sectors. The NPFMC is considering a proposal to further divide cod catches by assigning separate cod TACs to the Eastern Bering Sea (EBS) and Aleutian Islands (AI) subareas. The basis for this proposal is the possibility that AI cod form an independent stock or stocks within the BSAI area, and that separate TACs for EBS and AI cod may provide for more effective management.

The purpose of this paper is to synthesize the biological information currently available for cod in the EBS and AI subareas. Much of this information is recent and has not yet been published in the peer-reviewed literature. This report considers the following issues:

1) Population genetics
2) Length at age
3) Size composition
4) Estimated age composition
5) Length-weight relationships
6) Reproductive potential
7) Egg fatty-acid profiles
8) Spawning locations
9) Movement and migration
10) Population dynamics
11) Ecosystem effects
12) Ongoing and future research

(1) Population genetics

Methods

Samples were collected from large spawning and pre-spawning aggregates of Pacific cod in eight locations across the northeastern Pacific Ocean from January-March (Fig. 1-1). Replicate samples were taken at 2-year intervals at two locations, Unimak Pass and Kodiak Island, Alaska Two samples from the central Aleutian Islands region in 2006, Adak (AD) and Atka (AT), were in relatively close proximity (180 and 275 km, respectively) to one sample collected during a trawl survey in 2005, Aleutian Islands (AI). Genomic DNA was extracted from pectoral fin tissue from approximately 90 individuals per sample and was screened for variation at 11 microsatellite markers.

Results

There was a highly significant pattern ($r^2 = 0.83$) of genetic isolation by distance among coastal samples across the North American range of Pacific cod, including samples taken within Alaska (Fig. 1-2). There was no genetic differentiation between temporal replicate samples taken at Unimak Pass and Kodiak Island. Exact tests of genetic differentiation (Table 1-1) showed that Kodiak Is. was significantly differentiated from the central Aleutian Islands. Unimak Pass also was significantly differentiated from the central Aleutian Is. prior to correction for multiple pairwise tests. Kodiak Island and Unimak Pass were not significantly differentiated from each other.

	Aleutian Islands	Unimak Pass	Kodiak Island
Aleutian Islands	---	**0.0050**	**0.0000**
Unimak Pass	0.0138*	---	0.3402
Kodiak Island	**<0.0001**	0.5213	---

Table 1-1. Probability (*P*) values from exact tests of genetic (above diagonal) and genotypic (below diagonal) differentiation between sample pairs in Alaska. Bolded values indicate sample pairs significantly differentiated following sequential Bonferonni correction for 21 multiple tests (initial $\alpha = 0.0024$). * significant prior to sequential correction.

Multilocus estimates of genetic divergence, F_{ST}, between sample pairs (Table 1-2) were significant between Kodiak Island and the central Aleutian Islands and significant between Unimak Pass and the central Aleutian Is. before correction for multiple tests. Estimates of F_{ST} were not significant between Kodiak Island and Unimak Pass.

	Aleutian Islands	Unimak Pass	Kodiak Island
Aleutian Islands	---	0.0012*	**0.0023**
Unimak Pass	0.0007	---	0.0004
Kodiak Island	-0.0006	0.0025	---

Table 1-2. Estimates of F_{ST} (above diagonal) and R_{ST} (below diagonal) between sample pairs in Alaska. Bolded F_{ST} values are significant following sequential Bonferroni correction for 21 multiple tests (initial $\alpha = 0.0024$); * significant prior to sequential correction.

Within Alaska, an analysis of molecular variance (AMOVA) for regional groupings of samples showed that pooling the Unimak Pass and Kodiak Is. samples as a group compared to the Aleutian Islands resulted in the highest overall F_{ST} value, no significant between-sample variance component within regional groups, and a significant between-group variance. In contrast, pooling Unimak Pass and central Aleutian Islands samples as a group resulted in a significant between-sample variance component within the group and an insignificant between-group variance when compared with Kodiak Island. Overall, the results indicate that Pacific cod stocks in the Aleutian Islands archipelago are distinct from those along the contiguous Alaska Peninsula.

(2) Length at age

Methods

In January-March 2005, scientists from the Alaska Fisheries Science Center (AFSC) collected Pacific cod samples in the central and western AI and north of Unimak Island in the EBS (Fig. 2-1). Samples in the AI were collected by an AFSC scientist conducting research aboard a factory trawler during the course of normal commercial fishing operations. EBS samples were collected aboard chartered crab vessels during two pot surveys conducted by the Fisheries Interaction Team (FIT) at the AFSC. Because the collections were part of an ongoing study of cod reproduction, sexually mature females formed a greater part of the datasets in both areas (Table 2-1). Cod were selected randomly from the catch according to a schedule of length bins. Length was measured, and body and ovary (gonad) weight were measured using a motion-compensated scale. Otoliths were removed for age analysis, which was conducted by the Age and Growth laboratory at the AFSC.

Length at age was modeled using the Schnute parameterization of the von Bertalanffy growth model (Quinn and Deriso 1999):

$$Y(t) = \left\{ y_1 + \left(y_2 - y_1\right) \frac{1 - \exp\left[-\kappa(t - \tau_1)\right]}{1 - \exp\left[-\kappa(\tau_2 - \tau_1)\right]} \right\}$$

where *Y(t)* is the length at age *t*, τ_1 and τ_2 are the youngest and oldest ages in the dataset respectively, and y_1, y_2, and κ are constants. Males and females were treated separately and statistical differences between the AI and EBS areas were analyzed using likelihood ratio tests (Quinn and Deriso 1999).

Results

Length at age was greater in the AI subarea for female and male cod (Table 2-1; Figs. 2-2 & 2-3). This difference is present at all ages.

Females			**Males**		
	AI	EBS		AI	EBS
y_1	43.26	37.79	y_1	48.43	46.45
y_2	116.06	110.57	y_2	109.26	95.97
κ	0.079	0.039	κ	0.099	0.092
τ_1	3	3	τ_1	4	4
τ_2	12	12	τ_2	11	11
N	256	305	N	66	153
X^2 statistic	199.97		X^2 statistic	68.00	
p-value	<0.0001		p-value	<0.0001	

Table 2-1. Growth model parameters and test results for male and female Pacific cod from the Aleutian Islands (AI) and Eastern Bering Sea (EBS).

(3) Size composition

Methods
The size composition of cod in the different regions was examined using data collected by the AFSC North Pacific Observer Program. Observers routinely collect length frequency data on target species and major components of the catch for selected hauls. From the observer database, we identified all of the observed hauls for which cod length frequency data were collected during the January-March cod ‘A’ Season in 2004, 2005, and 2006. Because pot and longline gear are known to be size-selective for larger fish, only hauls using bottom trawl gear were selected. Data from NMFS statistical area 509 (northeast of Unimak Pass) were selected to represent EBS cod. Data from each of the three AI statistical areas (eastern AI 541, central AI 542, western AI 543) were also selected.

Results
In each of the three years, there were differences in length frequency between the EBS and AI areas (Figs. 3-1, 3-2, 3-3). In each year, the mode of area 509 frequencies was between 65 and 70 cm, with a sharp drop-off above 75 cm and relatively few fish longer than 90 cm. In 2005 and 2006, there were clear secondary peaks at lengths of 35-40 and 45-50 cm, perhaps representing younger year classes. Length frequencies in the eastern AI (area 541) had modes in the 80-85 cm range, with smaller numbers of fish from 50-70 cm and a larger fraction in the 90-100 cm size range than in the EBS. Length frequencies for the central and western AI (areas 542 and 543) were similar to each other but very distinct from the EBS, with few fish under 70 cm and sizeable fractions of fish 100 cm or more.

The results show different size distributions in catches from the EBS and the AI. Because only the largest catcher-processors harvest fish in the central and western AI, it is possible that differences in gear selectivity may affect these results. Length frequencies were examined using data only from vessels classified as catcher-processors (all over 100 ft), and patterns were similar to those in the figures presented.

(4) Estimated age composition

Methods
Section 2 of this report demonstrated significant differences in length at age among EBS and AI cod. To determine whether this growth difference alone accounted for the difference in observed length frequencies, we combined 2005 length-frequency data from section 3 with region- and sex-specific length-age curves to estimate age composition. Length-age curves for cod collected from FIT studies in the EBS in March 2005 were used to predict ages for fish from statistical area 509. Length-age curves for cod from the 2005 collection in the AI were used to predict ages for pooled length frequency data from statistical areas 542 and 542.

Results
For both sexes the estimated age frequencies differ between the EBS and the AI (Fig. 4-1). Both regions show relatively low numbers of 2 and 3 year old fish in the catch, probably due to low selectivity of these ages by trawl gear. The majority of the EBS catch is 5-8 year olds of both

sexes. Numbers of age 9 and older cod are low for both males and females in the EBS. Catches in the AI are dominated by 6-10 year olds, with a substantial fraction of females 9-11 years old. In both regions the largest specimens have an estimated age of approximately 14 years.

While variability in length at age will result in some uncertainty in these age estimates, there does appear to be a difference in age composition between the two regions. For both sexes there is a larger proportion of older fish in the AI. The relative absence of younger fish in the AI may reflect different year-class structure or may result from the fact that commercial trawl grounds in the AI are further from inshore shallows and nursery grounds. The dominance of AI samples by older fish is also consistent with a pattern where the EBS would serve as a nursery ground for both subareas, with fish migrating to the AI at some stage of their life cycle.

(5) Length-weight relationships

Methods

The cod samples used in this analysis are identical to those used in (2) above. Somatic weight, determined by subtracting the weight of ovaries and stomach contents from total body weight, was used in the analysis of length-weight relationships. Weight and ovary weight were modeled using power curves of the form $y=\alpha x^{\beta}$ where y is weight or ovary weight, x is length, and α and β are constants. Males and females were treated separately and statistical differences between the AI and EBS areas were analyzed using likelihood ratio tests (Quinn and Deriso 1999).

Results

No statistically significant differences were observed in the length-weight relationships for male and female cod or in the length-ovary weight relationship for female cod (Table 5-1; Figs. 5-1, 5-2).

length-weight, females			length-weight, males		
	AI	EBS		AI	EBS
N	69	106	N	257	307
X^2 statistic	5.35		X^2 statistic	1.20	
p-value	0.15		p-value	0.75	

Table 5-1. Sample size and test statistics for length-weight relationships in female and male Pacific cod.

(6) Reproductive potential

Methods

Ovary samples were collected for a subset of the females used in the analyses in (2) and (5) above. Ovaries were weighed to the nearest gram on a motion-compensated specimen scale frozen at -20°C for subsequent analysis. Fecundity was determined using the gravimetric method, and egg samples were freeze-dried to a constant weight for determination of individual egg dry weight (used as a measure of egg size).

Results
Total gonad (ovary) weight was used as a proxy for reproductive potential, which comprises fecundity and egg size, for samples collected from the AI (N = 137) and EBS (N = 44) in 2005 (see Fig. 2-1 for sampling locations). Reproductive potential increased approximately with the cube of the length, and this relationship did not differ between the AI and EBS (Figure 6-1A; $F = 0.71$, $p = 0.4918$). However, females from the two areas achieved equivalent reproductive potential through different means. Fecundity at length was slightly greater in the EBS (Figure 6-1B; $F = 8.50$, $p = 0.0003$), while average egg size (as measured by dry weight) was slightly greater in the AI (AI = 0.103 ± 0.001 mg, EBS = 0.097 ± 0.002 mg; $F = 10.87$, $p = 0.0012$). While differences in fecundity and egg size were significant, they were quite small and may not be biologically relevant.

(7) Egg fatty-acid profiles

Rationale
The composition of fatty acids (FA) in fish egg lipids may affect hatching success and larval survival. In addition, fatty acid composition has been used to discriminate among genetically distinct stocks of several marine fish species as well as lobsters (Castell et al. 1994, Joensen and Grahl-Nielsen 2004, Joensen et al. 2000, Pickova et al. 1997). While fatty acid composition of lipids is influenced by diet, this appears to occur mainly in the neutral lipids, which are used as a source of energy. The fatty acid composition of polar lipids, which are used primarily as structural components and hormone precursors, is thought to be highly regulated and less influenced by diet (Pickova et al. 1997). As a result, differences in polar-lipid fatty acid composition may reflect local adaptation and genetic differentiation among stocks.

Methods
This analysis compared the fatty acid composition of eggs collected from the EBS in 2004 (N = 7) and the AI in 2005 (N= 21). All eggs were collected from females in spawning condition and immediately frozen in liquid nitrogen. Fatty acid analysis of the polar lipids was performed by a commercial laboratory. Principal component analysis (PCA) was used to separate individual females according to 1) a full set of 23 fatty acids and 2) a subset of 8 fatty acids that have been shown to affect egg quality.

Results
In both cases, there was a clear separation between the eggs of females from the AI and EBS, with the exception of one sample that was intermediate to the two main groups (Figure 7-1). This analysis of area effects on FA composition was complicated by maternal length effects on several fatty acids and size differences of sampled females from the AI and EBS. The fractions of three fatty acids in the polar lipids were related to maternal total length: linoleic acid ($R^2 = 0.63$, $p = 0.0001$), α-linolenic acid ($R^2 = 0.38$, $p = 0.0051$), and arachidonic acid (AA; $R^2 = 0.26$, $p = 0.0242$). Regression analysis was conducted for only the eggs from the AI (Figure 7-2; only the results for AA are shown). Because the female cod from the EBS were smaller than those in the AI, maternal length effects could confound the analysis of area effects. For example, EBS eggs have higher AA content, smaller females have higher AA content, and the EBS females we collected were on average smaller, so it is possible that area-related variability in AA is the result

of area-related size differences. In addition, neither the AI or the EBS sample sets includes the full size spectrum of female cod in each area.

Despite age and size differences between the EBS and AI and the incomplete representation of EBS and AI cod populations, there are several reasons why the area differences in FA composition are likely due to either diet or adaptation and not maternal size. The best evidence for this conclusion is the separation of samples by the various PCAs. Separation into area groups is very distinct, and despite overlap in female size between the two areas (Figure 7-2) there is no overlap between the two areas in the PCA. The range of size-related variability in AA within the AI samples is also much smaller than the difference in AA between areas. Finally, several of the FAs that differed between areas (e.g. oleic acid) were not related to maternal length.

(8) Spawning locations

Very little is known about preferred spawning habitat for Pacific cod and about the spatial distribution of cod spawning in the BSAI. Spawning is known to occur in the southeast Bering Sea near Unimak Pass, and areas of high cod density (indicative of spawning aggregations) have been observed in the AI. In order to better document cod spawning locations, the FIT and the North Pacific Observer Program are conducting a special project using fishery observers to classify and record the gonad maturity of cod from selected hauls. This project is providing data regarding the date and location of hauls containing fish in ripe or near-ripe condition, which can be used to map putative spawning areas. Preliminary results suggest that cod spawn in several areas of the AI, as well as throughout the EBS (Fig. 8-1).

(9) Movement and migration

As part of field studies conducted in 2002-2004, FIT scientists tagged and released cod in the southeast Bering Sea between Cape Sarichef and Amak Island. These releases were primarily intended to develop methodology for spaghetti tagging of Pacific cod caught with pots and to gain some qualitative description of cod movement during and after the spawning season. The majority of the tags were released in February 2003. Tag recovery has been solely through commercial fisheries.

Out of 5935 spaghetti tags released in the Bering Sea, 2331 (39%) have been recovered as of December 2005. Of the recovered tags, the majority of the recoveries were from the Bering Sea. A total of 148 tags were recovered in the western GOA, indicating some movement of fish through Unimak Pass. Only two tags from the FIT Bering Sea releases were recovered in the AI. These results are consistent with an earlier study that demonstrated little movement of EBS cod to the AI (Shimada and Kimura 1994).

These data are difficult to interpret because the releases were not designed to look for movement between the regions. The small number of recoveries in the AI suggests that movement from the Bering Sea to the AI might be rare, but this may also be an artifact of the relatively small level of cod fishing effort in the AI. Fish released in the EBS were also adults; no information is available on movement of juvenile cod.

(10) Population dynamics

Unequal exploitation rates

An unintentional effect of the BSAI wide Pacific cod TAC was a difference in exploitation rates for EBS and AI cod in 2007. Catches reported in the SAFE (Thompson et al. 2007) were 136,430 t in the EBS and 33,724 t in the AI and were complete through early October 2007. The assessment-estimated exploitable biomass of cod was 806,400 t in the EBS, and the AI estimate of exploitable biomass of 153,600 t was estimated in the assessment based on the assumption that the AI exploitable biomass should reflect the ratio of AI survey biomass to EBS survey biomass; 0.16. If this is correct, then the exploitation rate in the AI was 33,724 t / 153,600 t or 22% in 2007, while the EBS exploitation rate was 136,430 t / 806,400 t or 17% in 2007. The overall exploitation rate for the BSAI was 18% based on these numbers; therefore, statistics based on the BSAI are more representative of exploitation rates in the EBS than in the AI.

Different population trajectories

The BSAI Pacific cod SAFE models the EBS portion of the population only, and until recently, there was no separate population model for the AI portion of the population. Kinzey and Punt (in review) have developed an AI cod population model using AI data and an assessment framework developed at the AFSC (AMAK, developed by J. Ianelli). There are differences in the population trajectories estimated for each area. For example, the EBS cod stock was estimated to have been at a historic low in 1976, to have increased rapidly to a historic high in 1983-1985, and to have declined to an intermediate biomass and fluctuated within that range between the 1990s and 2000s (Figure 10-1; Thompson et al. 2007). In contrast, the AI cod stock was estimated to have been near a historic high in 1976, and has undergone a general decline since then with the exception of a small peak in the early 1990's (Figure 10-2; Kinzey and Punt in review). All AI model structures (both standard single species and experimental models including predation) suggest a decline in AI cod spawning biomass from the mid-1990's to the present, while the EBS model suggests a slight increase in spawning biomass from 1998-2003 with a decline since then.

(11) Ecosystem effects

The following information is summarized from the 2007 BSAI Pacific cod SAFE, and is included here so that this report can be considered separately. The food web relationships of cod are different between the EBS and AI ecosystems, both due to spatial distribution and diet differences. Because the AI has a much smaller area of shelf relative to the EBS, the smaller survey biomass estimate of cod in this area translates into a higher density in tons per square kilometer relative to the density in the EBS (Figure 11-1, left panel). Cod have diverse diets in both ecosystems, but with important differences (Figure 11-2). Pollock account for 25% of cod diet in the EBS. Commercially important crab species such as snow crab (C. opilio) and tanner crab (C. bairdi) make up 9% of cod diets in the EBS, but less than 3% in the AI, reflecting the stronger benthic energy flow in the EBS. In contrast, pollock comprise less than 5% of AI cod diet, while Atka mackerel account for 15%. Squids make up over 6% of cod diets in the AI, but are very small proportions of diets in the EBS, reflecting the stronger pelagic energy flow in the AI. Myctophids are found in cod diets only in the AI, reflecting the oceanic nature of the food web there.

Fisheries are the most important predators of Pacific cod in both the AI and EBS (Figure 11-3). Simulated impacts of changing cod fishing mortality differ by ecosystem as well, with the impacts felt most strongly and with highest certainty in the AI ecosystem according to this analysis (Figure 11-4). In particular, limited diet data suggest an interaction between cod and (juvenile) sablefish in the AI that was not present in the EBS. The larger impact of cod mortality in the AI observed in these simulations is a combined result of different diet relationships and the higher biomass per unit area in the AI relative to the EBS; the difference in fishery exploitation rates observed above was not included in the ecosystem simulation analysis. Separate management of the cod fishery in the AI would ensure that any potential ecosystem effects of changing fishing mortality might be monitored at the appropriate scale.

(12) Ongoing and future research

There are several projects that are either underway or soon to begin that may provide additional information for consideration of an EBS vs. AI TAC division. All of these projects are funded by the North Pacific Research Board (NPRB); descriptions of these projects can be found on the NPRB website (www.nprb.org) using the project numbers given here. Logerwell and Neidetcher (#618) are conducting an analysis of the distribution of spawning Pacific cod, “Spatial and temporal patterns in Pacific cod reproductive maturity in the Bering Sea”, and some of the preliminary data from that project are included in this report (Fig. 8-1). Spies (#817) received funding in 2008 for a project titled “A landscape genetics approach to Pacific cod (*Gadus macrocephalus*) population structure in the Bering Sea and Aleutian Islands; investigation of ecological barriers to connectivity between potentially distinct population components”, which should provide additional information on genetic variation within the EBS and AI. Munro et al. (#815) will conduct a large-scale tagging project, “Pacific cod (*Gadus macrocephalus*) migration and distribution related to spawning in the eastern Bering Sea: a mark-recapture experiment on a large geographic scale”. While this project is focused on the EBS, it may provide additional information on movement between the EBS and AI. Hurst and Miller (#816) are conducting the project “Estimating source contribution and dispersal histories of Pacific cod recruits using otolith elemental composition”, which also deals primarily with the EBS. There are additional projects being conducted as part of the NPRB’s Bering Sea Integrated Research Program (bsierp.nprb.org) that may provide useful information.

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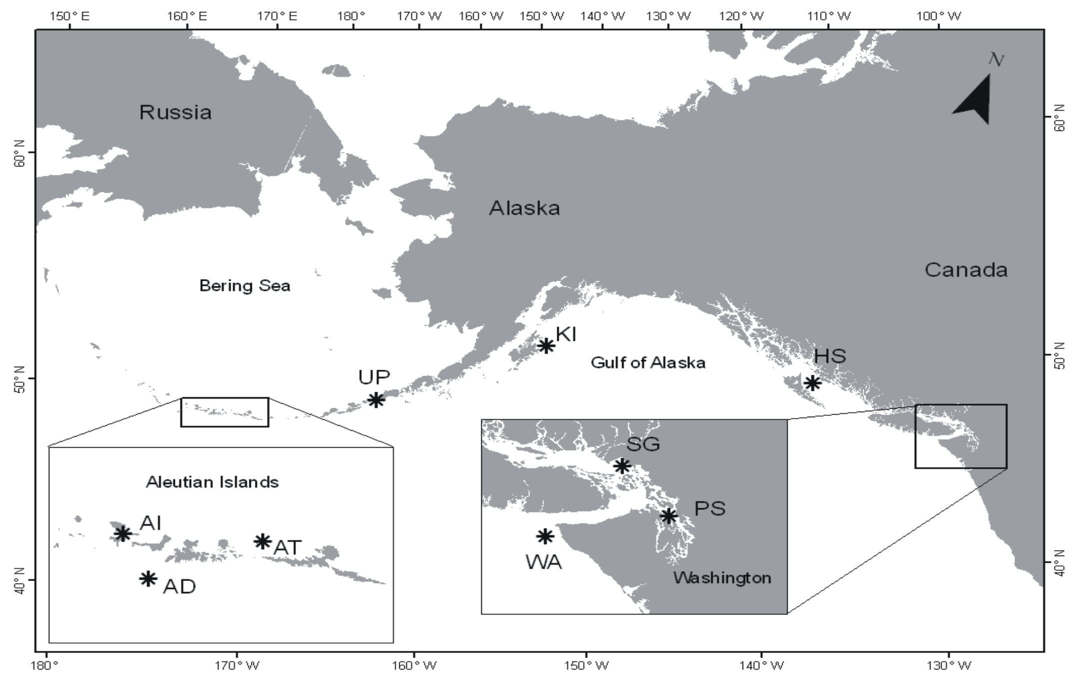


Figure 1-1. Sample locations for Pacific cod. Sample abbreviations are Unimak Pass (UP), Kodiak Island (KI), Hecate Strait (HS), coastal Washington State (WA), Puget Sound (PS), and Strait of Georgia (SG). For the central Aleutian Islands, sample labels indicate samples taken from Aleutian Islands (AI), Adak Island (AD), and Atka Island (AT).

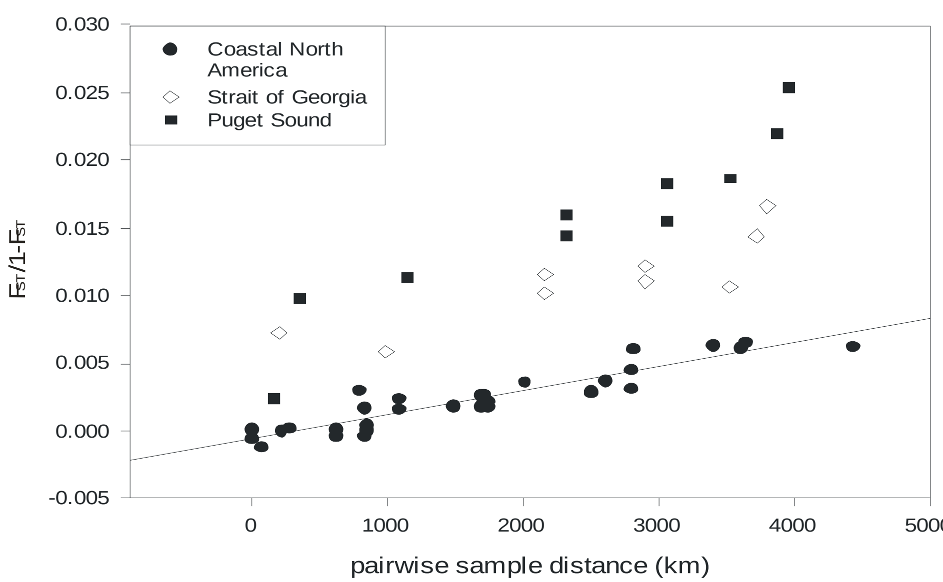


Figure 1-2. Linearized F_{ST} values versus geographic distance for Pacific cod. Regression line is fitted to data from coastal samples in North America (closed circles).

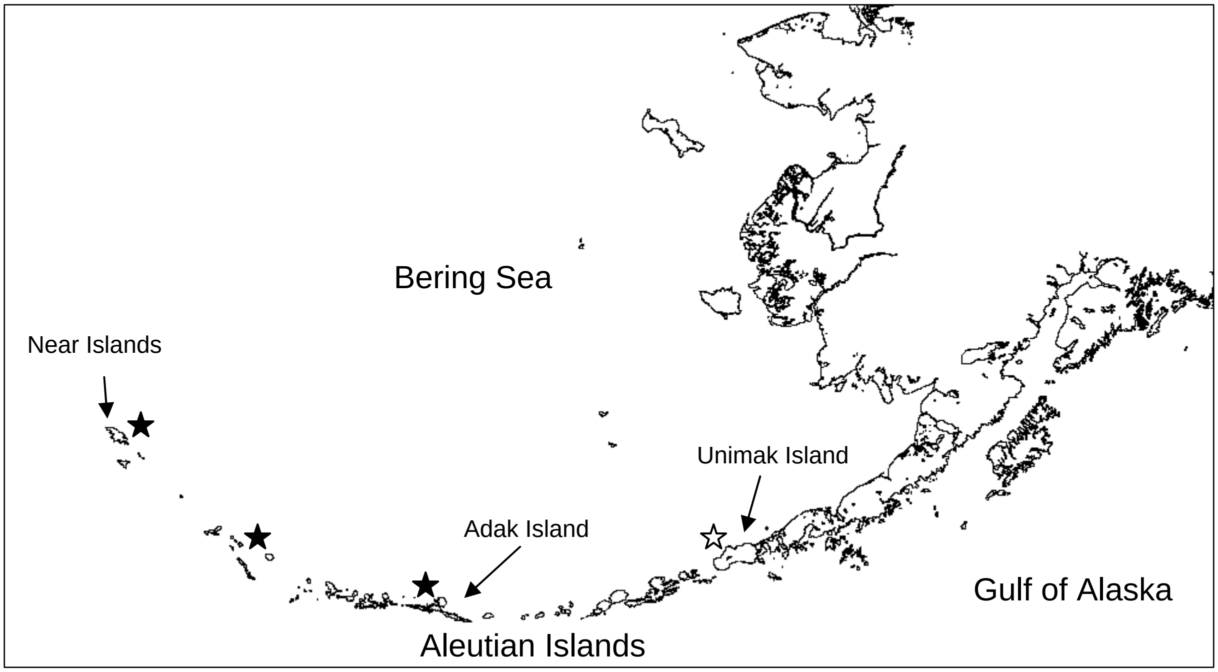


Figure 2-1. Map of the Bering Sea and Aleutian Islands. Solid stars = areas where Aleutian Islands samples were collected for analyses in sections 2, 5, 6, & 7; white star = area where Eastern Bering Sea samples were collected for analyses in sections 2, 5, 6, & 7.

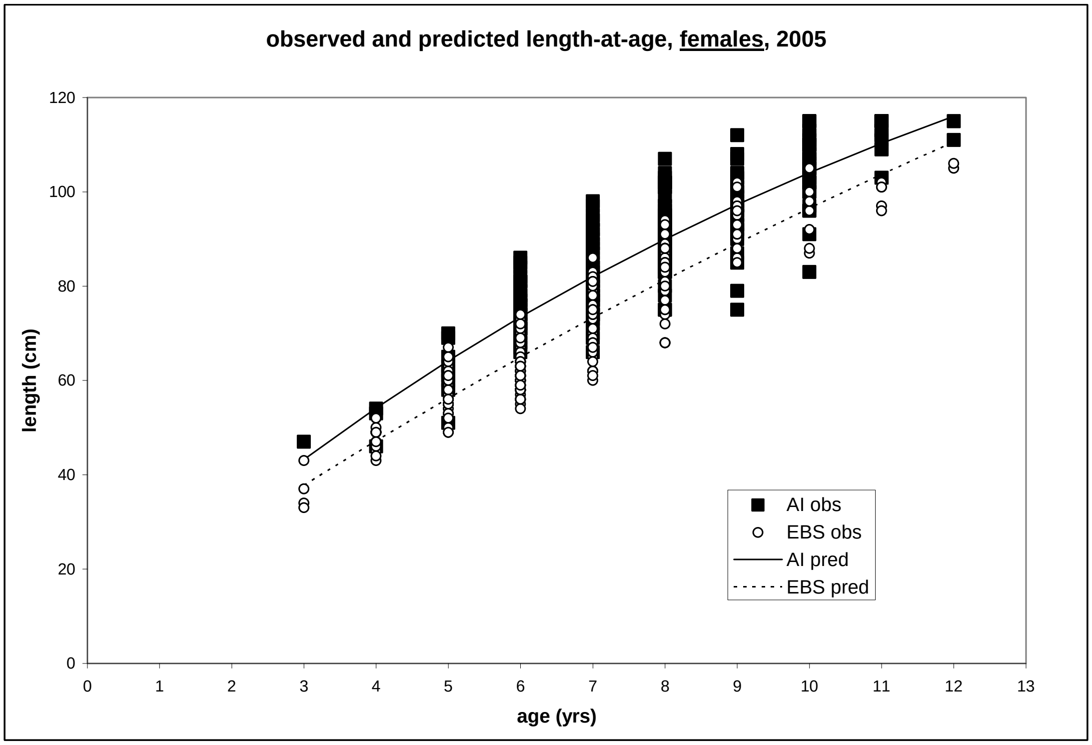


Figure 2-2. Observed and predicted length at age for female cod from the Aleutian Islands and Eastern Bering Sea.

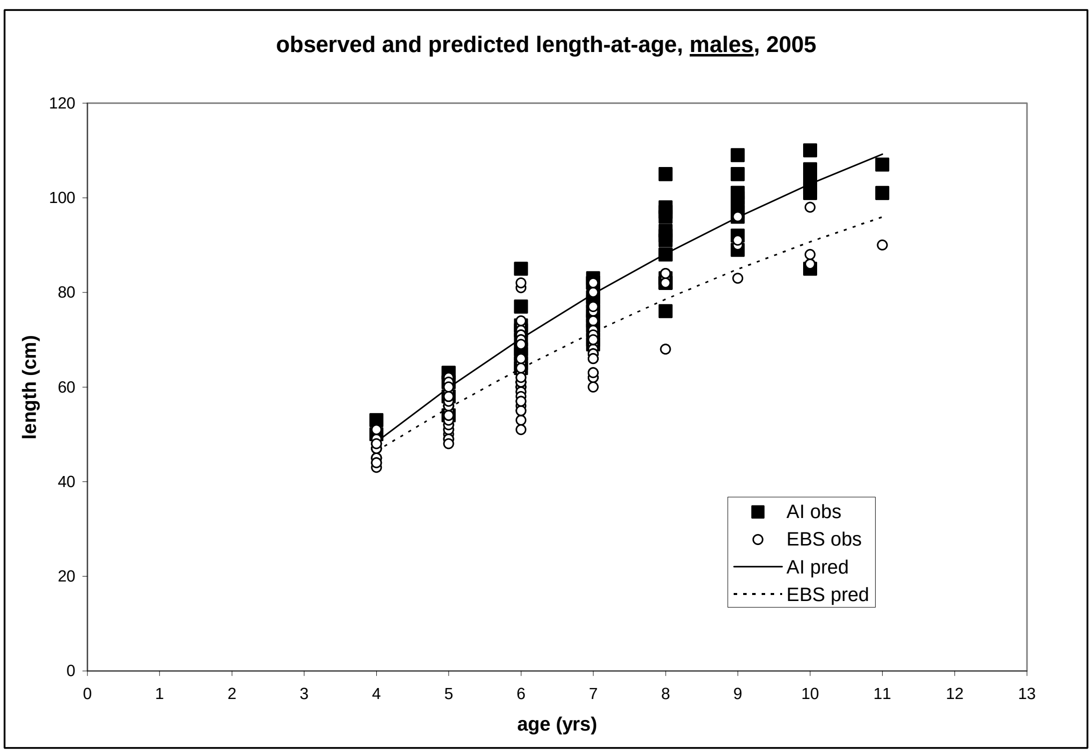


Figure 2-3. Observed and predicted length at age for male cod from the Aleutian Islands and Eastern Bering Sea.

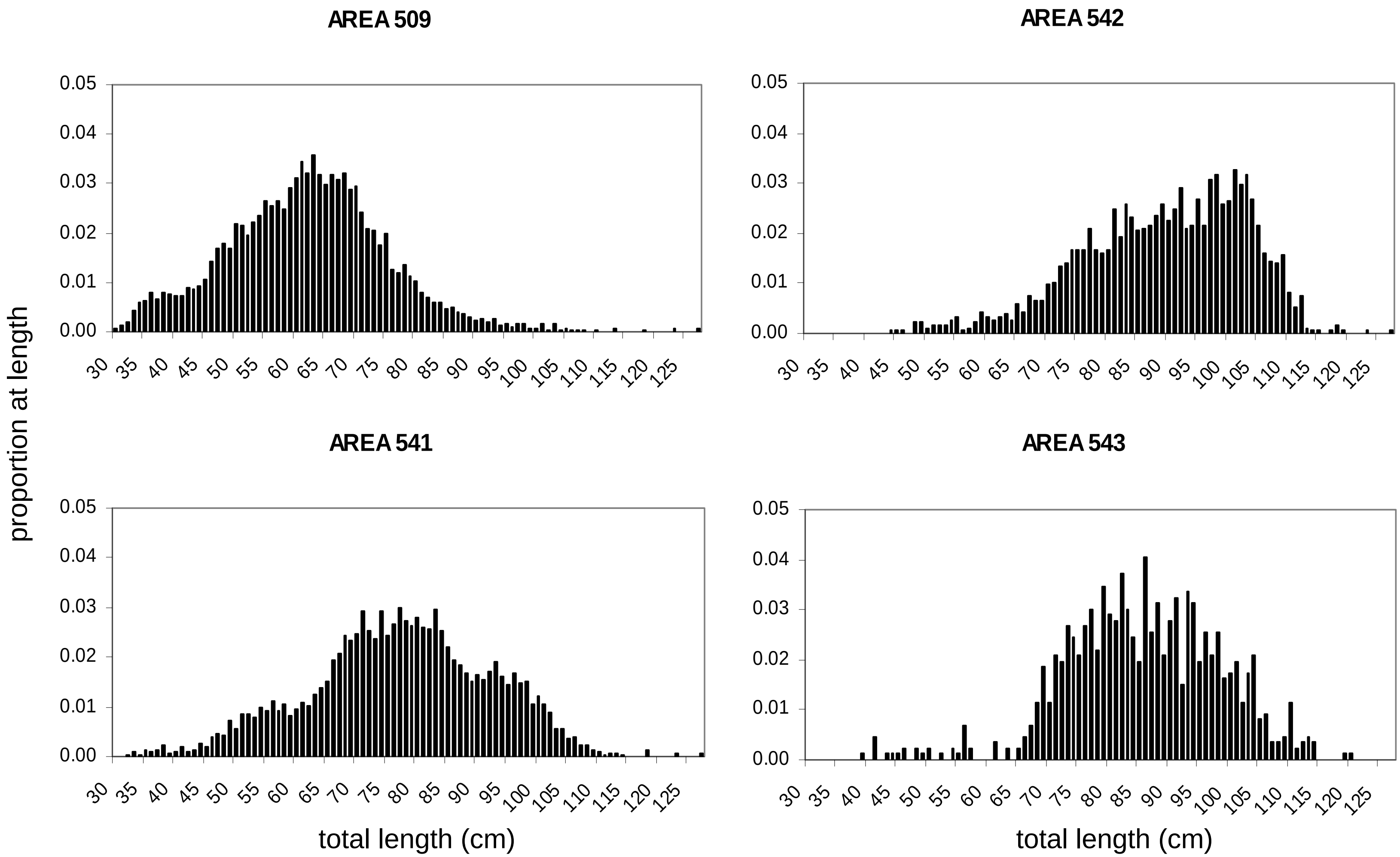


Figure 3-1. Length frequency proportions of Pacific cod from all observed hauls using bottom trawl gear, **January-March 2004**. Both sexes of cod are included. Areas are NMFS statistical reporting areas: 509 Southeastern Bering Sea, 541 Eastern Aleutian Islands, 542 Central Aleutian Islands, 543 Western Aleutian Islands.

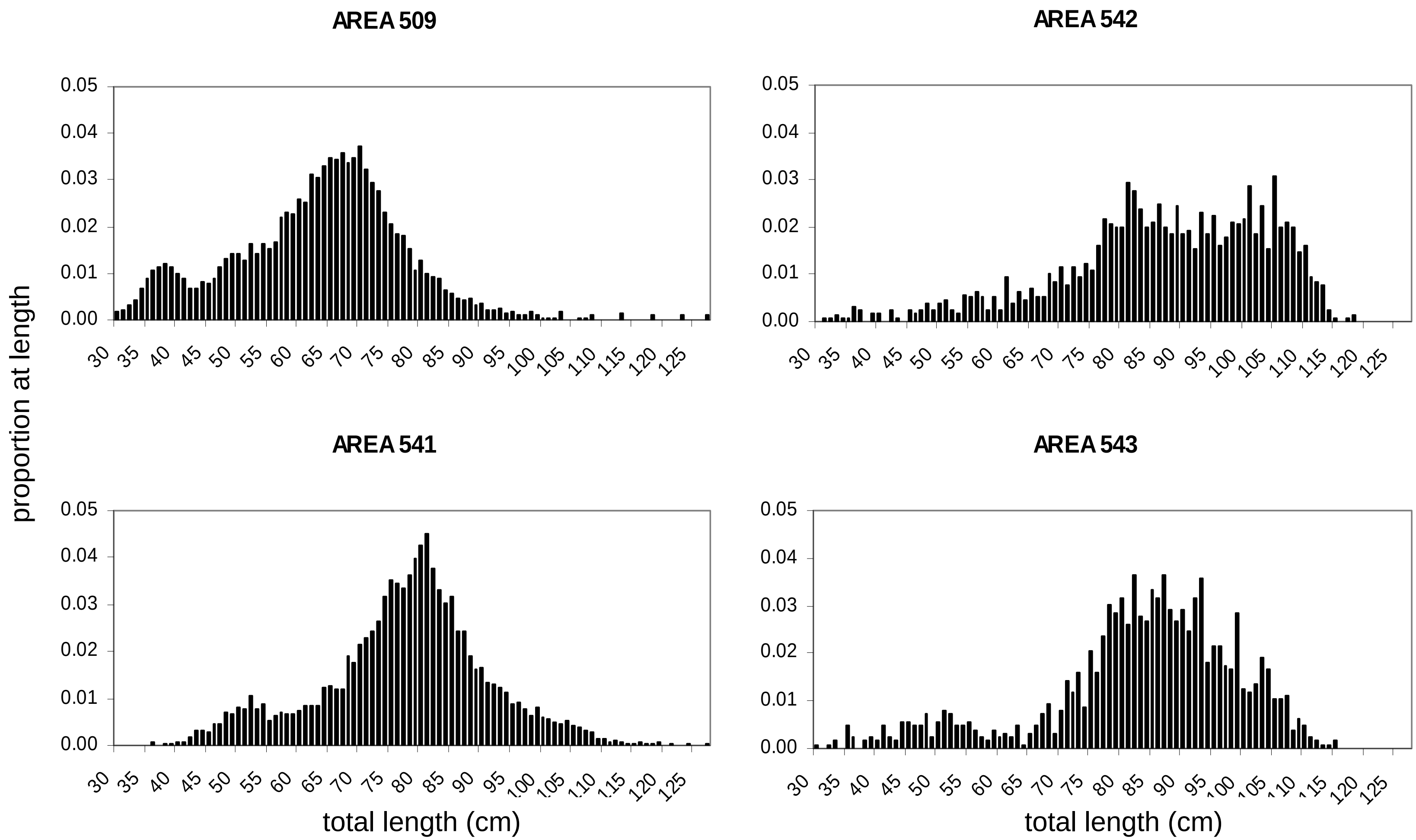


Figure 3-2. Length frequency proportions of Pacific cod from all observed hauls using bottom trawl gear, **January-March 2005**. Both sexes of cod are included. Areas are NMFS statistical reporting areas: 509 Southeastern Bering Sea, 541 Eastern Aleutian Islands, 542 Central Aleutian Islands, 543 Western Aleutian Islands

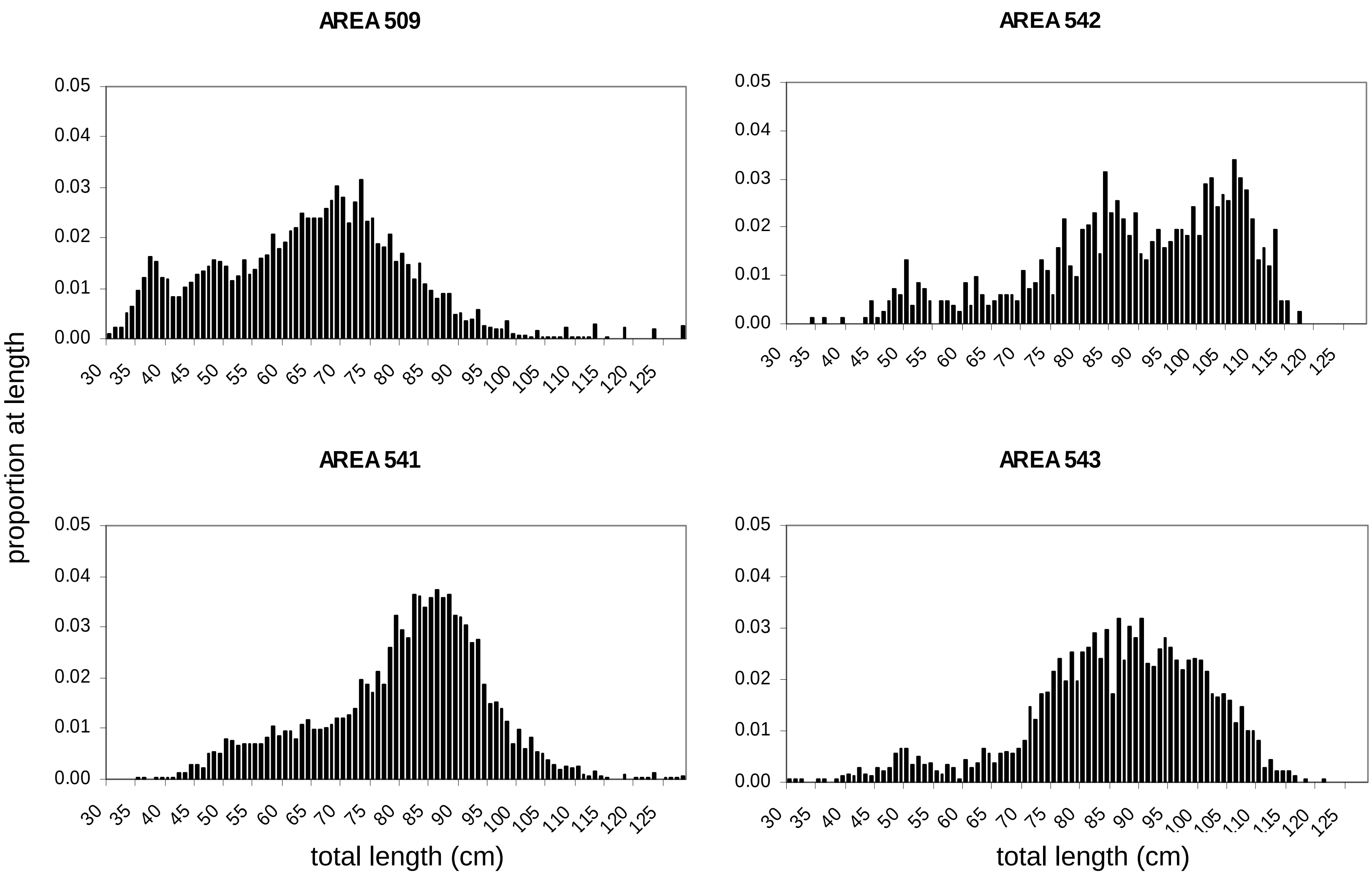
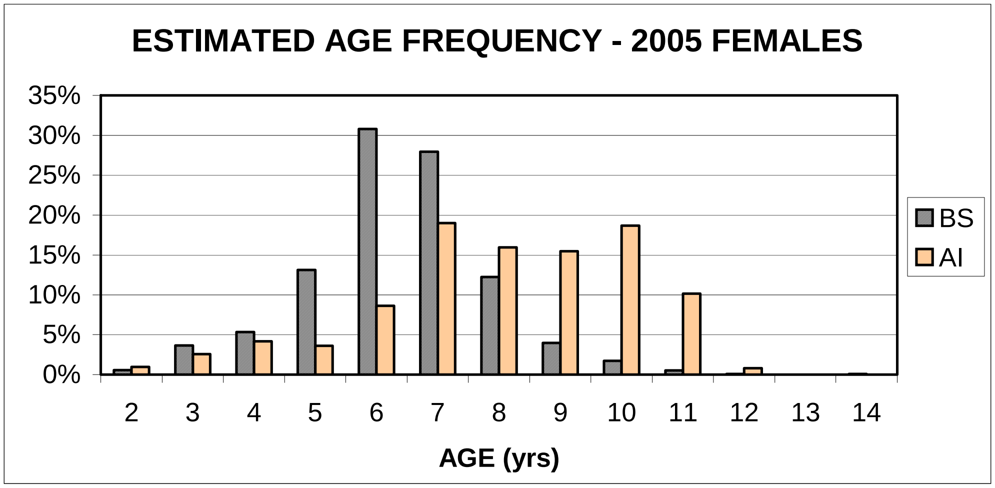


Figure 3-3. Length frequency proportions of Pacific cod from all observed hauls using bottom trawl gear, **January-March 2006**. Both sexes of cod are included. Areas are NMFS statistical reporting areas: 509 Southeastern Bering Sea, 541 Eastern Aleutian Islands, 542 Central Aleutian Islands, 543 Western Aleutian Islands



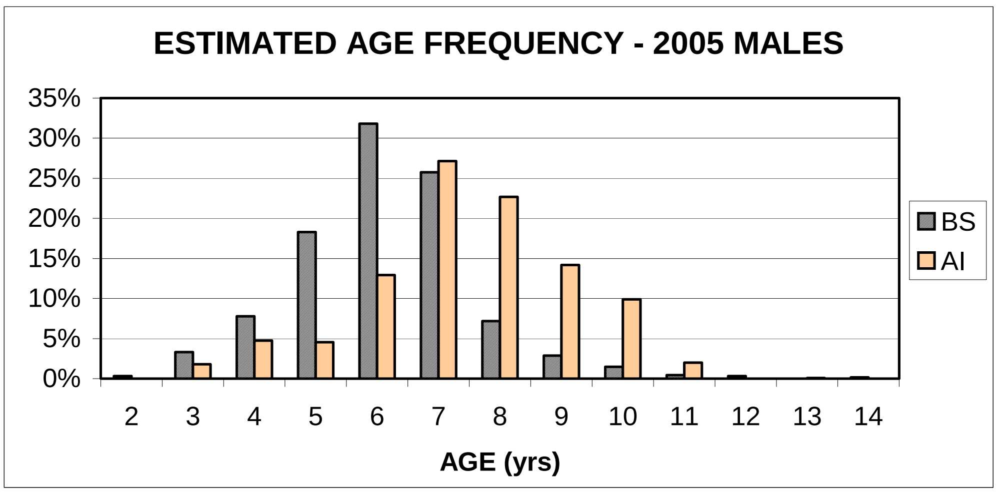


Figure 4-1. Estimated age frequency of Pacific cod by sex in the southeastern Bering Sea (area 509) and in the central and western Aleutian Islands (areas 542 and 543). Bottom trawl length frequency data for January –March 2005 was combined with length-age models fit in section 1 to produce age frequency.

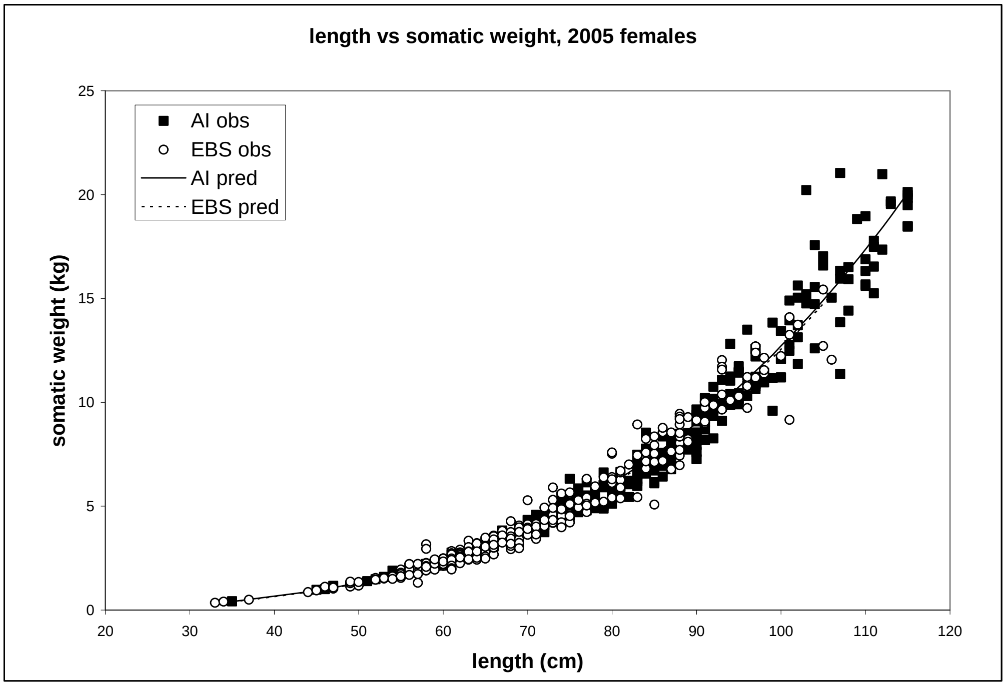


Figure 5-1. Observed and predicted somatic weight for female cod from the Aleutian Islands (AI) and Eastern Bering Sea (EBS).

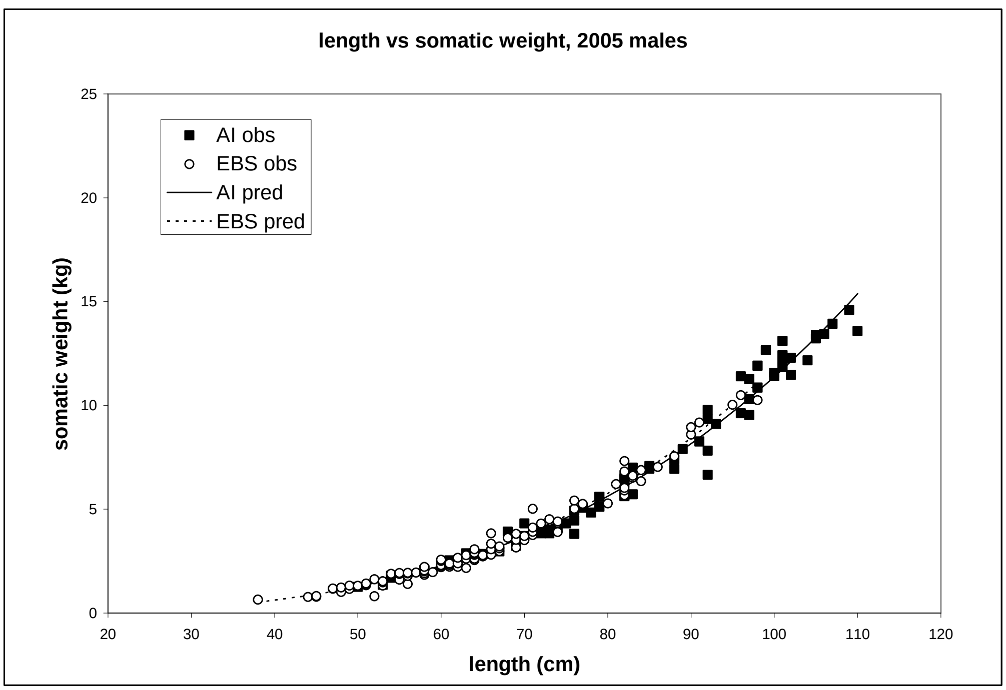


Figure 5-2. Observed and predicted somatic weight for male cod from the Aleutian Islands (AI) and Eastern Bering Sea (EBS).

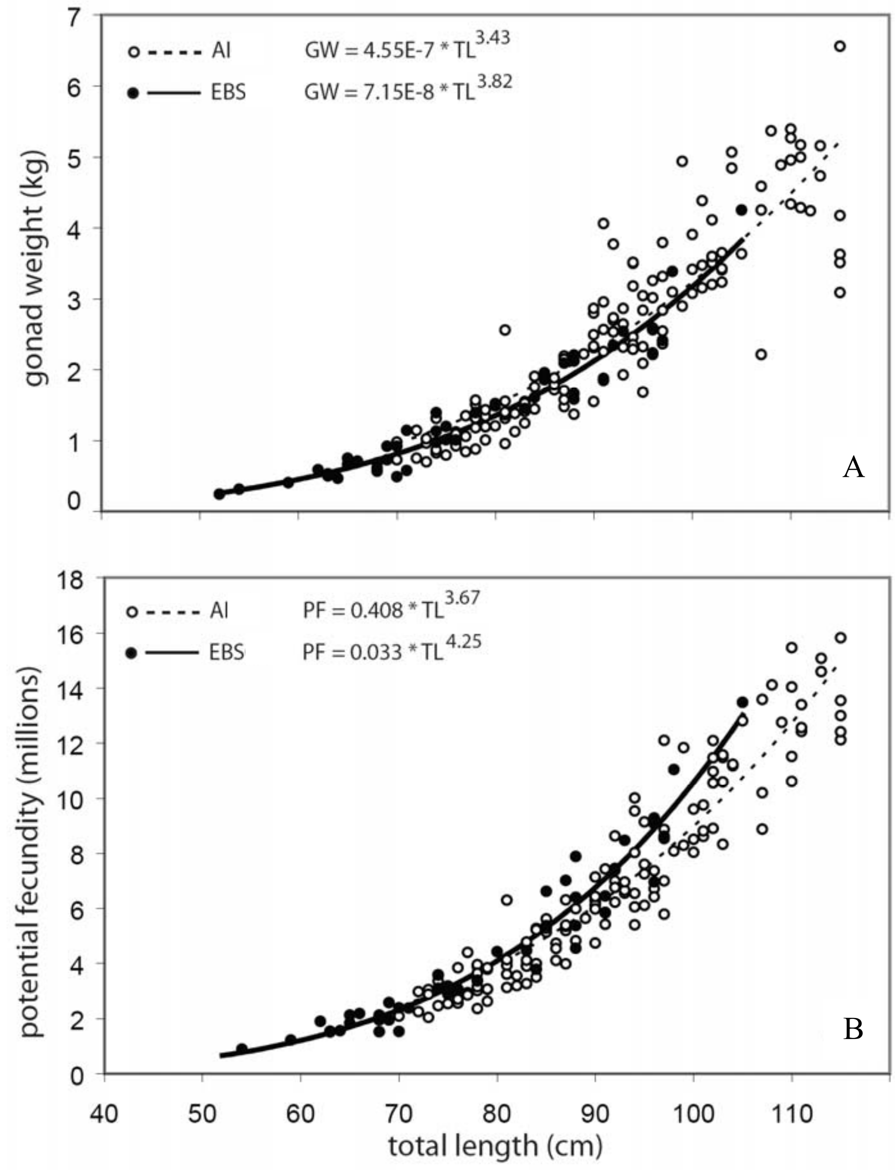


Figure 6-1. Relationship between maternal total length and A) gonad weight (GW) and B) potential fecundity (PF) of female Pacific cod from the Aleutians Islands (AI) and eastern Bering Sea (EBS) in 2005. Sample size: AI = 137, EBS = 44.

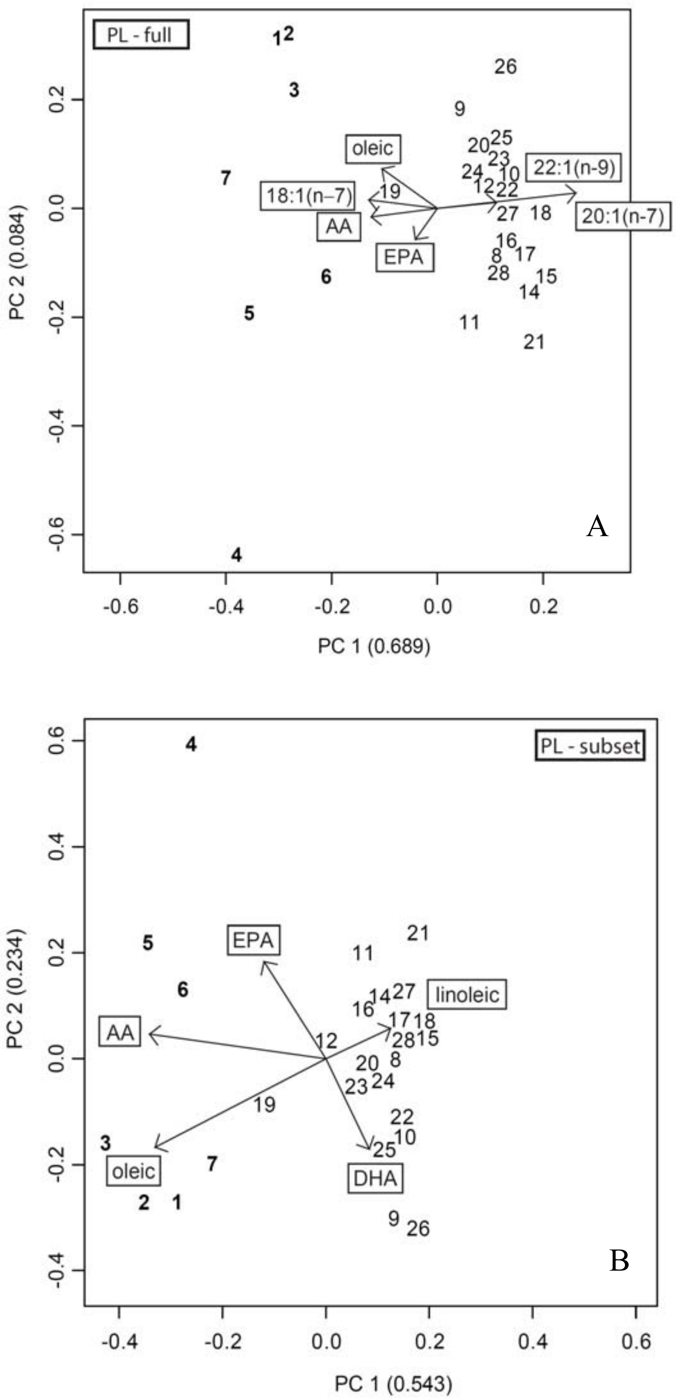


Figure 7-1. Principal component (PC) analysis for fatty acid (FA) composition in the polar lipids (PL) of Pacific cod eggs, using (A) all polyunsaturated FAs (PUFAs) and any FA contributing more than 1% of the total FA pool and (B) only the subset of FAs of potential importance to egg quality. Values following each axis label are the proportions of variability in the dataset explained by each of the first 2 two PCs. Numbers 1-7 (bold) are EBS samples; numbers 8–28 are AI samples. Text boxes indicate the four most important FAs in the first PC and the two most important FAs in the second PC. Length of arrows indicates the relative contribution of that FA in forming the PCs. Direction of arrows indicates the relative contribution of that FA to each of the two PCs. AA = arachidonic acid, EPA = eicosapentaenoic acid, DHA = docosahexaenoic acid .

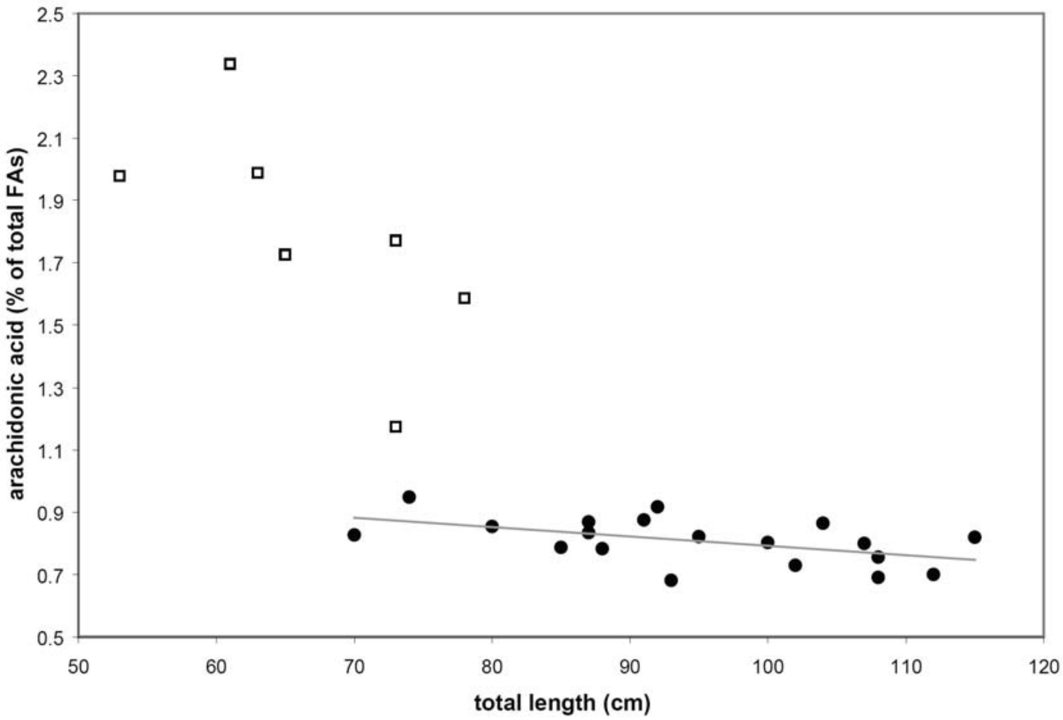


Figure 7-2. Maternal total length versus arachidonic acid , 20:4(n-6), content of polar lipids from Pacific cod eggs. Data are shown as % of total fatty acid (FA) pool in that lipid class. Open squares, EBS; solid circles, AI. Line is the result of least-squares linear regression.

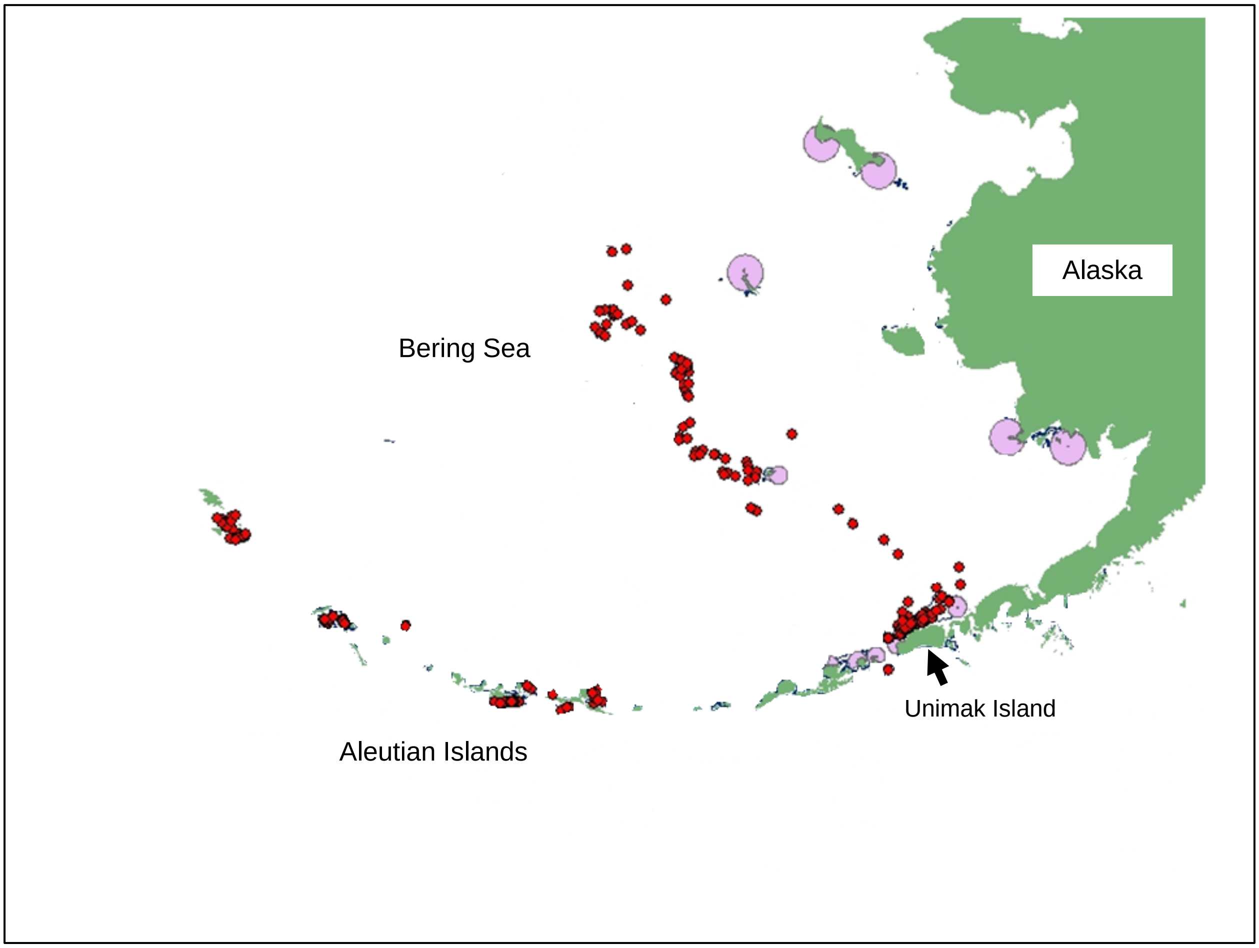


Figure 8-1. Locations in the AI and EBS where females in spawning condition have been observed in commercial fishery hauls. Red (or dark gray) dots indicate catch locations of spawning female cod.

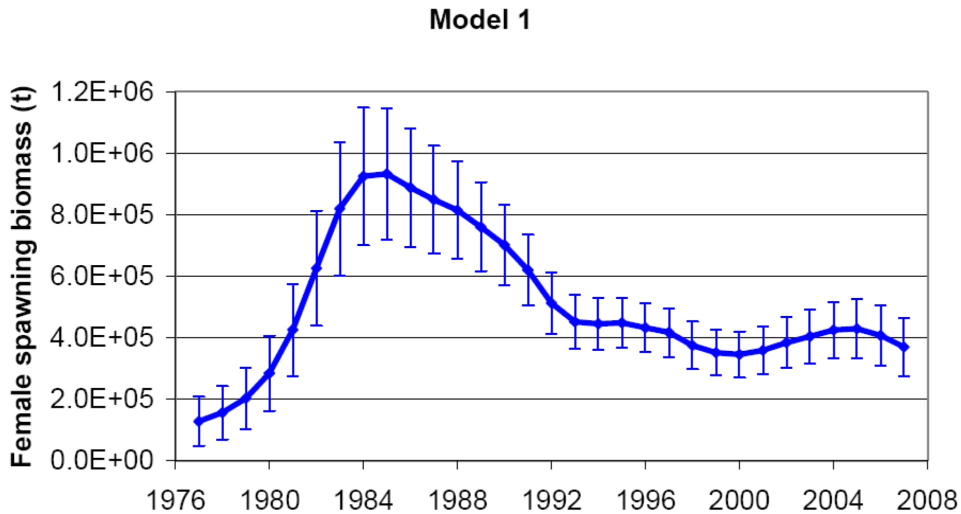


Figure 10-1. Model-estimated female spawning biomass (t) of Pacific cod in the EBS, reprinted from Thompson et al., 2007, Figure 2.3.

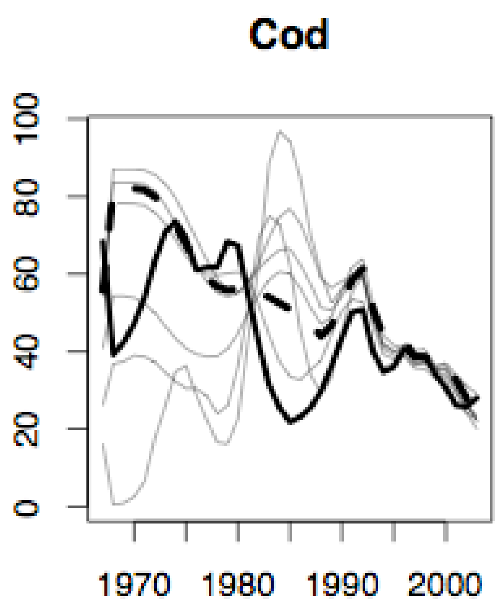


Figure 10-2. Model-estimated total spawning biomass (1000 t) of Pacific cod in the AI, reprinted from Kinzey and Punt, in review, Figure 4. The dashed bold line indicates the standard single species model run. The solid lines indicate multispecies model runs with predation included, with the bold line indicating the best fit of the multispecies models.

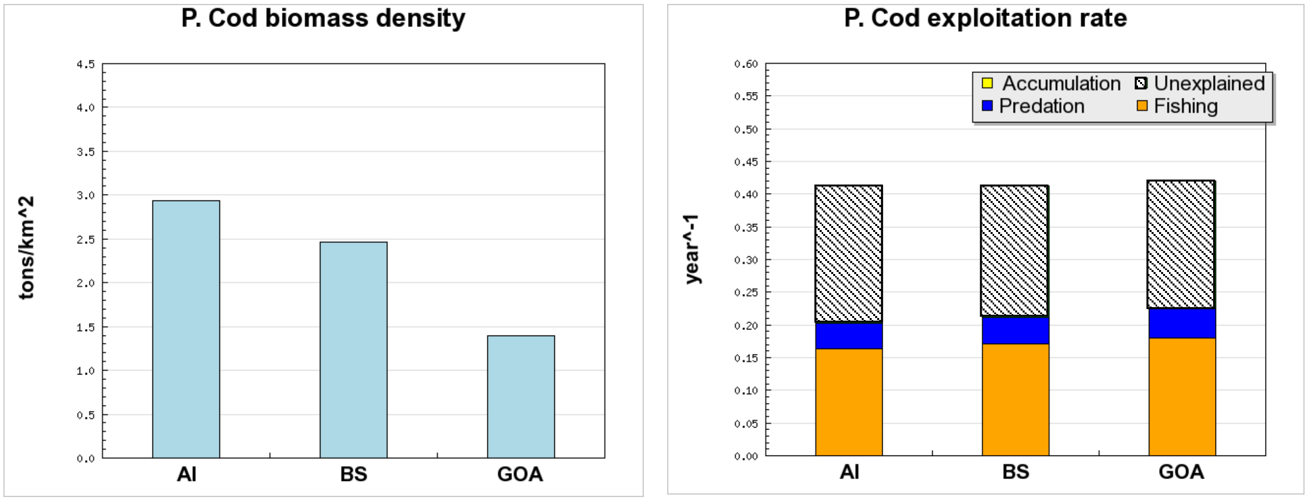


Figure 11-1. Comparative biomass density (left) and mortality sources (right) for Pacific cod in the AI, EBS, and GOA ecosystems. For the AI and GOA, biomass density (left) is the average biomass from early 1990s NMFS bottom trawl surveys divided by the total area surveyed. For the EBS, biomass density is the stock assessment estimated adult (age 3+) biomass for 1991 (Thompson and Dorn 2005) divided by the total area covered by the EBS bottom trawl survey. Total cod production (right) is derived from cod stock assessments for the early 1990's, and partitioned according to fishery catch data and predation mortality estimated from cod predator diet data (Aydin et al. 2007).

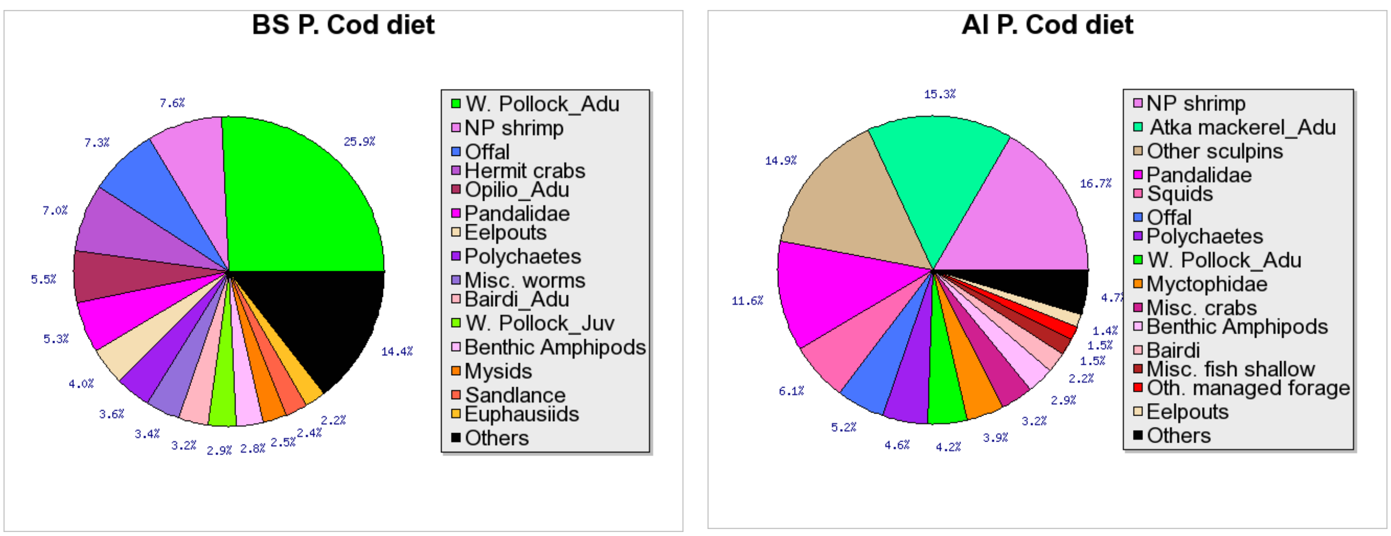
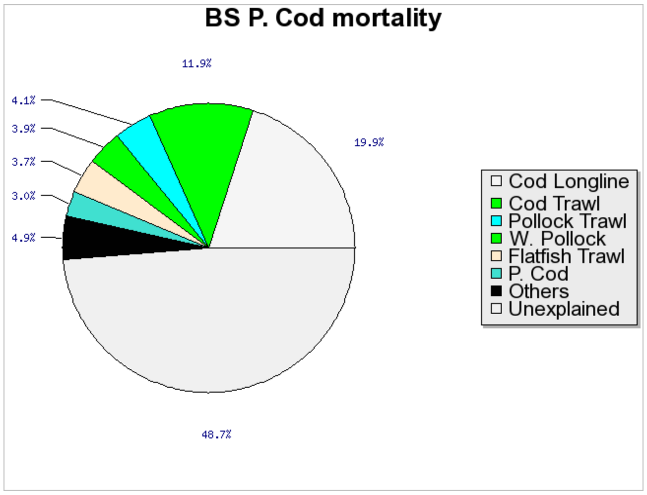


Figure 11-2. Comparison of Pacific cod diet compositions for the EBS (left) and AI (right) ecosystems. Diets are estimated from stomach collections taken aboard NMFS bottom trawl surveys in 1991 (EBS) and in 1991-1994 (AI).



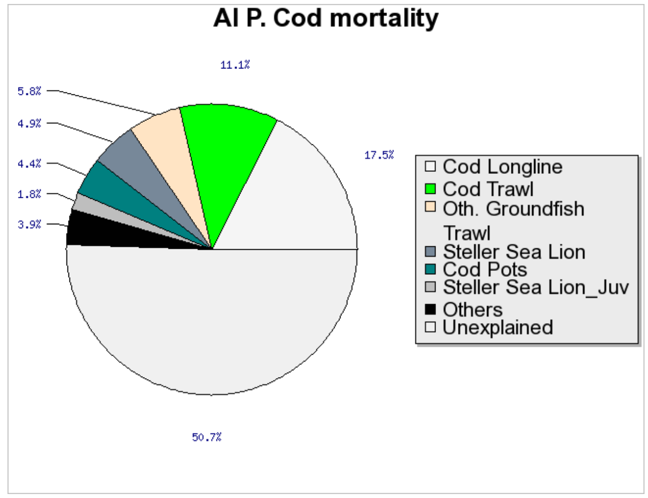
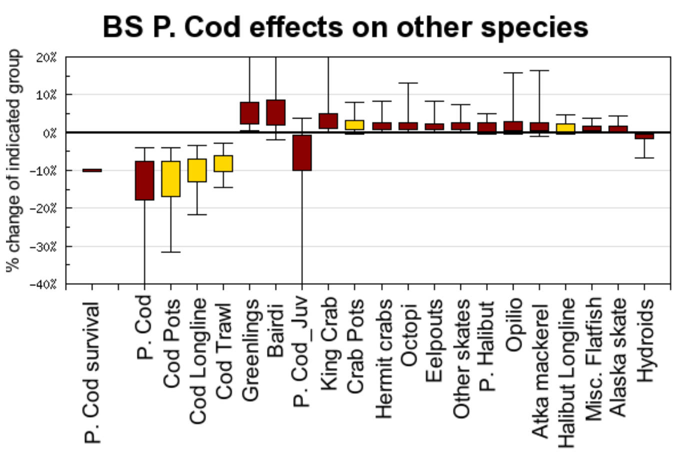


Figure 11-3. Comparison of Pacific cod mortality sources for the EBS (left) and AI (right) ecosystems. Mortality sources reflect cod predator diets estimated from stomach collections taken aboard NMFS bottom trawl surveys in 1991 (EBS) and in 1991-1994 (AI), cod predator consumption rates estimated from stock assessments and other studies, and catch of cod by all fisheries in the same time periods (Aydin et al. 2007).



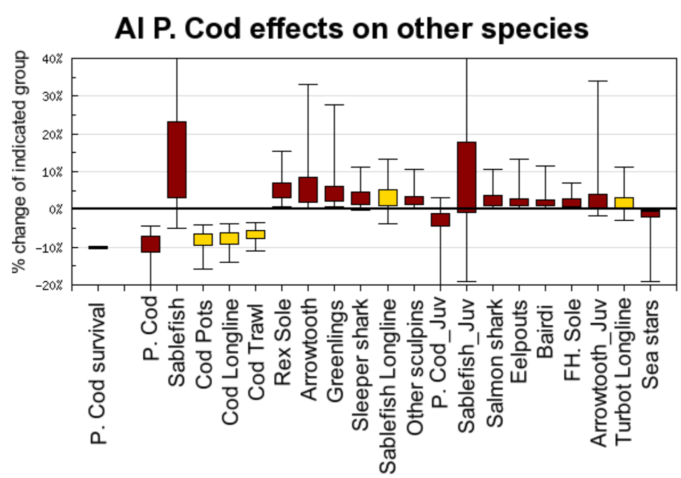


Figure 11-4. Effect of changing cod survival on fishery catch (yellow) and biomass of other species (dark red): EBS (left) and AI (right), from a simulation analysis where cod survival was decreased by 10% and the rest of the ecosystem adjusted to this decrease for 30 years. Note the differences in y-axis scale. Boxes show resulting percent change in the biomass of each species on the x axis after 30 years for 50% of feasible ecosystems, error bars show results for 95% of feasible ecosystems (see Aydin et al. 2007 for detailed methods).