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# Status of the coastal Pacific hake/whiting stock in U.S. and Canada in 1998

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## Abstract

The coastal population of Pacific hake (*Merluccius productus*, also called Pacific whiting) was assessed using an age-structured assessment model. The U.S. and Canadian fisheries were treated as distinct fisheries in which selectivity changed over time. Catch and age data from these fisheries were supplemented with survey data from the Alaska Fisheries Science Center (AFSC) triennial acoustic survey, the AFSC triennial shelf trawl survey, the Department of Fisheries and Oceans acoustic survey, and the Southwest Fisheries Science Center midwater trawl recruit survey. New data in this assessment included updated catch at age, recruitment indices from the SWFSC recruit survey, and results from the triennial acoustic and shelf trawl surveys conducted in summer of 1998.

The hake stock is at a moderate level of abundance. Stock biomass increased to a historical high of 5.7 million t in 1987 due to exceptionally large 1980 and 1984 year classes, then declined as these year classes passed through the population and were replaced by more moderate year classes. Stock size has been stable over the past four years at 1.7-1.9 million t. The mature female biomass in 1998 is estimated to be 38% of an unfished stock. The exploitation rate was below 10% prior to 1993, then increased to 17% during 1994-98. Total U.S. and Canadian catches have exceeded the ABC by an average of 12% since 1993 due to disagreement on the allocation between U.S. and Canadian fisheries. The recommended yields for 1999 range from 266 to 329 thousand t, coastwide.

Major sources of uncertainty in the assessment are the poor fit of the acoustic survey to the overall time series of abundance and the significant changes in juvenile and adult distribution that have occurred since 1994. The presence of juveniles from Oregon to British Columbia suggest that spawning and juvenile settlement has spread northwards. It is not yet clear whether these changes will be a benefit or a detriment to stock productivity and stability. For instance hake eggs and larvae may be subject to unfavorable transport, and juveniles to increased predation from cannibalism and to increased vulnerability to fishing mortality.

**Résumé**

La population côtière du merlu du Pacifique (*Merluccius productus*) a été évaluée en utilisant un modèle structuré en fonction de l'âge. Les pêches du Canada et des États-Unis ont été traitées comme des pêches distinctes dont la sélectivité a changé avec le temps. Les données de capture à l'âge de ces pêches ont été ajoutées à celles des relevés suivants : relevé acoustique triennal de *l'Alaska Fisheries Science Center (AFSC)*, relevé triennal au chalut de l'*AFSC* sur le plateau, relevé acoustique du Ministère des Pêches et des Océans et relevé du recrutement au chalut pélagique du *Southwest Fisheries Science Center (SWFSC)*. Les nouvelles données comprises dans cette évaluation incluent la mise à jour des captures â l'âge, des indices de recrutement du relevé du *SWFSC* ainsi que des résultats des relevés acoustiques triennaux et au chalut effectués sur le plateau au cours de l'été 1998.

Le stock de merlu du Pacifique est à un niveau d'abondance moyen. En 1987, la biomasse a atteint le sommet historique de 5,7 millions de tonnes, en raison de l'ampleur exceptionnelle des classes de 1980 et de 1984. Puis elle a diminué à mesure que ces classes, avançant dans leur cycle de vie, ont été remplacées par de nouvelles classes moins abondantes. L'importance du stock s'est maintenue entre 1,7 et 1,9 millions de tonnes au cours des quatre dernières années. En 1998, celle des femelles matures a été estimée à 38 % du stock non exploité. Le taux d'exploitation, qui était inférieur à 10 % avant 1993, est passé à 17 % au cours de la période de 1994 à 1998. En moyenne, depuis 1993, les prises totales effectuées par les États-Unis et le Canada ont dépassé de 12 % les prises biologiques permises, en raison de disputes à propos de l'allocation entre les pêcheries des deux pays. Les rendements recommandés pour 1999 varient de 266 à 329 milliers de tonnes, cela à l'échelle de la côte.

Les principales sources d'incertitude liées à l'évaluation ont trait à l'ajustement médiocre des résultats du relevé acoustique à la série chronologique générale de l'abondance et aux importantes modifications de la répartition des juvéniles et des adultes survenues depuis 1994. La présence de juvéniles de l'Orégon à la Colombie-Britannique porte à croire que le frai et la fixation des juvéniles se soient déplacés vers le nord. On ne sait pas si ces changements auront des effets favorables ou nuisibles sur la productivité et la stabilité du stock. Ainsi, les œufs et les larves de merlu pourront souffrir de conditions de déplacement défavorables et les juvéniles pourront subir une prédation accrue par cannibalisme et devenir plus vulnérables à la mortalité par pêche.

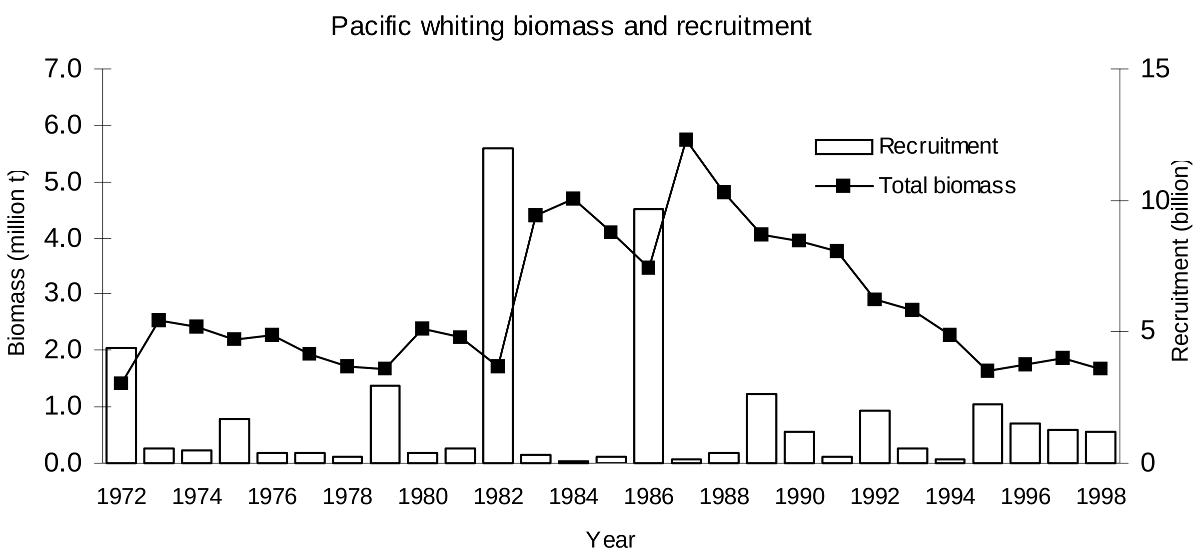
## Summary of Stock Status

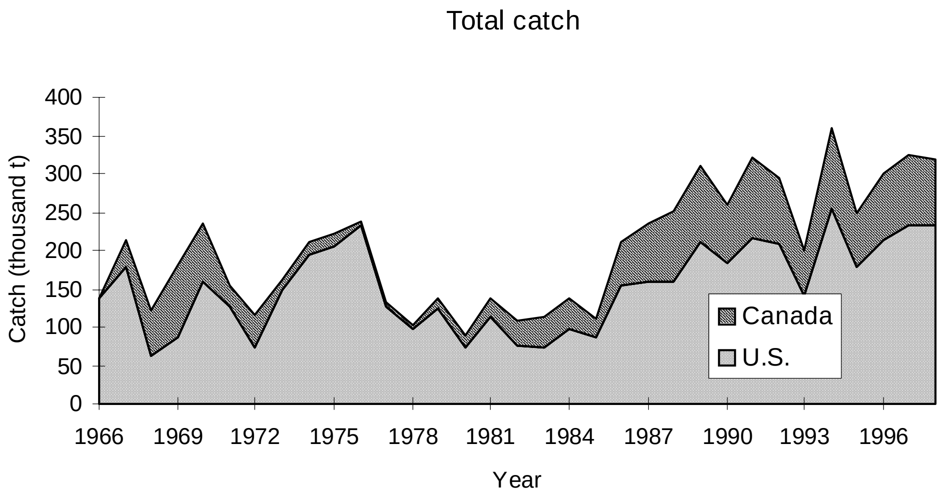
The coastal population of Pacific whiting (*Merluccius productus*, also called Pacific hake) was assessed using an age-structured assessment model. The U.S. and Canadian fisheries were treated as distinct fisheries in which selectivity changed over time. Catch and age data from these fisheries were supplemented with survey data from the Alaska Fisheries Science Center (AFSC) triennial acoustic survey, the AFSC triennial shelf trawl survey, the Department of Fisheries and Oceans acoustic survey, and the Southwest Fisheries Science Center midwater trawl recruit survey. New data in this assessment included updated catch at age, recruitment indices from the SWFSC recruit survey, and results from the triennial acoustic and shelf trawl surveys conducted in summer of 1998.

**Status of Stock:** The whiting stock is at moderate abundance. Stock biomass increased to a historical high of 5.7 million t in 1987 due to exceptionally large 1980 and 1984 year classes, then declined as these year classes passed through the population and were replaced by more moderate year classes. Stock size has been stable over the past four years at 1.7-1.8 million t. The mature female biomass in 1998 is estimated to be 37% of an unfished stock. Although 1998 stock size is near a historical low, it is close to average stock size under current harvest policies. The exploitation rate was below 10% prior to 1993, then increased to 17% during 1994-98. Total U.S. and Canadian catches have exceeded the ABC by an average of 12% since 1993 due to disagreement on the allocation between U.S. and Canadian fisheries.

Pacific whiting (hake) catch and stock status table (catches in thousands of metric tons and biomass in millions of metric tons):

| Year | 1988 | 1989 | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| U.S. landings | 161 | 211 | 184 | 218 | 209 | 141 | 253 | 178 | 213 | 233 | 233 |
| Canadian landings | 90 | 100 | 77 | 105 | 86 | 59 | 106 | 70 | 88 | 91 | 87 |
| Total | 251 | 311 | 260 | 322 | 295 | 200 | 359 | 248 | 301 | 324 | 319 |
| ABC | 327 | 323 | 245 | 253 | 232 | 178 | 325 | 223 | 265 | 290 | 290 |
| Age 3+ stock biomass | 4.8 | 4.1 | 4.0 | 3.8 | 2.9 | 2.7 | 2.3 | 1.7 | 1.8 | 1.8 | 1.7 |
| Female mature biomass | 2.4 | 2.1 | 2.0 | 1.9 | 1.5 | 1.4 | 1.2 | 0.9 | 0.9 | 0.9 | 0.8 |
| Exploitation rate | 5% | 8% | 7% | 9% | 10% | 7% | 16% | 15% | 17% | 18% | 19% |






**Data and Assessment**: An age-structured assessment model was developed using AD model builder, a modeling environment for developing and fitting multi-parameter non-linear models. Earlier assessments of whiting used the stock synthesis program. Comparison of models showed that nearly identical results could be obtained under the same statistical assumptions. The treatment of fishery and survey data was similar to previous assessments, except that a new approach to modeling changes in fishery selectivity was introduced.

**Major Uncertainties:** The whiting assessment is highly dependent on survey estimates of abundance. Since 1993, the assessment has relied primarily on an absolute biomass estimate from the AFSC acoustic survey. The acoustic target strength of Pacific whiting, used to scale acoustic data to biomass, is based on a small number of *in situ* observations. The fit to the entire acoustic survey time series is relatively poor. The AFSC shelf trawl survey biomass shows an increasing trend, conflicting with the decreasing trend in the acoustic survey.

**Target Fishing Mortality Rates:** An evaluation of whiting harvest policy led to the recommendation that the 40-10 option be considered for whiting. The 40-10 option results in similar harvest rates as the hybrid F policy used previously for whiting, and may improve economic performance of the fishery by dampening variability in harvests. An appendix to the assessment described a meta-analysis of hake stock-recruit relationships. Results indicated that the genus Merluccius may be less resilient to fishing than other gadoids. A Bayesian decision analysis produced estimates of FMSY in the F40% to F45% range depending on the degree of risk-aversion.

**Projection table (Coastwide yield in thousands of tons, biomass in millions of tons):**

| | Coastwide yield | | | 3+ Biomass | | |
|---|---|---|---|---|---|---|
| Harvest policy | 1999 | 2000 | 2001 | 1999 | 2000 | 2001 |
| F35% | 405 | 350 | 298 | 1.5 | 1.4 | 1.1 |
| F40% | 320 | 297 | 266 | 1.5 | 1.4 | 1.2 |
| F40% (40-10 option) | 301 | 275 | 238 | 1.5 | 1.5 | 1.2 |
| F45% | 259 | 251 | 234 | 1.5 | 1.5 | 1.3 |
| F45% (40-10 option) | 243 | 236 | 215 | 1.5 | 1.5 | 1.3 |

**Other considerations:** Unusual juvenile and adult distribution patterns have been seen in Pacific whiting population in recent years. Frequent reports of large numbers of juveniles from Oregon to British Columbia suggest that spawning and juvenile settlement has spread northwards. It is not yet clear whether these changes will be a benefit or a detriment to stock productivity and stability. From an assessment perspective, the strength of recruiting year classes may be overestimated--although the use of time-varying fishery selectivity in the assessment model should counteract this tendency. More importantly, whiting eggs and larvae may be subject to unfavorable transport, and juveniles to increased predation from cannibalism and to increased vulnerability to fishing mortality.

# INTRODUCTION

This assessment has been developed by U.S. and Canadian scientists through the Pacific hake working group of the Technical Sub-Committee (TSC) of the Canada-U.S. Groundfish Committee. Prior to 1997, separate Canadian and U.S. assessments were submitted to each nation's assessment review process. In the past, this has resulted in differing yield options being forwarded to managers. Multiple interpretations of stock status made it difficult to coordinate overall management policy for this trans-boundary stock. To address this problem, the working group agreed in 1997 to present scientific advice in a single assessment. To further coordinate scientific advice, this report was submitted to a joint Canada-U.S. technical review that satisfied the requirements of both the U.S. Pacific Fisheries Management Council (PFMC) and the Canadian Pacific Stock Assessment Review Committee (PSARC). The Review Group meeting was held in White Rock, British Columbia, during Feb 17-18, 1999. While this report forms the basis for scientific advice to managers, final advice on appropriate yield will be provided to Canadian DFO managers by the PSARC Groundfish Sub-committee and the PSARC Steering Committee, and to the U.S. Pacific Fisheries Management Council by the Groundfish Management Team.

In summer of 1998, a cooperative U.S.-Canada acoustic survey of whiting was conducted by scientists from National Marine Fisheries Service (NMFS) and Department of Fisheries and Oceans (DFO). Because information from this survey was considered essential for evaluating current stock status, this assessment was delayed so that survey results could be used in the assessment.

## Stock Structure and Life History

Pacific whiting (*Merluccius productus*), also called Pacific hake, is a codlike species distributed off the west coast of North America from 25° N. to 51° N. lat. The coastal stock is currently the most abundant groundfish population in the California current system. Smaller populations of whiting occur in the major inlets of the north Pacific Ocean, including the Strait of Georgia, Puget Sound, and the Gulf of California. Electrophoretic studies indicate that Strait of Georgia and the Puget Sound populations are genetically distinct from the coastal population (Utter 1971). Genetic differences have also been found between the coastal population and whiting off the west coast of Baja California (Vrooman and Paloma, 1977). The coastal stock is distinguished from the inshore populations by larger body size, seasonal migratory behavior, and a pattern of low median recruitment punctuated by extremely large year classes.

The coastal stock typically ranges from southern California to Queen Charlotte Sound. Spawning occurs off south-central California during January-March. Due to the difficulty of locating major spawning concentrations, spawning behavior of whiting remains poorly understood (Saunders and McFarlane, 1997). In spring, adult Pacific whiting migrate onshore and to the north to feed along the continental shelf and slope from northern California to Vancouver Island. In summer, whiting form extensive midwater aggregations near the continental shelf break, with highest densities located over bottom depths of 200-300 m (Dorn et al. 1994). The prey of whiting include euphausiids, pandalid shrimp, and pelagic schooling fish (such as eulachon and herring) (Livingston and Bailey, 1985). Larger whiting become increasingly piscivorous, and herring are large component of whiting diet off Vancouver Island.

Although whiting are cannibalistic, the geographic separation of juveniles and adults usually prevents cannibalism from being an important factor in their population dynamics (Buckley and Livingston, 1997).

Older (age 5+), larger, and predominantly female whiting migrate into the Canadian zone. During El Niños, a larger proportion of the stock migrates into Canadian waters, apparently due to intensified northward transport during the period of active migration (Dorn 1995). Range extensions to the north also occur during El Niños, as evidenced by reports of whiting from S.E. Alaska during warm water years. During the warm period experienced in 1990s, there have been changes in typical patterns of distribution. Spawning activity has been recorded north of California, and frequent reports of unusual numbers of juveniles from Oregon to British Columbia suggest that juvenile settlement patterns have also shifted northwards. Because of this, juveniles may be subjected to increased predation from cannibalism and to increased vulnerability to fishing mortality.

## Fisheries

The fishery for the coastal population of Pacific whiting occurs primarily during April-November along the coasts of northern California, Oregon, Washington, and British Columbia. The fishery is conducted almost exclusively with midwater trawls. Most fishing activity occurs over bottom depths of 100-500 m, but offshore extensions of fishing activity have occurred. The history of the coastal whiting fishery is characterized by rapid changes brought about by the development of foreign fisheries in 1966, joint-venture fisheries in the early 1980's, and domestic fisheries in 1990's (Fig. 1).

Large-scale harvesting of Pacific whiting in the U.S. zone began in 1966 when factory trawlers from the former Soviet Union began targeting on Pacific whiting. During the mid 1970's, the factory trawlers from Poland, Federal Republic of Germany, the former German Democratic Republic and Bulgaria also participated in the fishery. During 1966-1979, the catch in U.S. waters averaged 137,000 t per year (Table 1). A joint-venture fishery was initiated in 1978 between two U.S. trawlers and Soviet factory trawlers acting as motherships. By 1982, the joint-venture catch surpassed the foreign catch. In the late 1980's, joint-ventures involved fishing companies from Poland, Japan, former Soviet Union, Republic of Korea and the People's Republic of China. In 1989, the U.S. fleet capacity had grown to a level sufficient to harvest entire quota, and no foreign fishing was allowed.

Historically, the foreign and joint-venture fisheries produced fillets and headed and gutted products. In 1989, Japanese motherships began producing surimi from Pacific whiting, using a newly developed process to inhibit myxozoan-induced proteolysis. In 1990, domestic catcher-processors and motherships entered the Pacific whiting fishery in the U.S. zone. Previously, these vessels had engaged primarily in Alaskan pollock fisheries. The development of surimi production techniques made Pacific whiting a viable alternative. In 1991, joint-venture fishery for Pacific whiting ended because of the high level of participation by domestic catcher-processors and motherships, and the growth of shore-based processing capacity. Shore-based processors of Pacific whiting had been constrained historically by a limited domestic market for Pacific whiting fillets and headed and gutted products. The construction of surimi plants in Newport and Astoria led to a rapid expansion of shore-based landings in the early 1990's.

The Pacific whiting fishery in Canada exhibits a similar pattern, although phasing out of the foreign and joint-venture fisheries has lagged a few years relative to the U.S. experience. Since 1968, more Pacific whiting have been landed than any other species in the groundfish fishery on Canada's west coast (Table 1). Prior to 1977, the former Soviet Union caught the majority of whiting in the Canadian zone, with Poland and Japan harvesting much smaller amounts. Since declaration of the 200-mile extended fishing zone in 1977, the Canadian fishery has been divided into shore-based, joint-venture, and foreign fisheries. In 1990, the foreign fishery was phased out. Since the demand of Canadian shore-based processors remains below the available yield, the joint-venture fishery will continue through 2000. Poland is the only country that participated in the 1998 joint-venture fishery. The majority of the shore-based landings of the coastal whiting stock are processed into surimi, fillets, or mince by processing plants at Ucluelet, Port Alberni, and Delta. Small deliveries were made in 1998 to plants in Washington and Oregon. Although significant aggregations of whiting are found as far north as Queen Charlotte Sound, in most years the fishery has been concentrated below 49° N lat. off the south coast of Vancouver Island, where there are sufficient quantities of fish in proximity to processing plants.

## Management of Pacific whiting

Since implementation of the Fisheries Conservation and Management Act in the U.S. and the declaration of a 200 mile fishery conservation zone in Canada in the late 1970's, annual quotas have been the primary management tool used to limit the catch of Pacific whiting in both zones by foreign and domestic fisheries. The scientists from both countries have collaborated through the TSC, and there has been informal agreement on the adoption of an annual fishing policy. However, overall management performance has been hampered by a long-standing disagreement between the U.S. and Canada on the division of the acceptable biological catch (ABC) between U.S. and Canadian fisheries. In 1991-92, U.S. and Canadian managers set quotas that summed to 128% of the ABC, while in 1993-98, the combined quotas were 112% of the ABC on average.

*United States*

Prior to 1989, catches in the U.S. zone were substantially below the harvest guideline, but since 1989 the entire harvest guideline has been caught. The total U.S. catch has not significantly exceeded the harvest guideline for the U.S. zone (Table 2), indicating that in-season management procedures have been very effective.

In the U.S. zone, participants in the directed fishery are required to use pelagic trawls with a codend mesh that is at least 7.5 cm (3 inches). Regulations also restrict the area and season of fishing to reduce the bycatch of chinook salmon. At-sea processing and night fishing (midnight to one hour after official sunrise) are prohibited south of 42° N lat. Fishing is prohibited in the Klamath and Columbia River Conservation zones, and a trip limit of 10,000 pounds is established for whiting caught inside the 100-fathom contour in the Eureka INPFC area. During 1992-95, the U.S. fishery opened on April 15, however in 1996 the opening date was moved to May 15. Shore-based fishing is allowed after March 1 south of 42° N. lat. Prior to 1997, at-sea processing was prohibited by regulation when 60 percent of the harvest guideline was reached. A new allocation agreement, effective in 1997, divided the U.S. non-tribal harvest guideline between factory trawlers (34%) , vessels delivering to at-sea processors (24%), and vessels delivering to shore-based processing plants (42%).

Shortly after this allocation agreement was approved by the PFMC, fishing companies with factory trawler permits established the Pacific Whiting Conservation Cooperative (PWCC). The primary role of the PWCC is to allocate the factor trawler quota between its members. Anticipated benefits of the PWCC include more efficient allocation of resources by fishing companies, improvements in processing efficiency and product quality, and a reduction in waste and bycatch rates relative to the former "derby" fishery in which all vessels competed for a fleet-wide quota. The PWCC also conducts research to support whiting stock assessment. As part of this effort, PWCC sponsored a juvenile recruit survey in summer of 1998 in collaboration with NMFS scientists.

*Canada*

The Canadian Department of Fisheries and Oceans (DFO) is responsible for managing the Canadian whiting fishery. Prior to 1987, the quota was not reached due to low demand for whiting. In subsequent years the quota has been fully subscribed, and total catch has been successfully restricted to ±5% of the quota (Table 2).

Domestic requirements are given priority in allocating yield between domestic and joint-venture fisheries. During the season, progress towards the domestic allocation is monitored and any anticipated surplus is re-allocated to the joint-venture fishery. The Hake Consortium of British Columbia coordinates the day-to-day fleet operations within the joint-venture fishery. Through 1996, the Consortium split the available yield equally among participants or pools of participants. In 1997, Individual Vessel Quotas (IVQ) were implemented for the British Columbia trawl fleet. IVQs of Pacific whiting were allotted to licence holders based on a combination of vessel size and landing history. Vessels are allocated proportions of the domestic or joint-venture whiting quota. There is no direct allocation to individual shoreside processors. Licence holders declare the proportion of their whiting quota that will be landed in the domestic market, and shoreside processors must secure catch from vessel licence holders.

## Overview of Recent Fishery and Management

*1997*

United States

The Groundfish Management Team (GMT) recommended a 1997 ABC of 290,000 t based on an average of projected yields for two 1994 year class recruitment scenarios: a scenario based on median recruitment and a scenario based on 75th percentile recruitment. For both scenarios, the moderate risk harvest strategy was used. The PFMC adopted the recommended ABC and allocated 80 percent of the ABC (232,000 t ) to U.S. fisheries.

The 1997 at-sea fishery began on May 15 for both motherships and factory trawlers. Ten vessels operated as catcher-processors, and six vessels operated as motherships. Aggregate daily catches averaged 2,800 t for the mothership fleet, and 2,600 t for the factory trawler fleet. The mothership fishery closed on June 1, for an opening of 18 days, while factory trawler fishery continued until June 10, for an opening of 27 days. Fishing occurred mainly along the outside edge of Hecata Bank, and from Willapa Bay to Cape Flattery off the Washington coast (Fig. 2).

The total shore-based U.S. landings in 1997 were 87,410 t. The leading ports were Newport, Oregon (36,306 t), Astoria, Oregon (37,425 t), Washington coastal ports (Westport and Illwaco) (7,231 t) , and Crescent City, California (5,922 t). In aggregate, these ports accounted for more than 99% of all shore-based whiting landings. The shore-based fishery in Newport and Astoria began in June and continued to August when the harvest guideline was attained. In Crescent City, landings began in April and continued to August. Trawling locations by the shore-based fleet operating from Oregon ports were distributed more widely along the coast in comparison to previous years (Fig. 3).

In 1997, the Makah Indian Tribe secured an allocation of 25,000 t of Pacific whiting under their treaty right to fish in their usual and accustomed places. The Makah fishery was conducted as a mothership fishery, with a single at-sea processing vessel receiving deliveries from tribal catcherboats. The fishery operated within the Makah usual and accustomed fishing area, an area bounded by 48° 02′15″N. lat., 125° 44′00″ W. long. and the U.S.-Canada border. The fishery operated from June 9 to August 16, then reopened during October 14-19 to harvest the remaining allocation. The total 1997 landings in the Makah fishery were 24,840 t.

Canada

Canadian managers allocated 99,400 t to Canadian fisheries, so that 30 percent of the expected U.S. and Canadian harvest would again go to the Canadian fishery. The all-nation catch in the Canadian zone was 90,630 t in 1997, up from 88,240 t in 1996 due to the increase in available yield (Table 1). Canadian shore-based landings increased in 1997 to 48,065 t from 22,644 t in 1996 due to more favorable market prices for surimi and expanding processor capacity. The distribution of joint-venture fishing effort in 1997 in the Canadian zone is presented in Figure 4.

*1998*

United States

The GMT recommended a status quo ABC of 290,000 t for 1998 (i.e. the same as 1997). The ABC recommendation was based on a decision table with alternative recruitment scenarios for the 1994 year class, which was again considered a major source of uncertainty in current stock status. Recommendations were based on the moderate risk harvest strategy. The PFMC adopted the recommended ABC and allocated 80 percent of the ABC (232,000 t ) to U.S. fisheries.

The 1998 at-sea fishery began on May 15 for both motherships and factory trawlers. Seven vessels operated as catcher-processors, and six vessels operated as motherships. Aggregate daily catches averaged 3,000 t for the mothership fleet, and 850 t for factory trawler fleet. The mothership fishery closed on May 31, for an opening of 17 days. The factory trawler fishery continued until August 6, for an opening of 84 days. Both the protracted factory trawler season and the lower daily catch rates reflect the PWCC's allocation of the factory trawler quota to individual fishing companies. Fishing occurred mainly from Cape Flattery south to the Columbia River mouth off the Washington coast, and along the outside edge of Hecata Bank (Fig. 5).

The total shore-based U.S. landings in 1998 were 87,548 t. The leading ports were Newport, Oregon (45,324 t), Astoria, Oregon (26,237 t), Washington coastal ports (Westport and Illwaco) (9,997 t) , and Crescent City, California (5,162 t). In aggregate, these ports accounted for more than 99% of all shore-based whiting landings. The shore-based fishery in Newport and Astoria began in June and continued to October when the harvest guideline was attained. In Crescent City, landings began in April and continued to August.

In 1998, the Makah Indian Tribe again secured an allocation of 25,000 t of Pacific whiting. The fishery operated from June 7 to August 16, then reopened during October 30 - November 12 to harvest the remaining allocation. The total 1998 landings in the Makah fishery were 24,509 t.

<u>Canada</u>

The PSARC groundfish subcommittee recommended to DFO managers a coastwide range of 116-233,000 t choosing the less optimistic view of the 1994 year-class. Canadian managers adopted the high end of that coastwide range (233,000) and using the allocation scheme described above allocated 80,000 t to Canadian fisheries. The all-nation catch in the Canadian zone was 86,738 t in 1998, down from 90,630 t in 1997 due to the decrease in available yield (Table 1). DFO managers allow a 15% discrepancy between the quota and total catch. The quota may be exceeded by up to 15%, which is then taken off the quota for the subsequent year. If less than the quota is taken, up to 15% can be carried over into the next year. The overage in 1998 (Table 2) is due to carry-over from 1997 when 9% of the quota was not taken. Canadian shore-based landings in 1998 were 47,074 t (2% lower than 1997). The joint-venture fishery was active over the period June 1-September 3, while the domestic fishery extended through November 15.

## ASSESSMENT

### Modeling Approaches

Age-structured assessment models have been used to assess Pacific whiting since the early 1980's. Modeling approaches have evolved as new analytical techniques have been developed. Initially, a cohort analysis tuned to fishery CPUE was used (Francis et al. 1982). Later, the cohort analysis was tuned to NMFS triennial survey estimates of absolute abundance at age (Hollowed et al. 1988a). Since 1989, a stock synthesis model that utilizes fishery catch-at-age data and survey estimates of population biomass and age composition has been the primary assessment method (Dorn and Methot, 1990).

In this assessment, we develop an age-structured model using AD model builder (Fournier 1996), a modeling environment for developing and fitting multi-parameter non-linear models. In contrast, stock synthesis is an software program expressly designed to fit age or length-structured population models, in which the analyst selects among multiple options those most appropriate for the stock (Methot 1989). The conversion from stock synthesis to AD model builder consisted of programming the population dynamics and likelihood equations in the model implementation language (a superset of C++). Our approach was to construct a model with similar features to the stock synthesis model used in previous assessments, validate the model using side-by-side comparisons, and then explore alternative treatments of process error that are not possible in stock synthesis. AD model builder includes post-convergence routines to calculate standard errors (or likelihood profiles) for any quantity of interest, allowing for a unified approach to the treatment of uncertainty in estimation and forward projection.

## Data Sources

The data used in the stock assessment model (SAM) included:

- Total catch from the U.S. and Canadian fisheries (1972-98).
- Catch at age from the U.S. (1973-98) and Canadian fisheries (1977-96).
- Biomass and age composition from AFSC acoustic/midwater trawl surveys (1977, 1980, 1983, 1986, 1989, 1992, 1995, 1998).
- Biomass and age composition from the AFSC bottom trawl surveys (1977, 1980, 1983, 1986, 1989, 1992, 1995, 1998)
- Biomass and age composition from the DFO acoustic surveys of Pacific whiting (1990-96).
- Indices of young-of-the-year abundance from the SWFSC Tiburon laboratory larval rockfish surveys (1986-98).

The model also uses biological parameters to characterize the life history of whiting. These parameters are used in the model to estimate spawning and population biomass, and obtain predictions of fishery and survey biomass from the parameters estimated by the model:

- Proportion mature at age.
- Weight at age and year by fishery and by survey
- Natural mortality (*M*)

*Total catch*

Table 1 gives the catch of Pacific whiting for 1966-98 by nation and fishery. Catches in U.S. waters for 1966-80 are from Bailey et al. (1982). Prior to 1977, the at-sea catch was reported by foreign nationals without independent verification by observers. Bailey et al. (1982) suggest that the catch from 1968 to 1976 may have been under-reported because the apparent catch per vessel-day for the foreign feet increased after observers were placed on foreign vessels in the late 1970's. For 1981-98, the shore-based landings are from Pacific Fishery Information Network (PacFIN). Foreign and joint-venture catches for 1981-90, and domestic at-sea catches for 1991-98 are estimated by the North Pacific Groundfish Observer Program (NPGOP).

At-sea discards are included in the foreign, joint-venture, at-sea domestic catches in the U.S. zone, but not in the shore-based fishery. The majority of vessels in the U.S. shore-based fishery operate under experimental fishing permits that require them to retain all catch and bycatch for sampling by plant observers. Canadian joint-venture catches are monitored by at-sea observers, which are placed on all processing vessels. Observers use volume/density methods to estimate total catch. Domestic Canadian landings are recorded by dockside monitors using total catch weights provided by processing plants.

*Fishery age composition*

Catch at age for the foreign fishery in the U.S. zone during 1973-1975 is given in Francis and Hollowed (1985), and was reported by Polish and Soviet scientists at bilateral meetings. Estimates of catch at age for the U.S. zone foreign and joint-venture fisheries in 1976-90, and the at-sea domestic fishery in 1991-98, were derived from length-frequency samples and length-stratified otolith samples collected by observers. Sample size information is provided in Table 3. In general, strata were defined by the combination of three seasonal time periods and three geographic areas. Methods and sample sizes by strata are given in Dorn (1991, 1992). During 1992-98, fishing took place only in the early part of the year (April-June) north of 42° N. lat., so only two spatial strata were used (north and south of Cape Falcon, 45° 46′ N. lat.), and no seasonal strata were defined. The Makah fishery (1996-98) was defined as a separate strata because of its restricted geographic limits and different seasons.

Biological samples from the shore-based fishery were collected by port samplers at Newport, Astoria, Crescent City, and Westport in 1997 and 1998. A stratified random sampling design is used to estimate the age composition of the landed catch (sample size information provided in Table 3). Shore-based strata are defined on the basis of port of landing. In 1997 and 1998, four strata defined 1) northern California (Eureka and Crescent City), 2) southern Oregon (Newport and Coos Bay), and 3) northern Oregon (Astoria and Warrenton), and Washington coastal ports (Illwaco and Westport). No seasonal strata have been used for the shore-based fishery; however, port samplers are instructed to distribute their otolith samples evenly throughout the fishing season. Since the otolith samples from the 1998 fishery have not yet been aged, we obtained a preliminary age composition by compiling age-length keys using the acoustic survey age samples collected within the geographic strata defined for the fishery, then applying the fishery length composition to those keys.

Biological samples from the Canadian joint-venture fishery were collected by fisheries observers, placed on all foreign processing vessels in 1997 and 1998. Shore-based Canadian landings are sampled by port samplers. The Canadian catch at age is estimated from random otoliths samples.

Figure 6 shows the estimated age composition for the 1997 shore-based fishery by port in U.S. zone. Between 44% and 83% of the catch in each port was composed of age-3 and age-4 fish. The age-3 fish were more abundant in the Astoria and Washington coastal port landings, while the age-4 were more abundant in the Newport and Crescent City landings. The age and size composition in Newport during 1991-98 show the recruitment of 1993 and 1994 year classes to the fishery (Fig. 7). In 1998, the mean size of fish was lower (40.6 cm) than in previous years, and the preliminary age composition indicated that two previously unobserved year classes, the 1995 year class (age-3) and the 1996 year class (age-2) composed 46% of the catch. The presence of these year classes in the Newport landings may be partly due to northward shifts in distribution brought about by El Niño conditions during 1997 and 1998.

Table 4 (Figs. 8-9) gives the estimated U.S. fishery (1973-98) and Canadian fishery catch at age (1977-96). The U.S. fishery catch at age was compiled from the NORPAC database maintained by the North Pacific Groundfish Observer Program, and from an additional database of shore-based biological sampling maintained by the Marine Assessment and Resource Ecology Task at AFSC. The Canadian catch at age for 1977-97 was compiled from a database at the Pacific Biological Station.

Ages assigned by U.S. and Canada age readers were compared using otoliths from the 1997 Makah fishery. The main purpose of the comparison was to calibrate ageing criteria between agencies for the 1990 (age 7 in 1997) and the 1991 (age 6) year classes. Based on earlier U.S. ageing data, the 1991 year class was apparently weak, but age samples from the Canadian fishery in 1995 and 1996 suggested that it may be nearly as strong as the 1990 year class. A total of 89 otoliths were aged by both AFSC and DFO age readers. Overall agreement was 73% (65/89) , and 90% (80/89) of the assigned ages agreed to within one year (Fig. 10). Despite good overall agreement, several potential problems were identified. There was a tendency for the U.S. reader to assign older ages than the Canadian age reader. The problem was most evident for the age 3 and 4 fish (which normally have high reader-tester agreement), where 29% (6/21) of the fish assigned age 4 by the U.S. reader were assigned age 3 by the Canadian reader. There was a high percentage of age 6 fish out of the age 6-7 fish for *both* the U.S. and Canadian readers (U.S. 12/22 and Canadian 8/15). However, 50% (6/12) of the fish that were assigned age 6 by the U.S. reader were assigned younger ages by the Canadian reader, suggesting that annuli recognition may be especially difficult for otoliths within this age range. U.S. and Canadian age readers resolved disagreements at the 1998 meeting of the Committee of Age Readers (CARE). Additional comparisons are needed to further calibrate ageing criteria between agencies.

*AFSC Triennial Acoustic Survey (Biomass and Age Composition*)

The Alaska Fisheries Science Center has conducted an echo-integration trawl (EIT) survey along the US and Canadian west coasts on a triennial basis since 1977 (Wilson and Guttormsen 1997). In 1995 and 1998, the coastwide acoustic survey was conducted cooperatively by AFSC and DFO. However, we refer to this survey as the AFSC survey to distinguish it from the annual DFO survey, which covers only the Canadian zone. This survey is specifically designed to estimate the distribution and abundance of Pacific whiting. The AFSC surveys follow a standard procedure in which echo integration data are collected as the vessel runs a series of transects, laid out to adequately cover the entire geographical range of the target species. Mid-water trawls are also conducted during the survey to identify the species composition of the echo sign, and to provide the biological information needed to estimate whiting abundance.

In 1996, research on whiting acoustic target strength (Traynor 1996) resulted in a new target strength model of TS = 20 log L - 68. Target strength (TS) is a measure of the acoustic reflectivity of the fish and is necessary to scale relative acoustic estimates of fish abundance to absolute estimates of abundance. Biomass estimates for the 1977-89 acoustic surveys were re-estimated using the new target strength. To correct for the limited geographic coverage of these earlier surveys, deep water and northern expansion factors were also used to adjust the total acoustic backscatter (Dorn 1996). The revised acoustic time series averages 31% higher than the original time series for 1977-89, indicating that the decrease in biomass due to the change in target strength is more than offset by the increase due to the northern and deep water expansion factors. Biomass and age composition for the 1992 and 1995 surveys at TS = 20 log L - 68 are given in Wilson and Guttormsen (1997). Because of their dependence on the deep water and northern expansion factors, the 1977-89 biomass estimates were assumed to be more uncertain (CV = 0.5) than the 1992-98 biomass estimates (CV = 0.1). Age composition and biomass for the AFSC acoustic survey are given in Table 5 (Fig. 11).

The most recent survey was cooperative survey between AFSC and DFO, and was carried out from July 6 to August 27, 1998, by the NOAA ship *Miller Freeman* and the DFO ship *W. E. Ricker*. The area surveyed by the *Miller Freeman* extended from Monterey Bay (36°30' N. lat.) to Queen Charlotte Sound (51° 45' N. lat.). The *W. E. Ricker* carried out simultaneous survey operations to the north of the area surveyed by the *Miller Freeman*. A primary goal of the *W. E. Ricker* was to establish the northern limit of the stock during El Niño conditions.

Aggregations of Pacific whiting were distributed throughout much of the area surveyed by NOAA and DFO scientists (Figs. 12-13). Major aggregations were observed off Oregon between Cape Blanco and Coos Bay; near the US-Canada border, between northern Vancouver Island and southern Queen Charlotte Sound, and to lesser extent along the west side of the Queen Charlotte Islands, northern Hecate Strait, and Dixon Entrance. Whiting were found as far north as 58° N. lat. in the Gulf of Alaska. The 1998 survey results indicate a moderate decline of about 15% in whiting biomass relative to the previous coastwide survey in 1995. There was also a large northward shift in the distribution of biomass compared to previous surveys. For example, only about 35% of the total biomass in 1998 occurred south of 47°30'N (i.e., Monterey, Eureka, and Columbia INPFC areas) in contrast to nearly 80% which occurred in this area in 1995. The biomass in Canadian waters was nearly triple the level reported in 1995.

*AFSC Triennial Shelf Trawl Survey (Biomass and Age Composition*)

The Alaska Fisheries Science Center has conducted a triennial bottom trawl survey along the west coast of North America since 1977 (Wilkins et al. 1998). This is a multi-purpose survey designed to monitor the abundance and distribution of a variety of groundfish stocks off the Pacific coast between southern California and southern British Columbia. Data are collected from each haul on the weight and number of each species caught, length distributions of commercially important species, and biological data providing information on age, maturity stage, length-weight relationships, and feeding habits. Biomass and population number estimates are calculated from bottom trawl CPUE using area-swept calculations. Changes in depth and latitudinal coverage from survey to survey affect whether an area-swept biomass estimate can be considered index of abundance. The initial trawl survey in 1977 extended inshore to only 91 m, rather than to 55 m as in all subsequent years. The deeper limit of the survey has been 366 m in most years (1980-1992), but extended to 475 m in 1977 and to 500 m in 1995 and 1998. The trawl survey did not extend into Canadian waters in 1977 and 1986. The biomass estimates for 1977 and 1986 were adjusted as described in Dorn et al. (1991) to make them comparable to the other surveys, which extended north to 49° 30′N lat. The presence of significant densities of whiting both offshore and to the north of the area covered by the trawl survey limits the usefulness of this survey to assess the whiting population.

The most recent survey was carried out from June 1 to August 9, 1998, from Point Conception (34°30′ N. lat.) to the middle of Vancouver Island (49°30′ N. lat.) aboard two chartered commercial trawlers. The vessels were equipped with the RACE Division's standardized high-opening Noreastern bottom trawls, constructed of polyethylene mesh and equipped with 35-cm bobbin roller gear. Pacific whiting were caught at 489 of the 527 successfully sampled stations. Catch rates of whiting were highest in the Eureka and the U.S. Vancouver INPFC areas, and catch rates over the entire survey area increased with depth. Figures 14-17 show the distribution of whiting CPUE by size ranges that correspond to age-0, age-1, age-2, and age-3+ fish. Age-0 and age-1 fish, which are not usually detected by the bottom trawl survey, were most prominent in the southernmost hauls and in areas just north and south of the Columbia River, often in relatively deep hauls. Age-2 whiting were plentiful in the shallower hauls between Cape Mendocino and Cape Lookout.

Biomass and population numbers within the survey area were estimated to be 497 thousand tons and 1.47 billion fish, respectively. Age composition estimates for the AFSC trawl surveys are given in Table 6. Since the otolith samples from the 1998 trawl survey have not yet been aged, we obtained a preliminary age composition by compiling age-length keys from the acoustic survey age samples by geographic strata, then applying the bottom trawl survey length composition to those keys. This procedure is biased if bottom trawl-caught fish have a different age distribution at length than fish caught by mid-water trawl. However, we use bottom trawl survey in the base-run model primarily for comparison, so the consequences of any bias on model results would be negligible.

*DFO Acoustic Survey (Biomass and Age Composition*)

The Department of Fisheries and Oceans has conducted an annual acoustic survey of whiting in the Canadian zone since 1990. These surveys occur in August, when the whiting population is thought to be at the northern limit of its annual migration cycle. The objective of the DFO acoustic survey is to estimate the total biomass of whiting in the Canadian zone; however, in some years time constraints have prevented the survey from extending to the northern limit of the stock. In the triennial survey years of 1995 and 1998, surveying operations were coordinated between AFSC and DFO, and a single biomass estimate was produced for the Canadian zone. In 1995, this biomass estimate is used as part of the DFO survey series as well as being included as part of the AFSC total acoustic biomass. Since the fraction of the population migrating into the Canadian zone during the summer can vary substantially from one year to the next, this survey has limited usefulness for monitoring population-wide trends in biomass. Estimated biomass and age composition at a target strength of -35 dB/kg (the DFO survey biomass estimates have not been updated for a target strength of TS = 20 log L - 68) is given in Table 7.

*Comparison of Survey Trends*

Pacific whiting biomass trends from these surveys show different patterns (Fig. 18). The biomass from the AFSC acoustic survey shows an increase to 1986, followed by a decline which appears to have slowed in the last decade. The AFSC shelf trawl survey trend is generally upwards throughout the time period, although there is a slight decrease from 1995 to 1998. The DFO acoustic survey shows a large increase during the 1992 El Niño, followed by a rapid decline. The AFSC acoustic survey, because of its greater latitudinal and depth coverage, should be considered the most reliable index of abundance, particularly since 1992. The area-swept biomass estimated by the trawl survey is less than 50% of the acoustic biomass estimate, suggesting that catchability is low for this survey. Consequently, relatively small changes in the availability of fish to the trawl survey, as would occur, for example, with an onshore shift in distribution, could significantly affect the catchability. Changes in availability are even more of a problem with the DFO acoustic survey, where the El Niño signal overpowers any information on the trend in total abundance.

*SWFSC Midwater Trawl Recruit Survey*

The SWFSC has conducted annual surveys since 1983 to estimate the relative abundance of pelagic juvenile rockfish off central California. Although not specifically designed to sample juvenile whiting, young-of-the-year juvenile whiting occur frequently in the midwater trawl catches. In this assessment, we evaluate the usefulness of an index of recruitment strength derived from the trawl CPUE (Table 8) . This index was obtained from a generalized linear model (GLM) fit to the log-transformed CPUEs as described in Ralston et al. (1998). The year effect from the GLM was back-transformed to obtain an index of abundance. We used the index derived from the Monterey outside stratum because of its higher correlation with whiting recruitment. Additional details are given in Ralston et al.(1998) and Sakuma and Ralston (1996).

*PWCC midwater trawl survey*

In 1998, the PWCC conducted a midwater trawl survey from Point Conception (34°30′ N. lat.) to Bodega Bay (38°30′ N. lat.) aboard a chartered commercial trawler during July 8-28 (Wespestad and Shimada 1998). The purpose of the survey was to assess the feasibility of surveying prerecruit Pacific whiting with midwater trawling. Following the survey, the chartered vessel also towed on low density acoustic targets as directed by the Field Party Chief on the AFSC acoustic survey vessel (21 hauls). Information on the species composition of different acoustic targets assists in determining whether or not the echo returns from those targets should be included in the whiting biomass estimate. The primary survey found very low whiting CPUE south of Monterey Bay, however CPUE increased to the north of Monterey Bay. In general, Pacific whiting CPUE was low throughout the survey, indicating either low abundance or low vulnerability of whiting to the survey gear. The size distribution of Pacific whiting indicated that age-1 and age-2 fish were the most common age classes the catch, with modal lengths of 20 and 27 cm, respectively. These modes are lower than ususal for age-1 and age-2 fish, and may reflect a reduced growth due to the El Niño conditions off the West Coast during the previous year. This survey represents the first datum of time series of relative abundance indices, so results cannot be used quantitatively in the assessment model.

*Weight at age*

Year-specific weights at age are used in all years for each fishery and survey and for the population because significant variation in Pacific whiting weight at age has been observed (Table 9) (Dorn 1995). In particular, weight at age declined substantially during the 1980's, then remained fairly constant to 1998. Weight at age is inversely correlated with sea-surface temperature and (to a lesser extent) adult biomass (Dorn 1992). Weight at age estimates for 1977-87 are given in Hollowed et al. (1988b). Weight-at-age vectors since 1987 were derived from the length-weight relationship for that year and unbiased length at age calculated using age length keys (Dorn 1992). In some cases, a linear interpolation of the weight at age of the strong year classes was used for the weaker year classes whose weight at age was poorly estimated or not available due to small sample sizes. This was necessary only for the older or less abundant age groups. Population weight at age, used to calculate spawning biomass, was assumed to be equal to the nearest AFSC acoustic survey weight-at-age.

*Age at Maturity*

Dorn and Saunders (1997) estimate female maturity at age with logistic regression using ovary collections and visual maturity determinations by observers during 1990-92 as

| Age | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
| 0.000 | 0.176 | 0.661 | 0.890 | 0.969 | 0.986 | 0.996 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |

*Natural mortality*

The natural mortality currently used for Pacific whiting stock assessment and population modeling is 0.23. This estimate was obtained by tracking the decline in abundance of a year class from one triennial acoustic survey to the next (Dorn et. al 1994). Pacific whiting longevity data, natural mortality rates for Merluciids worldwide, and previously published estimates of Pacific whiting natural mortality indicate that natural morality rates in the range 0.20-0.30 could be considered plausible for Pacific whiting (Dorn 1996).

## Model Development

*Population dynamics*

The age-structured model for whiting describes the relationships between population numbers by age and year. The modeled population includes individuals from age 2 to age 15, with age 15 defined as a "plus" group, i.e., all individuals age 15 and older. The model extends from 1972 to 1998 (27 yrs). The Baranov (1918) catch equations are assumed, so that

$$c_{ijk} = N_{ij} \frac{F_{ijk}}{Z_{ij}} [1 - \exp(-Z_{ij})]$$

$$N_{i+1\ j+1} = N_{ij} \exp(-Z_{ij})$$

$$Z_{ij} = \sum_k F_{ijk} + M$$

except for the plus group, where

$$N_{i+1,15} = N_{i,14} \exp(-Z_{i,14}) + N_{i,15} \exp(-Z_{i,15})$$

where $N_{ij}$= population abundance at the start of year *i* for age *j* fish, $F_{ijk}$ = fishing mortality rate in year *i* for age *j* fish in fishery *k*, and $c_{ijk}$ = catch in year *i* for age *j* fish in fishery *k*. A constant natural mortality rate, *M*, irrespective of year and age, is assumed.

The U.S. and Canadian fisheries are modeled as distinct fisheries. Fishing mortality is modeled as a product of year-specific and age-specific factors (Doubleday 1976)

$$F_{ijk} = s_{jk} f_{ik}$$

where $s_{jk}$ = age-specific selectivity in fishery *k*, and $f_{ik}$ = the annual fishing mortality rate for fishery *k*. To ensure that the selectivities are well determined, we require that $\max(s_{jk}) = 1$ for each fishery. Following previous assessments, a scaled double-logistic function (Dorn and Methot 1990) was used to model age-specific selectivity

$$s_j^{/} = \left( \frac{1}{1 + \exp[-\beta_1(j - \alpha_1)]} \right) \left( 1 - \frac{1}{1 + \exp[-\beta_2(j - \alpha_2)]} \right)$$

$$s_j = s_j^{/} \; / \; \max_j \; (s_j^{/})$$

where $\alpha_1$ = inflection age, $\beta_1$ = slope at the inflection age for the ascending logistic part of the equation, and $\alpha_2$ , $\beta_2$ = the inflection age and slope for the descending logistic part. The subscript $k$ , used to index a fishery or survey, has been suppressed in the above and subsequent equations in the interest of clarity.

*Measurement error*

Model parameters were estimated by maximum likelihood (Fournier and Archibald 1982, Kimura 1989, 1990, 1991). Fishery observations consist of the total annual catch in tons, $C_i$, and the proportions at age in the catch, $p_{ij}$ . Predicted values from the model are obtained from

$$\hat{C}_i = \sum_j w_{ij} \; c_{ij}$$

$$\hat{p}_{ij} = c_{ij} \; / \; \sum_j \; c_{ij}$$

where $w_{ij}$ is the weight at age $j$ in year $i$ . Year- and fishery-specific weights at age are used because of the changes in weight at age during the modeled time period.

Log-normal measurement error in total catch and multinomial sampling error in the proportions at age give a log-likelihood of

$$\log \; L_k = -\sum_i [\log(C_i) - \log(\hat{C}_i)]^2 \; / \; 2\sigma_i^2 + \sum_i \; m_i \sum_j \; p_{ij} \log( \; \hat{p}_{ij} \; / \; p_{ij})$$

where $\sigma_i$ is standard deviation of the logarithm of total catch (~ $CV$ of total catch) and $m_i$ is the size of the age sample. In the multinomial part of the likelihood, the expected proportions at age have been divided by the observed proportion at age, so that a perfect fit to the data for a year gives a log likelihood value of zero

(Fournier and Archibald 1982). This formulation of the likelihood allows considerable flexibility to give different weights (i.e. emphasis) to each estimate of annual catch and age composition. Expressing these weights explicitly as CVs (for the total catch estimates), and sample sizes (for the proportions at age) assists in making reasonable assumptions about appropriate weights for estimates whose variances are not routinely calculated.

Survey observations from age-structured surveys (AFSC acoustic, AFSC bottom trawl, DFO acoustic) consist of a total biomass estimate, $B_i$, and survey proportions at age $\pi_{ij}$. Predicted values from the model are obtained from

$$\hat{B}_i = q \sum_j w_{ij}\ s_j\ N_{ij}\ \exp[-\varphi_i\ Z_{ij}]$$

where $q$ = survey catchability, $s_j$ = selectivity at age for the survey, and $\varphi_i$ = fraction of the year to the mid-point of the survey. Survey selectivity was modeled using a double-logistic function of the same form used for fishery selectivity. The expected proportions at age in the survey in the *i*th year are given by

$$\hat{\pi}_{ij} = s_j\ N_{ij}\ \exp[-\varphi_i\ Z_{ij}]\ /\ \sum_j s_j\ N_{ij}\ \exp[-\varphi_i\ Z_{ij}]$$

Log-normal errors in total biomass and multinomial sampling error in the proportions at age give a log-likelihood for survey *k* of

$$\log\ L_k = -\sum_i [\log(B_i) - \log(\hat{B}_i)]^2\ /\ 2\sigma_i^2 + \sum_i\ m_i \sum_j\ \pi_{ij}\ \log(\ \hat{\pi}_{ij}\ /\ \pi_{ij})$$

where $\sigma_i$ is the standard deviation of the logarithm of total biomass (~ CV of the total biomass) and $m_i$ is the size of the age sample from the survey.

For surveys that produce only an index of recruitment at age 2, $R_i$ , predicted values from the model are

$$\hat{R}_i = q\ N_{i2}$$

Log-normal measurement error in the survey index gives a log-likelihood of

$$\log\ L_k\ =\ -\sum_i [\log(R_i)\ -\ \log(\hat{R}_i)]^2\ /\ 2\sigma_i^2$$

where $\sigma_i$ is the standard deviation of the logarithm of recruitment index. Since the recruitment surveys occur several years before recruitment at age 2, the indices need to be shifted forward the appropriate number of years.

*Process error and Bayes priors*

Process error refers to random changes in parameter values from one year to the next. Annual variation in recruitment and fishing mortality can be considered types of process error (Schnute and Richards 1995). In the whiting model, these are estimated as free parameters, with no additional error constraints. We use a process error to describe changes in fisheries selectivity over time. Process error can be modeled in two ways: as uncorrelated random variation about a mean value (Dorn and Saunders 1997), or as a random walk (Gudmundsson 1996). These two approaches represent the endpoints of possible positive correlation patterns to annual variation.

To model temporal variation in a parameter $\gamma$ , the year-specific value of the parameter is given by

$$\gamma_i\ =\ \overline{\gamma}\ +\ \delta_i$$

where $\overline{\gamma}$ is the mean value (on either a log scale or linear scale), and $\delta_i$ is an annual deviation subject to the constraint $\sum\ \delta_i\ =\ 0$. If these annual deviations are normally distributed, the log-likelihood is

$$\log\ L_{Proc.\ Err.}\ =\ -\sum_i \frac{\delta_i^{\,2}}{2\sigma_i^2}$$

where $\sigma_i$ is the standard deviation of the annual deviations. For a random walk where annual *changes* are normally distributed, the log-likelihood becomes

$$\log\ L_{Proc.\ Err.}\ =\ -\sum \frac{(\delta_i\ -\ \delta_{i+1})^2}{2\sigma_i^2}$$

where $\sigma_i$ is now the standard deviation of the annual change in the parameter. We use a process error model for all four parameters of the U.S. fishery double-logistic curve. For the Canadian fishery double-logistic curve, a process error model was used only for the two parameters of the ascending part of the curves. Since the descending portion is almost asymptotic, little improvement in fit can be obtained by including process error for those parameters.

Bayesian methods offer a number of conceptual and methodological advantages in stock assessment (Punt and Hilborn 1997). We adopt an incremental approach of adding Bayes priors to what is essentially a maximum likelihood model. In non-linear optimization, the usual practice is to place upper and lower bounds on estimated parameters (a feature of both stock synthesis and AD model builder). From a Bayesian perspective, placing bounds on the possible values of a parameter corresponds to using a uniform prior for that parameter. Additional constraints are imposed on a parameter $\gamma$ by adding the log likelihood for a log-normal prior,

$$\log\ L_{Prior} = \frac{-[\log(\gamma) - \log(\tilde{\gamma})]^2}{2\sigma^2}$$

where $\tilde{\gamma}$ is the prior mean, and $\sigma$ is the standard deviation of the logarithm of the prior. In this assessment, we continue to use a prior for the slope of ascending part of the AFSC acoustic survey double-logistic function. We anticipate adding more Bayesian elements in subsequent assessments as we gain experience and confidence in applying these techniques in stock assessment models.

The total log likelihood is the sum of the likelihood components for each fishery and survey, plus terms for process error and priors,

$$Log\ L = \sum_k Log\ L_k + \sum_p Log\ L_{Proc.\ Err.} + Log\ L_{Prior}\ .$$

Likelihood components and variance assumptions for the base-run assessment model are given in the following table:

| Likelihood component | Error model | Variance assumption |
|---|---|---|
| U.S. fishery total catch | Log-normal | CV = 0.05 |
| U.S. age composition | Multinomial | Sample size = 80 |
| Canadian fishery total catch | Log-normal | CV = 0.05 |
| Canadian fishery age composition | Multinomial | Sample size = 80 |
| AFSC acoustic survey biomass | Log-normal | CV = 0.10, CV = 0.50 for 1977-89 |
| AFSC acoustic survey age composition | Multinomial | Sample size = 80 |
| AFSC shelf trawl survey biomass | Log-normal | CV = 100.0 (de-emphasized) |
| AFSC shelf trawl survey age composition | Multinomial | Sample size = 0.01 (de-emphasized) |
| DFO survey age biomass | Log-normal | CV = 100.0 (de-emphasized) |
| DFO survey age composition | Multinomial | Sample size = 0.01 (de-emphasized) |
| Tiburon larval rockfish survey | Log-normal | CV = 10.0 |
| Age-1 index from AFSC shelf trawl survey | Log-normal | CV = 10.0 |
| Fishery selectivity random walk process error | Slope: Log-normal<br>Inflection age: Normal | CV = 0.25<br>SE = 1.0 |
| Prior on acoustic survey slope | Log-normal | Prior mean = 0.9, Prior CV = 0.2 |

*Ageing error*

The model was configured to accumulate the marginal age groups at different ages to prevent obvious instances of aging error from affecting the model fit. This approach was used most frequently when a portion of an incoming strong year classes was misaged into an adjacent year class. We also used this approach to obtain reliable estimates of initial age composition in 1972. Marginal age groups were combined in the following situations:

- Accumulate the older fish at age 13 in 1973 at age 14 in 1974. Rationale: an age 12+ group is estimated for the initial age composition in 1972.

- Accumulate the older fish in the fishery and survey data at age 7 in 1978, age 8 in 1979, age 9 in 1980, etc.. The Canadian age data was only accumulated in 1978 and 1979, but not in subsequent years. Rationale: large numbers of the strong 1970 year class were misaged into the 1971 year class starting in 1978.

- Accumulate the younger fish at age-3 fish in 1979. Rationale: The strong 1977 year class appeared as 3-year-old fish in 1979 due to a small sample size in the age-length key for that year.

- Accumulate the younger fish to age 4 in 1984 and age 5 in 1985 in the Canadian fishery age composition. Rationale: The strong 1980 year class was misaged into the 1981 year class.

- Accumulate the younger fish to age 3 in the 1986 U.S. fishery age composition. Rationale: The strong 1984 year class (2-year-old fish) was misaged into the 1983 year class (3-year-old fish).

- Accumulate the younger fish to age 5 in 1995 and age 6 in 1996 in the Canadian fishery age composition. Rationale: In the 1995 Canadian age composition, the number of 4-year-old fish was greater than the number of 5-year-old fish. In 1996, the age 5-fish were 75% as abundant as the age-6 fish in the Canadian fishery age composition, but only 35% as abundant in the U.S. fishery age composition. The 1991 year class (4-year-old fish in 1995) has been much less common in U.S. fishery samples than the 1990 year class (5-year-old fish in 1995) in each year during 1992-95. It is likely that the 4-year-old fish in the Canadian age composition data are misaged fish from the 1990 year class.

*Optimization algorithm and convergence criteria*

The optimizer in AD model builder is a quasi-Newton routine that uses auto-differentiation to obtain the gradient (Press et al. 1972). The model is determined to have converged when the maximum gradient component is less than a small constant (set to 1 x $10^{-4}$ for the whiting model). Optimization occurs over a number of phases, in which progressively more parameters are estimated. Typically the initial phase consists of a catch curve analysis (Ricker 1973) to obtain rough estimates of mean recruitment and fishing mortality. The intermediary stages correspond to separable age-structured models (Deriso et al 1987), while the final stages also include the parameters for time varying selectivity. Thus the model mimics the entire historical development of quantitative stock assessment during a single estimation run. Identical parameter estimates (to 5 decimal places) were obtained when the initial values for mean recruitment and mean fishing mortality were halved and doubled ( R = 0.5, 1.0, 2.0 billion, F = 0.1, 0.2, 0.4), suggesting that final parameter estimates were independent of initial values. After the model converges, the Hessian is estimated using finite differences. Standard errors are obtained using the inverse Hessian method. We also assess uncertainty using AD model builder routines for obtaining likelihood profiles and Markov chain Monte Carlo samples from the likelihood function.

Model parameters can be classified as follows:

| Population process modeled | Number of parameters estimated | Estimation details |
|---|---|---|
| Initial age structure | Ages 3-12 (age 12 is the plus group in 1972) = 10 | Estimated as log deviances from the log mean |
| Recruitment | Years 1972-98 = 27 | Estimated as log deviances from the log mean |
| Average selectivity to fisheries and age-structured surveys | 4 * (No. of fisheries + No. of surveys) = 4 * (2 + 3) = 20 | Slope parameters estimated on a log scale, a prior is used for the acoustic survey ascending slope parameter. |
| Annual changes in fishery selectivity | 4 * (No. of fisheries) * (No. of yrs -1) = 4 * 1.5 * 26 = 156 | Estimated as deviations from mean selectivity and constrained by random walk process error |
| Year and age-specific selectivity for the 1994 year class | 1996 & 1997 = 2 | Bounded by (0,1) |
| Survey catchability | No. of surveys = 5 | Acoustic survey catchability not estimated, other catchabilities estimated on a log scale |
| Natural mortality | Age- and year-invariant = 1 | Not estimated |
| Fishing mortality | No. of fisheries * (No. of yrs) = 2 * 27 = 54 | Estimated as log deviances from the log mean |
| Total | 117 conventional parameters + 156 process error parameters + 2 fixed parameters = 275 | |

## Model selection and evaluation

*Comparison with the stock synthesis program*

Moving to a new modeling environment affords an opportunity to check for errors both the new and old assessment models and to compare optimization algorithms. A similar result with similar data and assumptions allows one to have higher confidence in both modeling approaches. For the comparison with the stock synthesis model we used identical data with all time series updated to 1998. Our objective was to compare models with identical population dynamics and statistical assumptions using the final configuration in the last whiting assessment. This goal was not entirely achieved because stock synthesis has options for defining different temporal periods within the year and truncating age compositions at different ages in different years that we chose not implement in the new model. These differences, however, were very minor.

Figure 19 shows side by side comparisons of population biomass, recruitment, fits to survey biomass estimates and age composition, and selectivity patterns. Overall, the models produce very similar results. Population biomass differed by no more than 4% throughout the modeled time period, and the average difference was close to zero, indicating that there were no consistent differences between models. Recruitment estimates were less similar, particularly near the end of the modeled period, but differed by no more than 11%. The average difference in recruitment was also close to zero. AD model builder obtained a closer fit to the age composition data than stock synthesis, but since the actual code for the multinomial likelihoods in stock synthesis is not immediately accessible, we have no knowing whether there are subtle differences in how the likelihoods are calculated. We also tested a simple prototype of the whiting model with simulated data, and were able to confirm that model estimates of recruitment and biomass would converge to the correct answer as the error in the simulated data was reduced.

*Model selection*

Before considering alternate model configurations, we made several minor modifications to the model based on reviews of the 1997 whiting assessment. We set the CV for the acoustic survey biomass estimates in 1977 and 1980 to 0.5 to better reflect their uncertainty. We did not accumulate older fish in the Canadian fishery age composition data after 1979 because a reviewer pointed out that the Canadian data did not show the same pattern of misageing the 1970 year class into the 1971 year class as the U.S. age reader data.

We used random walk process error to model annual changes in the selectivity of the U.S. and Canadian fisheries. Time-varying selectivity can be caused by a number of factors. First, and probably the most important for the Canadian fishery, is the variability in the northward migration of fish due to changes on ocean currents and temperature (Dorn 1995). Second, north-south shifts in fishing operations, as have occurred in the U.S. fishery, would affect selectivity. Third, changes in the selectivity of older fish may have occurred because of changes in the design and size of midwater trawls used to fish for Pacific whiting, and changes in the horsepower of the fishing vessels in the fleet. Fourth, the mean length at age of Pacific whiting declined substantially over the period 1977-1989 (Dorn 1992). If fishery selectivity is determined primarily by length, rather than by age, a decrease in the length at age of the older fish would tend to increase fishery selectivity at age. Finally, the depth distribution of fishing may have changed to reduce salmon and rockfish bycatch.

A comparison of time varying selectivity for random walk process error and random variation process error models is shown in Figure 20. The patterns are similar for both error models, and indicate that the selectivity of the younger fish to the U.S. fishery was low from 1973-83, high from 1984-1993, dipped downwards in 1995 and 1996, and then increased again in 1997 and 1998. The selectivity of the older fish to the U.S. fishery increased to 1990, but has remain relatively stable since then. The selectivity of the younger fish in the Canadian fishery is strongly related to the 1983 and 1992 El Niños.

We also estimate year- and age-specific selectivity parameters for the 1994 year class in the 1996 and 1997 U.S. fishery. Both surveys and anecdotal reports from fishermen indicated that unusual numbers of the 1994 year class were present off northern California to Queen Charlotte Sound. The center of abundance of this year class was located to the north of the 1993 year class, which was most abundant in northern California (Wilson and Guttormsen, 1997). Since selectivity in the whiting fishery is strongly related to latitude, a reversal in the usual latitudinal distribution by age implies a non-smooth selectivity pattern. The estimated selectivity coefficients were 0.39 at age 2 in 1996, and 1.0 at age 3 in 1997, compared to the average selectivity at age 2 of 0.08, and at age 3 of 0.33.

The whiting assessment, like most assessments, is highly dependent on survey estimates of trends in abundance. Since 1993, the base-run whiting assessment model has relied primarily on an absolute biomass estimate from the AFSC acoustic surveys starting with the 1992 survey. Earlier acoustic surveys were de-emphasized because of incomplete geographic coverage and a number of other considerations (Dorn 1996), as were the AFSC shelf trawl survey and DFO acoustic surveys. Based on reviews of whiting assessment, we examined three models with alternative variance assumptions for the survey biomass estimates:

Model 1: A base-run model with an acoustic survey biomass CV of 0.5 in 1977-89 and a CV = 0.1 in 1992-98. The AFSC shelf trawl survey is de-emphasized (CV = 100.0). These are status quo assumptions used to provide management advice since 1993.

Model 2: The entire acoustic survey time series has an assumed CV = 0.1.

Model 3: Acoustic survey as in base-run model, but with a CV of 0.1 for the AFSC shelf trawl survey.

Models 1 and 2 estimate a similar biomass trend except that the increase in biomass in the mid-1980s is not as large in model 2 (Fig. 21). Interestingly, the biomass for model 2 is higher than model 1 towards the end of the period when the same variances are used for the surveys. The largest percent difference (25%) is in the final year. Model 2 improves the fit to the earlier surveys by shifting the selectivity curve to right, so that the estimated selectivity of the age 3-5 fish, which make up a large fraction of the population biomass, have lower selectivity. Because the acoustic survey covers the entire latitudinal range of the U.S. fishery, it is difficult to reconcile this selectivity pattern with the U.S. fishery selectivity, which is close to 1.0 by age 5. The biomass for Model 3 begins at a lower level, but increases and peaks in 1987 like Models 1 and 2. After 1992, the biomass for model 3 again increases to over 5.0 million t in 1998. Model 3 shows an adequate fit to both the acoustic and trawl survey biomass, however the estimated acoustic selectivity pattern is even less plausible for Model 2. These alternative models suggest that biomass in 1998 is unlikely to be lower than estimated by base-run model.

*Model Evaluation*

Residual plots were prepared to examine the goodness of fit of the base-run model to the age composition data. The Pearson residuals for a multinomial distribution are

$$r_i = \frac{p_i - \hat{p}_i}{\sqrt{(\hat{p}_i(1-\hat{p}_i)/m)}} \ ,$$

where $p_i$ is the observed proportion at age, and $m$ is the nominal sample size (McCullagh and Nelder 1983). Figures 22, 23, and 24 show Pearson residuals of the fit to the U.S. fishery, Canadian fishery, and acoustic survey age compositions. Although there are large residuals for some ages and years, no severe pattern of residuals is evident in the fishery age composition. There is a moderate residual pattern of positive residuals for the strong year classes and negative residuals for the weak year classes, particularly for the older fish. This pattern is strongest in the Canadian fishery age composition, but is also present to some degree in the U.S. fishery age composition. A tendency for age readers to prefer the strong year classes as fish become older and more difficult to age could account for this pattern (Kimura et al. 1992).

The model shows an improved fit to the AFSC acoustic biomass estimates compared to previous assessment models, although the overall fit is still relatively poor (Fig. 25). The model fits closely the most recent surveys in 1995 and 1998. As in previous assessments, the age composition data favors an increase biomass to 1986 followed by a decline to at least 1995. The acoustic biomass time series is highest in 1986, but otherwise is relatively flat. Both the 1983 and 1986 acoustic surveys may have underestimated the biomass present in those years. In 1983, the onset of El Niño conditions off the west coast produced strong northward transport which may have displaced fish beyond the northern limits of the survey (Dorn 1995). In 1986, there was a 1.7 dB drop in the acoustic source level between pre- and post-survey calibrations. Biomass was estimated using the pre-survey source level, because the resulting biomass was consistent with 1983 biomass estimate. Had the post-survey source level been used, the biomass would have been 48% higher (Hollowed 1988a).

Tiburon recruitment index was compared to model predictions under the assumption of a high CV (10) for the index. The number of age-1 fish from the AFSC shelf trawl survey, which was not included in the trawl biomass estimate, was also evaluated. Both survey indices show a positive correlation with the model estimates of age-2 abundance (Fig. 26) . The relationship appears fairly linear through the origin for the Tiburon survey, but less so for the trawl survey age-1 index. These indices were used to predict recruitment in 1999 and 2000 as described in the section on yield projections.

## Base-run Results

Parameter estimates and model output for the base-run model are presented in a series of tables and figures. Estimated selectivity for the U.S. and Canadian fisheries, and the AFSC triennial acoustic and shelf trawl surveys are given in Table 10 and Figure 27. Table 11 gives the estimated population numbers at age for the years 1972-98 for the base-run model. Table 12 gives estimated time series of population biomass, age-2 recruitment, and percent utilization of the total age 3+ biomass by the U.S. and Canadian fisheries for 1972-98 (see also Fig. 28). In the early 1980s, biomass increased substantially as the 1980 and 1984 year classes recruited to the population. Population biomass peaked in 1987, then declined as the 1980 and 1984 year class were replaced by more moderate year classes. The harvest rate of age-3+ Pacific whiting was generally below 10% during 1972-93, then increased to 17% in 1994-98.

## Uncertainty and Sensitivity Analyses

*Sensitivity to natural mortality and survey catchability assumptions*

The base-run model assumes an acoustic survey catchability of 1.0 and a natural mortality rate of 0.23. The sensitivity of model results to these assumptions was examined with likelihood profiles for survey catchability and natural mortality. A likelihood profile was obtained for survey catchabilities ranging from 0.1 to 1.5 with natural mortality held constant at 0.23. Then, the survey catchability was held constant at 1.0 and a likelihood profile was obtained for natural mortalities ranging from 0.05 to 0.35.

The best model fits are obtained at the second lowest survey catchability considered (q = 0.2, 1998 population biomass =8.5 million t) (Fig. 29). This result is consistent with results reported in the 1997 and earlier assessments (Dorn and Saunders 1997), and indicates that there is insufficient information to establish the absolute level abundance when the assumption that q = 1.0 is relaxed.

The likelihood profile across natural mortality for a model with a survey catchability of 1.0 gave a maximum at M = 0.06 for the base-run model (Fig 30), lower than the maximum of M = 0.13 obtained for a similar analysis in the 1997 assessment (Dorn and Saunders 1997). This result is driven largely by the acoustic biomass time series, and may more indicative of the difficulty in fitting the abundance trend rather than the longevity of Pacific whiting. A natural mortality of 0.06 is lower than is plausible for a fish with whiting life history. A model with asymptotic selectivity for the U.S. and Canadian fishery, and for the AFSC acoustic survey showed a profile with a maximum at M = 0.19 (Fig 30). This suggests an interaction between the shape of the descending portion of the fishery and survey selectivity curves and the estimate of natural mortality (Thompson 1994).

*Uncertainty in 1998 stock size*

Uncertainty in current stock size was explored using several approaches. The likelihood profile algorithm in AD model builder performed poorly with this problem, with frequent program crashes and equivocal results. We compare a log-normal probability distribution derived from inverse-Hessian estimates of the standard error to a Markov chain Monte Carlo (MCMC) sampling distribution (Fig. 31). Although MCMC has been used mostly in Bayesian applications, it can also be used to obtain likelihood-based confidence regions. It has the advantage of producing the true marginal likelihood of the parameter, rather than the conditional mode, as with the likelihood profile. The two methods give similar results, and indicate that 1998 stock size has high probability (>95%) of being 1.35 and 2.20 million t. It should be stressed that these estimates of uncertainty depend on model assumptions of a known natural mortality rate and survey catchability, and thus would underestimate the actual uncertainty.

*Retrospective analyses*

A retrospective comparison of stock assessment models for the years 1993-98 is given in Figure 32 (upper panel). The current estimates of spawning biomass for 1977-98 are fairly consistent with previous estimates. All of the time series show a similar pattern of increasing spawning biomass to early 1980's, followed by a decrease. A retrospective analysis was also conducted for the base-run assessment model. The final year of the base-run assessment model was stepped backwards one year at a time from 1998 to 1993 (Fig. 32, lower panel). Years that use the same series of survey biomass estimate produce highly consistent results. The biomass time series shifts upwards with the addition of the 1995 biomass estimate, but not with the addition of the 1998 biomass estimate, suggesting that there has been some improvement in our ability to model the whiting population with the current set of assumptions. The greatest differences occur in the first part of the time series, reflecting both the lack of survey data, and the high CV's assigned to the early acoustic surveys.

## TARGET FISHING MORTALITY RATES

The Magnuson-Stevens Act and the NMFS National Standards Guidelines (NSG) establish new guidelines for setting harvest rates in U.S. fisheries. The PFMC is required to update its Fisheries Management Plan (FMP) to conform to these guidelines. In this section, we evaluate whether the hybrid F strategy, used to manage the whiting fishery since 1991, conforms to the new framework for setting optimum yield (OY). Although the proposed FMP amendment includes provisions for deviating from default policies, if the new policies result in harvest rates similar to the hybrid F strategy, or offer significant advantages, moving to more standard approach for whiting may be desirable. The FMP amendment includes definitions of 1) a MSY rule ($F_{MSY}$) that maximizes long-term average yield; 2) an OY rule that reduces fishing mortality when stock size is below $B_{MSY}$; 3) and guidelines for reducing OY to account for uncertainty in stock status. Default proxies are defined for $F_{MSY}$ and $B_{MSY}$ based on spawning biomass per recruit (SPR).

The hybrid F harvest strategy, a modification of the variable F algorithm (Shuter and Koonce, 1985), uses a constant fishing mortality when spawning biomass is above the mean, but reduces fishing mortality when spawning biomass is lower according to

$$F = F_{\max}(B/\bar{B}) ,$$

where $F_{max}$ is the maximum fishing mortality, $B$ is the spawning biomass in the current year, and $\bar{B}$ is the mean spawning biomass (919,000 t). Three harvest rates (low, moderate, and high) are presented to bracket viable alternatives. These rates are determined by the probability that spawning biomass drops below a cautionary level. The cautionary spawning biomass is defined as the 0.1 percentile (i.e., on average, one year out of 1,000) of spawning biomass of an unfished population. At a low harvest rate, the probability of falling below the cautionary female spawning biomass level is 0.10; for a moderate harvest rate it is 0.20; and for high harvest rate it is 0.30. These percentiles are obtained by stochastic simulation of the whiting stock in which recruitments are generated by bootstrap sampling from historical recruitments.

In the past, moderate hybrid F strategy has resulted in harvest rates that reduce SPR to 38-51% of unfished, and thus tends to result in more conservative harvest rates than an F35% policy. However, the simulations used to estimate the hybrid F harvest rate are sensitive to changes in the recruitment estimates used for the bootstrap samples. For example, when the recruitments for 1960-71 were omitted from the bootstrap because of their unreliability, the SPR for the moderate hybrid F policy was reduced from 46% to 38% (Dorn 1996). This significant change in harvest rates occurred without any intentional decision to modify the harvest policy, and without strong evidence that this change represented a positive step towards the overall goal of sustainable fisheries management. We have been assessing the SPR of the hybrid-F policies for a number of years because of this concern.

Both $F_{SPR}$ and hybrid F strategies are based on a comparison of an unfished stock with an exploited stock:

| Strategy | Unfished stock property | Harvested stock property | Objective of harvest strategy |
|---|---|---|---|
| $F_{SPR}$ | Spawning biomass per recruit | Spawning biomass per recruit | 35-45% percent of unfished stock |
| Hybrid F | 0.1 percentile of spawning biomass | 10-30 percentile of spawning biomass | Same as unfished stock |

This comparison suggests that $F_{SBR}$ policies are likely to be more robust than hybrid F policies for a number of reasons: 1) $F_{SBR}$ policies are based on average characteristics rather than the extreme lower quantiles, 2) $F_{SBR}$ policies can be calculated from life history and fishery selectivity patterns only, while the hybrid F strategies also require recruitment estimates and extensive simulation; 3) the lower quantiles of spawning biomass are likely to be strongly affected by autocorrelation in recruitment and compensatory processes. Bootstrap sampling from historical recruitment captures neither of these properties. 4) the justification for the different fishing mortality rates (high, medium, and low) is *ad hoc* for the hybrid F strategy, while $F_{SBR}$ strategies have been explicitly developed as proxies for $F_{MSY}$ (Clark 1991). For these reasons, adopting a $F_{SBR}$ strategy for whiting seems advisable. The past reluctance to adopt the default PFMC harvest rate of F35% was due the highly uncertain relationship between stock size and recruitment for whiting. However, the new PFMC harvest policies are flexible enough to allow a different $F_{SBR}$ rate for whiting if warranted.

The NSGs require that stocks be managed using harvest control laws which specify the target (OY) and the upper limit to fishing mortality (MSY) as a function of stock biomass. An important property of these control laws is that they reduce the harvest rate when the stock is below the MSY level. The hybrid F strategy also has this property, since fishing mortality rates decline linearly when biomass is below the mean. Many of the new control laws developed under the NSGs have additional features, such as a non-zero intercept (NMFS, 1996), or an *ad hoc* buffer between the mean and the point at which fishing mortality is reduced (Restrepo et al. 1998). Fine-tuning the hybrid-F strategy may be possible based on our experience managing whiting and advances in the design of harvest control laws.

When the harvest rate decreases linearly, the catch decreases in proportion to the square of the change in biomass. As a result, significant reductions in catch can occur with the hybrid F strategy when the stock size is only moderately below its mean. The large interannual variability in whiting recruitment produces in a skewed biomass distribution, i.e., stock size will be below its arithmetic mean considerably more than 50% of the time. Under constant $F_{MSY}$ harvest rates stocks will fluctuate above and below $B_{MSY}$ due to recruitment variation, suggesting that harvest control laws should be able to accommodate moderate departures from $B_{MSY}$ without severely reducing catches (Restrepo et al. 1998). Furthermore, unnecessary interannual variability in harvests may hamper the economic performance of the whiting fishery. The 40-10 option in the FMP amendment provides a more gradual response to declining stock sizes by reducing *catches* linearly, rather than fishing mortality. The 40-10 option can be expressed approximately in fishing mortality as

$$F_{ABC} = F_{40\%} \frac{B_{40\%}}{B} \left[ \frac{B - B_{10\%}}{B_{40\%} - B_{10\%}} \right],$$

Figure 33 compares hybrid F strategy and 40-10 option, scaled so that the harvest rate begins declining at B40% for both harvest control laws. The 40-10 option results in approximately the same overall reduction in harvest rates as the hybrid F strategy. The 40-10 option is less conservative than the hybrid F strategy when stock size is moderately below the $B_{MSY}$, but becomes more conservative when the stock is less than 13.3% of unfished biomass. The above comparisons suggest that a control law of the general form of 40-10 policy would be an improvement over the current hybrid F strategy.

The appendix provides advice on whiting harvest rates based on a Bayesian meta-analysis of Merluciid stock recruit relationships. The results suggest that a high percentage of maximum expected yield could be obtained at $F_{SPR}$ rates in the range of F48%-F29%, and that F40-F45% may be appropriate proxies for $F_{MSY}$ depending of the level of risk aversion. The following estimates of F35%, F40%, and F45% were obtained using the life history vectors in Table 13. The Canadian F multiplier is used to scale the Canadian fishing mortality so that the mean yield per recruit for the U.S. and Canadian fisheries corresponds to the historical distribution of catches (~25%). Previous work has demonstrated that overall yield per recruit is relatively insensitive to the allocation of yield within the range in dispute. Unfished spawning biomass was based on mean 1972-98 recruitment (1.776 billion) from the base-run model and SPR at F=0 (1.216 kg/recruit).

| SPR rate | U.S. Fishing mortality | Canadian F multiplier | Equilibrium harvest rate |
|---|---|---|---|
| F35% | 0.310 | 0.885 | 25.8% |
| F40% | 0.246 | 0.763 | 21.3% |
| F45% | 0.199 | 0.680 | 17.7% |
| Unfished female spawning biomass | 2.159 million t | | |
| B40% | 0.864 million t | | |

For comparison, $\bar{B}$ , the inflection point hybrid F strategy, was estimated in Dorn (1996) as 0.919 million t of female spawning biomass. The 1998 estimate of spawning biomass is 0.807 million t, which is 37% of unfished spawning biomass. It should be recognized that the estimate of unfished stock size is strongly affected by the extremely large 1980 and 1984 year classes. When the average recruitment is estimated without these year classes, the estimate of B40% is reduced to 0.511 million t.

## HARVEST PROJECTIONS

For harvest projections, model estimates of population numbers at age in 1998 and their variance were projected forward for the years 1999-2003. Estimates of future recruitment, $N_{i2}$, are also needed for the projections. Survey indices of age-2 recruitment are available for 1999 and 2000 from the Tiburon larval rockfish survey. In addition, an index for 1999 is available from the numbers of age-1 fish in the AFSC shelf trawl survey in 1998. Recruitment estimates should account for two sources of variability: random variation in recruitment (process error), and sampling variability of the index (measurement error). For example, if recruitment itself is not highly variable, an index that shows an extremely low or high value should be shrunk towards the mean, particularly if it is known that sampling variability for that index is large. The appropriate tradeoff between these different sources of uncertainty is obtained by adding a log likelihood term for future recruitments in the final estimation phase. Assuming that both recruitment variability and sampling variability are log normal,

$$\log\ L_{Fut.\ Recr.} = -\frac{1}{2\sigma_r^2}\sum_i[\log(N_{i2}) - \overline{\log(N_2)}\ ]^2 - \sum_k\frac{1}{2\sigma_k^2}\sum_i[\log(q_k N_{i2}) - \log(R_i)]^2$$

where $\overline{\log(N_2)}$ is the mean log recruitment as estimated by the base-run model, $\sigma_r$ is the standard deviation of log recruitment, and $\sigma_k$ is the standard deviation of the log index from survey $k$ , which can be estimated using the prediction error of the index in the assessment model. These parameters were fixed at the values estimated by the base-run model. The standard deviations for log recruitment ($\sigma_r = 1.22$) and the Tiburon log index ( $\sigma_k = 1.20$ ) are similar, while the age-1 trawl survey index is larger ($\sigma_k = 2.58$), implying that estimates of future recruitment should be roughly an average of the mean recruitment and the Tiburon survey prediction. Future recruitments were estimated on a log scale and multiplied by the bias correction, $\exp(\sigma_r^2/2)$, to obtain the expected recruitment. In years when no survey indices are available, as in 2001-03, there is nothing to prevent estimated log recruitment from matching exactly the mean log recruitment; in this situation, uncertainty will be equal to the process error in recruitment. The estimates of recruitment in 1999 and 2000 are 1.442 and 0.490 billion respectively, indicating that below average indices from the Tiburon survey for those years reduced the recruitment estimate from the historical mean. The CVs of those estimates remain large, although there is a 30% reduction in the uncertainty relative to the recruitments in subsequent years, whose CVs are equal to recruitment variability.

Estimates of projected yield and biomass for 1999-2003 are given in Table 14. For comparison we show the projected yields for the moderate hybrid F strategy. We re-estimated the fixed points of the hybrid F strategy with the new maturity, recruitment, and fisheries selectivity vectors using the methods described in Dorn (1996). The new inflection point of the hybrid F strategy was 1.075 million (an increase from 0.919 million t in Dorn (1996)), and the new target fishing mortality for the moderate hybrid F strategy was F = 0.24 (a decrease from 0.31 in Dorn (1996)). The projected yield in 1999 for the moderate hybrid F strategy (214,000 t) is 19% lower than would have been projected using the old fixed points of the hybrid F strategy (264,000 t).

The projected yield under the 40-10 option is obtained by

$$OY = C_{40\%} \frac{B_{40\%}}{B} \left[ \frac{B - B_{10\%}}{B_{40\%} - B_{10\%}} \right],$$

where $C_{40\%}$ is the projected catch at F40% and $B$ is the current spawning biomass (Alec MacCall pers. comm., Jan 22. 1999).

Estimates of yield in 1999 for SPR rates in the 45-40% range were between 259,000 and 320,000 t. A moderate decline in yield is projected for 2000 with a range of 251-297,000 t. The 40-10 option with F40% as the proxy for FMSY projects yields of 301,000 t in 1999 and 275,000 t in 2000. The population biomass is projected to decline over the next three years regardless of the harvest policy within the range considered. The CVs of population biomass, spawning biomass, and yield are similar in magnitude, and increase from 0.15 in 1999 to approximately 0.50 in 2003, indicating that projections of these quantities are increasingly uncertain they become influenced by the variability in future recruitment.

Since a major source of the uncertainty in the whiting assessment is proportionality between the acoustic survey biomass and population biomass, a decision table is presented showing the repercussions of alternative assumptions for the acoustic survey catchability in the range of 0.8 to 1.2 (Table 15). It could be argued that this range under-represents the true uncertainty in acoustic survey catchability. The main consequence of incorrectly assuming a lower catchability (= higher population biomass) is that harvest rates are higher than intended, and the decline in biomass is more severe. The opposite error, i.e.

incorrectly assuming a lower catchability (= lower population biomass), has the beneficial effect of reducing the decline in biomass, but at a cost of unnecessarily low harvests.

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Table 1. Annual catches of Pacific whiting (1,000 t) in U.S. and Canadian management zones by foreign, joint venture (JV), domestic at-sea, domestic shore-based, and tribal fisheries, 1966-98.

| | U.S. | | | | | | Canada | | | | U.S. and Canada |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Domestic | | | | | | | | |
| Year | Foreign | JV | At-sea | Shore | Tribal | Total | Foreign | JV | Shore | Total | total |
| 1966 | 137.000 | 0.0 | 0.0 | 0.0 | 0.0 | 137.000 | 0.700 | 0.0 | 0.0 | 0.700 | 137.700 |
| 1967 | 168.699 | 0.0 | 0.0 | 8.963 | 0.0 | 177.662 | 36.713 | 0.0 | 0.0 | 36.713 | 214.375 |
| 1968 | 60.660 | 0.0 | 0.0 | 0.159 | 0.0 | 60.819 | 61.361 | 0.0 | 0.0 | 61.361 | 122.180 |
| 1969 | 86.187 | 0.0 | 0.0 | 0.093 | 0.0 | 86.280 | 93.851 | 0.0 | 0.0 | 93.851 | 180.131 |
| 1970 | 159.509 | 0.0 | 0.0 | 0.066 | 0.0 | 159.575 | 75.009 | 0.0 | 0.0 | 75.009 | 234.584 |
| 1971 | 126.485 | 0.0 | 0.0 | 1.428 | 0.0 | 127.913 | 26.699 | 0.0 | 0.0 | 26.699 | 154.612 |
| 1972 | 74.093 | 0.0 | 0.0 | 0.040 | 0.0 | 74.133 | 43.413 | 0.0 | 0.0 | 43.413 | 117.546 |
| 1973 | 147.441 | 0.0 | 0.0 | 0.072 | 0.0 | 147.513 | 15.125 | 0.0 | 0.001 | 15.126 | 162.639 |
| 1974 | 194.108 | 0.0 | 0.0 | 0.001 | 0.0 | 194.109 | 17.146 | 0.0 | 0.004 | 17.150 | 211.259 |
| 1975 | 205.654 | 0.0 | 0.0 | 0.002 | 0.0 | 205.656 | 15.704 | 0.0 | 0.0 | 15.704 | 221.360 |
| 1976 | 231.331 | 0.0 | 0.0 | 0.218 | 0.0 | 231.549 | 5.972 | 0.0 | 0.0 | 5.972 | 237.521 |
| 1977 | 127.013 | 0.0 | 0.0 | 0.489 | 0.0 | 127.502 | 5.191 | 0.0 | 0.0 | 5.191 | 132.693 |
| 1978 | 96.827 | 0.856 | 0.0 | 0.689 | 0.0 | 98.372 | 3.453 | 1.814 | 0.0 | 5.267 | 103.639 |
| 1979 | 114.909 | 8.834 | 0.0 | 0.937 | 0.0 | 124.680 | 7.900 | 4.233 | 0.302 | 12.435 | 137.115 |
| 1980 | 44.023 | 27.537 | 0.0 | 0.792 | 0.0 | 72.352 | 5.273 | 12.214 | 0.097 | 17.584 | 89.936 |
| 1981 | 70.365 | 43.556 | 0.0 | 0.839 | 0.0 | 114.760 | 3.919 | 17.159 | 3.283 | 24.361 | 139.121 |
| 1982 | 7.089 | 67.464 | 0.0 | 1.024 | 0.0 | 75.577 | 12.479 | 19.676 | 0.002 | 32.157 | 107.734 |
| 1983 | 0.0 | 72.100 | 0.0 | 1.050 | 0.0 | 73.150 | 13.117 | 27.657 | 0.0 | 40.774 | 113.924 |
| 1984 | 14.722 | 78.889 | 0.0 | 2.721 | 0.0 | 96.332 | 13.203 | 28.906 | 0.0 | 42.109 | 138.441 |
| 1985 | 49.853 | 31.692 | 0.0 | 3.894 | 0.0 | 85.439 | 10.533 | 13.237 | 1.192 | 24.962 | 110.401 |
| 1986 | 69.861 | 81.640 | 0.0 | 3.463 | 0.0 | 154.964 | 23.743 | 30.136 | 1.774 | 55.653 | 210.617 |
| 1987 | 49.656 | 105.997 | 0.0 | 4.795 | 0.0 | 160.448 | 21.453 | 48.076 | 4.170 | 73.699 | 234.147 |
| 1988 | 18.041 | 135.781 | 0.0 | 6.876 | 0.0 | 160.698 | 39.714 | 50.182 | 0.594 | 90.490 | 251.188 |
| 1989 | 0.0 | 203.578 | 0.0 | 7.418 | 0.0 | 210.996 | 31.589 | 66.256 | 1.687 | 99.532 | 310.528 |
| 1990 | 0.0 | 170.972 | 4.713 | 8.115 | 0.0 | 183.800 | 3.976 | 69.293 | 3.411 | 76.680 | 260.480 |
| 1991 | 0.0 | 0.0 | 196.905 | 20.600 | 0.0 | 217.505 | 6.043 | 76.254 | 22.225 | 104.522 | 322.027 |
| 1992 | 0.0 | 0.0 | 152.449 | 56.127 | 0.0 | 208.576 | 0.0 | 68.000 | 18.370 | 86.370 | 294.946 |
| 1993 | 0.0 | 0.0 | 99.103 | 42.119 | 0.0 | 141.222 | 0.0 | 47.172 | 11.611 | 58.783 | 200.005 |
| 1994 | 0.0 | 0.0 | 179.073 | 73.656 | 0.0 | 252.729 | 0.0 | 84.154 | 22.018 | 106.172 | 358.901 |
| 1995 | 0.0 | 0.0 | 102.624 | 74.965 | 0.0 | 177.589 | 0.0 | 26.580 | 43.838 | 70.418 | 248.007 |
| 1996 | 0.0 | 0.0 | 112.776 | 85.127 | 14.999 | 212.902 | 0.0 | 65.596 | 22.644 | 88.240 | 301.142 |
| 1997 | 0.0 | 0.0 | 121.173 | 87.410 | 24.840 | 233.423 | 0.0 | 42.565 | 48.065 | 90.630 | 324.053 |
| 1998 | 0.0 | 0.0 | 120.452 | 87.548 | 24.509 | 232.509 | 0.0 | 39.664 | 47.074 | 86.738 | 319.247 |
| Average 1966-98 | | | | | | 152.053 | | | | 51.044 | 203.097 |

Table 2. Harvest strategies, coastwide ABCs, quotas or havest guidelines for U.S. and Canadian zones, and Pacific whiting catches (t) in the U.S. and Canadian zone (1978-98).

| Year | Harvest strategy | Acceptable Biological Catch (t) (coastwide) | U.S. harvest guideline or quota (t) | U.S. catch (t) | % of U.S. harvest guideline utilized | Canadian scientific recommendations, low to high risk (t), (CAN) = Canadian zone only | Canadian quota (t) | Canadian catch (t) | % of Canadian quota utilized | Total Catch (t) | % of ABC harvested |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1978 | N/A | --- | 130,000 | 98,372 | 75.7 | NA | NA | 5,267 | NA | 103,639 | --- |
| 1979 | N/A | --- | 198,900 | 124,681 | 62.7 | 35,000 (CAN) | 35,000 | 12,435 | 35.5 | 137,116 | --- |
| 1980 | N/A | --- | 175,000 | 72,353 | 41.3 | 35,000 (CAN) | 35,000 | 17,584 | 50.2 | 89,937 | --- |
| 1981 | N/A | --- | 175,000 | 114,762 | 65.6 | 35,000 (CAN) | 35,000 | 24,361 | 69.6 | 139,123 | --- |
| 1982 | N/A | --- | 175,500 | 75,578 | 43.1 | 35,000 (CAN) | 35,000 | 32,157 | 91.9 | 107,735 | --- |
| 1983 | N/A | --- | 175,500 | 73,151 | 41.7 | 35-40,000 (CAN) | 45,000 | 40,774 | 90.6 | 113,925 | --- |
| 1984 | N/A | 270,000 | 175,500 | 96,381 | 54.9 | 35-40,000 (CAN) | 45,000 | 42,109 | 93.6 | 138,490 | 51.3 |
| 1985 | N/A | 212,000 | 175,000 | 85,440 | 48.8 | 45-67,000 (CAN) | 50,000 | 24,962 | 49.9 | 110,402 | 52.1 |
| 1986 | N/A | 405,000 | 295,800 | 154,963 | 52.4 | 75-150,000 (CAN) | 75,000 | 55,653 | 74.2 | 210,616 | 52.0 |
| 1987 | N/A | 264,000 | 195,000 | 160,449 | 82.3 | 75-150,000 (CAN) | 75,000 | 73,699 | 98.3 | 234,148 | 88.7 |
| 1988 | Variable effort | 327,000 | 232,000 | 160,690 | 69.3 | 98-176,000 (CAN) | 98,000 | 90,490 | 92.3 | 251,180 | 76.8 |
| 1989 | Variable effort | 323,000 | 225,000 | 210,992 | 93.8 | 87-98,000 (CAN) | 98,000 | 99,532 | 101.6 | 310,524 | 96.1 |
| 1990 | Variable effort - high risk | 245,000 | 196,000 | 183,800 | 93.8 | 32-70,000 (CAN) | 73,500 | 76,680 | 104.3 | 260,480 | 106.3 |
| 1991 | Hybrid -mod. risk | 253,000 | 228,000 | 217,505 | 95.4 | 175-311,000 | 98,000 | 104,522 | 106.7 | 322,027 | 127.3 |
| 1992 | Hybrid -mod. risk | 232,000 | 208,800 | 208,576 | 99.9 | 160-288,000 | 90,000 | 86,370 | 96.0 | 294,946 | 127.1 |
| 1993 | Hybrid -mod. risk | 178,000 | 142,000 | 141,222 | 99.5 | 122-220,000 | 61,000 | 58,783 | 96.4 | 200,005 | 112.4 |
| 1994 | Hybrid-low risk | 325,000 | 260,000 | 252,729 | 97.2 | 325-555,000 | 110,000 | 106,172 | 96.5 | 358,901 | 110.4 |
| 1995 | Hybrid-low risk | 223,000 | 178,400 | 176,107 | 98.7 | 223-382,000 | 76,500 | 70,418 | 92.0 | 246,525 | 110.5 |
| 1996 | Hybrid-low risk | 265,000 | 212,000 | 212,900 | 100.4 | 161-321,000 | 91,000 | 88,240 | 97.0 | 301,140 | 113.6 |
| 1997 | Hybrid-moderate risk | 290,000 | 232,000 | 233,423 | 100.6 | 161-321,000 | 99,400 | 90,630 | 91.2 | 324,053 | 111.7 |
| 1998 | Hybrid-moderate risk | 290,000 | 232,000 | 232,509 | 100.2 | 116-233,000 | 80,000 | 86,738 | 108.4 | 319,247 | 110.1 |

Table 3. Length and age sample sizes for estimates of Pacific whiting age composition for U.S. surveys and fisheries. A. AFSC acoustic survey, B. AFSC bottom trawl survey, C. U.S. shore-based fishery, D. U.S. at-sea fishery.

A. AFSC acoustic survey

| Year | No. hauls | No. lengths | No. aged |
|---|---|---|---|
| 1977 | 116 | 11,695 | 4,262 |
| 1980 | 72 | 8,296 | 2,952 |
| 1983 | 38 | 8,614 | 1,327 |
| 1986 | 48 | 12,702 | 2,074 |
| 1989 | 25 | 5,606 | 1,730 |
| 1992 | 62 | 15,852 | 2,184 |
| 1995 | 95 | 22,896 | 2,118 |
| 1998 | 108 | 33,347 | 2,417 |

B. AFSC bottom trawl survey

| Year | No. hauls | No. lengths | No. aged |
|---|---|---|---|
| 1977 | 189 | 36,927 | 4,456 |
| 1980 | 133 | 14,828 | 3,619 |
| 1983 | 224 | 36,345 | 4,419 |
| 1986 | 215 | 32,781 | 1,999 |
| 1989 | 240 | 38,774 | 946 |
| 1992 | 305 | 45,896 | 966 |
| 1995 | 281 | 55,165 | 572 |
| 1998 | 491 | 84,377 | --- |

C. U.S. shore-based fishery

| Year | Number of samples | No. aged |
|---|---|---|
| 1990 | 15 | 660 |
| 1991 | 26 | 934 |
| 1992 | 47 | 1,062 |
| 1993 | 36 | 845 |
| 1994 | 50 | 1,457 |
| 1995 | 51 | 1,441 |
| 1996 | 34 | 1,123 |
| 1997 | 58 | 1,759 |
| 1998 | 66 | --- |

Estimation methods:

A. Acoustic survey. Age-length keys by geographic strata (Wilson and Guttormsen 1997)

B. Bottom trawl survey. Age-length keys by geographic strata (Dorn et al. 1994). Number of hauls are those where length samples were taken.

C. U.S. shore-based fishery. Stratified random design with strata based on port groups.

D. U.S. at-sea fishery. Age-length keys by geographic strata (Dorn 1991). Number of hauls are those where length samples were taken.

D. U.S. at-sea fishery

| Year | No. hauls | No. lengths | No. aged |
|---|---|---|---|
| 1973 | | NA | |
| 1974 | | NA | |
| 1975 | | NA | |
| 1976 | 279 | 53,429 | 4,077 |
| 1977 | 1,103 | 142,971 | 7,698 |
| 1978 | 832 | 124,771 | 5,839 |
| 1979 | 1,156 | 173,356 | 3,124 |
| 1980 | 682 | 102,248 | 5,336 |
| 1981 | 905 | 135,740 | 4,268 |
| 1982 | 1,145 | 171,816 | 4,258 |
| 1983 | 1,112 | 166,858 | 3,232 |
| 1984 | 1,625 | 243,684 | 3,310 |
| 1985 | 1,780 | 267,010 | 2,440 |
| 1986 | 3,161 | 474,107 | 3,070 |
| 1987 | 2,876 | 431,454 | 3,175 |
| 1988 | 2,801 | 420,144 | 3,043 |
| 1989 | 2,666 | 368,807 | 3,041 |
| 1990 | 2,101 | 268,083 | 3,112 |
| 1991 | 1,022 | 112,477 | 1,335 |
| 1992 | 848 | 78,626 | 2,175 |
| 1993 | 423 | 33,100 | 1,196 |
| 1994 | 645 | 47,917 | 1,775 |
| 1995 | 434 | 30,285 | 690 |
| 1996 | 530 | 33,209 | 1,333 |
| 1997 | 632 | 49,592 | 1,147 |
| 1998 | 744 | 47,789 | --- |

Table 4. Catch at age (millions of fish) for the Pacific whiting fisheries, 1973-98. Separate tables are given for U.S. and Canadian fisheries. The aggregate catch from all foreign, joint venture, domestic fisheries is included in these estimates. Catch at age for 1998 is preliminary.

| | Age | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Year | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | Total |
| U.S. fisheries | | | | | | | | | | | | | | | | |
| 1973 | 0.00 | 0.00 | 55.92 | 9.67 | 21.72 | 40.22 | 25.16 | 23.01 | 21.51 | 10.33 | 4.51 | 1.94 | 1.08 | 0.00 | 0.00 | 215.07 |
| 1974 | 29.31 | 1.30 | 0.98 | 150.14 | 20.52 | 35.50 | 44.29 | 25.73 | 11.40 | 3.58 | 1.63 | 0.98 | 0.33 | 0.00 | 0.00 | 325.69 |
| 1975 | 0.00 | 88.43 | 2.69 | 3.70 | 128.11 | 21.86 | 23.54 | 38.00 | 17.15 | 7.40 | 3.70 | 1.35 | 0.34 | 0.00 | 0.00 | 336.27 |
| 1976 | 0.00 | 0.33 | 36.85 | 29.29 | 29.62 | 185.27 | 27.65 | 13.82 | 4.93 | 0.99 | 0.33 | 0.00 | 0.00 | 0.00 | 0.00 | 329.09 |
| 1977 | 0.00 | 1.81 | 3.80 | 54.35 | 11.23 | 19.93 | 68.11 | 11.05 | 5.80 | 2.72 | 1.45 | 0.73 | 0.18 | 0.00 | 0.00 | 181.16 |
| 1978 | 0.01 | 0.02 | 4.56 | 8.58 | 51.87 | 9.48 | 20.32 | 38.57 | 5.74 | 2.48 | 1.28 | 0.52 | 0.20 | 0.05 | 0.01 | 143.69 |
| 1979 | 0.00 | 4.34 | 8.74 | 17.41 | 10.15 | 48.01 | 15.47 | 29.48 | 20.82 | 4.25 | 1.70 | 0.50 | 0.22 | 0.05 | 0.03 | 161.17 |
| 1980 | 0.00 | 0.13 | 24.67 | 2.16 | 6.90 | 7.16 | 20.11 | 9.57 | 11.99 | 9.92 | 1.74 | 1.35 | 1.01 | 0.59 | 0.14 | 97.44 |
| 1981 | 13.38 | 1.25 | 2.30 | 97.62 | 6.89 | 9.64 | 6.77 | 23.33 | 6.26 | 7.24 | 7.05 | 0.95 | 0.48 | 0.12 | 0.13 | 183.41 |
| 1982 | 0.00 | 27.51 | 1.93 | 1.57 | 57.88 | 5.02 | 5.78 | 5.02 | 11.96 | 2.43 | 2.53 | 4.64 | 0.34 | 0.13 | 0.03 | 126.77 |
| 1983 | 0.00 | 0.00 | 86.60 | 7.22 | 3.63 | 36.79 | 4.68 | 3.72 | 3.32 | 5.24 | 1.62 | 1.00 | 1.00 | 0.16 | 0.14 | 155.12 |
| 1984 | 0.00 | 0.00 | 2.59 | 164.97 | 7.18 | 5.18 | 17.54 | 2.17 | 1.24 | 0.82 | 1.34 | 0.21 | 0.20 | 0.31 | 0.03 | 203.78 |
| 1985 | 2.27 | 0.55 | 1.32 | 12.36 | 113.50 | 9.74 | 4.30 | 6.75 | 0.61 | 0.34 | 0.24 | 0.36 | 0.00 | 0.00 | 0.00 | 152.34 |
| 1986 | 0.00 | 62.92 | 12.88 | 1.85 | 9.34 | 171.79 | 21.55 | 10.76 | 12.45 | 1.53 | 1.05 | 0.38 | 0.79 | 0.15 | 0.05 | 307.49 |
| 1987 | 0.00 | 0.00 | 124.20 | 6.58 | 1.68 | 2.72 | 151.56 | 7.89 | 3.09 | 14.87 | 0.57 | 0.15 | 0.15 | 1.25 | 0.00 | 314.71 |
| 1988 | 0.00 | 1.22 | 1.31 | 172.76 | 8.02 | 1.40 | 2.60 | 96.93 | 5.16 | 0.72 | 8.32 | 0.15 | 0.24 | 0.00 | 0.65 | 299.48 |
| 1989 | 0.00 | 8.65 | 9.57 | 3.88 | 257.20 | 7.80 | 2.46 | 2.74 | 106.63 | 6.62 | 0.87 | 5.37 | 0.03 | 0.12 | 0.57 | 412.51 |
| 1990 | 0.00 | 5.69 | 85.34 | 10.97 | 1.92 | 152.02 | 2.56 | 1.14 | 0.71 | 95.97 | 0.47 | 0.00 | 6.07 | 0.00 | 0.41 | 363.27 |
| 1991 | 0.00 | 0.95 | 43.96 | 98.32 | 19.35 | 6.00 | 151.49 | 6.63 | 1.31 | 0.93 | 60.10 | 2.11 | 0.00 | 9.74 | 0.65 | 401.54 |
| 1992 | 0.97 | 18.53 | 9.94 | 51.95 | 109.58 | 10.27 | 5.09 | 131.94 | 4.84 | 2.38 | 0.79 | 42.06 | 0.63 | 0.20 | 1.88 | 391.05 |
| 1993 | 0.00 | 1.90 | 70.49 | 9.07 | 42.90 | 59.65 | 3.75 | 3.06 | 81.86 | 1.81 | 0.43 | 0.20 | 20.95 | 0.12 | 2.47 | 298.66 |
| 1994 | 0.00 | 0.23 | 16.48 | 121.89 | 4.82 | 76.93 | 104.64 | 3.29 | 2.04 | 115.38 | 0.46 | 2.06 | 0.22 | 29.13 | 3.65 | 476.31 |
| 1995 | 0.20 | 1.02 | 0.41 | 19.96 | 114.38 | 3.32 | 27.40 | 66.22 | 3.09 | 0.53 | 58.19 | 1.09 | 0.91 | 0.10 | 18.55 | 315.36 |
| 1996 | 0.00 | 102.26 | 71.90 | 6.75 | 34.60 | 97.87 | 1.81 | 17.17 | 46.84 | 0.90 | 0.17 | 50.38 | 0.00 | 0.49 | 14.81 | 445.94 |
| 1997 | 0.00 | 2.00 | 173.73 | 163.98 | 3.01 | 27.17 | 48.41 | 3.05 | 10.71 | 18.59 | 0.39 | 0.77 | 17.33 | 0.47 | 8.38 | 477.97 |
| 1998 | 0.55 | 47.88 | 137.93 | 82.88 | 126.13 | 6.61 | 22.01 | 48.98 | 5.69 | 0.80 | 22.85 | 0.54 | 0.86 | 12.87 | 5.24 | 521.82 |

Table 4. Continued. Canadian catch at age.

| | Age | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Year | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | Total |
| | | | | | | | | Canadian fisheries | | | | | | | | |
| 1977 | 0.00 | 0.01 | 0.01 | 0.25 | 0.09 | 0.30 | 1.83 | 0.53 | 0.50 | 0.42 | 0.40 | 0.35 | 0.16 | 0.00 | 0.00 | 4.85 |
| 1978 | 0.00 | 0.00 | 0.00 | 0.20 | 0.35 | 0.28 | 1.06 | 1.31 | 1.12 | 0.62 | 0.48 | 0.21 | 0.18 | 0.09 | 0.00 | 5.90 |
| 1979 | 0.00 | 0.00 | 0.00 | 0.21 | 0.62 | 1.30 | 1.14 | 2.10 | 3.02 | 1.10 | 0.79 | 0.37 | 0.25 | 0.17 | 0.12 | 11.19 |
| 1980 | 0.00 | 0.00 | 0.00 | 0.00 | 0.47 | 0.62 | 2.46 | 0.92 | 1.18 | 6.74 | 1.27 | 0.62 | 0.62 | 0.20 | 0.00 | 15.10 |
| 1981 | 0.00 | 0.00 | 0.00 | 1.01 | 0.27 | 1.41 | 1.38 | 4.28 | 0.85 | 2.36 | 6.18 | 1.49 | 0.60 | 0.85 | 0.00 | 20.68 |
| 1982 | 0.00 | 0.00 | 0.00 | 0.69 | 13.35 | 1.10 | 1.44 | 1.41 | 4.41 | 1.00 | 0.78 | 6.04 | 0.59 | 0.47 | 0.00 | 31.28 |
| 1983 | 0.00 | 0.06 | 14.02 | 1.03 | 1.80 | 32.15 | 1.29 | 1.87 | 1.67 | 5.59 | 0.77 | 0.26 | 3.41 | 0.26 | 0.13 | 64.31 |
| 1984 | 0.00 | 0.00 | 1.11 | 13.27 | 1.73 | 9.26 | 20.86 | 2.04 | 2.35 | 1.54 | 4.81 | 0.93 | 0.80 | 2.65 | 0.37 | 61.72 |
| 1985 | 0.00 | 0.06 | 0.06 | 2.45 | 8.03 | 1.65 | 3.25 | 9.62 | 0.49 | 0.55 | 0.55 | 1.65 | 0.37 | 0.00 | 1.59 | 30.32 |
| 1986 | 0.00 | 0.14 | 0.14 | 0.28 | 3.97 | 38.41 | 2.41 | 2.41 | 11.48 | 1.28 | 0.57 | 0.99 | 1.42 | 0.43 | 1.42 | 65.35 |
| 1987 | 0.00 | 0.00 | 0.90 | 0.60 | 0.15 | 2.56 | 70.71 | 2.86 | 2.86 | 10.38 | 0.60 | 0.45 | 1.20 | 0.90 | 1.20 | 95.37 |
| 1988 | 0.00 | 0.00 | 0.31 | 15.28 | 0.62 | 1.13 | 2.36 | 66.66 | 2.26 | 1.44 | 7.90 | 0.51 | 0.21 | 0.21 | 0.62 | 99.51 |
| 1989 | 0.00 | 0.00 | 0.20 | 0.59 | 35.55 | 0.20 | 0.39 | 0.59 | 69.34 | 1.76 | 1.37 | 8.59 | 0.39 | 0.20 | 1.17 | 120.34 |
| 1990 | 0.00 | 0.00 | 2.80 | 2.08 | 0.21 | 48.67 | 0.73 | 0.21 | 0.00 | 27.50 | 0.42 | 0.00 | 1.25 | 1.04 | 2.08 | 86.99 |
| 1991 | 0.00 | 0.00 | 0.11 | 6.11 | 2.46 | 0.43 | 70.60 | 0.54 | 0.00 | 0.21 | 47.47 | 0.21 | 0.11 | 2.25 | 0.11 | 130.61 |
| 1992 | 0.00 | 0.00 | 0.67 | 7.63 | 17.81 | 3.55 | 0.40 | 56.83 | 0.27 | 0.00 | 0.13 | 30.79 | 0.07 | 0.13 | 1.21 | 119.49 |
| 1993 | 0.00 | 0.07 | 0.77 | 2.52 | 12.91 | 17.54 | 1.89 | 0.21 | 40.62 | 0.21 | 0.14 | 0.14 | 12.49 | 0.21 | 0.21 | 89.93 |
| 1994 | 0.00 | 0.00 | 0.70 | 2.87 | 3.07 | 15.20 | 26.86 | 4.20 | 0.80 | 67.45 | 0.87 | 0.27 | 0.13 | 22.73 | 1.33 | 146.48 |
| 1995 | 4.88 | 0.04 | 0.53 | 6.31 | 5.03 | 3.21 | 10.72 | 15.96 | 3.25 | 0.67 | 33.81 | 0.68 | 0.04 | 0.15 | 9.41 | 94.70 |
| 1996 | 0.00 | 12.46 | 2.89 | 1.44 | 12.03 | 16.06 | 4.31 | 14.28 | 17.05 | 2.84 | 1.10 | 34.27 | 0.06 | 0.00 | 10.01 | 128.80 |
| 1997 | 0.00 | 0.81 | 22.17 | 19.19 | 2.52 | 17.21 | 16.22 | 2.25 | 11.08 | 14.42 | 3.24 | 0.54 | 18.65 | 1.35 | 4.06 | 133.73 |
| 1998 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |

Table 5. AFSC acoustic survey estimates of Pacific whiting biomass and age composition. Surveys in 1995 and 1998 were cooperative surveys between AFSC and DFO. Biomass and age composition for 1977-89 were adjusted as described in Dorn (1996) to account for changes in target strength, depth and geographic coverage. Biomass estimates at 20 log l - 68 in 1992 and 1995 are from Wilson and Guttormson (1997). The biomass in 1995 includes 27,251 t of Pacific whiting found by the DFO survey vessel W.E. Ricker in Queen Charlotte Sound. (This estimate was obtained from 43,200 t, the biomass at -35 dB/kg multiplied by 0.631, a conversion factor from -35 dB/kg to 20 log l - 68 for the U.S. survey north of 50°30' N lat.). In 1992, 1995, and 1998, 20,702 t, 30,032 t, and 8,034 t of age-1 fish respectively is not included in the total survey biomass.

| | Total biomass at 20 log l - 68 (1,000 t) | Number at age (million) | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Year | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
| 1977 | 1596.422 | 0.22 | 135.48 | 121.24 | 718.01 | 63.29 | 87.41 | 745.78 | 106.23 | 78.20 | 40.90 | 39.47 | 21.80 | 8.49 | 2.18 | 2.25 |
| 1980 | 1701.482 | 0.00 | 14.45 | 1641.32 | 151.15 | 91.20 | 70.79 | 326.83 | 110.38 | 248.08 | 97.65 | 60.94 | 9.71 | 16.66 | 3.71 | 2.89 |
| 1983 | 1364.656 | 0.00 | 1.23 | 2918.17 | 50.86 | 20.64 | 304.29 | 31.84 | 34.78 | 26.00 | 51.01 | 12.46 | 13.39 | 14.84 | 2.69 | 0.00 |
| 1986 | 2397.386 | 0.00 | 3610.65 | 91.38 | 17.56 | 112.09 | 1701.85 | 179.58 | 131.65 | 181.21 | 21.62 | 21.03 | 1.47 | 10.37 | 2.35 | 0.00 |
| 1989 | 1805.603 | 0.00 | 571.25 | 200.82 | 39.29 | 1864.35 | 38.91 | 15.27 | 24.54 | 626.89 | 30.64 | 2.77 | 53.71 | 0.00 | 0.00 | 2.00 |
| 1992 | 1417.327 | 190.54 | 227.03 | 45.97 | 235.77 | 502.09 | 57.21 | 19.85 | 994.22 | 28.52 | 16.85 | 6.93 | 323.37 | 17.19 | 0.00 | 14.81 |
| 1995 | 1385.205 | 316.41 | 880.52 | 117.80 | 32.62 | 575.90 | 26.58 | 88.78 | 403.38 | 5.90 | 0.00 | 429.34 | 0.96 | 17.42 | 0.00 | 130.39 |
| 1998 | 1185.932 | 98.31 | 414.33 | 460.41 | 386.81 | 481.76 | 34.52 | 135.59 | 215.61 | 26.41 | 39.14 | 120.27 | 7.68 | 4.92 | 104.47 | 29.19 |

Table 6. AFSC trawl survey estimates of Pacific whiting biomass (1,000 t) and age composition (million). The biomass estimates for 1977 and 1986, when the trawl survey did not extend into the Canadian zone, were adjusted as described in Dorn et al. (1991). In 1995, 53,730 t of age-1 fish is not included in the biomass estimate. In 1998, 20,658 t of age-1 fish is not included in the biomass estimate.

| Year | Area-swept biomass estimate (1,000 t) | Number at age (million) | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
| 1977 | 76.307 | 0.57 | 7.96 | 4.05 | 16.87 | 3.28 | 7.46 | 33.45 | 7.70 | 6.11 | 3.96 | 2.21 | 1.14 | 0.41 | 0.02 | 0.08 |
| 1980 | 188.299 | 0.30 | 1.80 | 234.42 | 6.91 | 12.53 | 11.37 | 22.31 | 14.32 | 16.93 | 11.96 | 4.63 | 2.28 | 1.20 | 0.99 | 1.43 |
| 1983 | 128.808 | 0.11 | 0.27 | 201.77 | 7.40 | 1.43 | 34.06 | 8.53 | 6.63 | 8.57 | 10.71 | 4.36 | 3.16 | 2.20 | 0.24 | 0.43 |
| 1986 | 254.566 | 0.00 | 203.50 | 8.95 | 2.81 | 1.33 | 202.20 | 10.37 | 5.21 | 59.96 | 2.23 | 2.20 | 0.55 | 8.88 | 0.20 | 0.69 |
| 1989 | 379.810 | 114.10 | 44.57 | 14.09 | 11.93 | 172.32 | 10.24 | 15.84 | 4.97 | 270.64 | 9.69 | 1.43 | 36.48 | 0.14 | 0.33 | 2.65 |
| 1992 | 352.538 | 56.14 | 47.95 | 5.72 | 28.12 | 78.63 | 9.10 | 3.32 | 202.78 | 3.60 | 3.25 | 2.61 | 74.35 | 3.43 | 0.00 | 4.85 |
| 1995 | 529.527 | 592.70 | 171.38 | 22.12 | 20.88 | 97.14 | 6.48 | 49.25 | 233.89 | 0.00 | 0.00 | 181.53 | 0.00 | 4.61 | 0.00 | 142.41 |
| 1998 | 476.459 | 212.14 | 442.40 | 285.14 | 132.36 | 151.01 | 12.48 | 34.31 | 72.23 | 12.36 | 7.24 | 46.03 | 0.68 | 4.55 | 33.74 | 14.03 |

Table 7. DFO acoustic survey estimates of Pacific whiting biomass (1,000 t) and age composition (proportion in numbers) in the Canadian zone. The biomass and age composition in 1995 are from the U.S.-Canadian joint survey of the Canadian zone, and is reported in Wilson and Guttormsen (1997).

| | Total biomass at -35 dB/kg (1,000 t) | Number at age (million) | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Year | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
| 1990 | 317.338 | 0.00 | 0.00 | 37.40 | 10.33 | 0.98 | 287.37 | 2.95 | 0.00 | 0.00 | 145.16 | 1.97 | 0.00 | 3.94 | 0.00 | 0.98 |
| 1991 | 563.308 | 0.00 | 0.00 | 2.96 | 54.46 | 10.69 | 1.48 | 448.06 | 1.48 | 0.00 | 1.48 | 346.79 | 3.49 | 1.48 | 23.97 | 0.00 |
| 1992 | 1101.328 | 0.00 | 0.00 | 8.58 | 88.95 | 214.54 | 54.69 | 1.04 | 840.57 | 3.24 | 0.00 | 0.00 | 351.39 | 0.52 | 4.29 | 7.77 |
| 1993 | 638.906 | 0.00 | 0.35 | 12.34 | 14.79 | 97.23 | 154.49 | 24.32 | 9.55 | 421.22 | 4.03 | 1.86 | 2.49 | 173.32 | 1.44 | 7.66 |
| 1994 | 224.907 | 0.00 | 1.44 | 5.96 | 7.87 | 8.34 | 36.86 | 53.37 | 10.35 | 2.33 | 138.50 | 1.08 | 0.00 | 0.00 | 37.16 | 0.74 |
| 1995 | 374.400 | 112.05 | 0.00 | 0.00 | 1.49 | 71.19 | 7.40 | 29.33 | 144.78 | 2.84 | 0.00 | 181.00 | 0.00 | 10.15 | 0.00 | 38.41 |
| 1996 | 447.410 | 1.18 | 77.89 | 21.83 | 7.08 | 79.07 | 61.96 | 29.51 | 57.83 | 92.06 | 18.88 | 8.26 | 175.26 | 17.11 | 3.54 | 41.31 |
| 1997 | 649.793 | 0.00 | 1.30 | 179.48 | 143.06 | 15.61 | 120.95 | 115.75 | 13.01 | 72.83 | 94.94 | 10.40 | 5.20 | 146.97 | 1.30 | 24.71 |

Table 8. Tiburon Midwater trawl laval rockfish survey estimates of log whiting abundance (Sakuma and Ralston 1997).

| | | All Strata | | Monterey outside stratum only | |
|---|---|---|---|---|---|
| Year class | Year of recruitment | log(numbers) | SE | log(numbers) | SE |
| 1986 | 1988 | 1.679 | 0.192 | 3.160 | 0.528 |
| 1987 | 1989 | 3.129 | 0.172 | 6.258 | 0.511 |
| 1988 | 1990 | 3.058 | 0.161 | 4.630 | 0.480 |
| 1989 | 1991 | 0.979 | 0.170 | 2.008 | 0.511 |
| 1990 | 1992 | 1.323 | 0.173 | 3.553 | 0.511 |
| 1991 | 1993 | 2.134 | 0.167 | 3.769 | 0.511 |
| 1992 | 1994 | 0.583 | 0.166 | 1.053 | 0.339 |
| 1993 | 1995 | 3.095 | 0.173 | 7.048 | 0.511 |
| 1994 | 1996 | 2.152 | 0.177 | 3.470 | 0.511 |
| 1995 | 1997 | 0.768 | 0.173 | 1.940 | 0.511 |
| 1996 | 1998 | 1.968 | 0.174 | 4.593 | 0.528 |
| 1997 | 1999 | 1.487 | 0.197 | 2.592 | 0.528 |
| 1998 | 2000 | 0.602 | 0.177 | 1.249 | 0.466 |

Table 9. Weight at age (kg) used in the stock assessment model.

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| U.S. fishery weight at age | | | | | | | | | | | | | | | |
| 1972-78 | 0.119 | 0.264 | 0.407 | 0.514 | 0.610 | 0.656 | 0.696 | 0.743 | 0.812 | 0.880 | 0.956 | 0.993 | 1.065 | 1.093 | 1.125 |
| 1979 | 0.143 | 0.264 | 0.456 | 0.570 | 0.667 | 0.734 | 0.793 | 0.831 | 0.905 | 0.944 | 1.016 | 1.088 | 1.156 | 1.071 | 1.208 |
| 1980 | 0.141 | 0.298 | 0.470 | 0.559 | 0.646 | 0.722 | 0.790 | 0.825 | 0.867 | 0.899 | 0.995 | 1.046 | 1.050 | 1.040 | 1.159 |
| 1981 | 0.137 | 0.286 | 0.429 | 0.547 | 0.632 | 0.697 | 0.760 | 0.809 | 0.858 | 0.888 | 0.934 | 1.000 | 1.055 | 1.075 | 1.176 |
| 1982 | 0.143 | 0.253 | 0.396 | 0.509 | 0.605 | 0.669 | 0.730 | 0.788 | 0.856 | 0.877 | 0.901 | 0.976 | 1.053 | 1.061 | 1.016 |
| 1983 | 0.150 | 0.253 | 0.328 | 0.447 | 0.525 | 0.589 | 0.637 | 0.680 | 0.721 | 0.791 | 0.806 | 0.850 | 0.878 | 1.005 | 0.999 |
| 1984 | 0.187 | 0.293 | 0.387 | 0.434 | 0.550 | 0.607 | 0.658 | 0.712 | 0.753 | 0.798 | 0.863 | 0.906 | 0.934 | 0.952 | 1.113 |
| 1985 | 0.213 | 0.321 | 0.412 | 0.491 | 0.545 | 0.619 | 0.679 | 0.796 | 0.777 | 0.831 | 0.920 | 0.961 | 1.023 | 1.004 | 1.111 |
| 1986 | 0.192 | 0.294 | 0.386 | 0.464 | 0.518 | 0.538 | 0.617 | 0.663 | 0.735 | 0.755 | 0.816 | 0.877 | 0.919 | 0.928 | 1.094 |
| 1987 | 0.187 | 0.297 | 0.394 | 0.460 | 0.517 | 0.546 | 0.563 | 0.627 | 0.681 | 0.720 | 0.748 | 0.834 | 0.856 | 0.893 | 0.975 |
| 1988 | 0.197 | 0.303 | 0.395 | 0.466 | 0.520 | 0.570 | 0.572 | 0.596 | 0.641 | 0.702 | 0.733 | 0.803 | 0.874 | 0.886 | 0.955 |
| 1989 | 0.192 | 0.232 | 0.320 | 0.402 | 0.454 | 0.502 | 0.538 | 0.565 | 0.577 | 0.584 | 0.668 | 0.752 | 0.826 | 0.900 | 0.854 |
| 1990 | 0.195 | 0.248 | 0.364 | 0.418 | 0.515 | 0.522 | 0.553 | 0.559 | 0.542 | 0.589 | 0.616 | 0.759 | 0.707 | 0.779 | 0.851 |
| 1991 | 0.195 | 0.291 | 0.374 | 0.461 | 0.505 | 0.527 | 0.576 | 0.629 | 0.604 | 0.566 | 0.641 | 0.601 | 0.802 | 0.866 | 0.887 |
| 1992 | 0.216 | 0.275 | 0.367 | 0.472 | 0.513 | 0.554 | 0.579 | 0.581 | 0.600 | 0.581 | 0.600 | 0.617 | 0.763 | 0.521 | 0.797 |
| 1993 | 0.196 | 0.283 | 0.348 | 0.402 | 0.468 | 0.511 | 0.509 | 0.524 | 0.557 | 0.556 | 0.569 | 0.603 | 0.587 | 0.636 | 0.615 |
| 1994 | 0.196 | 0.236 | 0.357 | 0.428 | 0.458 | 0.518 | 0.562 | 0.613 | 0.563 | 0.612 | 0.566 | 0.638 | 0.765 | 0.656 | 0.645 |
| 1995 | 0.120 | 0.277 | 0.468 | 0.488 | 0.493 | 0.514 | 0.591 | 0.590 | 0.601 | 0.619 | 0.636 | 0.617 | 0.651 | 0.655 | 0.669 |
| 1996 | 0.120 | 0.278 | 0.378 | 0.451 | 0.519 | 0.547 | 0.568 | 0.574 | 0.599 | 0.583 | 0.760 | 0.629 | 0.625 | 0.647 | 0.630 |
| 1997 | 0.097 | 0.340 | 0.421 | 0.471 | 0.536 | 0.532 | 0.572 | 0.584 | 0.603 | 0.625 | 0.746 | 0.657 | 0.684 | 0.623 | 0.716 |
| 1998 | 0.204 | 0.261 | 0.369 | 0.460 | 0.492 | 0.518 | 0.529 | 0.552 | 0.588 | 0.606 | 0.603 | 0.612 | 0.634 | 0.625 | 0.655 |
| Canadian fishery weight at age | | | | | | | | | | | | | | | |
| 1972-76 | 0.135 | 0.370 | 0.606 | 0.742 | 0.827 | 0.861 | 0.905 | 0.987 | 1.221 | 1.111 | 1.163 | 1.206 | 1.222 | 1.213 | 1.247 |
| 1977 | 0.143 | 0.355 | 0.570 | 0.744 | 0.824 | 0.871 | 0.875 | 0.957 | 1.020 | 1.104 | 1.164 | 1.222 | 1.240 | 1.207 | 1.273 |
| 1978 | 0.133 | 0.313 | 0.502 | 0.658 | 0.783 | 0.818 | 0.825 | 0.858 | 0.922 | 0.992 | 1.072 | 1.153 | 1.171 | 1.132 | 1.205 |
| 1979 | 0.141 | 0.332 | 0.532 | 0.701 | 0.830 | 0.916 | 0.935 | 0.969 | 0.989 | 1.046 | 1.137 | 1.175 | 1.266 | 1.237 | 1.299 |
| 1980 | 0.140 | 0.319 | 0.496 | 0.655 | 0.780 | 0.869 | 0.979 | 0.955 | 0.970 | 1.037 | 1.073 | 1.180 | 1.229 | 1.225 | 1.301 |
| 1981 | 0.136 | 0.309 | 0.479 | 0.660 | 0.741 | 0.829 | 0.891 | 0.985 | 0.961 | 0.977 | 1.137 | 1.096 | 1.172 | 1.204 | 1.272 |
| 1982 | 0.126 | 0.288 | 0.449 | 0.584 | 0.674 | 0.779 | 0.842 | 0.902 | 0.904 | 0.959 | 0.987 | 1.028 | 1.097 | 1.127 | 1.269 |
| 1983 | 0.120 | 0.264 | 0.399 | 0.515 | 0.607 | 0.630 | 0.730 | 0.785 | 0.824 | 0.789 | 0.890 | 0.926 | 0.883 | 0.960 | 1.091 |
| 1984 | 0.137 | 0.296 | 0.439 | 0.557 | 0.643 | 0.710 | 0.723 | 0.816 | 0.856 | 0.896 | 0.911 | 0.975 | 0.987 | 0.957 | 1.076 |
| 1985 | 0.142 | 0.311 | 0.465 | 0.584 | 0.712 | 0.740 | 0.792 | 0.871 | 0.889 | 0.931 | 0.978 | 1.048 | 1.037 | 1.012 | 1.067 |
| 1986 | 0.125 | 0.281 | 0.431 | 0.548 | 0.633 | 0.659 | 0.742 | 0.795 | 0.888 | 0.880 | 0.932 | 0.986 | 1.143 | 0.988 | 1.048 |
| 1987 | 0.149 | 0.314 | 0.457 | 0.566 | 0.643 | 0.692 | 0.706 | 0.768 | 0.801 | 0.827 | 0.877 | 0.919 | 0.943 | 0.940 | 0.978 |
| 1988 | 0.120 | 0.270 | 0.533 | 0.523 | 0.443 | 0.602 | 0.501 | 0.685 | 0.828 | 0.792 | 0.886 | 1.060 | 1.020 | 1.318 | 1.080 |
| 1989 | 0.192 | 0.232 | 0.689 | 0.723 | 0.757 | 0.795 | 0.838 | 0.879 | 0.909 | 0.952 | 0.998 | 1.051 | 1.117 | 1.203 | 1.289 |
| 1990 | 0.195 | 0.248 | 0.488 | 0.528 | 0.567 | 0.614 | 0.669 | 0.725 | 0.798 | 0.881 | 0.966 | 1.044 | 1.122 | 1.189 | 1.255 |
| 1991 | 0.195 | 0.291 | 0.616 | 0.669 | 0.723 | 0.781 | 0.828 | 0.867 | 0.902 | 0.923 | 0.937 | 0.972 | 1.029 | 1.094 | 1.159 |
| 1992 | 0.216 | 0.275 | 0.581 | 0.593 | 0.645 | 0.677 | 0.706 | 0.701 | 0.713 | 0.713 | 0.713 | 0.729 | 0.764 | 0.791 | 0.864 |
| 1993 | 0.196 | 0.283 | 0.525 | 0.590 | 0.609 | 0.634 | 0.658 | 0.663 | 0.667 | 0.676 | 0.677 | 0.677 | 0.685 | 0.685 | 0.685 |
| 1994 | 0.196 | 0.236 | 0.695 | 0.605 | 0.664 | 0.707 | 0.728 | 0.732 | 0.737 | 0.752 | 0.677 | 0.677 | 0.768 | 0.685 | 0.685 |
| 1995 | 0.120 | 0.220 | 0.658 | 0.664 | 0.680 | 0.722 | 0.759 | 0.768 | 0.785 | 0.804 | 0.803 | 0.801 | 0.811 | 0.842 | 0.842 |
| 1996 | 0.120 | 0.358 | 0.527 | 0.593 | 0.689 | 0.682 | 0.697 | 0.731 | 0.737 | 0.729 | 0.699 | 0.754 | 0.856 | 0.798 | 0.740 |
| 1997 | 0.120 | 0.499 | 0.532 | 0.570 | 0.671 | 0.696 | 0.682 | 0.743 | 0.737 | 0.752 | 0.745 | 0.803 | 0.790 | 0.858 | 0.817 |

Table 9.  Weight at age (kg) used in the stock assessment model (cont).

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| AFSC acoustic survey weight at age | | | | | | | | | | | | | | | |
| 1977 | 0.123 | 0.256 | 0.388 | 0.492 | 0.589 | 0.662 | 0.724 | 0.796 | 0.860 | 0.892 | 0.949 | 1.008 | 1.057 | 1.093 | 1.119 |
| 1980 | 0.107 | 0.261 | 0.455 | 0.561 | 0.672 | 0.759 | 0.861 | 0.894 | 0.948 | 1.003 | 1.081 | 1.122 | 1.170 | 1.176 | 1.205 |
| 1983 | 0.122 | 0.228 | 0.308 | 0.457 | 0.570 | 0.667 | 0.723 | 0.776 | 0.826 | 0.891 | 0.917 | 0.935 | 0.985 | 1.034 | 1.032 |
| 1986 | 0.165 | 0.262 | 0.367 | 0.465 | 0.532 | 0.558 | 0.658 | 0.715 | 0.815 | 0.823 | 0.865 | 0.908 | 1.006 | 0.995 | 1.069 |
| 1989 | 0.143 | 0.321 | 0.387 | 0.461 | 0.521 | 0.561 | 0.599 | 0.621 | 0.634 | 0.638 | 0.682 | 0.729 | 0.870 | 0.984 | 1.069 |
| 1992 | 0.119 | 0.205 | 0.357 | 0.508 | 0.554 | 0.578 | 0.654 | 0.642 | 0.688 | 0.655 | 0.758 | 0.705 | 0.697 | 0.734 | 0.800 |
| 1995 | 0.097 | 0.220 | 0.344 | 0.438 | 0.548 | 0.605 | 0.639 | 0.624 | 0.630 | 0.682 | 0.717 | 0.701 | 0.727 | 0.752 | 0.728 |
| 1998 | 0.081 | 0.189 | 0.343 | 0.527 | 0.534 | 0.587 | 0.658 | 0.631 | 0.645 | 0.766 | 0.709 | 0.830 | 0.735 | 0.744 | 0.790 |
| AFSC bottom trawl survey weight at age | | | | | | | | | | | | | | | |
| 1977 | 0.123 | 0.256 | 0.388 | 0.492 | 0.589 | 0.662 | 0.724 | 0.796 | 0.860 | 0.892 | 0.949 | 1.008 | 1.057 | 1.093 | 1.119 |
| 1980 | 0.107 | 0.261 | 0.455 | 0.561 | 0.672 | 0.759 | 0.861 | 0.894 | 0.948 | 1.003 | 1.081 | 1.122 | 1.170 | 1.176 | 1.205 |
| 1983 | 0.122 | 0.228 | 0.308 | 0.457 | 0.570 | 0.667 | 0.723 | 0.776 | 0.826 | 0.891 | 0.917 | 0.935 | 0.985 | 1.034 | 1.032 |
| 1986 | 0.165 | 0.262 | 0.367 | 0.465 | 0.532 | 0.558 | 0.658 | 0.715 | 0.815 | 0.823 | 0.865 | 0.908 | 1.006 | 0.995 | 1.069 |
| 1989 | 0.143 | 0.321 | 0.387 | 0.461 | 0.521 | 0.561 | 0.599 | 0.621 | 0.634 | 0.638 | 0.682 | 0.729 | 0.870 | 0.984 | 1.069 |
| 1992 | 0.119 | 0.205 | 0.357 | 0.508 | 0.554 | 0.578 | 0.654 | 0.642 | 0.688 | 0.655 | 0.758 | 0.705 | 0.697 | 0.734 | 0.800 |
| 1995 | 0.091 | 0.204 | 0.279 | 0.408 | 0.476 | 0.530 | 0.609 | 0.659 | 0.682 | 0.704 | 0.727 | 0.730 | 0.733 | 0.706 | 0.679 |
| 1998 | 0.097 | 0.189 | 0.339 | 0.480 | 0.502 | 0.532 | 0.534 | 0.575 | 0.583 | 0.655 | 0.669 | 0.639 | 0.762 | 0.670 | 0.710 |
| DFO acoustic survey weight at age | | | | | | | | | | | | | | | |
| 1990 | 0.119 | 0.205 | 0.533 | 0.575 | 0.592 | 0.647 | 0.623 | 0.646 | 0.646 | 0.669 | 0.656 | 0.957 | 0.957 | 0.957 | 0.957 |
| 1991 | 0.119 | 0.205 | 0.533 | 0.560 | 0.592 | 0.641 | 0.615 | 0.633 | 0.633 | 0.650 | 0.656 | 0.657 | 0.657 | 0.657 | 0.657 |
| 1992 | 0.119 | 0.205 | 0.629 | 0.600 | 0.653 | 0.685 | 0.686 | 0.705 | 0.657 | 0.698 | 0.698 | 0.739 | 0.744 | 0.744 | 0.810 |
| 1993 | 0.196 | 0.283 | 0.541 | 0.595 | 0.624 | 0.641 | 0.688 | 0.718 | 0.704 | 0.827 | 0.847 | 0.624 | 0.741 | 0.685 | 0.995 |
| 1994 | 0.196 | 0.567 | 0.585 | 0.614 | 0.654 | 0.694 | 0.720 | 0.782 | 0.775 | 0.761 | 1.083 | 0.935 | 0.935 | 0.787 | 0.810 |
| 1995 | 0.098 | 0.235 | 0.371 | 0.508 | 0.642 | 0.778 | 0.739 | 0.740 | 0.691 | 0.739 | 0.787 | 0.769 | 0.752 | 0.771 | 0.790 |
| 1996 | 0.330 | 0.403 | 0.482 | 0.582 | 0.655 | 0.650 | 0.665 | 0.693 | 0.686 | 0.688 | 0.684 | 0.705 | 0.779 | 0.798 | 0.671 |
| 1997 | 0.330 | 0.488 | 0.572 | 0.598 | 0.673 | 0.710 | 0.722 | 0.731 | 0.746 | 0.785 | 0.749 | 0.713 | 0.761 | 0.689 | 0.742 |
| Population weight at age | | | | | | | | | | | | | | | |
| 1972-78 | 0.123 | 0.256 | 0.388 | 0.492 | 0.589 | 0.662 | 0.724 | 0.796 | 0.860 | 0.892 | 0.949 | 1.008 | 1.057 | 1.093 | 1.119 |
| 1979-81 | 0.107 | 0.261 | 0.455 | 0.561 | 0.672 | 0.759 | 0.861 | 0.894 | 0.948 | 1.003 | 1.081 | 1.122 | 1.170 | 1.176 | 1.205 |
| 1982-84 | 0.122 | 0.228 | 0.308 | 0.457 | 0.570 | 0.667 | 0.723 | 0.776 | 0.826 | 0.891 | 0.917 | 0.935 | 0.985 | 1.034 | 1.032 |
| 1985-87 | 0.165 | 0.262 | 0.367 | 0.465 | 0.532 | 0.558 | 0.658 | 0.715 | 0.815 | 0.823 | 0.865 | 0.908 | 1.006 | 0.995 | 1.069 |
| 1988-90 | 0.143 | 0.321 | 0.387 | 0.461 | 0.521 | 0.561 | 0.599 | 0.621 | 0.634 | 0.638 | 0.682 | 0.729 | 0.870 | 0.984 | 1.069 |
| 1991-93 | 0.119 | 0.205 | 0.357 | 0.508 | 0.554 | 0.578 | 0.654 | 0.642 | 0.688 | 0.655 | 0.758 | 0.705 | 0.697 | 0.734 | 0.800 |
| 1994-96 | 0.097 | 0.220 | 0.344 | 0.438 | 0.548 | 0.605 | 0.639 | 0.624 | 0.630 | 0.682 | 0.717 | 0.701 | 0.727 | 0.752 | 0.728 |
| 1997-99 | 0.081 | 0.189 | 0.343 | 0.527 | 0.534 | 0.587 | 0.658 | 0.631 | 0.645 | 0.766 | 0.709 | 0.830 | 0.735 | 0.744 | 0.790 |
| Female multiplier for spawning biomass | | | | | | | | | | | | | | | |
| All yrs. | 0.511 | 0.510 | 0.511 | 0.510 | 0.512 | 0.522 | 0.525 | 0.535 | 0.543 | 0.547 | 0.569 | 0.568 | 0.572 | 0.581 | 0.589 |

Table 10. Selectivity at age for Pacific whiting fisheries and surveys for base-run model. The fisheries and surveys were modeled using double logistic selectivity functions, with random walk process error for the U.S. and Canadian fisheries. The fishery selectivity coefficients reported below are the average of the annual selectivity coefficients for all years (1972-98), and for the last ten years (1989-98).

| Age | U.S. fishery, all years | U.S. fishery, 1989-98 | Canadian fishery, all years | Canadian fishery, 1989-98 | Acoustic survey | Bottom trawl survey | DFO acoustic survey |
|---|---|---|---|---|---|---|---|
| 2 | 0.089 | 0.111 | 0.005 | 0.009 | 0.436 | 0.242 | 0.021 |
| 3 | 0.357 | 0.516 | 0.019 | 0.033 | 0.622 | 0.301 | 0.054 |
| 4 | 0.678 | 0.859 | 0.068 | 0.111 | 0.780 | 0.373 | 0.128 |
| 5 | 0.871 | 0.987 | 0.207 | 0.305 | 0.887 | 0.459 | 0.276 |
| 6 | 0.950 | 1.000 | 0.445 | 0.597 | 0.948 | 0.560 | 0.498 |
| 7 | 0.987 | 0.999 | 0.678 | 0.836 | 0.980 | 0.674 | 0.723 |
| 8 | 1.000 | 0.996 | 0.835 | 0.948 | 0.995 | 0.794 | 0.876 |
| 9 | 0.980 | 0.988 | 0.925 | 0.986 | 1.000 | 0.904 | 0.954 |
| 10 | 0.910 | 0.969 | 0.973 | 0.997 | 0.996 | 0.982 | 0.987 |
| 11 | 0.777 | 0.928 | 0.995 | 1.000 | 0.978 | 1.000 | 1.000 |
| 12 | 0.595 | 0.844 | 1.000 | 0.996 | 0.929 | 0.944 | 0.999 |
| 13 | 0.408 | 0.697 | 0.972 | 0.964 | 0.820 | 0.822 | 0.956 |
| 14 | 0.251 | 0.499 | 0.795 | 0.788 | 0.624 | 0.664 | 0.730 |
| 15 | 0.140 | 0.305 | 0.350 | 0.347 | 0.382 | 0.505 | 0.277 |

Table 11. Numbers at age (billions of fish) for the coastal stock of Pacific whiting estimated by the base-run model, 1972-1998.

| | Age | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
| 1972 | 4.399 | 0.652 | 0.512 | 0.539 | 0.303 | 0.212 | 0.144 | 0.060 | 0.034 | 0.017 | 0.011 | 0.000 | 0.000 | 0.000 |
| 1973 | 0.576 | 3.477 | 0.512 | 0.397 | 0.407 | 0.219 | 0.144 | 0.091 | 0.036 | 0.020 | 0.010 | 0.007 | 0.000 | 0.000 |
| 1974 | 0.518 | 0.454 | 2.715 | 0.392 | 0.292 | 0.283 | 0.141 | 0.087 | 0.053 | 0.021 | 0.012 | 0.006 | 0.005 | 0.000 |
| 1975 | 1.709 | 0.406 | 0.350 | 2.032 | 0.281 | 0.199 | 0.183 | 0.088 | 0.053 | 0.033 | 0.013 | 0.008 | 0.005 | 0.003 |
| 1976 | 0.384 | 1.319 | 0.307 | 0.258 | 1.459 | 0.196 | 0.135 | 0.122 | 0.058 | 0.036 | 0.023 | 0.010 | 0.006 | 0.006 |
| 1977 | 0.379 | 0.300 | 1.006 | 0.225 | 0.180 | 0.983 | 0.130 | 0.090 | 0.083 | 0.041 | 0.026 | 0.017 | 0.007 | 0.010 |
| 1978 | 0.234 | 0.299 | 0.232 | 0.753 | 0.163 | 0.129 | 0.705 | 0.094 | 0.065 | 0.061 | 0.031 | 0.020 | 0.013 | 0.013 |
| 1979 | 2.933 | 0.185 | 0.233 | 0.176 | 0.554 | 0.119 | 0.094 | 0.513 | 0.069 | 0.049 | 0.047 | 0.024 | 0.016 | 0.021 |
| 1980 | 0.418 | 2.320 | 0.144 | 0.174 | 0.126 | 0.392 | 0.084 | 0.066 | 0.364 | 0.050 | 0.036 | 0.036 | 0.019 | 0.029 |
| 1981 | 0.559 | 0.331 | 1.822 | 0.110 | 0.130 | 0.093 | 0.286 | 0.061 | 0.048 | 0.267 | 0.037 | 0.027 | 0.027 | 0.038 |
| 1982 | 12.002 | 0.442 | 0.258 | 1.365 | 0.080 | 0.092 | 0.065 | 0.199 | 0.042 | 0.034 | 0.193 | 0.028 | 0.021 | 0.051 |
| 1983 | 0.356 | 9.513 | 0.348 | 0.199 | 1.018 | 0.058 | 0.066 | 0.046 | 0.143 | 0.031 | 0.025 | 0.144 | 0.021 | 0.056 |
| 1984 | 0.114 | 0.282 | 7.469 | 0.267 | 0.149 | 0.746 | 0.042 | 0.048 | 0.034 | 0.104 | 0.023 | 0.019 | 0.109 | 0.060 |
| 1985 | 0.239 | 0.091 | 0.222 | 5.778 | 0.204 | 0.111 | 0.553 | 0.031 | 0.035 | 0.025 | 0.078 | 0.017 | 0.014 | 0.130 |
| 1986 | 9.650 | 0.189 | 0.071 | 0.172 | 4.473 | 0.157 | 0.085 | 0.419 | 0.024 | 0.027 | 0.019 | 0.060 | 0.013 | 0.114 |
| 1987 | 0.133 | 7.604 | 0.146 | 0.054 | 0.130 | 3.337 | 0.115 | 0.062 | 0.306 | 0.017 | 0.020 | 0.014 | 0.045 | 0.099 |
| 1988 | 0.411 | 0.105 | 5.926 | 0.111 | 0.040 | 0.096 | 2.446 | 0.084 | 0.045 | 0.222 | 0.013 | 0.015 | 0.011 | 0.112 |
| 1989 | 2.666 | 0.326 | 0.082 | 4.525 | 0.083 | 0.030 | 0.070 | 1.777 | 0.061 | 0.033 | 0.162 | 0.009 | 0.011 | 0.095 |
| 1990 | 1.229 | 2.109 | 0.251 | 0.061 | 3.318 | 0.060 | 0.021 | 0.050 | 1.261 | 0.043 | 0.023 | 0.117 | 0.007 | 0.082 |
| 1991 | 0.232 | 0.969 | 1.603 | 0.187 | 0.045 | 2.421 | 0.044 | 0.015 | 0.036 | 0.913 | 0.031 | 0.017 | 0.086 | 0.068 |
| 1992 | 1.993 | 0.183 | 0.731 | 1.173 | 0.135 | 0.032 | 1.712 | 0.031 | 0.011 | 0.025 | 0.644 | 0.022 | 0.012 | 0.116 |
| 1993 | 0.527 | 1.567 | 0.136 | 0.525 | 0.828 | 0.094 | 0.022 | 1.180 | 0.021 | 0.008 | 0.018 | 0.451 | 0.016 | 0.097 |
| 1994 | 0.149 | 0.416 | 1.186 | 0.099 | 0.376 | 0.587 | 0.066 | 0.016 | 0.833 | 0.015 | 0.005 | 0.013 | 0.327 | 0.086 |
| 1995 | 2.212 | 0.118 | 0.320 | 0.819 | 0.065 | 0.237 | 0.359 | 0.040 | 0.009 | 0.503 | 0.009 | 0.003 | 0.008 | 0.282 |
| 1996 | 1.505 | 1.756 | 0.093 | 0.233 | 0.545 | 0.042 | 0.149 | 0.223 | 0.025 | 0.006 | 0.314 | 0.006 | 0.002 | 0.209 |
| 1997 | 1.262 | 1.100 | 1.324 | 0.062 | 0.146 | 0.328 | 0.024 | 0.085 | 0.127 | 0.014 | 0.003 | 0.183 | 0.003 | 0.148 |
| 1998 | 1.159 | 0.998 | 0.725 | 0.887 | 0.039 | 0.089 | 0.193 | 0.014 | 0.049 | 0.073 | 0.008 | 0.002 | 0.110 | 0.106 |

Table 12. Time series of estimated biomass, recruitment, and utilization for 1972-96 for the base-run assessment model. U.S. and Canadian exploitation rate is the catch in biomass divided by the total biomass of age 3+ fish at the start of the year. Population biomass is in millions of tons of age-3 and older fish at the start of the year. Recruitment is given in billions of age-2 fish.

| Year | Population biomass (million t) | Female spawning biomass | Recruits (billion) | U.S. exploitation rate | Canada exploitation rate | Total exploitation rate |
|---|---|---|---|---|---|---|
| 1972 | 1.399 | 0.763 | 4.399 | 5.3% | 3.1% | 8.4% |
| 1973 | 2.524 | 1.062 | 0.576 | 5.8% | 0.6% | 6.4% |
| 1974 | 2.418 | 1.149 | 0.518 | 8.0% | 0.7% | 8.7% |
| 1975 | 2.187 | 1.116 | 1.709 | 9.4% | 0.7% | 10.1% |
| 1976 | 2.268 | 1.085 | 0.384 | 10.2% | 0.3% | 10.5% |
| 1977 | 1.932 | 0.968 | 0.379 | 6.6% | 0.3% | 6.9% |
| 1978 | 1.716 | 0.878 | 0.234 | 5.7% | 0.3% | 6.0% |
| 1979 | 1.674 | 0.934 | 2.933 | 7.4% | 0.7% | 8.2% |
| 1980 | 2.382 | 1.071 | 0.418 | 3.0% | 0.7% | 3.8% |
| 1981 | 2.226 | 1.102 | 0.559 | 5.2% | 1.1% | 6.2% |
| 1982 | 1.717 | 1.110 | 12.002 | 4.4% | 1.9% | 6.3% |
| 1983 | 4.412 | 1.770 | 0.356 | 1.7% | 0.9% | 2.6% |
| 1984 | 4.703 | 2.223 | 0.114 | 2.0% | 0.9% | 2.9% |
| 1985 | 4.110 | 2.080 | 0.239 | 2.1% | 0.6% | 2.7% |
| 1986 | 3.449 | 2.013 | 9.650 | 4.5% | 1.6% | 6.1% |
| 1987 | 5.737 | 2.499 | 0.133 | 2.8% | 1.3% | 4.1% |
| 1988 | 4.815 | 2.368 | 0.411 | 3.3% | 1.9% | 5.2% |
| 1989 | 4.056 | 2.147 | 2.666 | 5.2% | 2.5% | 7.7% |
| 1990 | 3.953 | 1.960 | 1.229 | 4.6% | 1.9% | 6.6% |
| 1991 | 3.779 | 1.898 | 0.232 | 5.8% | 2.8% | 8.5% |
| 1992 | 2.904 | 1.542 | 1.993 | 7.2% | 3.0% | 10.2% |
| 1993 | 2.722 | 1.352 | 0.527 | 5.2% | 2.2% | 7.3% |
| 1994 | 2.271 | 1.159 | 0.149 | 11.1% | 4.7% | 15.8% |
| 1995 | 1.656 | 0.915 | 2.212 | 10.7% | 4.3% | 15.0% |
| 1996 | 1.761 | 0.854 | 1.505 | 12.1% | 5.0% | 17.1% |
| 1997 | 1.844 | 0.884 | 1.262 | 12.7% | 4.9% | 17.6% |
| 1998 | 1.673 | 0.807 | 1.159 | 13.9% | 5.2% | 19.1% |
| Avg. 1972-98 | 2.826 | 1.397 | 1.776 | 6.5% | 2.0% | 8.5% |

Table 13. Life history and fishery vectors used to estimate spawning biomass per recruit (SPR) fishing mortalities.

| Age | Natural mortality | U.S. fishery selectivity (Avg. 1989-98) | Canadian fishery selectivity (Avg 1989-98) | U.S. fishery weight at age (kg) (Avg. 1978-98) | Canadian fishery weight at age (kg) (Avg. 1976-96) | Population weight at age (kg) (Avg. 1977-98) | Proportion of mature females | Multiplier for female weight at age |
|---|---|---|---|---|---|---|---|---|
| 2 | 0.23 | 0.111 | 0.009 | 0.278 | 0.294 | 0.243 | 0.176 | 0.510 |
| 3 | 0.23 | 0.516 | 0.033 | 0.392 | 0.530 | 0.369 | 0.661 | 0.511 |
| 4 | 0.23 | 0.859 | 0.111 | 0.472 | 0.619 | 0.489 | 0.890 | 0.510 |
| 5 | 0.23 | 0.987 | 0.305 | 0.538 | 0.689 | 0.565 | 0.969 | 0.512 |
| 6 | 0.23 | 1.000 | 0.597 | 0.581 | 0.742 | 0.622 | 0.986 | 0.522 |
| 7 | 0.23 | 0.999 | 0.836 | 0.622 | 0.778 | 0.689 | 0.996 | 0.525 |
| 8 | 0.23 | 0.996 | 0.948 | 0.659 | 0.829 | 0.712 | 1.000 | 0.535 |
| 9 | 0.23 | 0.988 | 0.986 | 0.688 | 0.872 | 0.756 | 1.000 | 0.543 |
| 10 | 0.23 | 0.969 | 0.997 | 0.715 | 0.894 | 0.794 | 1.000 | 0.547 |
| 11 | 0.23 | 0.928 | 1.000 | 0.766 | 0.937 | 0.835 | 1.000 | 0.569 |
| 12 | 0.23 | 0.844 | 0.996 | 0.801 | 0.985 | 0.867 | 1.000 | 0.568 |
| 13 | 0.23 | 0.697 | 0.964 | 0.853 | 1.027 | 0.906 | 1.000 | 0.572 |
| 14 | 0.23 | 0.499 | 0.788 | 0.853 | 1.038 | 0.939 | 1.000 | 0.581 |
| 15+ | 0.23 | 0.305 | 0.347 | 0.917 | 1.082 | 0.976 | 1.000 | 0.589 |

Table 14. Projections of whiting yield for 1999-2003 under different harvest rate policies for base-run model. (Coefficients of variation are in parentheses.) A meta-analysis of Merluciid stock-recruit relationships (see appendix) suggested that F40% is risk-neutral proxy for FMSY. Higher SPR rates are advised if a risk-averse approach is considered appropriate.

| Harvest rate policy | Year | Age 3+ biomass (million t) | | Spawning Biomass (million t) | | Age-2 Recruits (billion) | | Exploitation rate | | Total yield (t) | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| F35% | 1999 | 1.498 | (0.14) | 0.732 | (0.13) | 1.442 | (0.82) | 27.0% | (0.06) | 405,000 | (0.13) |
| | 2000 | 1.368 | (0.25) | 0.634 | (0.20) | 0.490 | (0.86) | 25.6% | (0.09) | 350,000 | (0.19) |
| | 2001 | 1.058 | (0.32) | 0.533 | (0.29) | 1.678 | (1.22) | 28.2% | (0.11) | 298,000 | (0.26) |
| | 2002 | 1.105 | (0.53) | 0.514 | (0.42) | 1.678 | (1.22) | 26.0% | (0.20) | 287,000 | (0.38) |
| | 2003 | 1.246 | (0.61) | 0.570 | (0.54) | 1.678 | (1.22) | 24.6% | (0.17) | 307,000 | (0.50) |
| F40% | 1999 | 1.498 | (0.14) | 0.732 | (0.13) | 1.442 | (0.82) | 21.4% | (0.06) | 320,000 | (0.13) |
| | 2000 | 1.448 | (0.24) | 0.675 | (0.20) | 0.490 | (0.86) | 20.5% | (0.09) | 297,000 | (0.18) |
| | 2001 | 1.175 | (0.30) | 0.594 | (0.27) | 1.678 | (1.22) | 22.7% | (0.10) | 266,000 | (0.24) |
| | 2002 | 1.233 | (0.49) | 0.581 | (0.39) | 1.678 | (1.22) | 21.2% | (0.19) | 261,000 | (0.35) |
| | 2003 | 1.381 | (0.57) | 0.639 | (0.50) | 1.678 | (1.22) | 20.1% | (0.17) | 278,000 | (0.46) |
| F40% (40-10 option) | 1999 | 1.498 | (0.14) | 0.732 | (0.13) | 1.442 | (0.82) | 20.1% | (0.07) | 301,000 | (0.19) |
| | 2000 | 1.467 | (0.24) | 0.684 | (0.19) | 0.490 | (0.86) | 18.7% | (0.06) | 275,000 | (0.26) |
| | 2001 | 1.211 | (0.27) | 0.613 | (0.25) | 1.678 | (1.22) | 19.6% | (0.12) | 238,000 | (0.35) |
| | 2002 | 1.290 | (0.45) | 0.610 | (0.35) | 1.678 | (1.22) | 18.4% | (0.14) | 238,000 | (0.50) |
| | 2003 | 1.452 | (0.52) | 0.676 | (0.45) | 1.678 | (1.22) | 18.5% | (0.15) | 269,000 | (0.61) |
| F45% | 1999 | 1.498 | (0.14) | 0.732 | (0.13) | 1.442 | (0.82) | 17.3% | (0.05) | 259,000 | (0.13) |
| | 2000 | 1.508 | (0.24) | 0.705 | (0.19) | 0.490 | (0.86) | 16.7% | (0.09) | 251,000 | (0.18) |
| | 2001 | 1.269 | (0.29) | 0.642 | (0.26) | 1.678 | (1.22) | 18.5% | (0.09) | 234,000 | (0.24) |
| | 2002 | 1.342 | (0.46) | 0.637 | (0.36) | 1.678 | (1.22) | 17.4% | (0.17) | 234,000 | (0.33) |
| | 2003 | 1.500 | (0.54) | 0.701 | (0.47) | 1.678 | (1.22) | 16.6% | (0.16) | 250,000 | (0.43) |
| F45% (40-10 option) | 1999 | 1.498 | (0.14) | 0.732 | (0.13) | 1.442 | (0.82) | 16.2% | (0.07) | 243,000 | (0.19) |
| | 2000 | 1.523 | (0.23) | 0.713 | (0.18) | 0.490 | (0.86) | 15.5% | (0.06) | 236,000 | (0.25) |
| | 2001 | 1.296 | (0.27) | 0.656 | (0.24) | 1.678 | (1.22) | 16.6% | (0.11) | 215,000 | (0.33) |
| | 2002 | 1.383 | (0.43) | 0.659 | (0.33) | 1.678 | (1.22) | 15.7% | (0.13) | 217,000 | (0.46) |
| | 2003 | 1.551 | (0.50) | 0.727 | (0.44) | 1.678 | (1.22) | 15.7% | (0.14) | 244,000 | (0.57) |
| Hybrid F Moderate | 1999 | 1.498 | (0.14) | 0.732 | (0.13) | 1.442 | (0.82) | 14.3% | (0.12) | 214,000 | (0.25) |
| | 2000 | 1.552 | (0.22) | 0.727 | (0.18) | 0.490 | (0.86) | 13.8% | (0.11) | 214,000 | (0.32) |
| | 2001 | 1.342 | (0.25) | 0.680 | (0.22) | 1.678 | (1.22) | 14.4% | (0.17) | 193,000 | (0.40) |
| | 2002 | 1.443 | (0.41) | 0.690 | (0.31) | 1.678 | (1.22) | 13.9% | (0.20) | 200,000 | (0.56) |
| | 2003 | 1.620 | (0.47) | 0.763 | (0.40) | 1.678 | (1.22) | 14.6% | (0.28) | 236,000 | (0.72) |

Table 15. Decision table showing the repercussions of different assumptions for AFSC acoustic survey catchability. The F40-10 option is applied to the F40% fishing mortality rate.

| | | True state of nature<br>Acoustic survey catchability<br>q = 1.2 | <br><br>q = 1.0 | <br><br>q = 0.8 |
|---|---|---|---|---|
| 1998 stock size (million t) | | 1.575 | 1.673 | 2.000 |
| 1998 spawning biomass (as percent of unfished) | | 37% | 37% | 41% |

| Management action | Assumed state of nature | Outcome: 2001/unfished spawning biomass | | Ratio |
|---|---|---|---|---|
| F35% | q = 1.2 | 25.3% | 25.5% | 29.3% |
| F40% | q = 1.2 | 28.1% | 28.2% | 31.7% |
| F45% | q = 1.2 | 30.4% | 30.3% | 33.6% |
| F40-10 | q = 1.2 | 28.8% | 28.8% | 32.3% |
| F35% | q = 1.0 | 24.3% | 24.6% | 28.4% |
| F40% | q = 1.0 | 27.3% | 27.4% | 31.0% |
| F45% | q = 1.0 | 29.7% | 29.6% | 33.0% |
| F40-10 | q = 1.0 | 28.1% | 28.2% | 31.7% |
| F35% | q = 0.8 | 21.0% | 21.4% | 25.5% |
| F40% | q = 0.8 | 24.5% | 24.7% | 28.6% |
| F45% | q = 0.8 | 27.3% | 27.4% | 31.0% |
| F40-10 | q = 0.8 | 25.1% | 25.3% | 29.1% |

| Management action | Assumed state of nature | Outcome: Average exploitation rate (1999-2000) | | | Average catch (1999-2000) |
|---|---|---|---|---|---|
| F35% | q = 1.2 | 25.8% | 24.6% | 20.1% | 353,000 |
| F40% | q = 1.2 | 20.6% | 19.6% | 16.2% | 289,000 |
| F45% | q = 1.2 | 16.7% | 15.9% | 13.2% | 239,000 |
| F40-10 | q = 1.2 | 19.4% | 18.5% | 15.2% | 264,000 |
| F35% | q = 1.0 | 27.7% | 26.3% | 21.6% | 378,000 |
| F40% | q = 1.0 | 22.0% | 21.0% | 17.3% | 309,000 |
| F45% | q = 1.0 | 17.8% | 17.0% | 14.0% | 255,000 |
| F40-10 | q = 1.0 | 20.6% | 19.6% | 16.2% | 288,000 |
| F35% | q = 0.8 | 34.7% | 32.9% | 26.8% | 458,000 |
| F40% | q = 0.8 | 27.3% | 26.0% | 21.3% | 374,000 |
| F45% | q = 0.8 | 22.0% | 20.9% | 17.2% | 309,000 |
| F40-10 | q = 0.8 | 26.3% | 25.0% | 20.5% | 371,000 |


Figure 1. Total catch of Pacific whiting in the U.S. and Canadian zones (1966-98) (upper panel). Percent catch by fishery within each zone (lower panels).

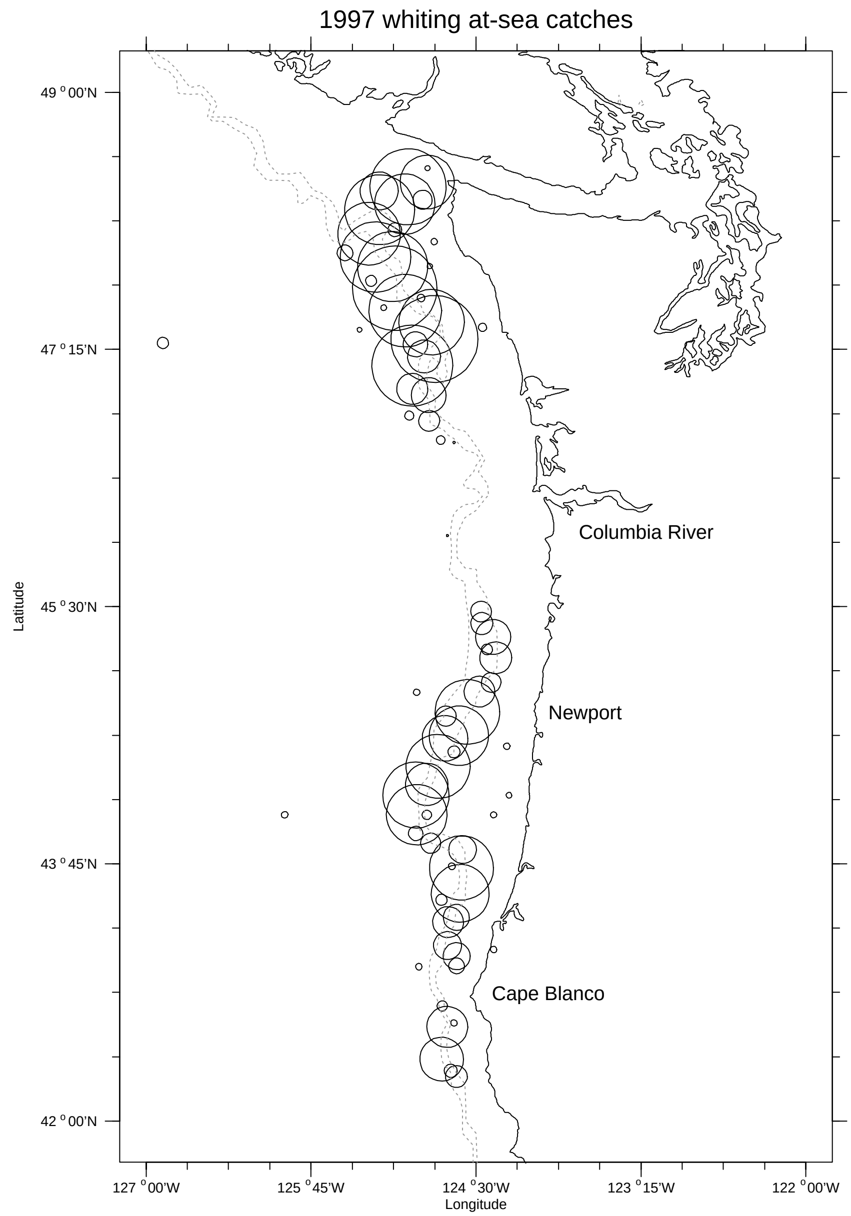



Figure 2. Catch by 20 $km^2$ block for factory trawlers and catcher boats (tribal and non-tribal) in the 1997 Pacific whiting fishery. The area of the circle is proportional to the total catch within the block. The 200 m and 300 m depth contours are shown in the figure.

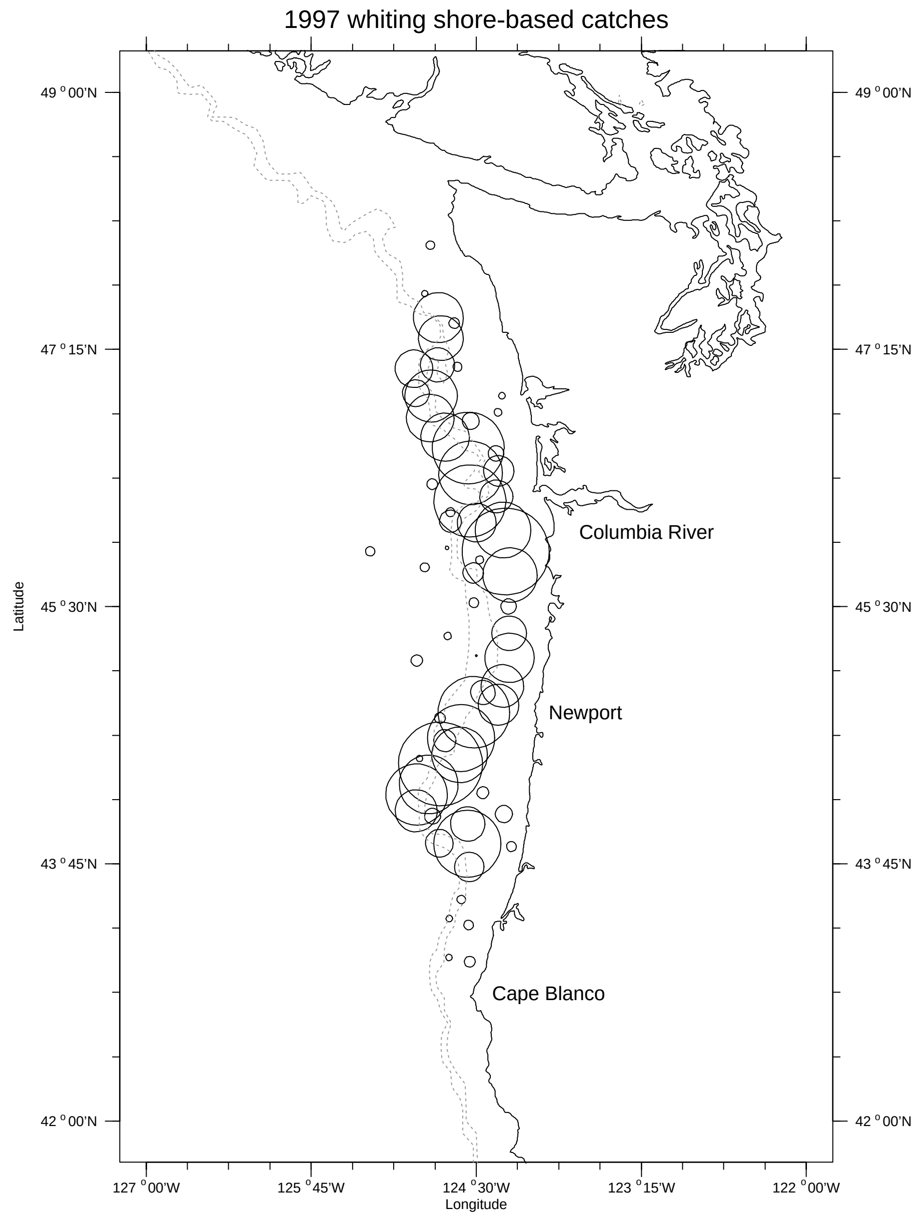



Figure 3. Catch by 20 $km^2$ blocks for shore-based boats in the 1997 Pacific whiting fishery. Position data is for landings in Oregon ports only. The 200 m and 300 m depth contours are shown in the figure.

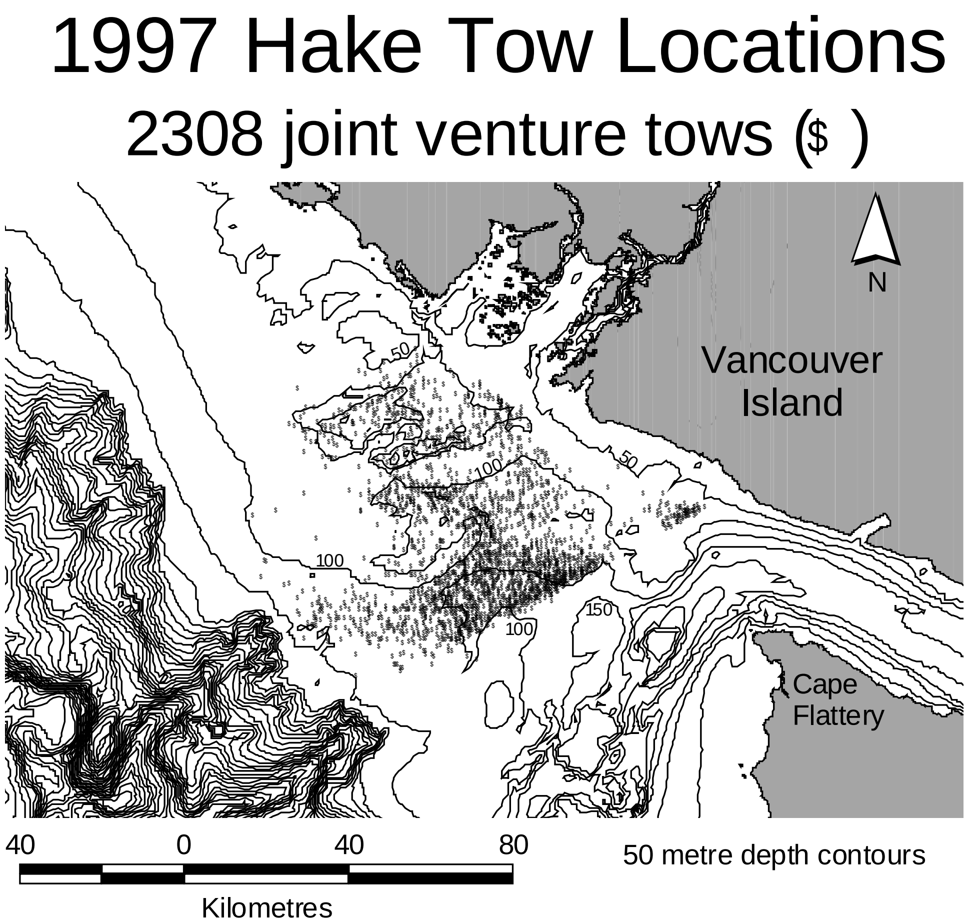



Figure 4. Trawl positions of boats participating in the 1997 Canadian joint-venture fishery for Pacific whiting.

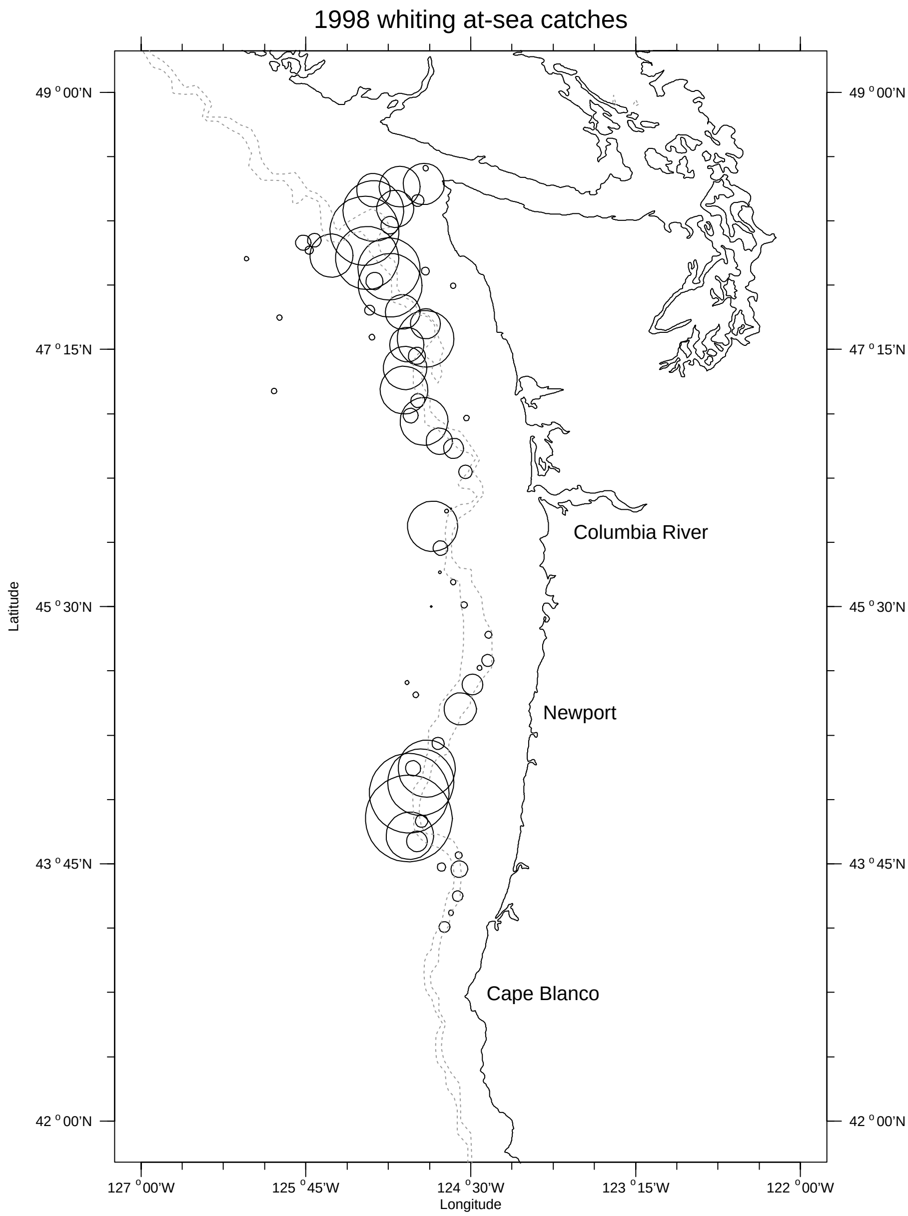



Figure 5.  Catch by 20 $km^2$ block for factory trawlers and catcher boats (tribal and non-tribal) in the 1998 at-sea fishery for Pacific whiting.  The area of the circle is proportional to the total catch within the block.  The 200 m and 300 m depth contours are shown in the figure.

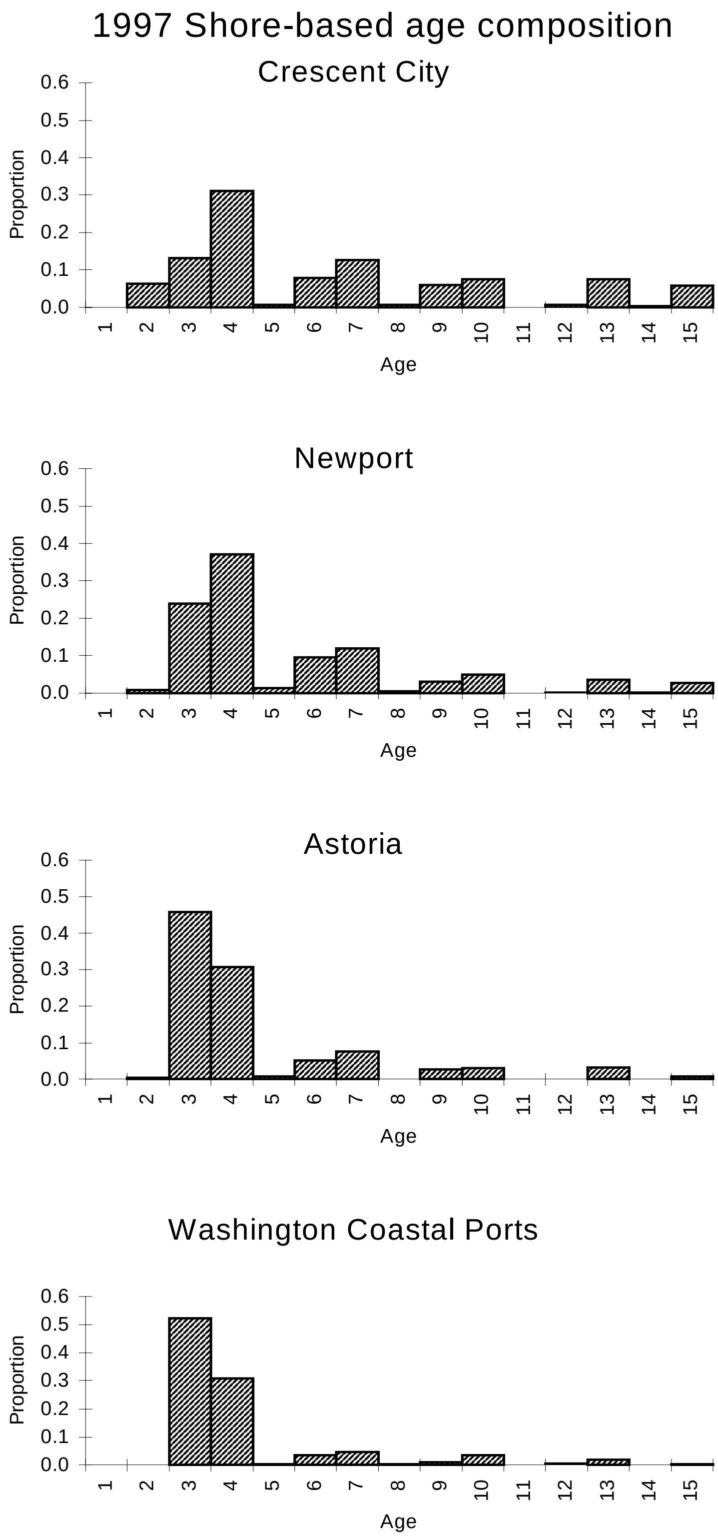



Figure 6. Pacific whiting proportion by age in shore-based landings by port in the U.S. zone in 1997.

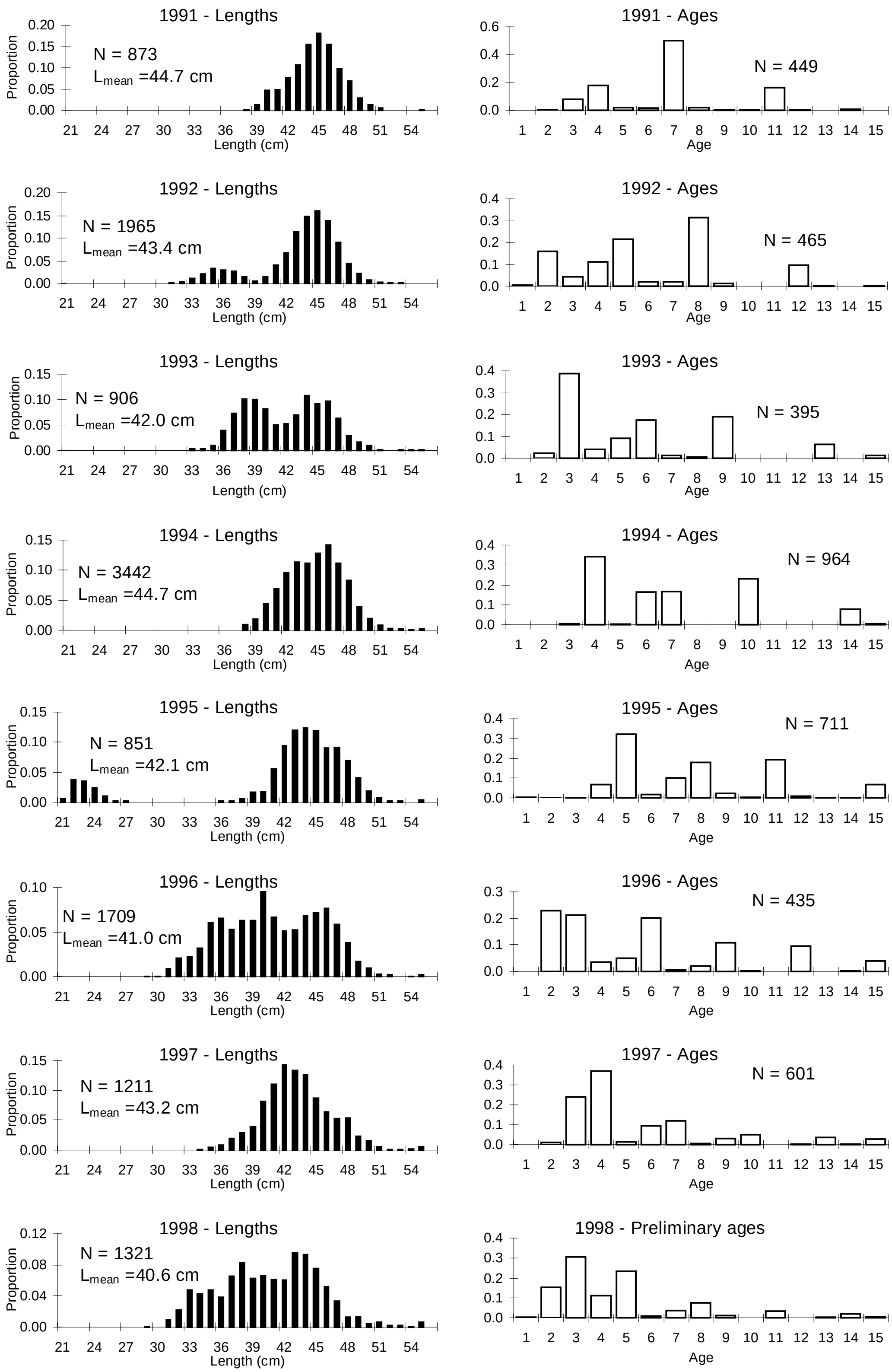



Figure 7. Pacific whiting length and age samples from Newport, Oregon, 1991-98.

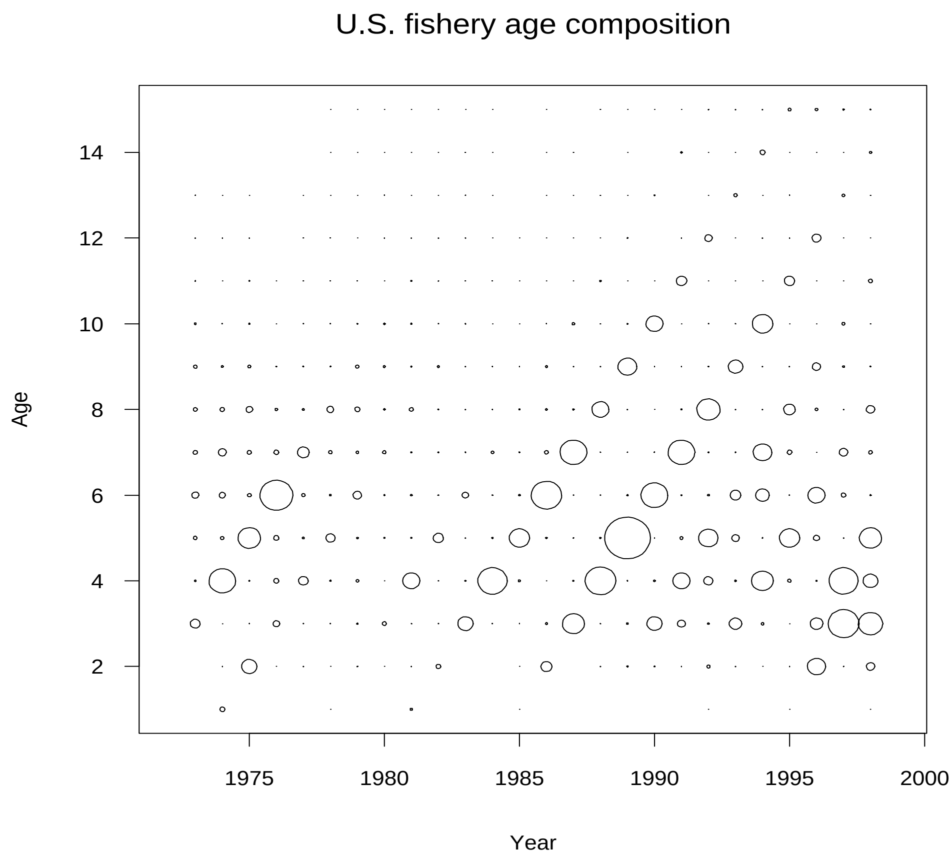



Figure 8. Catch at age of Pacific whiting in U.S. fisheries during 1973-1998. The diameter of the circle is proportional to the catch at age.

Canadian fishery age composition

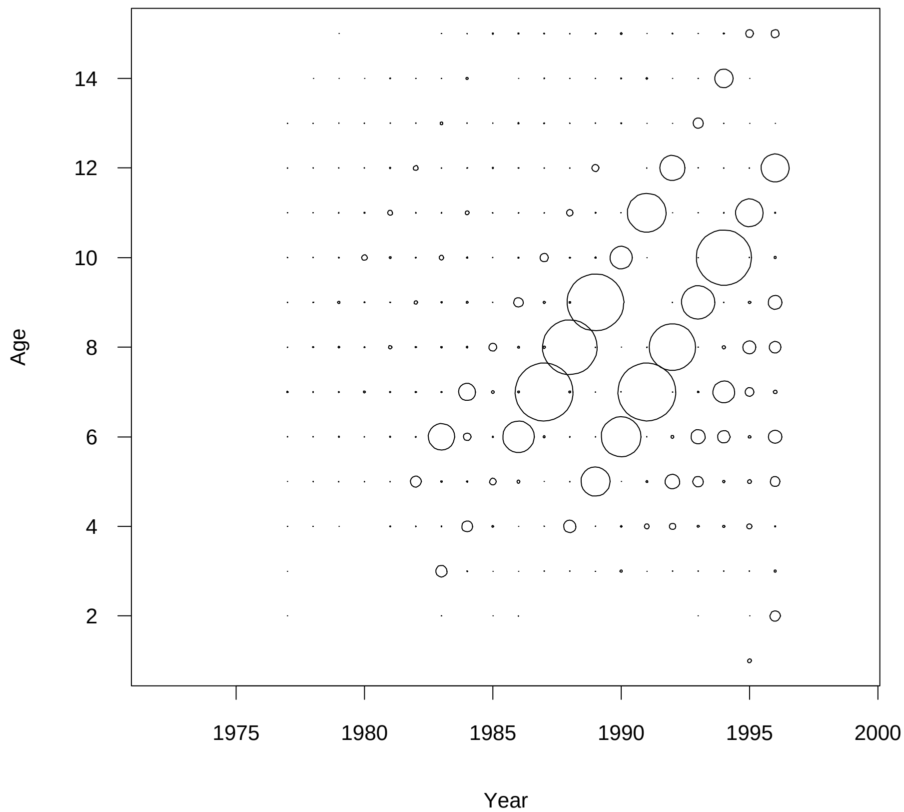



Figure 9. Catch at age of Pacific whiting in Canadian fisheries during 1977-1996. The diameter of the circle is proportional to the catch at age.

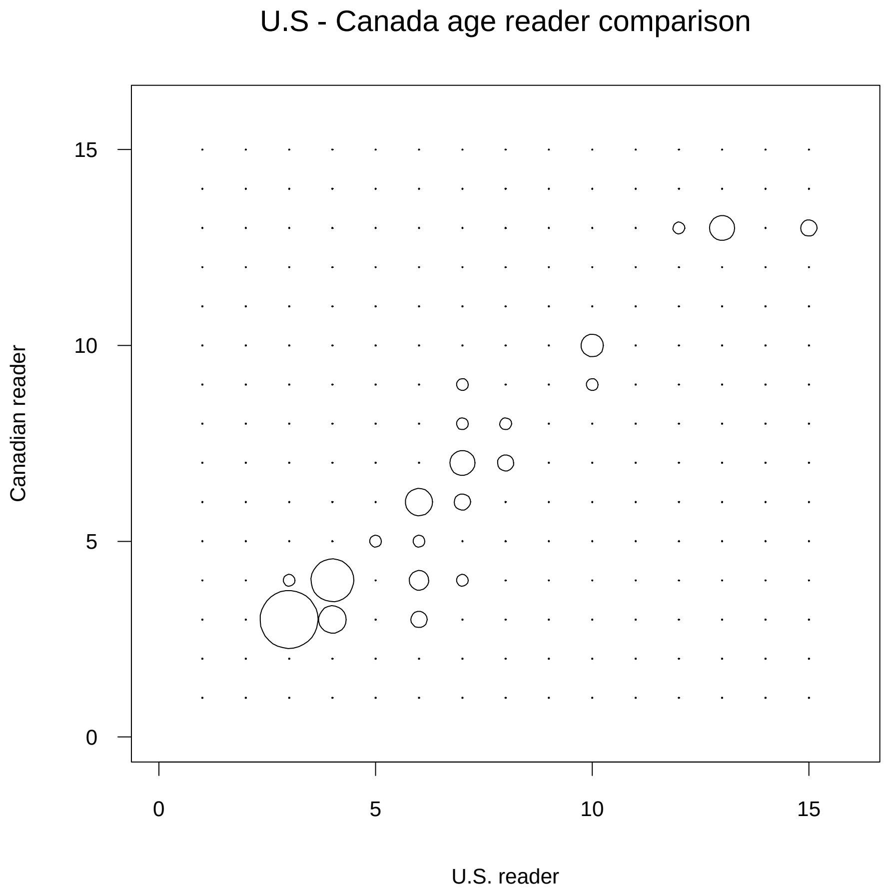



Figure 10. Comparison of ages by AFSC and DFO age readers for a sample of 89 Pacific whiting collected during the 1997 Makah fishery.

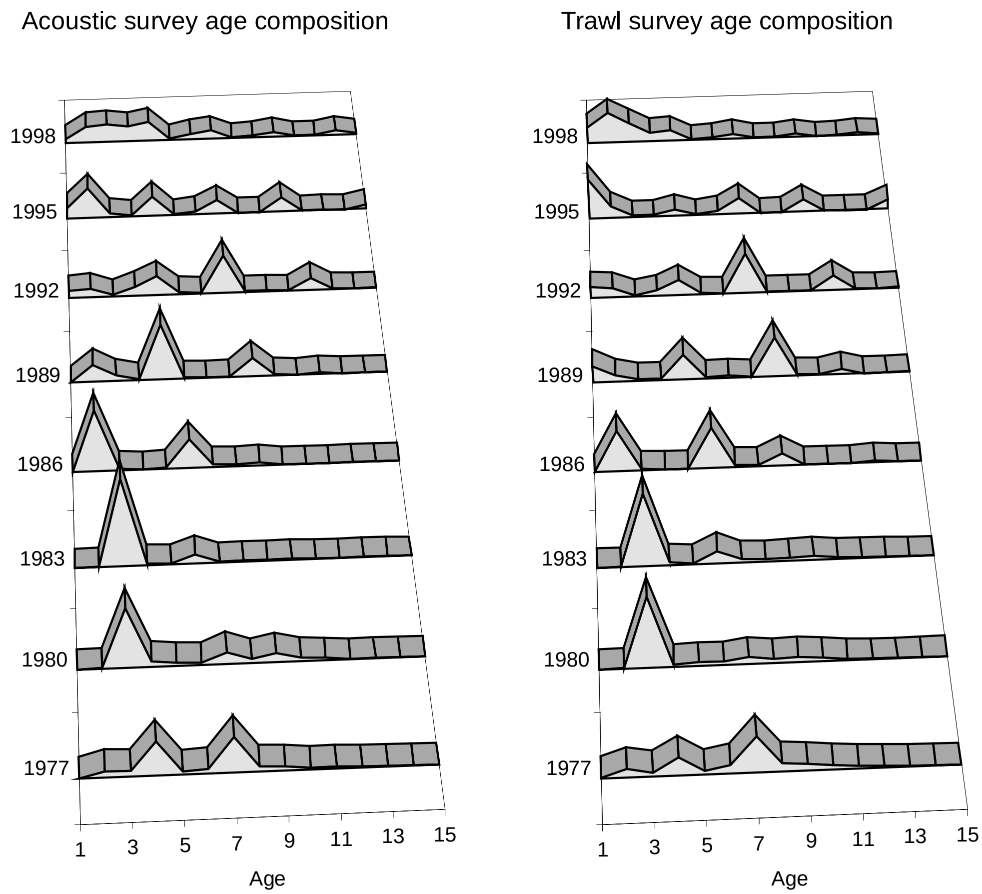



Figure 11. Numbers at age for the AFSC acoustic survey and AFSC shelf trawl survey (1977-98).

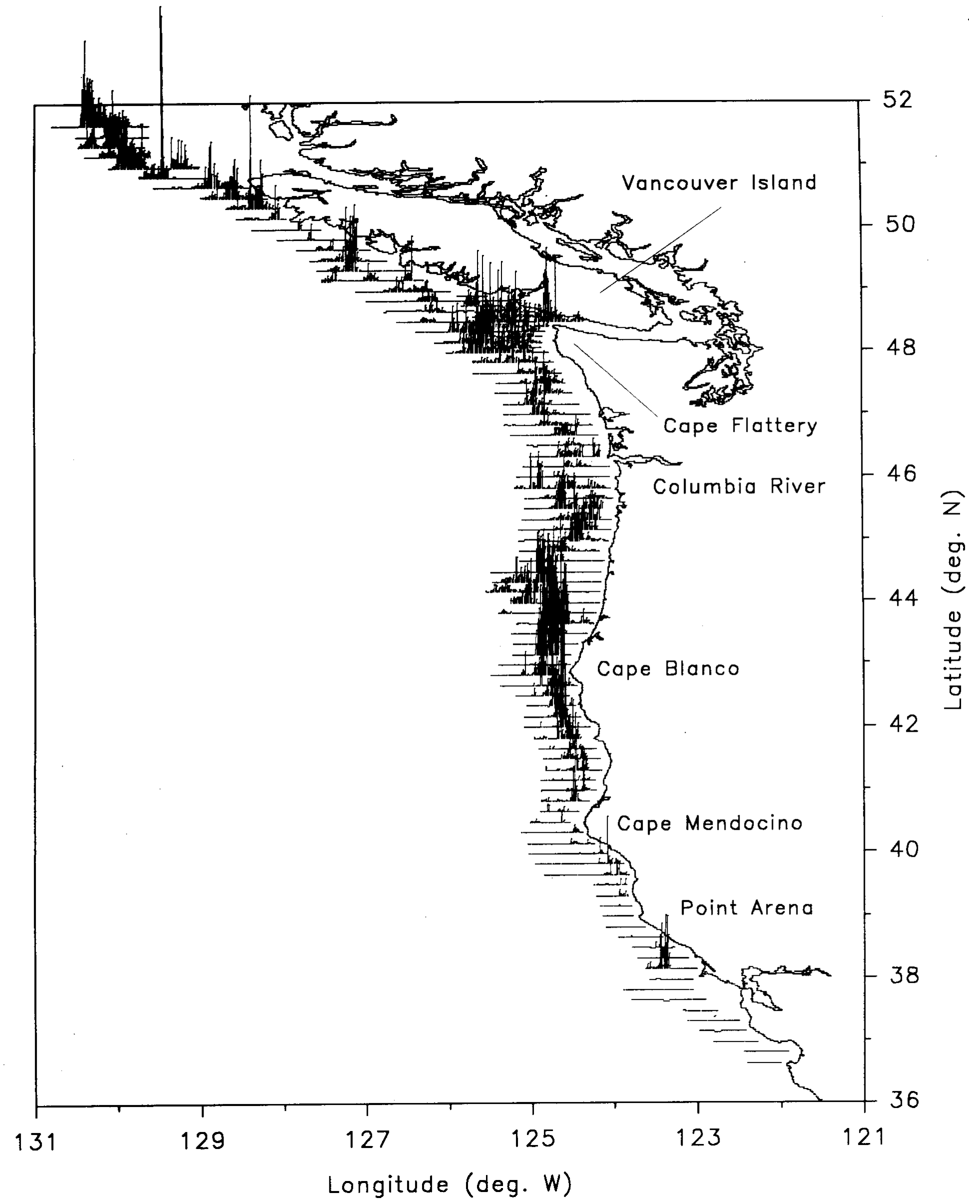



Figure 12. Acoustic backscattering (SA) attributed to Pacific whiting along transects off the U.S. and Canada west coast shelf and slope during the 1998 AFSC echo integration-trawl survey.

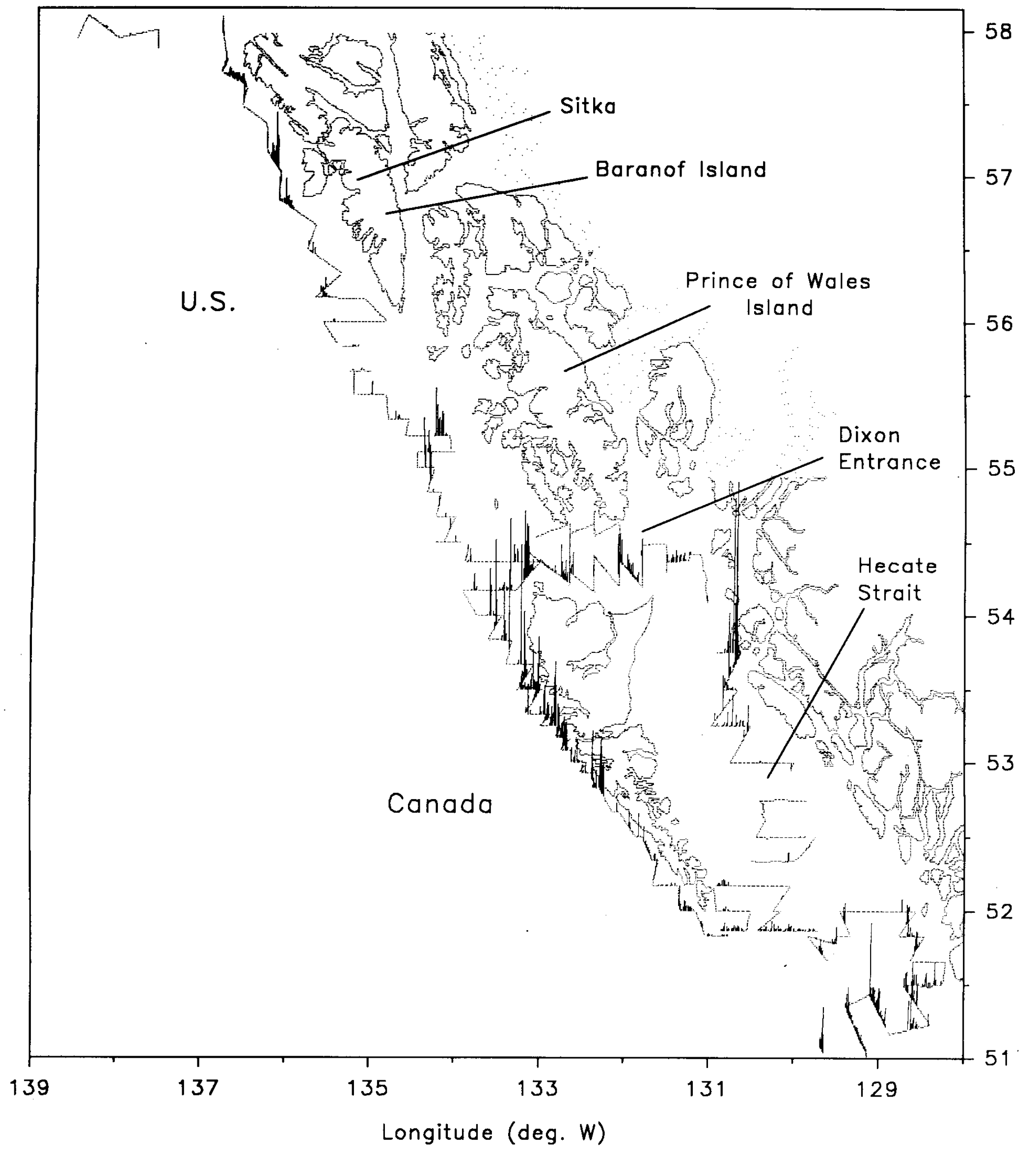



Figure 13. Acoustic backscattering (SA) attributed to Pacific whiting along transects off the U.S. and Canada west coast shelf and slope during the 1998 DFO echo integration-trawl survey.

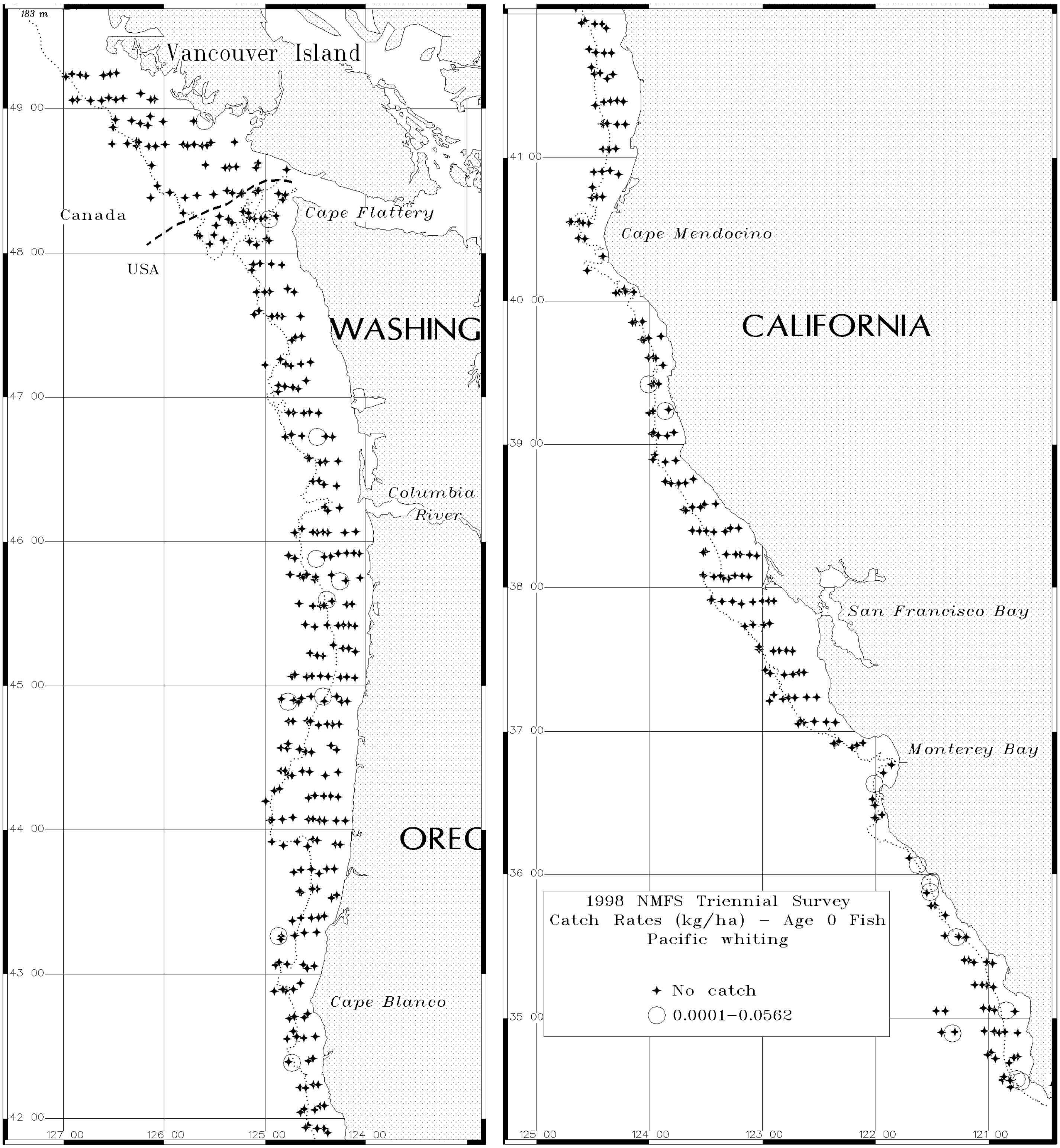



Figure 14. Catch rate (kg/ha) of age-0 Pacific whiting during the AFSC 1998 triennial shelf survey of groundfish resources.

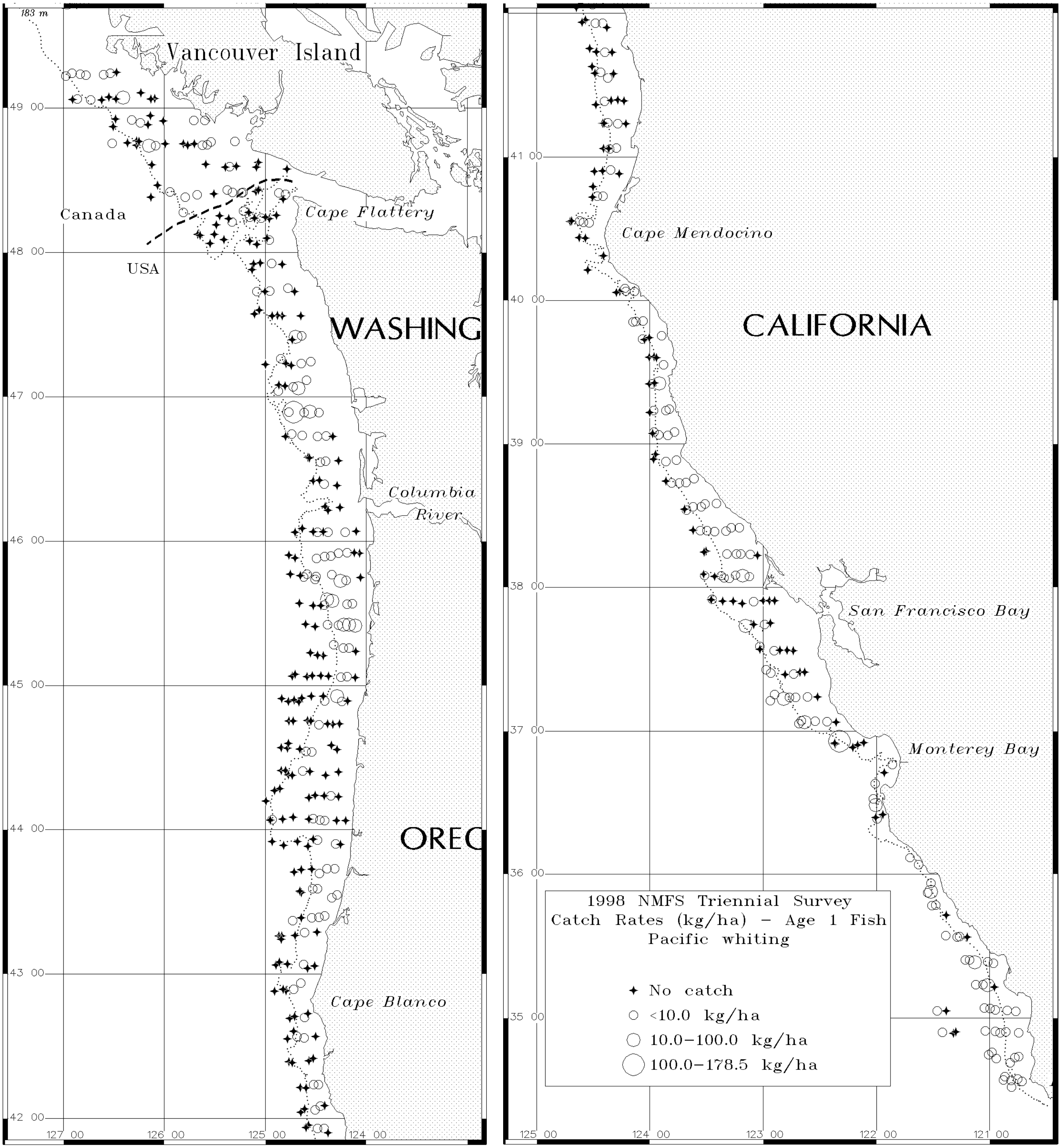



Figure 15. Catch rate (kg/ha) of age-1 Pacific whiting during the AFSC 1998 triennial shelf survey of groundfish resources.

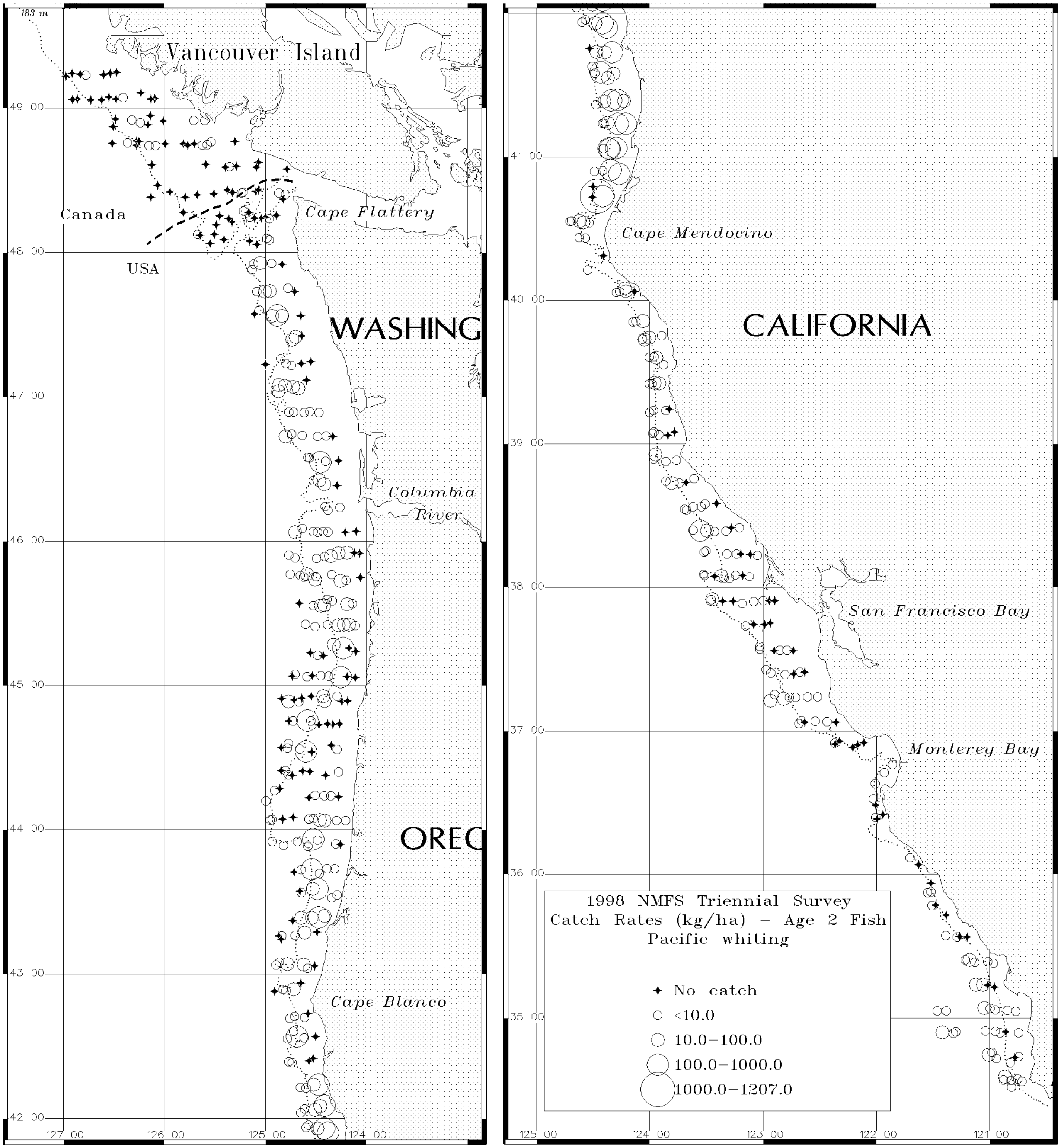



Figure 16. Catch rate (kg/ha) of age-2 Pacific whiting during the AFSC triennial shelf trawl survey of groundfish resources.

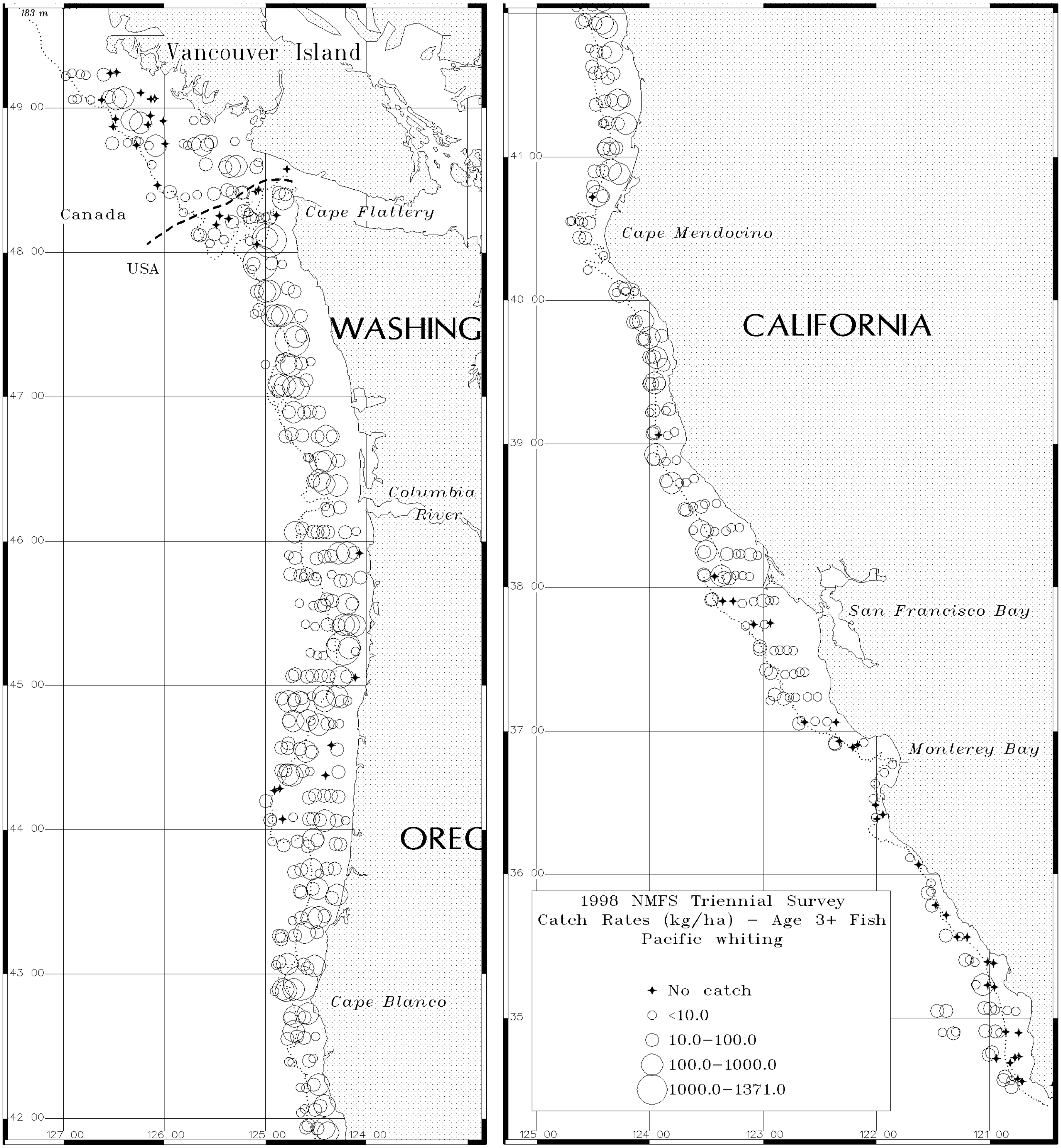



Figure 17. Catch rate (kg/ha) of age-3+ Pacific whiting during the AFSC 1998 triennial shelf trawl survey of groundfish resources.

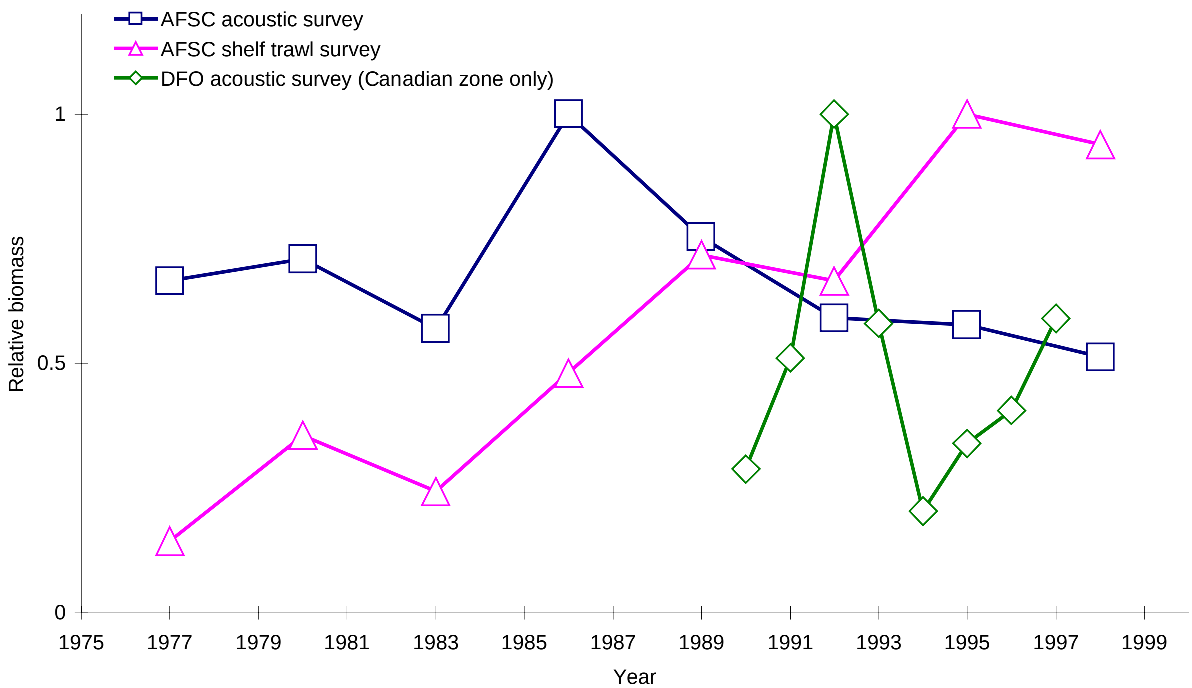



Figure 18. Trends in Pacific whiting biomass in the AFSC acoustic survey (1977-98), AFSC shelf trawl survey (1977-98), and DFO acoustic survey (1990-97).

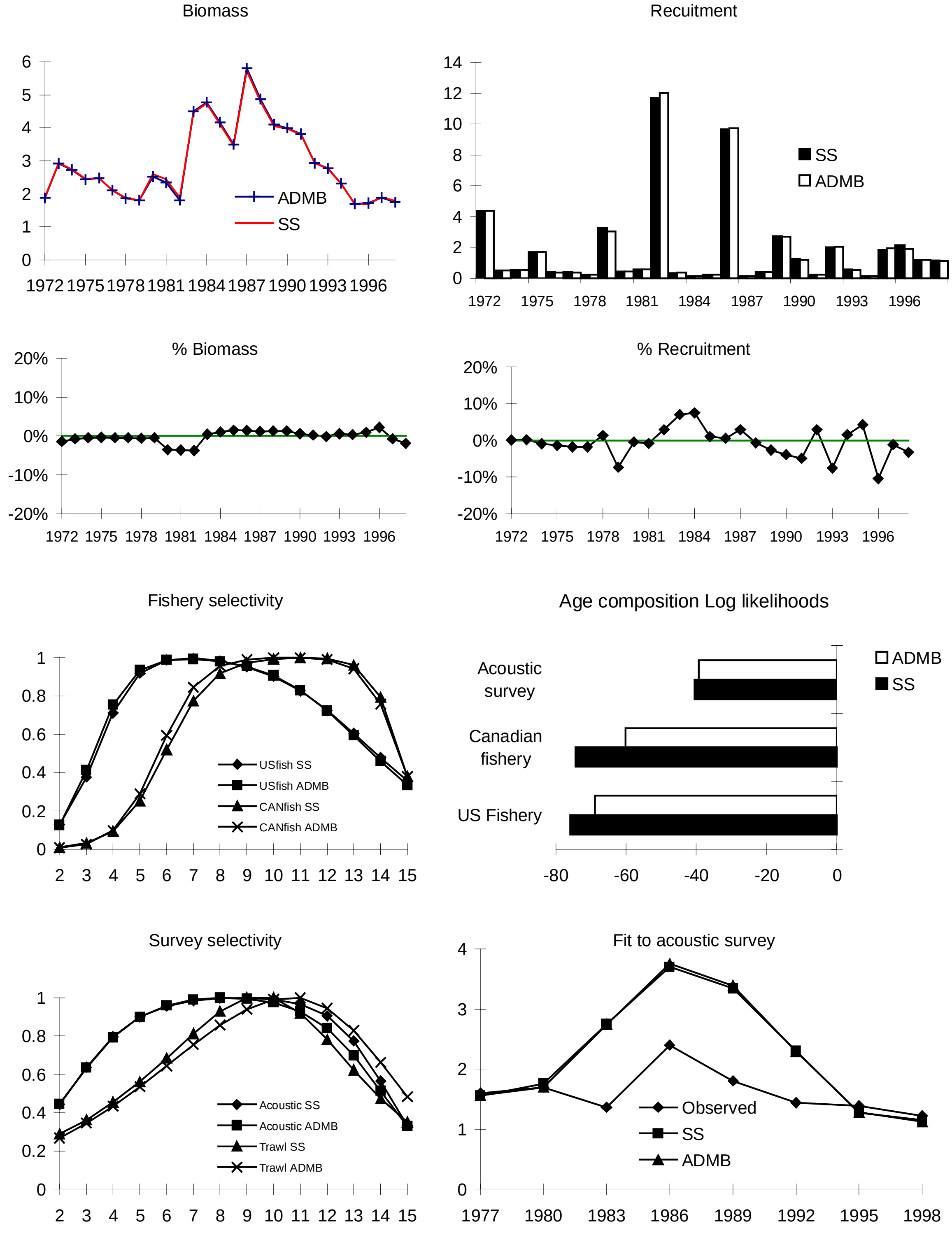



Figure 19. Comparison of model results for stock synthesis and AD model builder

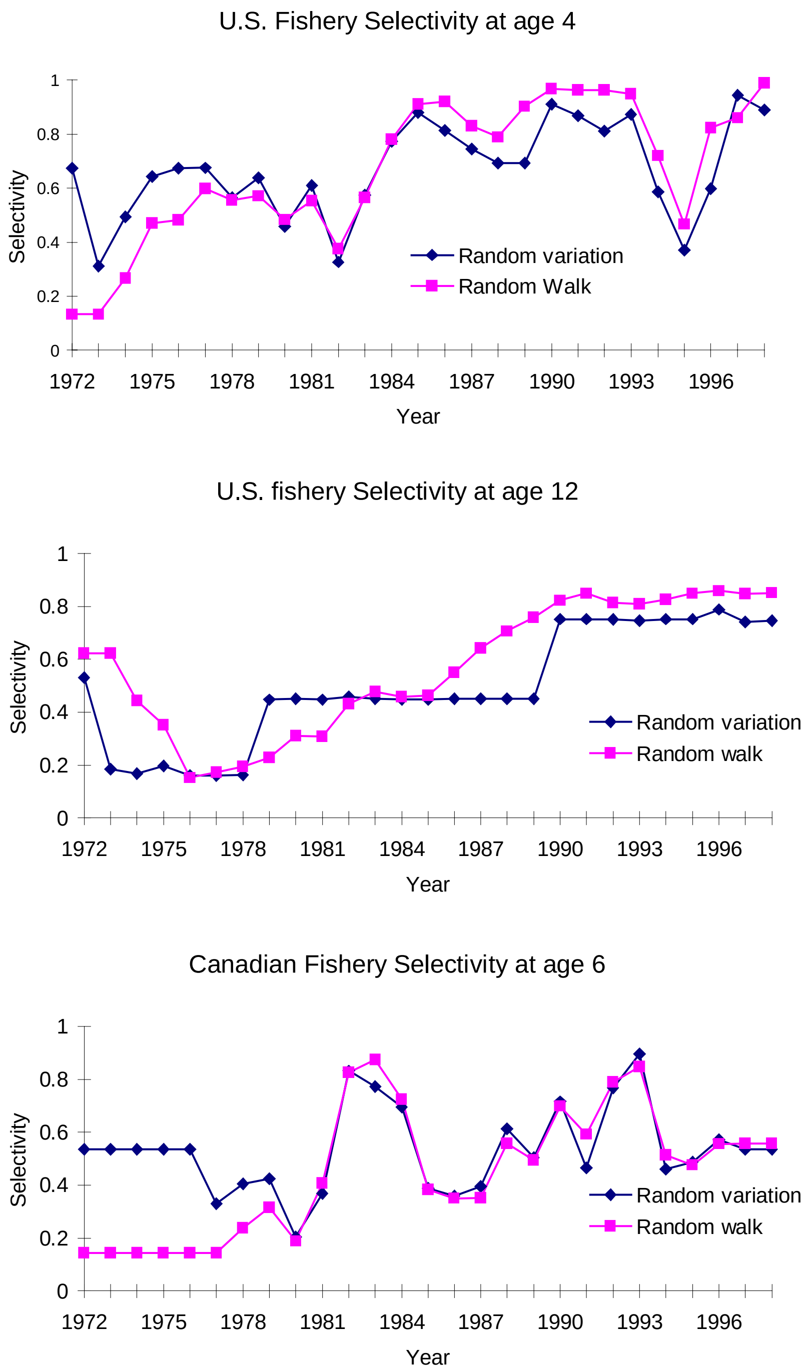



Figure 20. Time-varying selectivity at age 4 in the U.S. fishery (upper panel), selectivity at age 12 in the U.S. fishery (middle panel), and selectivity at age 6 in the Canadian fishery (lower panel). Selectivities are shown for two models: 1) random variation process error (RVPE), 2) random walk process error (RWPE). The RVPE model corresponds to previous models (Dorn and Saunders 1997), where annual variation was assumed only for the selectivity parameters of ascending portion of the double logistic function; for the descending portion, three selectivity stanzas were defined.

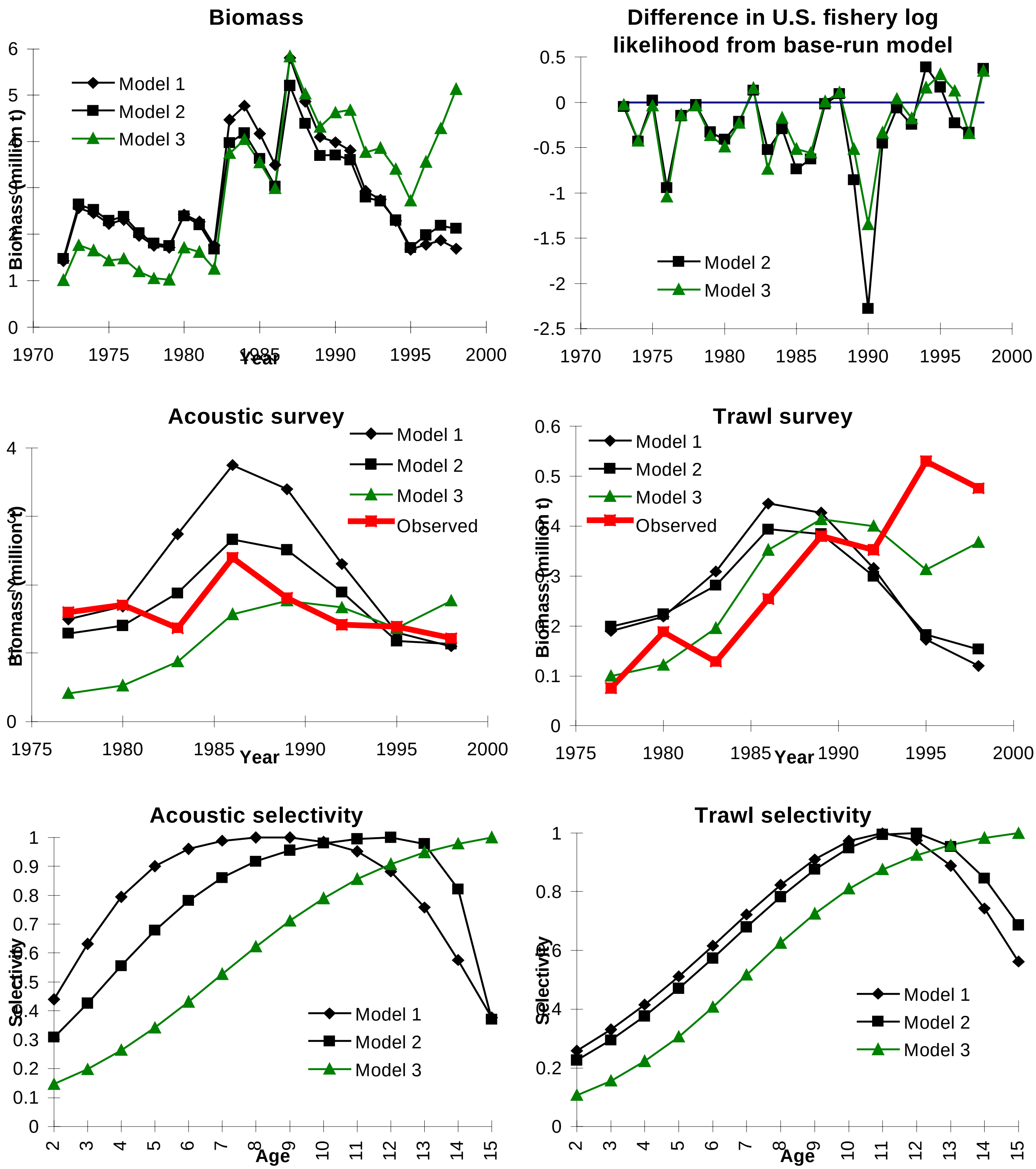



Figure 21. Comparison of results of three models: Model 1, a base-run model with an acoustic survey biomass CV of 0.5 in 1977-89 and a CV = 0.1 in 1992-98; Model 2: the entire acoustic survey time series has an assumed CV = 0.1; Model 3, acoustic survey as in base-run model, but with a CV of 0.1 for the AFSC shelf trawl survey.

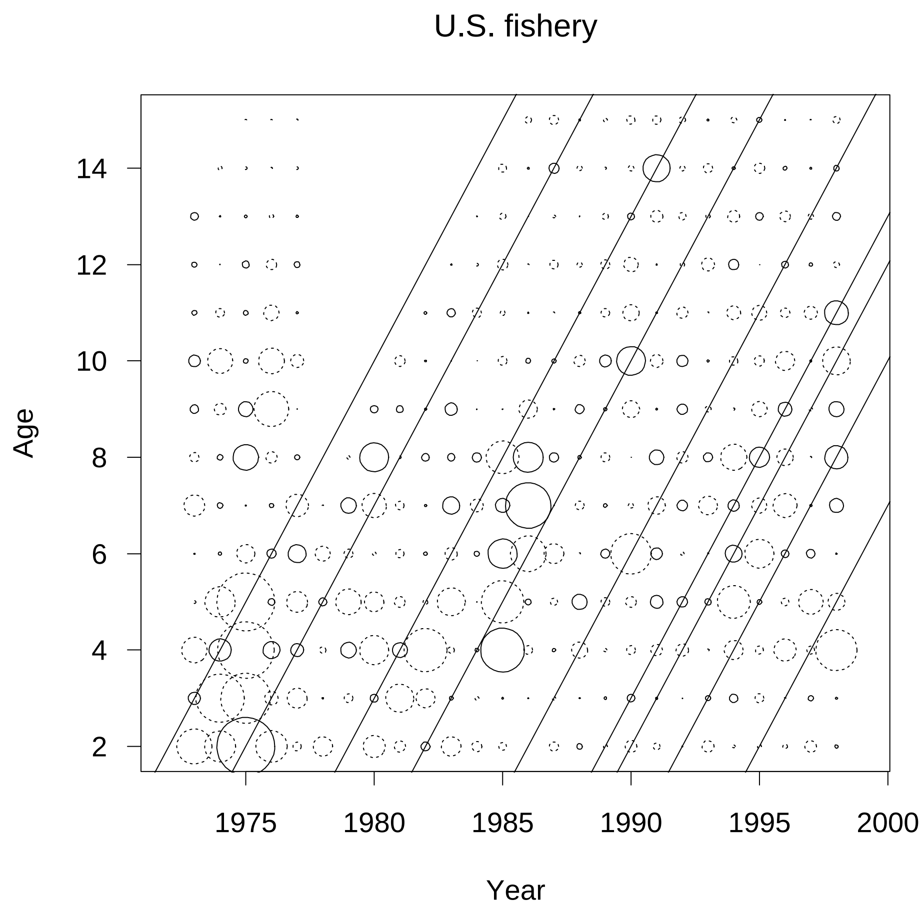



Figure 22. Pearson residuals from base-run model for the U.S. fishery age composition. Circle diameters are proportional to the magnitude of the residual. Circles drawn with dotted lines indicate negative residuals. The largest residual in absolute value is 3.7 for the age-2 fish in 1975. Diagonal lines show the strong year classes (1970, 1973, 1977, 1980, 1984, 1987, 1988, 1990, and 1993).

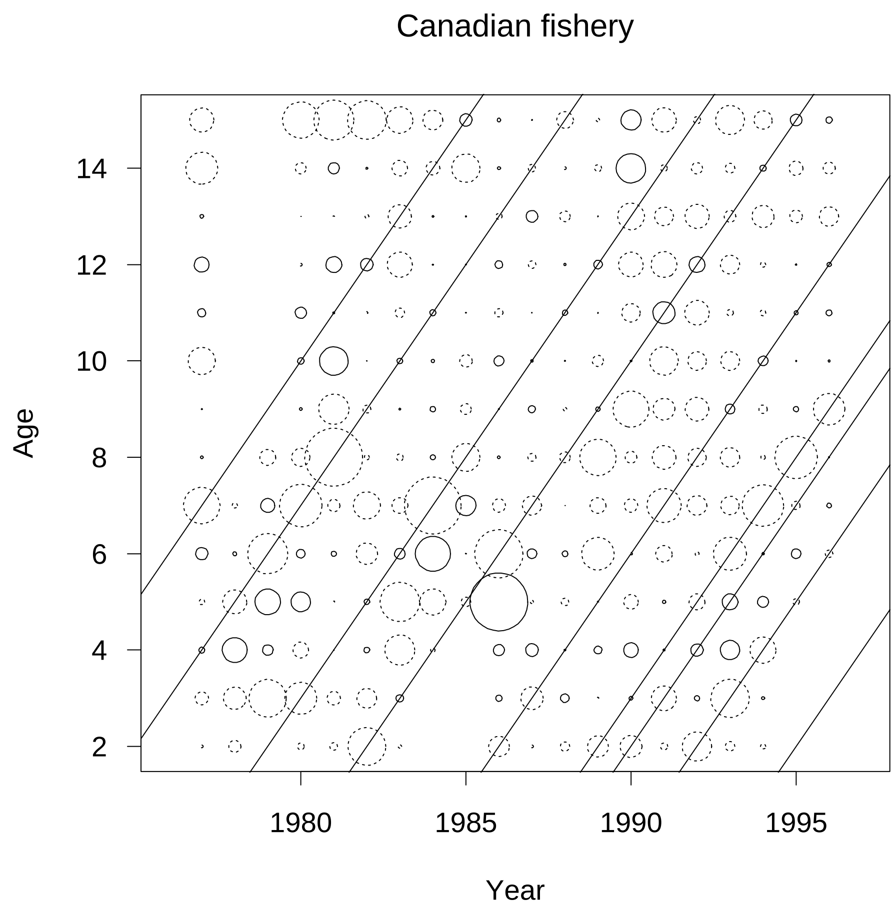



Figure 23. Pearson residuals from base-run model for the Canadian fishery age composition. Circle diameters are proportional to the magnitude of the residual. Circles drawn with dotted lines indicate negative residuals. The largest residual in absolute value is 5.1 for the age-5 fish in 1986. Diagonal lines show the strong year classes (1973, 1977, 1980, 1984, 1987, 1988, 1990, and 1993).

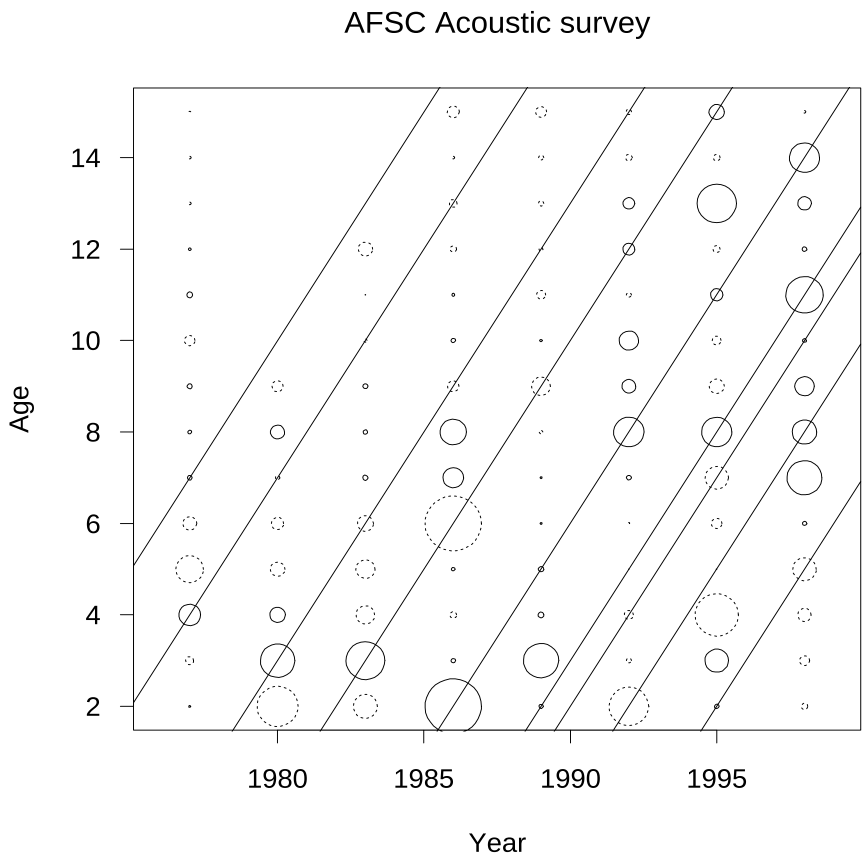



Figure 24. Pearson residuals from base-run model for the AFSC acoustic survey age composition. Circle diameters are proportional to the magnitude of the residual. Circles drawn with dotted lines indicate negative residuals. The largest residual in absolute value is -2.9 for the age-6 fish in 1986. Diagonal lines show the strong year classes (1973, 1977, 1980, 1984, 1987, 1988, 1990, and 1993).

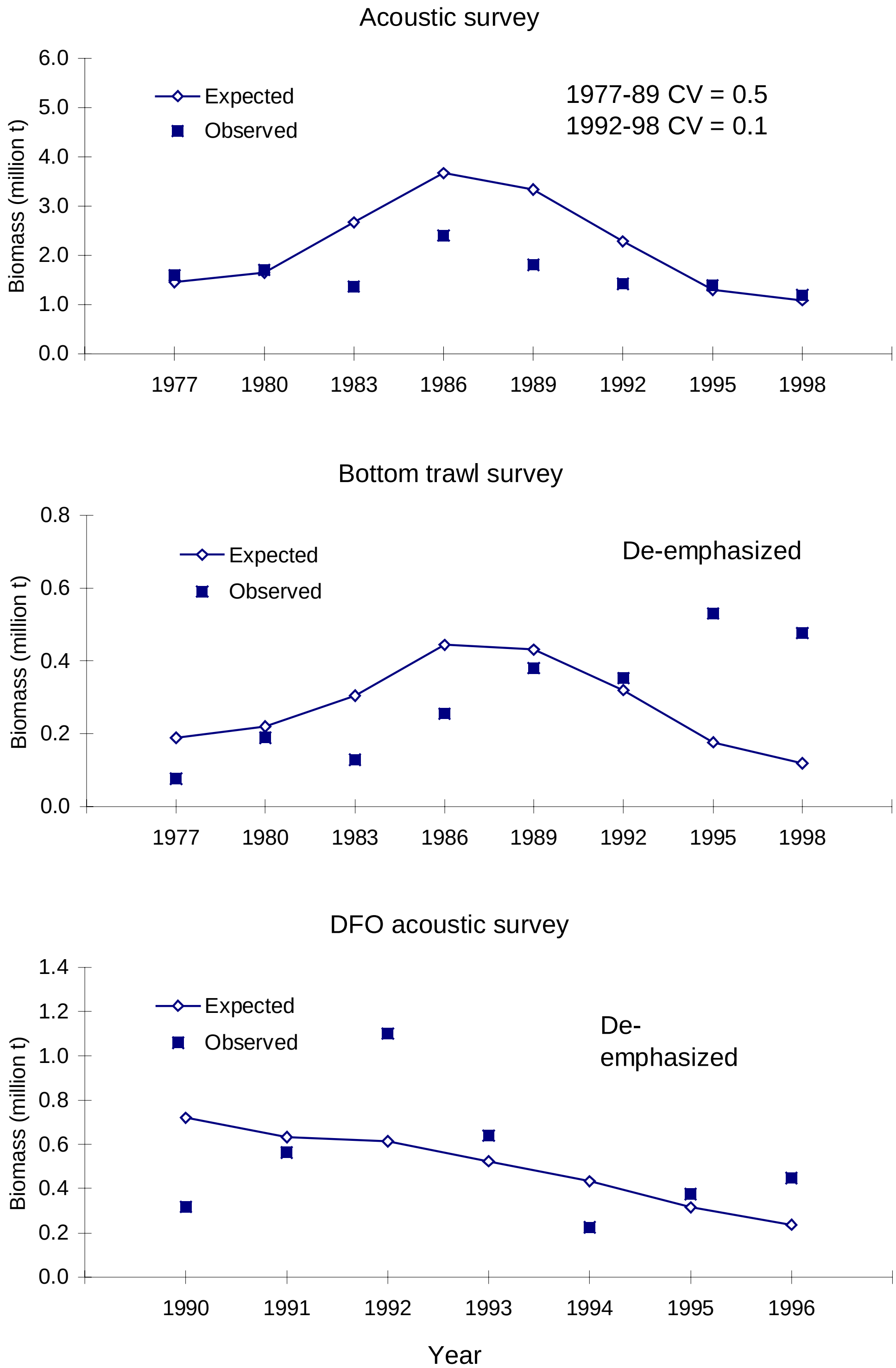



Figure 25. Observed and predicted AFSC acoustic survey biomass (top panel), AFSC shelf trawl survey biomass (middle panel), and DFO acoustic survey biomass (bottom panel) for the base-run model.

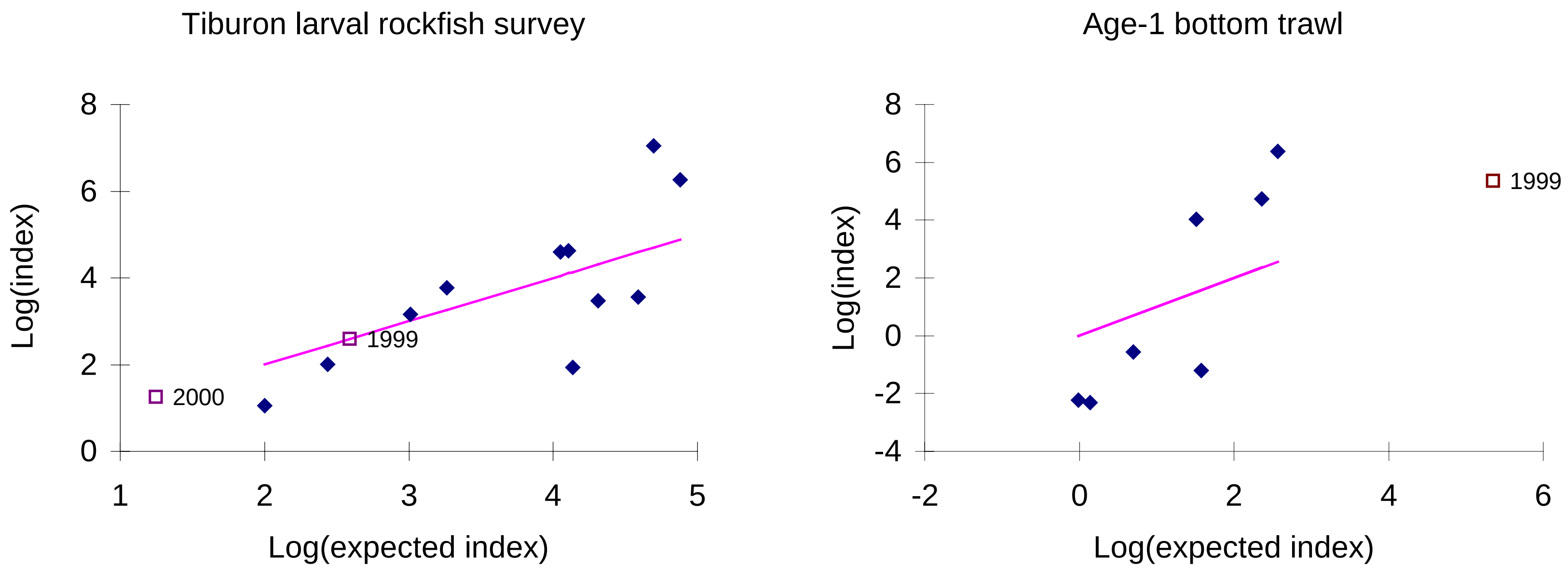



Figure 26. Observed and predicted recruitment indices from the Tiburon larval rockfish survey and an age-1 index from the AFSC shelf trawl survey for the base-run model.

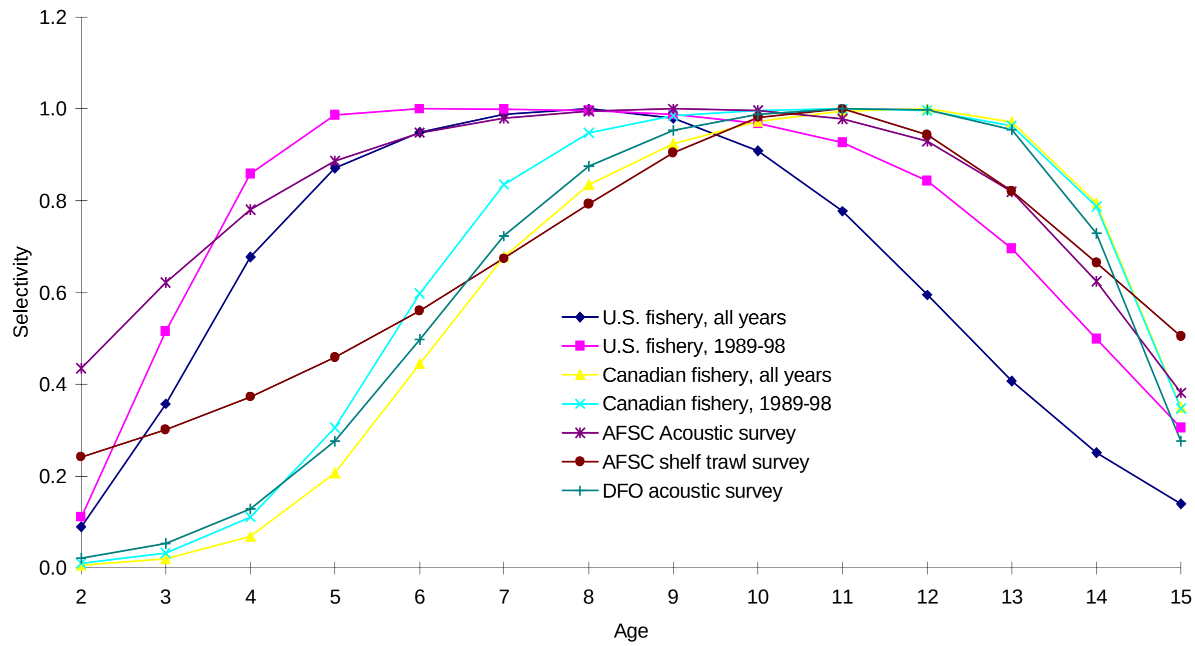
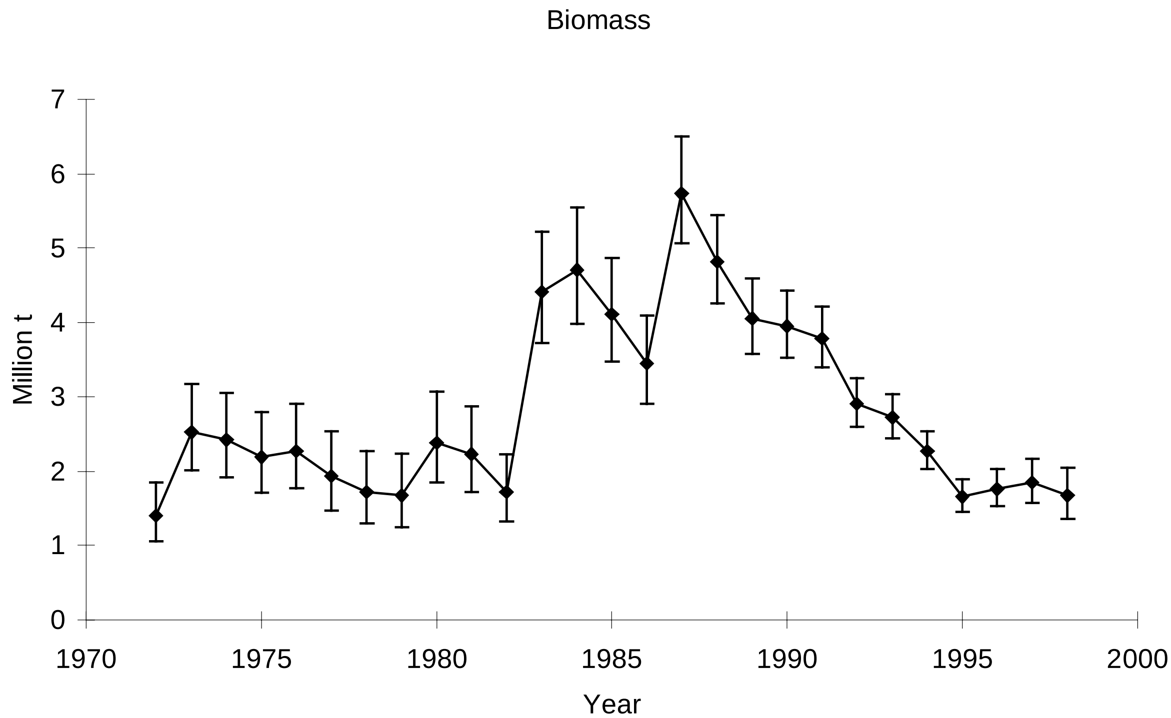



Figure 27. Selectivity at age for the U.S. fishery, Canadian fishery, AFSC trawl and acoustic surveys, and DFO acoustic survey.



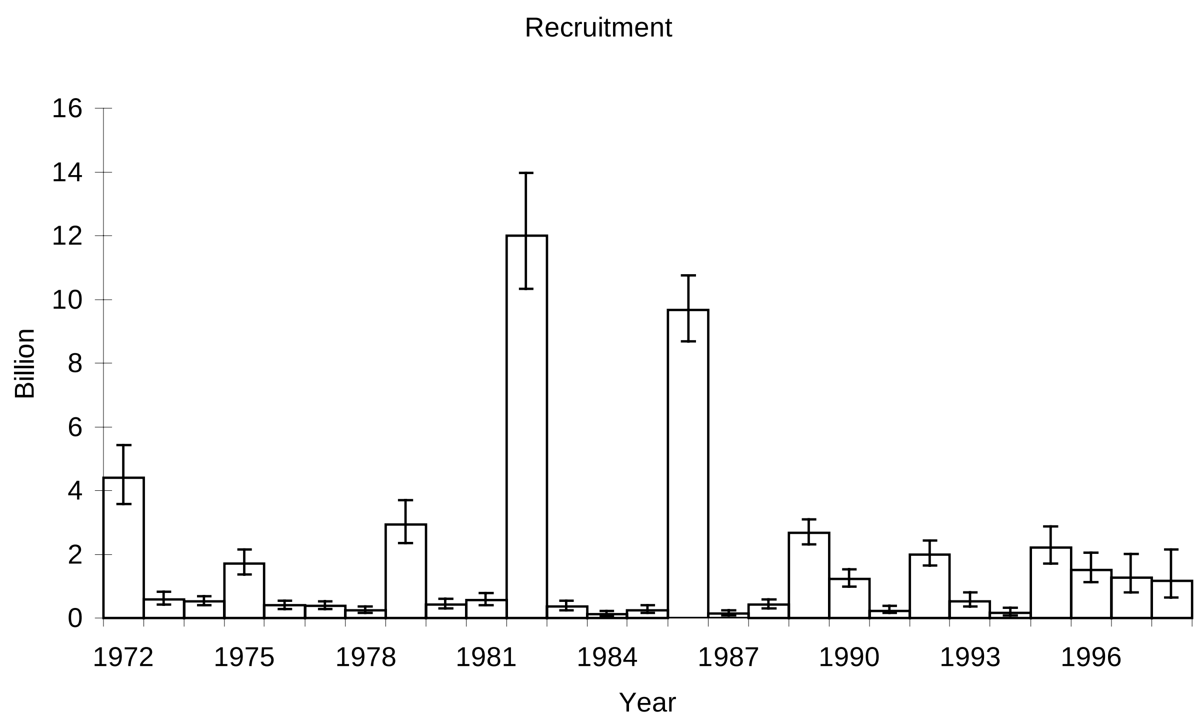




Figure 28. Estimated time series of Pacific whiting age 3+ biomass (million t) and age-2 recruitment (billions of fish) during 1972-98. Vertical bars represent two standard deviations.

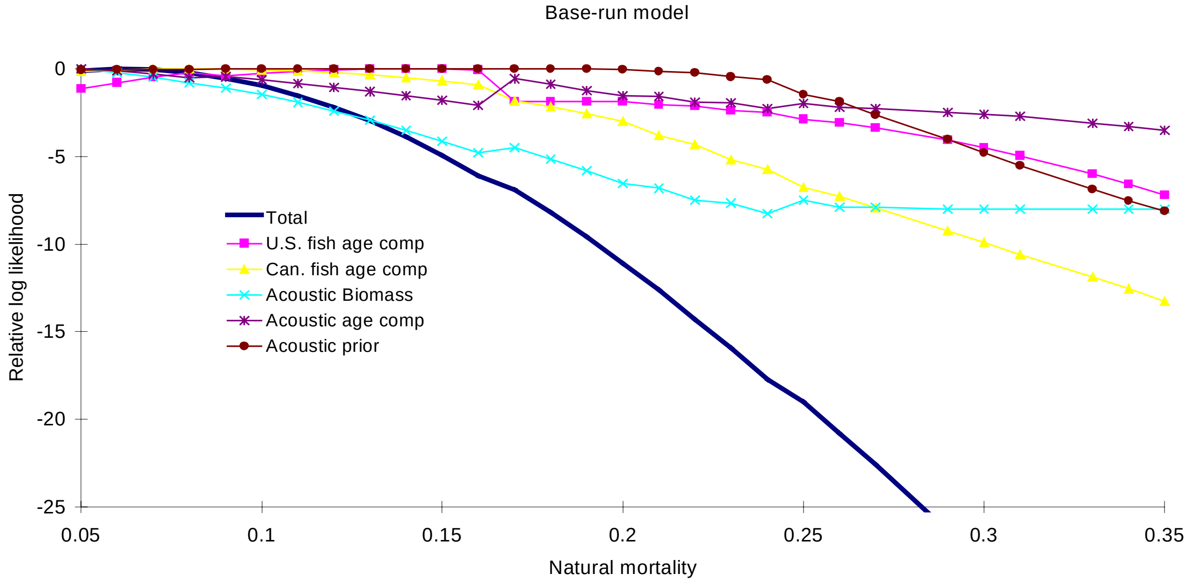
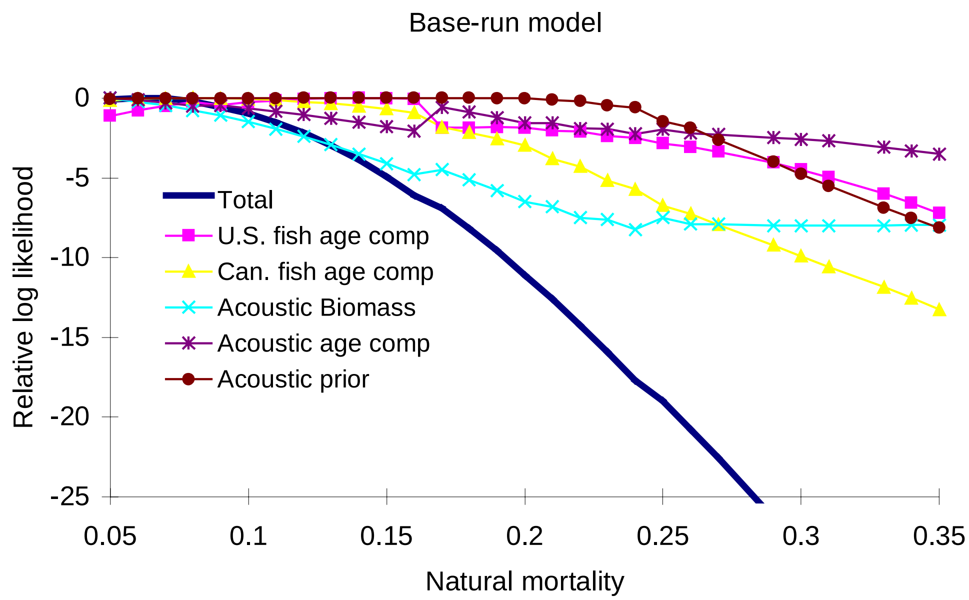



Figure 29. Likelihood profile for AFSC acoustic survey catchability (q).



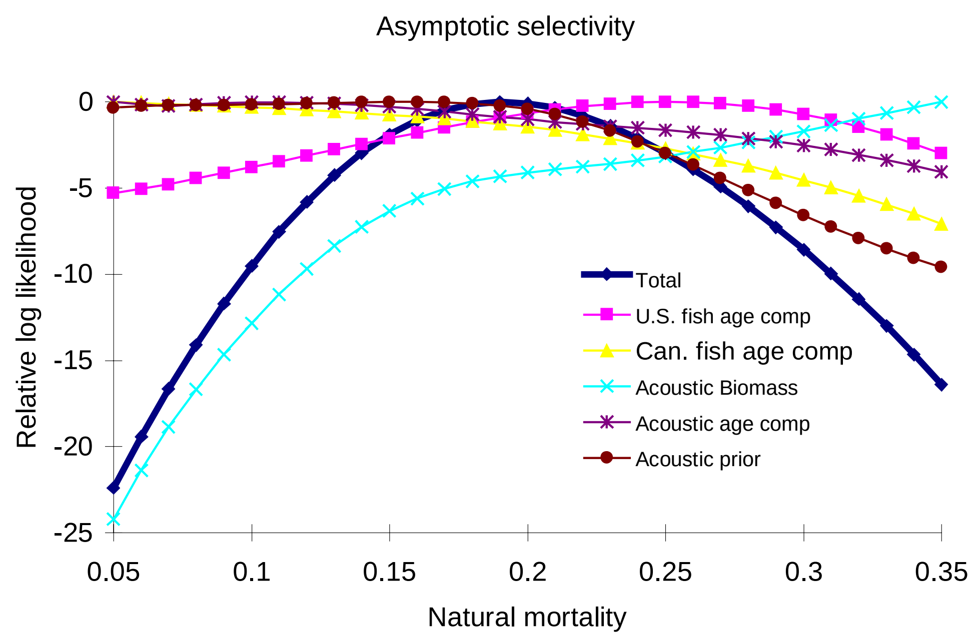




Figure 30. Likelihood profile for natural mortality for the base-run model (upper panel) and a model with asymptotic selectivity for the U.S. and Canadian fisheries and the AFSC acoustic survey (lower panel).

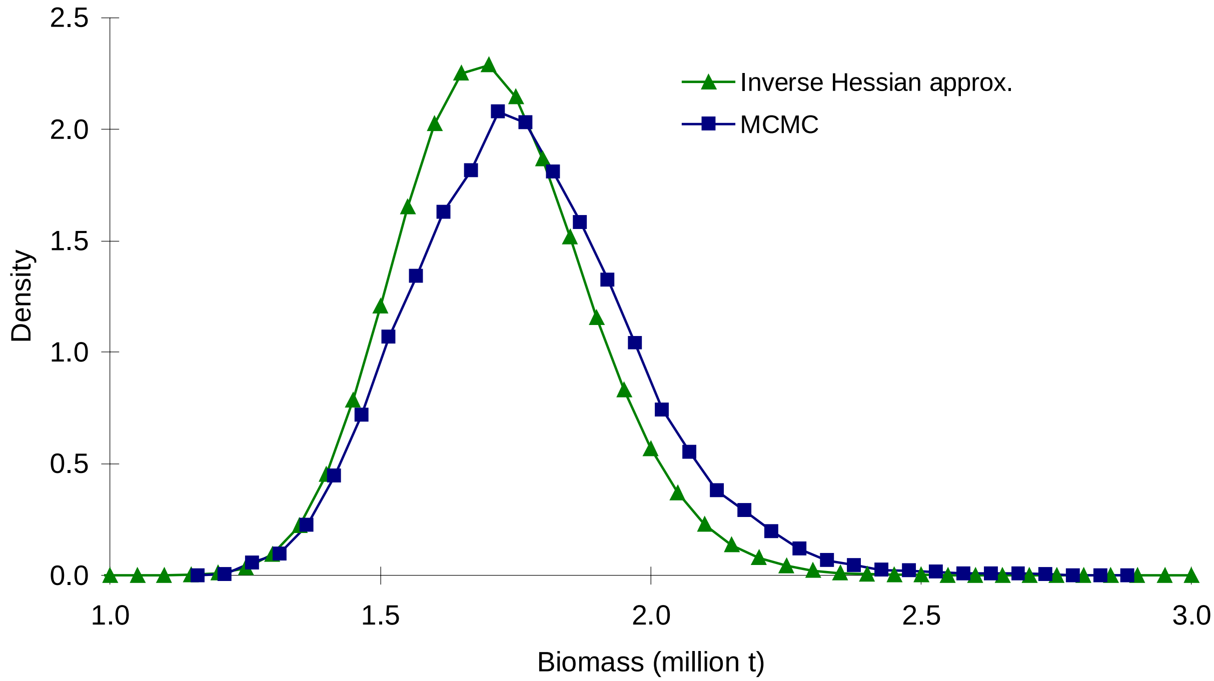
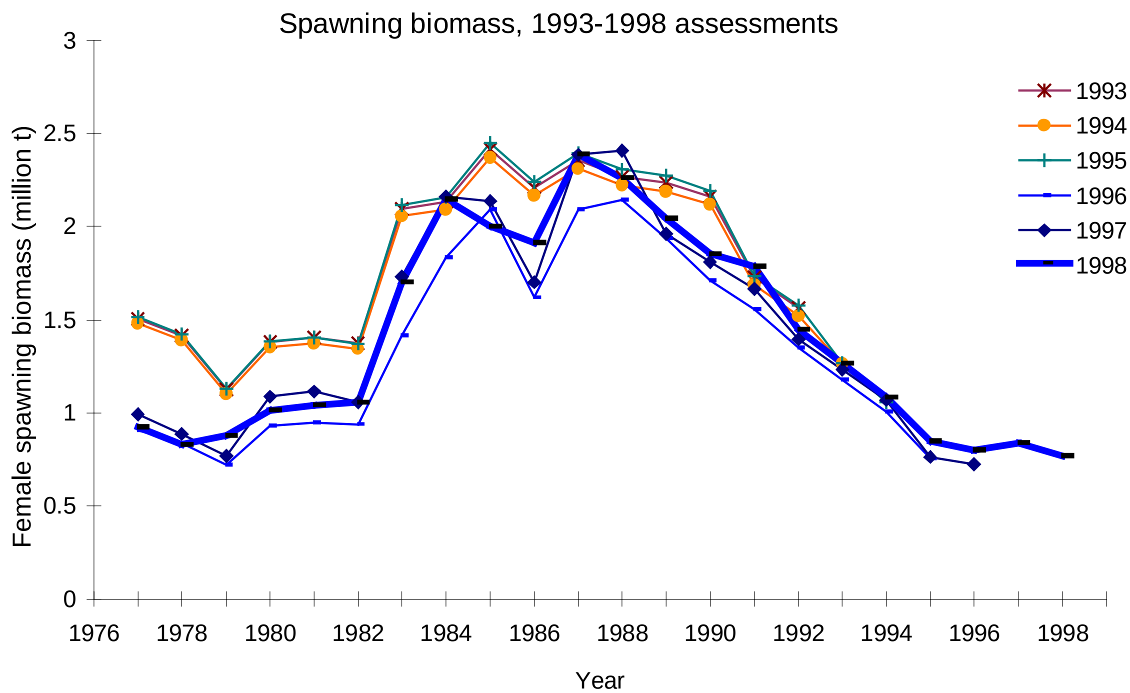



Figure 31. Uncertainty in 1998 age 3+ biomass for the base-run model using an inverse Hessian approximation and a Markov chain Monte Carlo sampling distribution from the likelihood function.



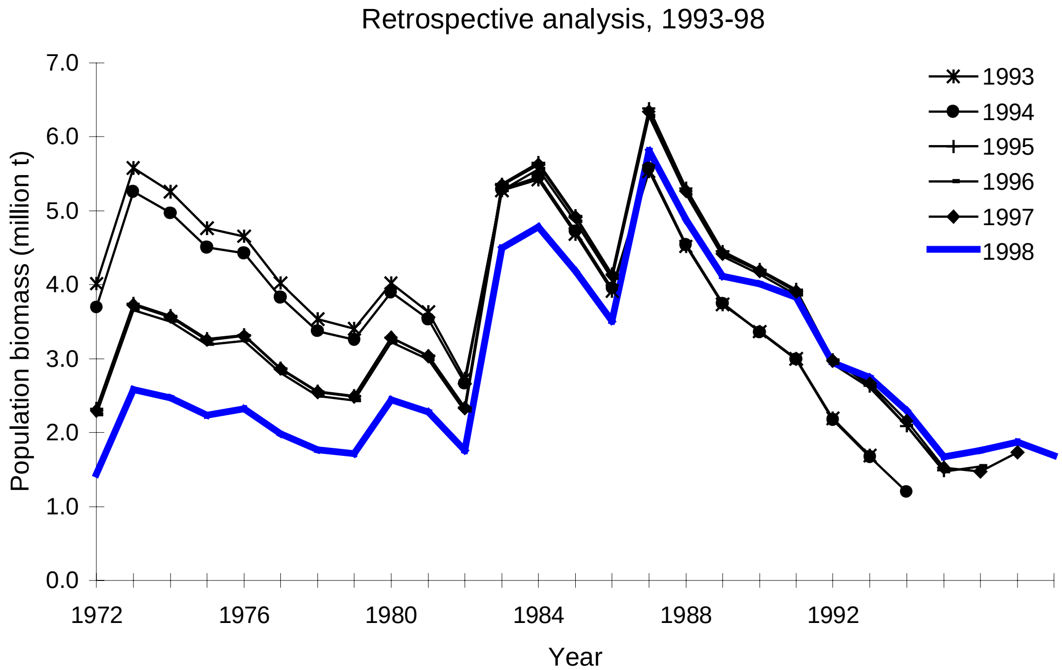




Figure 32. Retrospective plot of the estimated female spawning biomass for stock assessments in the years 1993-98 (upper panel), and times series of biomass estimates for models ending in 1993-98 with current model assumptions.

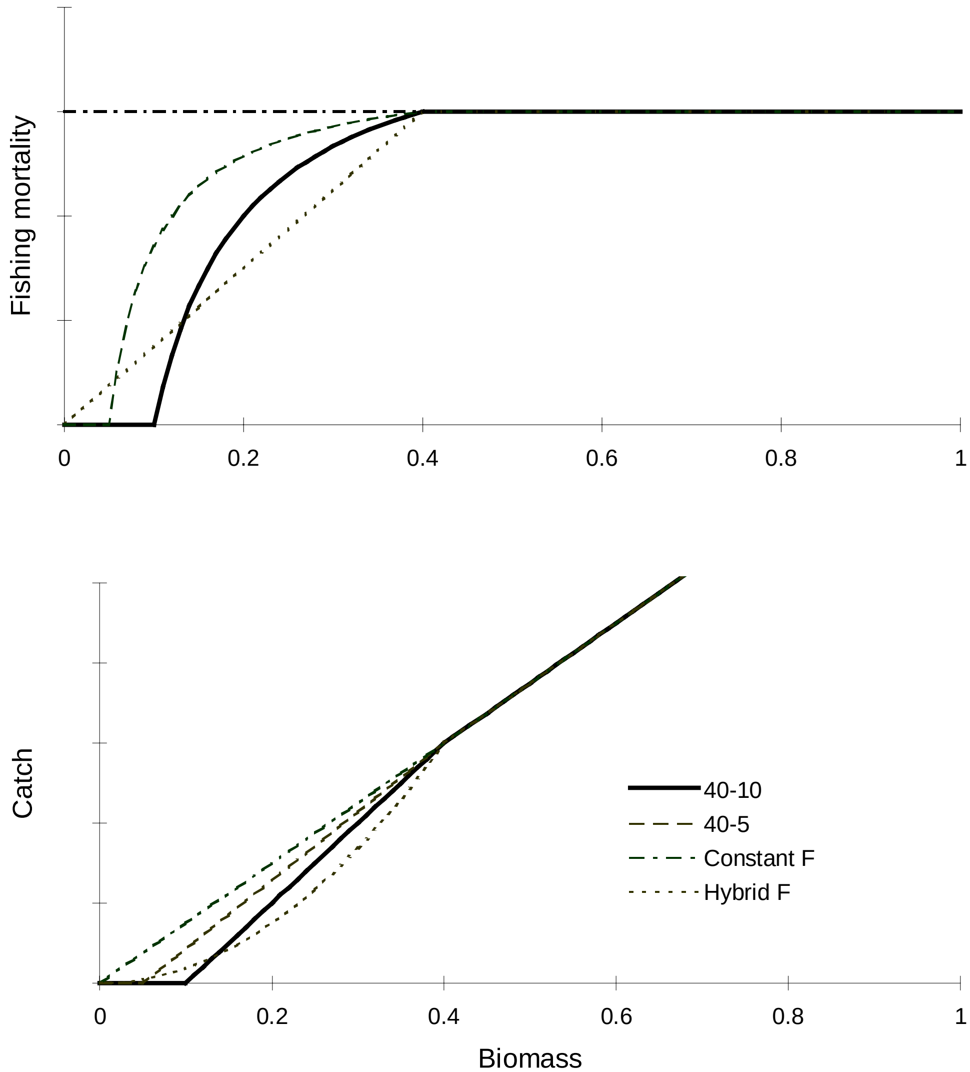



Figure 33. Comparison of hybrid F strategy and 40-10 option, each scaled so that the harvest rate begins declining at B40% for both harest policies.

**Appendix: Advice on Pacific whiting harvest rates from Bayesian meta-analysis of Merluciid stock-recruit relationships**

*Meta-analysis of Merluciid stock-recruit relationships*

The mean relationship between stock and recruitment for Pacific whiting is poorly known. The time series of stock and recruit data is short; there is a lack of contrast in Pacific whiting biomass; and the mean relationship is obscured by a large stochastic component–all common obstacles to the analysis of stock-recruitment relationships. In this appendix, a hierarchic model is developed to synthesize stock-recruit information from other Merluciid stocks compiled by Myers et al. (1995). Merluciids are a globally distributed genus with large populations located at mid-latitudes off the coasts of North and South America, Europe, and Africa (Alheit and Pitcher 1995).

A Beverton-Holt curve for a single stock is

$$R = \frac{a\,S}{b + S} \; ,$$

where $R$ is the recruitment produced by spawning biomass $S$ (or some other proxy of the annual spawning production of the stock). We re-parameterize the Beverton-Holt curve in relation to $R^*$, the expected recruitment at an unfished stock size of $S^*$, and a parameter that measures the resiliency of the stock, *h*, defined as the proportion of $R^*$ when the spawning stock is 20% the unfished stock size (i.e. the "steepness" parameter of Mace and Doonan (1988)),

$$hR^* = \frac{a\,(0.2\,S^*)}{b + 0.2\,S^*} \; .$$

For a steepness of 0.2, recruits are a linear function of spawners. For a steepness of 1.0, recruitment is independent of spawning biomass. The Beverton-Holt curve with parameters $R^*$, $S^*$ and *h* is

$$R = \frac{0.8\,h\,R^*S}{0.2\,(S^* - S) + h\,(S - 0.2\,S^*)} \; .$$

The problem of jointly estimating the stock-recruitment parameters for a taxon can be addressed by modeling the relationships (if any) between the $R^*$, $S^*$ and $h$ for the individual stocks using hierarchical priors–that is, by using probability distributions to describe the mean and variability of those parameters within the taxon. The parameters $R^*$ and $S^*$ are associated with the physical dimensions of the habitat occupied by the stock and the carrying capacity of that habitat. Since these are controlled by geography and oceanographic processes, the parameters $R^*$ and $S^*$ will be unrelated between stocks except to the extent that the habitats they occupy are alike.

The similarity of stocks within a taxon in their response to harvesting was modeled by assuming the logit of $h_k$ was normally distributed (after rescaling $h_k$ into the interval (0,1) ),

$$\beta_k = \log\left( \frac{h_k - 0.2}{1 - h_k} \right) \quad , \quad \beta_k \sim N(\mu,\tau^2) \ .$$

For $h_k$ in the interval (0.2,1.0), the logit $\beta_k$ ranges from $-\infty$ to $+\infty$.

A Bayesian hierarchic model consists of describing the joint posterior distribution of the parameters as a product of 1) the likelihood (the probability of the data given the parameters), 2) the prior (the probability distribution of the parameters), 3) and the hyperprior (the probability distribution of the parameters in the prior) (Gelman et al. 1995).

Likelihood–The usual assumption in stock-recruit models is that variability around the curve is log-normal, that is,

$$\log[R_{ik}] - \log[\hat{R}_{ik}(S,R^*{}_k,S^*{}_k,\beta_k)] \sim N(0,\sigma_k^2) \ ,$$

giving a negative log likelihood of

$$-\log \ L_1 = \sum_{k=1}^{K} \ \sum_i \frac{\left(\log[R_{ik}] - \log[\hat{R}_{ik}(S,R^*{}_k,S^*{}_k,\beta_k)]\right)^2}{2\sigma_k^2} + n_k \ \log \ \sigma_k \ .$$

Estimation after log transformation can result in parameters that are biased on the original scale. Because of the way that terms enter the re-parameterized Beverton-Holt curve, the bias correction term, $\exp(\sigma_k^2/2)$, affects only $R^*$, and not $h_k$. This is an important feature, because our goal is to model the relationship between the shape of the *expected* stock recruit curves, which will not be distorted by log transformation under this parameterization even if there are differences in recruitment variability between stocks.

Prior–The hierarchical structure was developed only for the "steepness" parameters, $h_k$. For $R^*$ and $\sigma_k$ locally uniform priors on a log scale were used. For $S^*$, the unfished stock size, an prior estimate was obtained by multiplying mean recruitment for spawning biomass greater than median by the lifetime spawning biomass per recruit without fishing, $\varphi_{F=0} = \sum w_a \pi_a \exp(-Ma)$, where $w_a$ is the weight at age $a$, $\pi_a$ is the proportion mature, and $M$ is the natural mortality rate. The deviations from this prior estimate were assumed log-normal, with CV = 0.4. Similar results are obtained for CVs in the range 0.1 to 0.7, indicating that this is not particularly critical assumption.

The negative log likelihood for the prior is proportional to

$$-\log L_2 = \frac{\sum (\beta_k - \mu)^2}{2\tau^2} + K\,\tau + \frac{\sum [\log(S^*_k) - \log(\hat{S}^*_k)]^2}{2(0.4)^2} .$$

This expression includes both the prior for $h_k$, which is our main interest, and log normal likelihood for $S^*$.

Hyperprior–The hyperprior specifies the probability distributions for $\mu$ and $\tau^2$. When possible, uninformative hyperpriors should be used to let the posterior distribution of $\mu$ and $\tau^2$ reflect the information about these parameters contained in data. For $\mu$, we use a locally uniform prior to reflect our lack of knowledge about this parameter. Obtaining a suitable prior for $\tau^2$, however, was difficult. A common uninformative prior for a scale parameter is to assume that it is uniform on a log scale, i.e. $\log(\tau) \propto 1$. In a hierarchical model, however, this assumption produces an improper posterior (Gelman et al. 1995). For the model developed here, other possibilities, such as assuming $\tau \propto 1$, also produced an improper posterior distributions. To circumvent this difficulty, we assumed that the prior for $\tau^2$ followed an inverse scaled Chi-square distribution, the conjugate prior for a normal distribution scale parameter, and evaluated the sensitivity of the results to different assumptions about this prior distribution. The negative log likelihood for an inverse scaled Chi-square distribution is proportional to

$$-\log L_3 = (\nu/2+1)\,\log\tau^2 + \frac{\nu s^2}{2\,\tau^2} ,$$

with parameters $\nu$ and $s^2$. This prior distribution can be regarded as providing the same information about $\tau^2$ as $\nu$ prior observations with a variance of $s^2$ (Gelman et al. 1995).

The log joint posterior distribution is the sum of the log likelihood, the prior log likelihood, and the hyperprior log likelihood,

$$L = \log L_1 + \log L_2 + \log L_3 \ .$$

*Decision-theoretic estimates of $F_{MSY}$ for Pacific whiting*

To estimate $F_{MSY}$ for a stock of interest, we seek the marginal posterior distribution of the stock recruit parameters for that stock, which is obtained by integrating joint posterior distribution with respect to the other parameters. Rather than evaluating this integral analytically, we used the Markov Chain Monte Carlo (MCMC) routine in AD model builder (Fournier 1996) to obtain random samples from the joint distribution. From these samples it is an easy matter to obtain empirical histograms which approximate the marginal distribution of any parameter of interest. MCMC algorithm simulates a Markov chain of random samples (i.e., each sample is conditionally dependent on the preceding sample) whose stationary distribution is the joint posterior distribution. The basic steps in the algorithm are: 1) draw an initial sample from an approximation of the posterior distribution (AD model builder uses a multivariate normal based on the Hessian at the posterior mode); 2) generate a candidate for the next sample using a random jumping distribution from the current sample; 3) calculate the importance ratio, *r*, from the value of the joint posterior distribution at the current sample and the candidate sample; 4) if *r* is greater than one, accept the sample; 4) if *r* is less than one, accept or reject the candidate sample with probability *r*. 5) begin the next cycle at step 2. Gelman (1995) provides a good introduction to MCMC methods, and documentation of Hastings-Metropolis algorithm as implemented in AD model builder is at *http://otter-rsch.com/cc/cctoc.html*.

Let $h_{(C)}$, $R^*_{(C)}$, and $S^*_{(C)}$ and $\sigma^2_{(C)}$ be a sample of the stock recruit parameters for Pacific whiting ($k=1$) from the joint posterior distribution generated by MCMC algorithm. For each sample, we calculate the equilibrium recruitment $R^{EQ}(F)_{(C)}$ for fishing mortalities $F$ in the range (0,1.0),

$$R^{EQ}(F)_{(C)} = \max\left(0,\ \frac{0.8 h_{(C)} R^*_{(C)} \varphi_F e^{\sigma^2_{(C)}/2} + 0.2 S^*_{(C)} (h_{(C)} - 1)}{\varphi_F (h_{(C)} - 0.2)}\right) \ .$$

where $\varphi_F$ is spawning biomass per recruit at fishing mortality *F*. Some combinations of fishing mortality and sampled stock recruit parameters result in a negative equilibrium recruitment, i.e. the fishing mortality rate is not sustainable--hence the use of the *max* function in the above equation.

To obtain the equilibrium yield, $Y^{EQ}(F)$, associated with $R^{EQ}(F)$, we use a standard age-structured exponential mortality model for a single cohort, and calculate yield with the Baranov catch equations. We explore risk aversion by defining a loss function, the negative of which measures the societal benefits of the yield from the fishery, i.e. the “utility”. From decision theoretic perspective, $F_{MSY}$ can be regarded as the fishing mortality rate which minimizes risk, where risk is defined as the expected loss. Thompson (1996) proposed a general loss function for fishery yield as

$$l(Y) = \frac{1 - Y^{\lambda}}{\lambda} ,$$

where $\lambda$ is used to control the degree of risk aversion. Linear loss is obtained when $\lambda=1$, while the logarithmic loss is obtained in the limit as $\lambda$ approaches zero. A linear loss function implies a risk- neutral approach, such that the expected yield is maximized, while any value of $\lambda < 1$ implies risk aversion. Although logarithmic loss is often used as a default risk-averse approach, using it in this problem would exclude any $F$ with a non-zero probability of zero yield, implying extreme risk aversion. Instead, we use $\lambda = ½$ as an example of a risk-averse approach, which corresponds to maximizing the expected square root of yield.

A decision-theoretic estimate of $F_{MSY}$ is

$$F_{MSY} = \min_{F} E\,[\,l(Y^{EQ}(F))\,]$$

The expected loss at a particular fishing mortality is obtained by averaging the loss associated with the equilibrium yield for each of the MCMC samples drawn from the joint posterior distribution. Of course, we will be interested in the relationship of fishing mortality to risk, and yield, as well as the point estimate..

*Results*

The Myers et al. (1995) database contains thirteen Merluciid stocks (including Pacific whiting). For many of the Merluciid stocks, only a relatively short time series of stock-recruit data is available (Appendix table 1). The data are most extensive for two stocks of Silver Hake (*Merluccius bilinearis*) in New England, which have probably been reduced to less than 5% of their estimated unfished abundance. The coastal Pacific whiting stock has the second largest unfished stock size, following the Argentinean Hake. Recruitment variability (as measured by the standard deviation of log(R/S)) is considerably higher for Pacific whiting than other Merluciids.

Preliminary models indicated that the posterior mode of $\tau^2$ was always lower than the prior mode, suggesting that the data most strongly supported a model with no variability in “steepness” between stocks. This may partly be because the data are not very informative about differences in $h_k$. We looked at four models with differing assumptions about the hyperprior for $\tau^2$: 1) no relationship between stocks (each $h_k$ estimated independently); 2) weak relationship between stocks (inverse Chi-square hyperprior with $\nu = 200$ and $s^2 = 1.0$, implying a standard deviation of 0.2 for $h_k$); 3) strong relationship between stocks (inverse Chi-square hyperprior with $\nu = 200$ and $s^2 = 0.25$, implying a standard deviation of 0.1 for $h_k$), and 4) no difference in $h_k$ between stocks. Setting $\nu = 200$ for the inverse Chi-square hyperprior effectively constrains the posterior estimate of $\tau^2$ to its prior value.

Appendix figures 1-2 show stock-recruit data for each stock and the estimated stock-recruit relationships for independent stock-recruit relationship model (model 1), and hierarchical model with a weak relationship between stocks (model 2). For the independent model, a steepness of 1.0 is estimated for four of the 13 stocks , implying that recruitment is unrelated to stock size. Moreover, steepness of 0.2 is estimated for two of the stocks, implying that there is no compensation in the stock-recruit relationship. For the hierarchical model, a plausible stock-recruit curve is estimated for each stock, even though the differences in steepness between stocks remains large.

Marginal posterior densities for $h_k$ were obtained by subsampling every 200th sample of the joint posterior distribution from 500,000 cycles of the MCMC algorithm after an initial burn-in of 50,000 cycles. Time series plots of the MCMC samples showed no obvious non-stationarity in the samples. Empirical histograms representing the marginal posterior distributions of $h_k$ are shown for models 1-4 in Appendix figure 3. The marginal posterior distributions of $h_k$ for several stocks are consistently different than the remaining stocks, even with a small prior variance. For example , the Gulf of Maine Silver Hake has a posterior mode near 0.3, indicating low resilience, while the South African hake has a mode near 0.9, indicating high resilience. The marginal distributions become more similar and more narrow as the variance in steepness is reduced, clearly showing the influence of the hyperprior for $\tau^2$. Pacific whiting has a posterior mode for steepness of approximately 0.6, and a wide posterior distribution indicating large uncertainty. Because Pacific whiting is in the middle of the range of the steepness, its mode is not strongly affected by the hyperprior.

Risk-neutral and risk-averse estimates of $F_{MSY}$ for Pacific whiting are given in Appendix table 2. For the independent model, where only stock recruit data from whiting is used to estimate its stock-recruit relationship, both the risk-neutral and risk-averse estimates of $F_{MSY}$ correspond to F48%. When a relationship between the steepness for the different stocks was assumed, the results were similar regardless of the strength of the relationship, and suggest that a risk-neutral estimate is approximately F39%, while a risk-averse estimate is close to F44%. The expected yield (expected square root yield for risk-averse estimates) as a function of fishing mortality and spawning biomass per recruit are shown in Appendix figure 4. There is a broad range of $F_{SPR}$ fishing rates that whose expected yield is at least 95% of the maximum expected yield (F48%-F29% for the model where a weak relationship between steepness for the stocks is assumed). This data-based result supports the more theoretical work by Clark (1991) on $F_{SPR}$ rates, at least for the example of Pacific whiting.

*Discussion*

This analysis was intended to provide advice on a target fishing mortality for Pacific whiting within the context of the National Standard Guidelines and the new PMFC harvest policies. The stock-recruit data for Pacific whiting, and most of other Merluciids, are not strongly informative, so we suggest that our results be viewed with healthy scepticism. The stock-recruit patterns of the few apparently informative stocks may represent environmentally-driven long term changes in productivity. However, we believe that statistical analyses of the kind presented here are a necessary complement to the theoretical work that up to now has been used to establish harvest policies. An average steepness of ~0.6 for Merluciids is lower than the default range of 0.7-0.9 obtained from stock and recruit data from all stocks in the Myers database

(Leirmann and Ianelli unpublished). However, a similar meta-analysis by Myers et al. (1996) also suggested Merluciids are less resilient to harvesting than other gadoids.

Recent target fishing mortality rates for the hybrid F policy for Pacific whiting have been roughly comparable to a F40% rate, which implies an average harvest rate of approximately 20% of the age 3+ biomass per year. This analysis suggests that target fishing mortality rates in the range of F40% to F45% may be appropriate proxies for $F_{MSY}$. A choice within this range will depend on the degree of risk aversion. However, we note that long-term expected gains from a more aggressive policy are minimal.

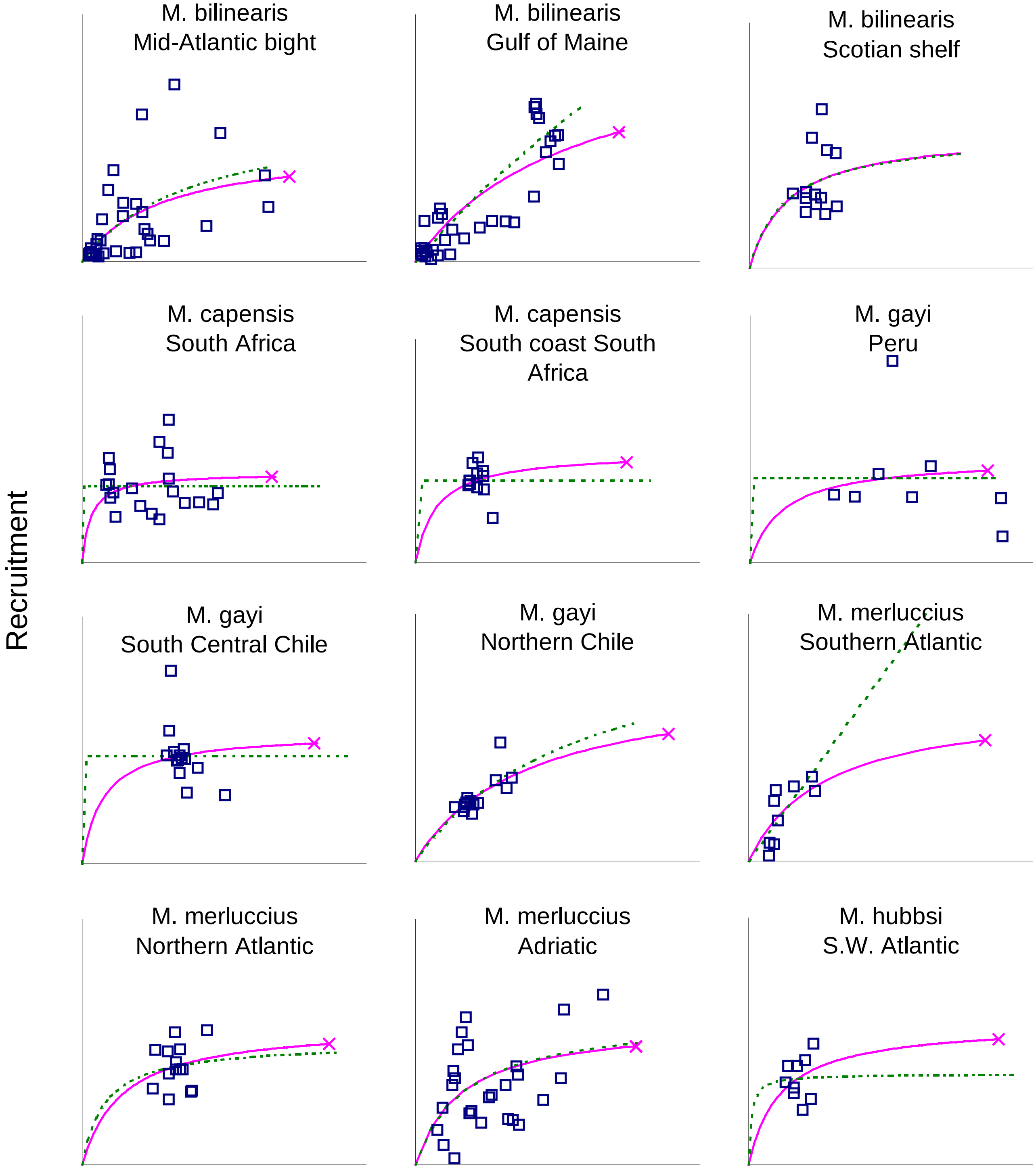
Although many peer-reviewed papers have been published using the Myers database, it is important to acknowledge that the stock-recruit data contained therein are a product of age-structured stock assessments that can be highly uncertain. From an hierarchic modeling perspective, it is clear that a cost-effective way to reduce the uncertainty for the more developed assessments would be to improve the quality of assessments of related stocks. This could be achieved by providing technical assistance in stock assessment to other agencies, and by continuing to support database compilation efforts like Myers et al. (1995).

Appendix Table 1. Summary of Merluccius stocks used in meta-analysis of stock recruit relationships. Unfished stock size was obtained by multiplying the kilograms per recruit at F=0 by the mean recruitment at stock sizes > median spawning stock size. Additional information on individual stocks at http://www.mscs.dal.ca/~myers/welcome.html.

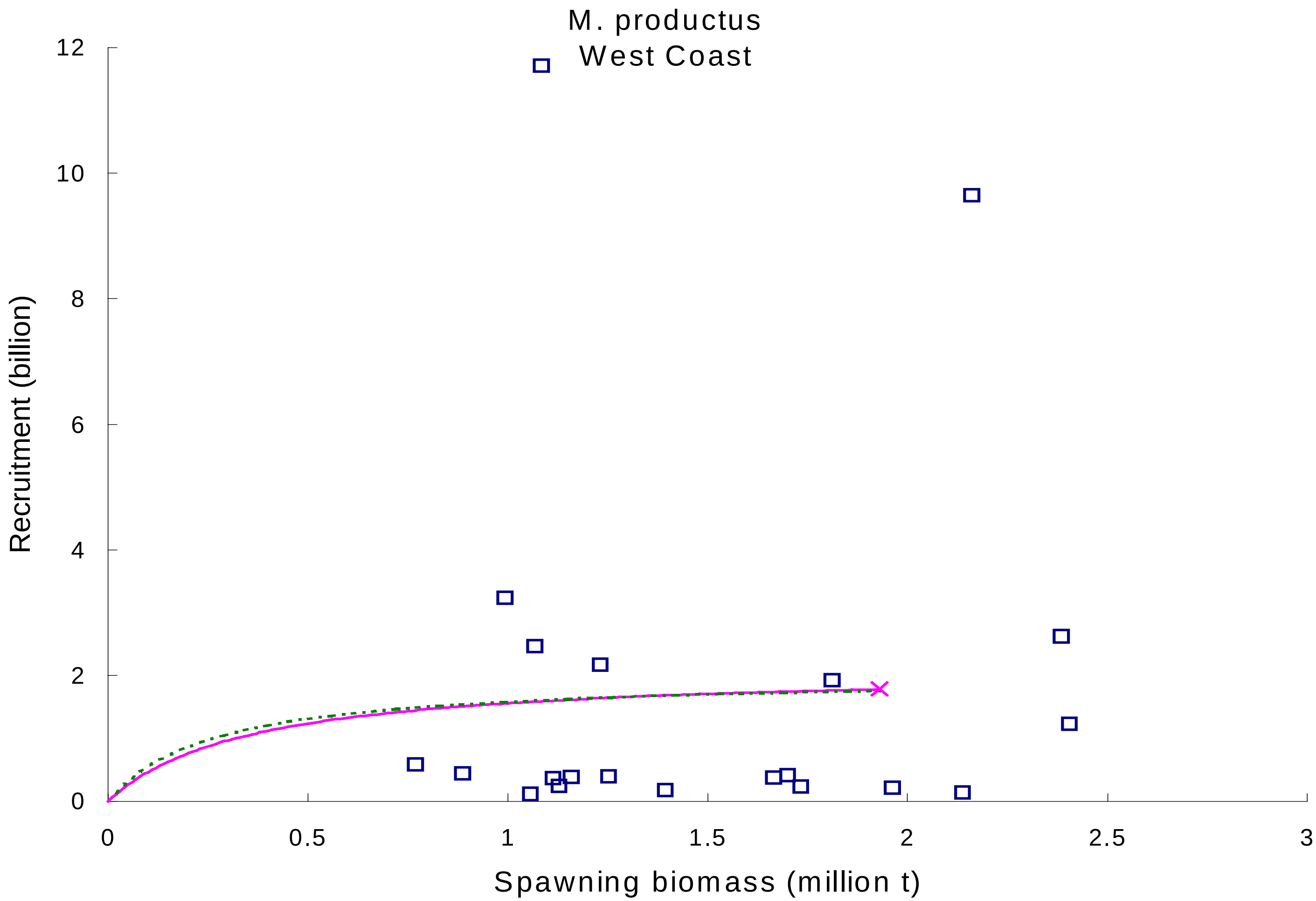
| Species | Stock | Myers database code | No. of Yrs | Kilograms of spawning biomass per recruit at F=0 | Average spawning biomass (million t) | Unfished stock size (million t) | Minimum observed stock size as percent of unfished | St. dev. of log(R/S) |
|---|---|---|---|---|---|---|---|---|
| *M. productus* | Coastal stock | PHAKEVANCON | 23 | 1.216 | 1.442 | 1.916 | 40% | 1.34 |
| *M. bilinearis* | Mid Atlantic Bight | SHAKEMAB | 33 | 0.450 | 0.174 | 0.652 | 4% | 0.80 |
| *M. bilinearis* | Gulf of Maine | SHAKE5ZE | 33 | 0.480 | 0.127 | 0.353 | 3% | 0.73 |
| *M. bilinearis* | Scotian shelf | SHAKE4VWX | 13 | 0.380 | 0.143 | 0.447 | 21% | 0.36 |
| *M. capensis* | South Africa | SAHAKE | 20 | 2.290 | 0.362 | 1.274 | 10% | 0.70 |
| *M. capensis* | South Africa - south coast | SHAKESC | 12 | 2.290 | 0.087 | 0.329 | 23% | 0.29 |
| *M. gayi* | Chile-south central zone | HAKEPERU | 8 | 1.738 | 0.405 | 0.618 | 34% | 0.80 |
| *M. gayi* | Chile-northern zone | HAKESCCHILE | 14 | 2.104 | 0.212 | 0.556 | 32% | 0.35 |
| *M. gayi* | Peru | HAKEFCHILE | 14 | 2.840 | 0.132 | 0.466 | 18% | 0.17 |
| *M. merluccius* | Atlantic, southern stock | HAKESOU | 9 | 1.548 | 0.028 | 0.168 | 9% | 0.72 |
| *M. merluccius* | Atlantic, northern stock | HAKENOR | 14 | 2.488 | 0.333 | 0.888 | 28% | 0.25 |
| *M. merluccius* | Adriatic | HAKEJAB | 26 | 1.669 | 0.048 | 0.138 | 10% | 0.73 |
| *M. hubbsi* | Argentina | HAKESWATL | 9 | 5.938 | 1.778 | 9.352 | 14% | 0.31 |
| | | Total | 228 | | | | | |

Appendix Table 2. Decision-theoretic estimates of $F_{MSY}$ for Pacific whiting. The range given in parentheses are fishing rates which the expected yield is a least 95% of the maximum yield (or square root yield for risk adverse estimates).

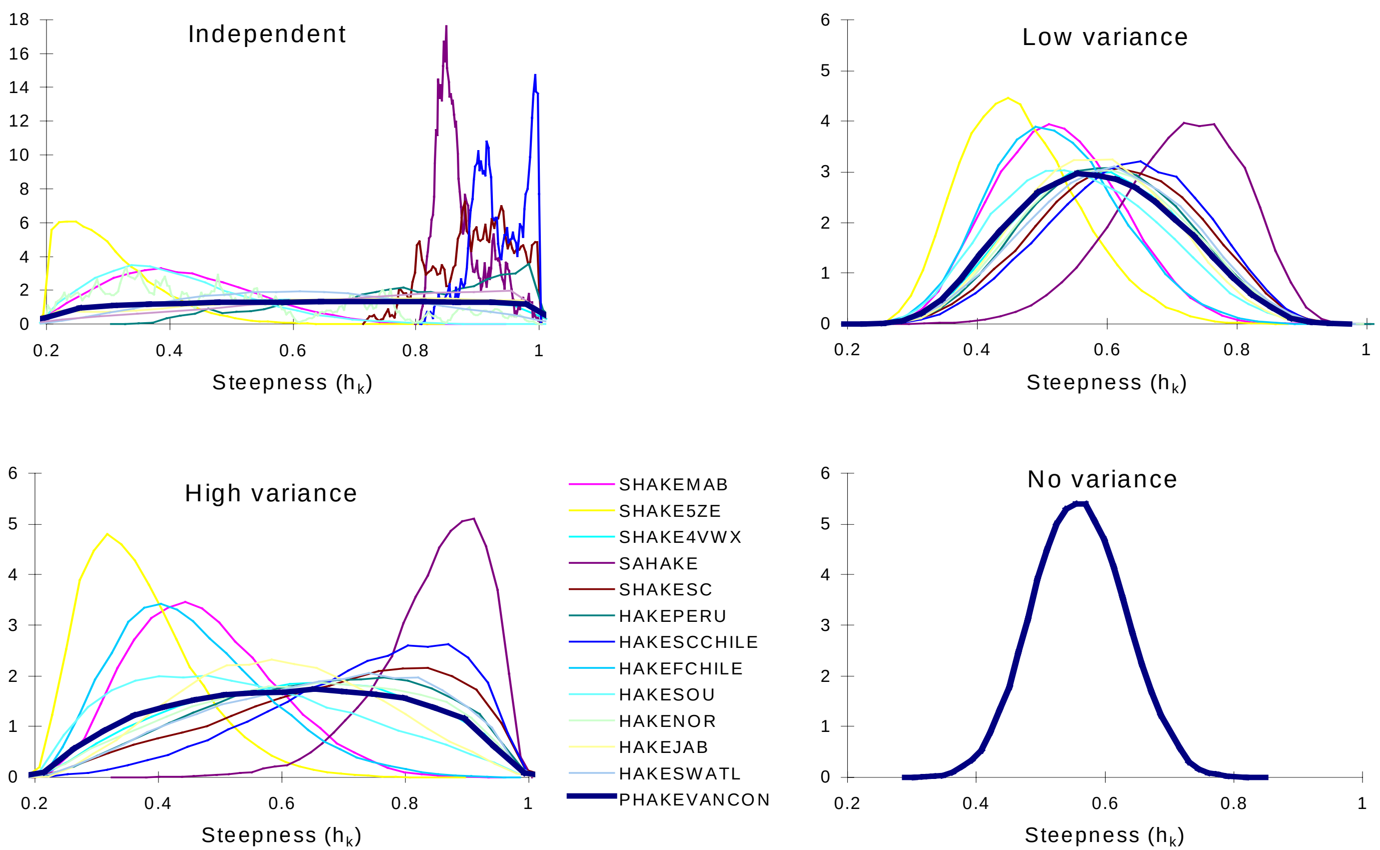
| Model | Fishing mortality (F) | Spawning biomass per recruit | Equilibrium havest rate (yield / 3+ biomass) |
|---|---|---|---|
| | | Risk neutral (expected yield) | |
| Model 1: No relationship in steepness between stocks | 0.18 (0.13-0.26) | 48% (56 - 39%) | 16% (12 - 22%) |
| Model 2: Weak relationship in steepness between stocks | 0.27 (0.18 - 0.43) | 38% (48 - 29%) | 23% (16 -34%) |
| Model 3: Strong relationship in steepness between stocks | 0.25 (0.17 - 0.37) | 40% (49 - 31%) | 22% (15 - 30%) |
| Model 4: No difference in steepness between stocks | 0.26 (0.18 - 0.38) | 39% (48 - 31%) | 22% (16 - 31%) |
| | | Risk adverse (expected square root yield) | |
| Model 1: No relationship in steepness between stocks | 0.18 (0.11 - 0.30) | 48% (60 - 36%) | 16% (10 - 25%) |
| Model 2: Weak relationship in steepness between stocks | 0.21 (0.13 - 0.35) | 44% (56 - 32%) | 19% (12 - 29%) |
| Model 3: Strong relationship in steepness between stocks | 0.20 (0.13 - 0.32) | 45% (56 - 34%) | 18% (12 - 27%) |
| Model 4: No difference in steepness between stocks | 0.22 (0.13 - 0.34) | 43% (56 - 33%) | 19% (12 - 28%) |



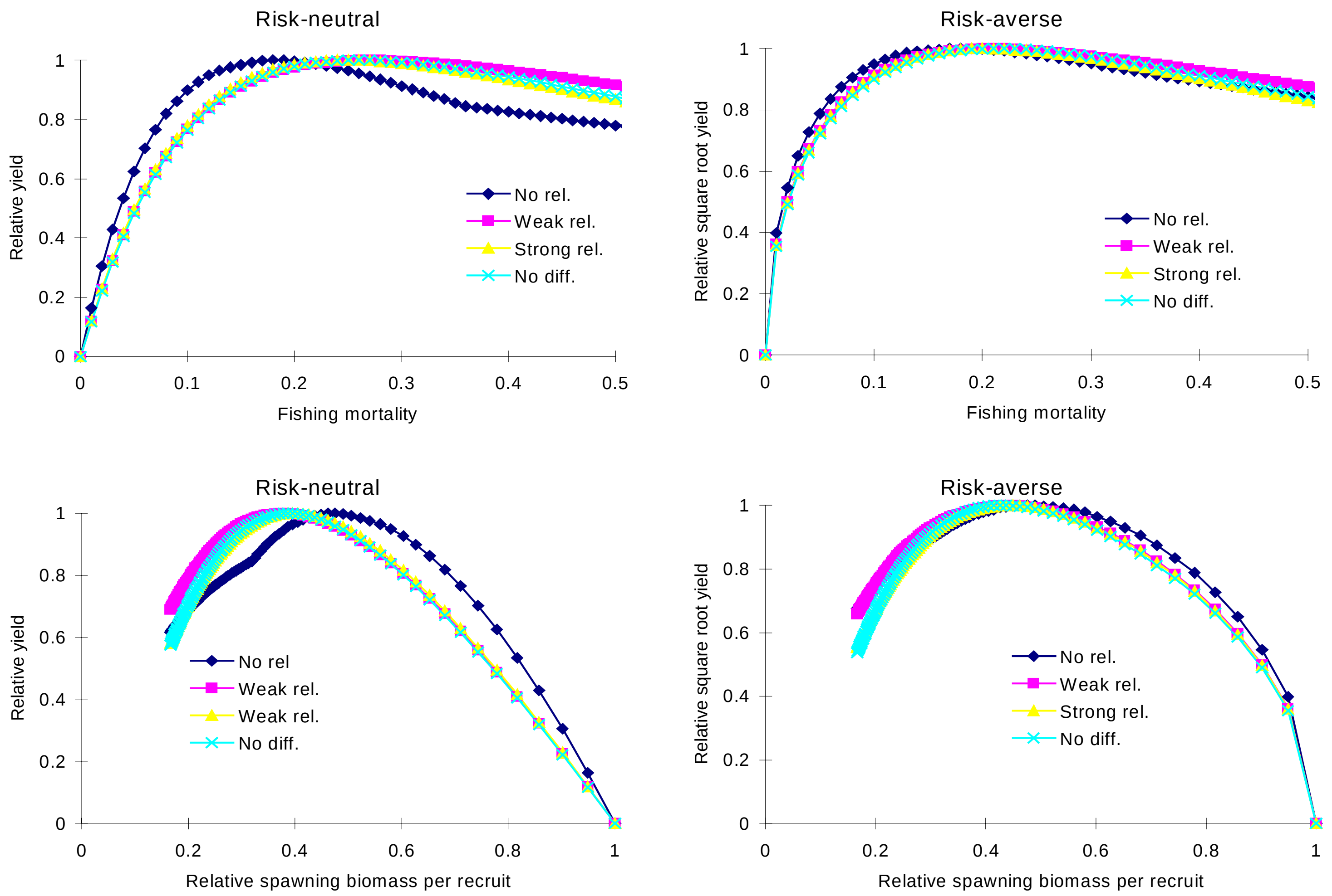

Appendix figure 1. Stock and recruitment data for 12 Merluciid stocks (Myers et al. 1995). Two fitted stock recruit curves are shown. The dotted lines shows the results of a model where no relationships between stocks are assumed. The solid lines shows the results of a hierarchical model with a weak relationship between steepness for the stocks. The endpoint of the solid line indicates the estimated unfished spawning stock size.




Appendix figure 2. Stock and recruitment data for Pacific whiting. Two fitted stock recruit curves are shown. The dotted line shows the results of a model where no relationships between stocks are assumed. The solid line shows the results of a hierarchical model with a weak relationship between the steepness parameter for the stocks. The endpoint of the solid line indicates the estimated unfished spawning stock size.




Appendix figure 3. Marginal posterior distributions of steepness for 13 Merluciid stocks from a Bayesian hierarchic model. The results are presented from four models with different assumptions about the relationship between the steepness parameters for the different stocks: 1) no relationship between stocks; 2) weak relationship between stocks; 3) strong relationship between stocks ; and 4) no difference between stocks.




Appendix figure 4. Expected yield (expected square root yield for risk-averse estimates) for Pacific whiting as a function of fishing mortality and spawning biomass per recruit for risk-neutral and risk adverse loss functions.