NOAA Technical Memorandum NMFS-NWFSC-44

Status Review of Pacific Hake, Pacific Cod, and Walleye Pollock from Puget Sound, Washington

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Status Review of Pacific Hake, Pacific Cod, and Walleye Pollock from Puget Sound, Washington

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EXECUTIVE SUMMARY

The Endangered Species Act (ESA) allows the listing of "distinct population segments"(DPSs) of vertebrate species or subspecies as threatened or endangered, if severe declines in abundance are indicated or substantial risks are facing the species. Thus, two key questions must be addressed in determining whether a listing under the ESA is warranted: 1) Is the entity in question a "species" as defined by the ESA? and 2) If so, is the "species" in danger of extinction (endangered) or likely to become so (threatened)? Guidance on what constitutes a "distinct population segment" is provided by the joint U.S. Fish and Wildlife Service (USFWS) and National Marine Fisheries Service (NMFS) interagency policy on vertebrate populations (USFWS-NMFS 1996). Once a DPS is identified, NMFS considers a variety of factors in determining whether a listing is warranted.

In response to a petition to list 18 species of marine fish in Puget Sound under the ESA (Wright 1999), NMFS initiated status reviews of seven of these species: Pacific hake, *Merluccius productus* (Ayres, 1855); Pacific cod, *Gadus macrocephalus* Tilesius, 1810; walleye pollock, *Theragra chalcogramma* (Pallas, 1815); Pacific herring, *Clupea pallasi* Valenciennes, 1847; brown rockfish, *Sebastes auriculatus* Girard, 1854; copper rockfish, *S. caurinus* Richardson, 1845; and quillback rockfish, *S. maliger* Jordan and Gilbert, 1880. NMFS formed a Biological Review Team (BRT), composed of scientists with expertise in one or more of these species, to conduct these status reviews. This report summarizes the biological and environmental information gathered in that process and the scientific conclusions reached by the BRT for Pacific hake, Pacific cod, and walleye pollock. Since these latter three species are members of the Order Gadiformes (Cohen et al. 1990, Robins et al. 1991, Eschmeyer 1998) they are jointly referred to as gadiforms throughout this document. This review is part of a larger effort by the National Marine Fisheries Service to complete status reviews for all seven of the petitioned species of marine fish in Puget Sound.

Marine Fish DPSs

The BRT examined environmental, geologic, biogeographic, life history, and genetic information in the process of identifying DPSs that satisfy ESA and joint interagency policy definitions (USFWS-NMFS 1996) of "discreteness" and "significance." In particular, geographically-discrete and temporally-persistent spawning aggregations, tagging data, biogeography, ecological and habitat factors, and variation in seasonal migration patterns, parasite incidence, and genetic population structure were found to be most informative for this process. Data relating to group or stock demographics (year-class strength, growth rate, body size at maturity, age at maturity, length frequency, fecundity, etc.) and morphometrics and meristics were less informative for DPS delineation, since the extent to which these characteristics are influenced by environmental or genetic differences is relatively unknown. Based on this examination, the BRT identified a DPS for Pacific hake and a DPS for walleye pollock in this region that can be considered species under the ESA. The BRT also concluded that there is good reason to believe that Pacific cod from Puget Sound are part of a DPS that extends beyond the boundaries of the Puget Sound ecosystem, to at least as far north as Dixon Entrance.

Assessment of Extinction Risk

The ESA (section 3) defines the term "endangered species" as "any species which is in danger of extinction throughout all or a significant portion of its range." The term "threatened species" is defined as "any species which is likely to become an endangered species within the foreseeable future throughout all or a significant portion of its range." According to the ESA, the determination of whether a species is threatened or endangered should be made on the basis of the best scientific information available regarding its current status, after taking into consideration conservation measures that are proposed or are in place. In this review, the BRT did not evaluate likely or possible effects of conservation measures, and therefore did not make recommendations as to whether identified DPSs should be listed as threatened or endangered species; rather, the BRT drew scientific conclusions about the risk of extinction faced by identified DPSs, under the assumption that present conditions will continue.

The majority of the BRT concluded that the Pacific hake DPS, the walleye pollock DPS, and all three potential DPS scenarios for Pacific cod in the Eastern Pacific are not in danger of extinction. Although the BRT concluded that none of the population segments of the three gadiform species examined is in danger of extinction, in each case, the BRT acknowledged that their level of concern would have been elevated if the geographic size of the DPSs or population segments examined had been smaller.

Georgia Basin Pacific Hake DPS

DPS delineation

The BRT concluded that inshore resident Pacific hake from Puget Sound and the Strait of Georgia constitute the Georgia Basin Pacific hake DPS (Fig. 1). The Georgia Basin is comprised of the marine waters of the Strait of Georgia, Puget Sound, and eastern Strait of Juan de Fuca. The BRT identified a variety of evidence to support their conclusion that Georgia Basin Pacific hake constitute a separate DPS relative to offshore Pacific hake: 1) Differences in annual migration behavior, 2) significant allozyme frequency differences between Puget Sound and offshore Pacific hake, 3) absence of the protozoan parasite *Kudoa paniformis* in inshore populations compared to its common occurrence in offshore Pacific hake, 4) differences in otolith morphology between Strait of Georgia and offshore Pacific hake, 5) distinctiveness of the habitats of inshore Pacific hake (they spawn in deep, inshore basins that receive large freshwater inputs and are the only populations of Pacific hake that inhabit fjord-like environments), 6) wide geographic separation of inshore and offshore spawning locales, and 7) demographic data showing that inshore Pacific hake are generally smaller for a given age, mature at a smaller size, and reach a smaller maximum length than offshore fish. The BRT expressed several concerns about the available data; for example: 1) it is not clear whether demographic differences between Georgia Basin and offshore Pacific hake are driven by environmental or genetic differences, 2) some of the allozyme loci that show differences between Puget Sound and offshore Pacific hake have been shown to be under selection in other animals, and 3) there is no obvious physical barrier preventing mixing of offshore and Georgia Basin Pacific hake, especially during the June-August period when offshore Pacific hake may occur near the mouth of the Strait of Juan de Fuca.

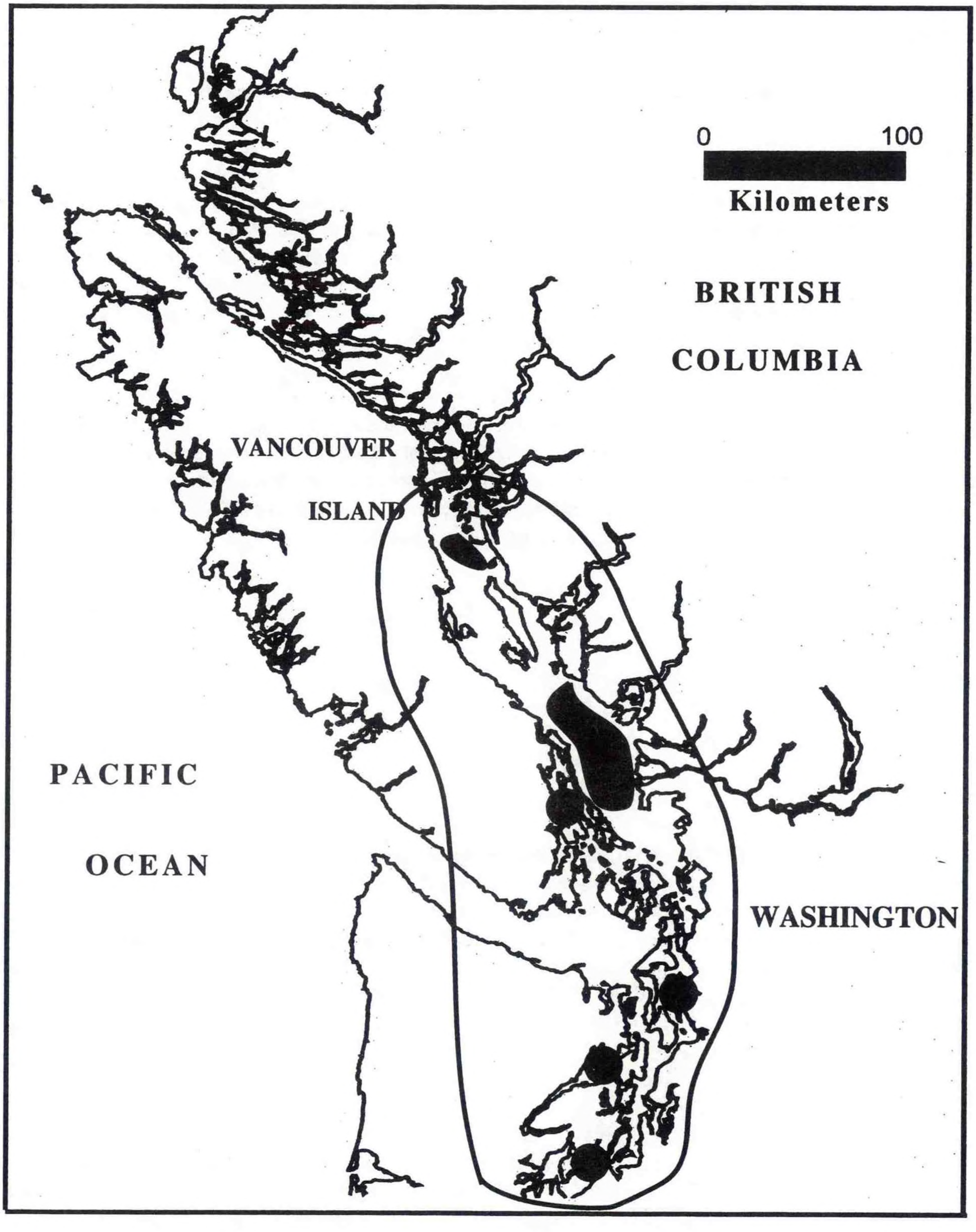

Figure 1. Approximate boundary (solid outline) of the marine waters that contain the Pacific hake spawning aggregations that constitute the Georgia Basin DPS. Members of the Georgia Basin DPS are products of these spawning aggregations. Known past and present Pacific hake spawning sites within the Georgia Basin are highlighted in gray.

Summary of BRT risk conclusions

The BRT concluded that the Georgia Basin Pacific hake DPS was not presently in danger of extinction, but could with nearly equal likelihood fall into either of two categories:
1) not in danger of extinction, nor likely to become so in the foreseeable future, or 2) not presently in danger of extinction, but likely to become so in the foreseeable future. As a whole, the BRT gave slightly higher support to the first category. The biomass of Pacific hake in Port Susan during the spawning period has declined by 85% over the past 15 years, yet numbers have fluctuated around 30 million fish until dropping to less than 11 million in 2000. Over the same period, size composition and size-at-maturity for females have also decreased substantially. In contrast, such significant declines in biomass, fish size, or maturity, are not evident for Pacific hake populations in the Canadian portion of the Strait of Georgia and these populations are much larger than the Port Susan population.

In addition to the concerns about the status of Puget Sound Pacific hake, the BRT identified several areas of uncertainty regarding the relationships among stocks and effects of potential risk factors. The extent of any mixing of spawning products or spawners among stocks within the Georgia Basin is unknown. Risk factors are also poorly known and for the most part, the BRT could only speculate on potential factors and their effects. For example, two hypothetical models of pinniped predation on Pacific hake in Port Susan were considered, but the results were inconclusive.

Over the next year, much new information is expected to become available that will likely resolve many of the uncertainties about the status and relationship of stocks of Pacific hake within the Georgia Basin DPS. When it is available, the BRT urges that this new information be considered and extinction risk be reevaluated.

Pacific Cod

DPS delineation

The majority opinion of the BRT was that there is good reason to believe that Pacific cod from Puget Sound are part of a DPS that is larger than Puget Sound and that this DPS extends northward to at least Dixon Entrance (Fig. 2). However, the BRT concluded that there is insufficient information available at present to identify the exact northern boundary of the DPS that incorporates Puget Sound Pacific cod. A high level of uncertainty concerning the northern boundary of the DPS was expressed during the decision-making process, and the BRT agreed that there is insufficient information available at present to identify DPSs of Pacific cod with a high degree of certainty. The BRT struggled with this decision and noted that the lack of suitable data to answer the DPS question for Pacific cod was a cause for concern.

The conclusion that the Pacific cod DPS is larger than Puget Sound was supported by:
1) genetic data that show a lack of significant heterogeneity among Pacific cod sampled largely during summer and fall at various locations in the northeastern Pacific Ocean (although it is possible that if collections had been of spawning fish the data might have shown greater population structure), 2) results of adult tagging studies in the Strait of Georgia and Puget Sound showing movement amongst inshore locations and some limited movement between inshore and coastal areas (although rare tagging studies on spawning fish do show some level of spawning site fidelity), and 3) the ecological similarity of fjord-type marine habitat in Puget Sound to habitat along the coasts of British Columbia and southern Alaska.

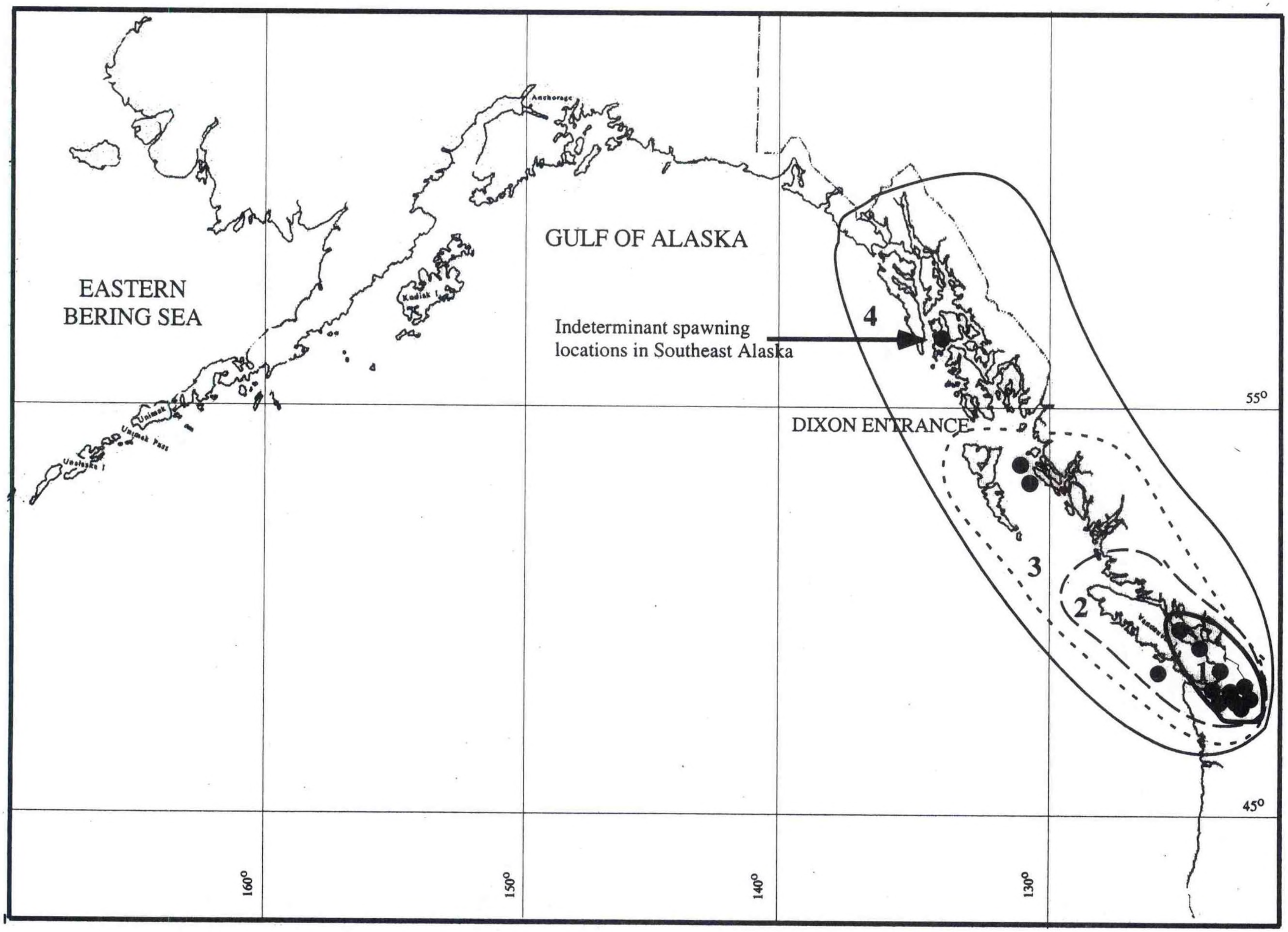

Figure 2. Approximate boundaries of areas containing the coastal marine waters for the four Pacific cod DPS scenarios considered by the BRT: 1) Georgia Basin, 2) Georgia Basin to the north end of Vancouver Island, 3) Georgia Basin to Dixon Entrance, and 4) Georgia Basin to all of Southeast Alaska. Known Pacific cod spawning sites within this area are indicated by solid circles (●).

The BRT considered several scenarios as to where the northern boundary of the DPS may occur, including: 1) the northern extent of the Georgia Basin (encompassing the Strait of Georgia, Puget Sound, and the eastern Strait of Juan de Fuca), 2) the north end of Vancouver Island (encompassing the Georgia Basin and Amphitrite Bank spawning aggregations), 3) Dixon Entrance, and 4) Southeast Alaska (Fig. 2). Although the BRT was unable to determine the exact northern boundary of the Pacific cod DPS, a majority of the BRT felt that the northern boundary of the Pacific cod DPS extends at least as far north as Dixon Entrance.

Although the BRT could not with any certainty identify multiple populations or DPSs of Pacific cod within the region south of Dixon Entrance/Southeast Alaska, they acknowledged the possibility that significant stock structuring does exist within this region and that a finer DPS structure might be revealed by further information on the behavior, ecology, and genetic population structure of Pacific cod. The BRT recognized that the DPS, that includes Puget Sound Pacific cod, may represent fish that are uniquely adapted to survive at the southern end of the species' range.

Summary of BRT risk conclusions

As with the northern boundary considerations for the Pacific cod DPS, the BRT struggled with the assessment of extinction risks. Of the four scenarios considered for the northern boundary of the DPS for Pacific cod (see summary above), the BRT did not distinguish between DPS scenarios 1 and 2 for its extinction risk assessment. The BRT considered risks for three DPS scenarios: 1) Georgia Basin, 2) Puget Sound to Dixon Entrance, and 3) Puget Sound through Southeast Alaska.

In general, as the size of the DPS grew to encompass more spawning locations and greater numbers of Pacific cod, the BRT considered the risks of extinction to diminish. The majority of the BRT concluded that Pacific cod encompassed by DPS scenarios 2 (Puget Sound to Dixon Entrance) and 3 (Puget Sound through Southeast Alaska) are not in danger of extinction, nor are they likely to become so in the foreseeable future. A minority of the BRT felt that Pacific cod within either DPS scenario 2 or 3, although not presently in danger of extinction, are likely to become so in the foreseeable future. In fact, most BRT members could not rule out the possibility that Pacific cod in DPS scenario 2 (Puget Sound to Dixon Entrance) are likely to become endangered in the foreseeable future.

The BRT was divided on the extinction risk status of Pacific cod encompassed by scenario 1 (Georgia Basin). Although the BRT agreed that Pacific cod in the Georgia Basin scenario are not presently in danger of extinction, the BRT was nearly equally divided on the question of whether Pacific cod in this population segment are likely to become endangered in the foreseeable future if present trends continue. As a whole, the BRT gave slightly higher support to placing Pacific cod in this population segment in the category of not in danger of extinction, nor likely to become so in the foreseeable future.

The BRT identified several concerns: 1) the apparent loss of the major, known spawning locations in Puget Sound, 2) general synchronicity in declining trends in Pacific cod abundance from Puget Sound to Southeast Alaska, and 3) relatively little quantitative information or understanding about the effects of potential risk factors. Overall, it is not certain which risk factors, either singly or in combination, may be significantly contributing to the current low stock sizes of Pacific cod.

Lower Boreal Eastern Pacific Walleye Pollock DPS

DPS delineation

The BRT concluded that aggregations of spawning walleye pollock in the eastern North Pacific Ocean, south of a provisional northern boundary of 140°W, are part of a single DPS, which is the Lower boreal Eastern Pacific walleye pollock DPS. The DPS name is derived from the zoogeographic literature, which describes the general area occupied by this unit as containing a "well-defined lower boreal fauna" (Briggs 1974, p. 278). The provisional northern boundary of the Lower boreal Eastern Pacific DPS coincides with the northern and western stock boundary for Southeast Alaska walleye pollock at 140°W (Fig. 3).

The BRT's conclusion that a walleye pollock DPS extends from Puget Sound northward to encompass all of Southeast Alaska, with a provisional northern boundary at 140°W, was supported by the following considerations: 1) the walleye pollock reproductive traits of pelagic spawning and pelagic distribution of eggs and larvae, 2) the ecological similarity of fjord-type marine habitat in Puget Sound to habitat along the coasts of British Columbia and Southeast Alaska, 3) the more or less continuous distribution of spawning sites for walleye pollock within the geographic confines of the DPS, 4) that regulatory agencies in the area consider walleye pollock in northern British Columbia and Southeast Alaska to consist of a single stock, 5) recognition of a significant zoogeographic faunal break in Southeast Alaska, 6) the consideration that walleye pollock from Puget Sound through Southeast Alaska are spawning in fjords, whereas further north walleye pollock are spawning in more open water, and 7) the unlikely potential for walleye pollock from Southeast Alaska to mix with walleye pollock from the central and western Gulf of Alaska. The BRT did not preclude the possibility that further information on the behavior, ecology, and genetic population structure might provide a basis for delineating smaller DPSs of walleye pollock within the Lower boreal Eastern Pacific DPS.

Although the BRT could not with any certainty identify multiple populations or DPSs of walleye pollock within the Lower boreal Eastern Pacific DPS, they acknowledged the possibility that more than one DPS for walleye pollock may exist in the range from Puget Sound to Southeast Alaska. However, the BRT was unable to find compelling evidence that this finer DPS structure exists. As an example of the uncertainty inherent in the walleye pollock DPS decision, it should be noted that none of the BRT members ruled out the possibility that there could be a DPS for walleye pollock at the level of the Georgia Basin.

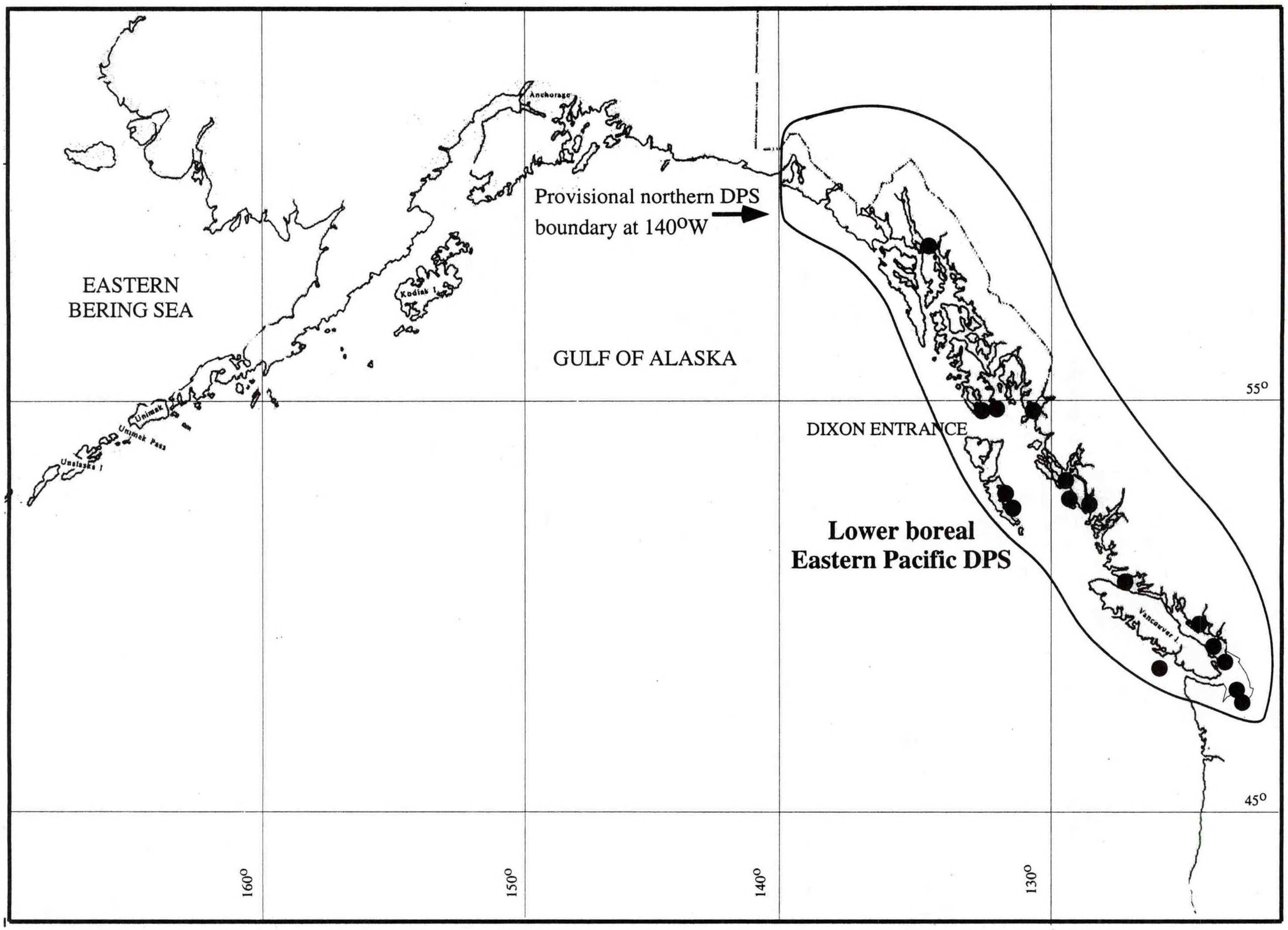

Figure 3. Approximate boundary (solid outline) of coastal marine waters that contain spawning aggregations of walleye pollock belonging to the Lower boreal Eastern Pacific DPS. Members of the Lower boreal Eastern Pacific DPS are products of these spawning aggregations. Known walleye pollock spawning sites within the area are indicated by solid circles (●).

Summary of BRT risk conclusions

The BRT concluded that walleye pollock in the Lower boreal Eastern Pacific DPS are not in danger of extinction, nor are they likely to become endangered in the foreseeable future if present trends continue. However, most BRT members could not entirely rule out the possibility that walleye pollock in this DPS, although not presently in danger of extinction, are likely to become so in the foreseeable future.

Information on the status of walleye pollock stocks in the DPS is very limited and usually based on catches or catch rates in recreational or commercial fisheries. The abundance of walleye pollock in Puget Sound is at low levels, especially in southern areas, but stocks outside Puget Sound do not appear to be at or declining to such low levels. As with Pacific hake and Pacific cod, little quantitative information is available about potential risk factors or their effects on the status of walleye pollock in the DPS. The lack of suitable data to assess extinction risk is a cause for concern.

Consideration of the Puget Sound Ecosystem

It is important to note that the BRT's considerations of the status and trends of Pacific hake, Pacific cod, and walleye pollock in the Puget Sound area did not, and should not, occur in a vacuum. In addition to these three species, several other fish species from this area have either been listed under the ESA, or have been petitioned for listing. These include 23 ESUs of anadromous salmonids in the Pacific Northwest, Pacific herring, and various species of rockfish–in or close to the Puget Sound area. A significance emerges from consideration of these species collectively that is not apparent when any one is considered alone. Joint consideration of these species together suggests ecosystem-level implications that are difficult or impossible to evaluate under terms of the ESA. It is possible, hypothetically, that the reduced or declining trends of each of the individual species in this group could be considered as insufficient for affording any of the species legal protection under the ESA. But taking no action, under such circumstances, might be a major mistake if this collective information is an indication that the Puget Sound area, as an ecosystem, is experiencing major change. Such changes could be of more far-ranging concern than could ever be recognized if any one species were considered individually. Environmental variation and general ecosystem dynamics, could easily lead to at least some of the declines in abundance observed for any one of these species. The commonalities and synchronous nature of the information is compelling, and scientifically, this raises the need to determine the degree to which these common changes are anthropogenic, both for individual species and within the Puget Sound ecosystem as a whole. The complexity of factors responsible for population fluctuations emphasizes the need for better understanding of the unique features of Puget Sound compared to surrounding and similar environments, many of which are interconnected with the Sound via such factors as the climate, currents, migrations, and dispersal of various species. It is important to understand the natural variation within such systems over various time scales from decades to thousands of years. The potential for stratigraphic sediment analysis is noted in this regard. So are studies of the dynamics of species compared across the observed diversity of life-history strategies. Measures of the ebb and flow, or the extinction, recolonization, and persistence of the populations of the various species in the Puget Sound ecosystem are important as a basis for judging how problematic the picture before us is, to what degree the changes are of anthropogenic origins, and how significant these changes are as a basis for taking management action. In the absence of such information, the BRT was restricted to a largely species by species consideration of the data.

ACKNOWLEDGMENTS

The status review for Puget Sound Pacific hake, Pacific cod, and walleye pollock was conducted by a team of researchers from the National Marine Fisheries Service's (NMFS) Northwest Fisheries Science Center (NWFSC) and Alaska Fisheries Science Center (AKFSC). This biological review team (BRT) relied on comments and informational reports submitted by the public and by state, tribal, and federal agencies (technical terms and abbreviations such as "BRT" are defined in the Glossary). The majority of the Pacific hake extinction risk assessment analyses are the contribution of Dr. William H. Lenarz. The authors acknowledge the efforts of all who contributed to this record, especially the Washington Department of Fish and Wildlife.

Numerous individual fishery scientists and managers provided information that aided in the preparation of this document and deserve special thanks. We particularly wish to thank Wayne Palsson from the Washington Department of Fish and Wildlife for updated information, data, opinions, and advice. Others who provided significant contributions to this effort include: Greg Bargmann, Jim West, and Steve Jeffries from WDFW; and Robert DeLong, Jeff Laake, and Patrick Gearin of NMFS' National Marine Mammal Laboratory (NMML).

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Kathleen Neely of the NWFSC provided graphical assistance with a number of the figures included in this report.

The BRT for Puget Sound Pacific hake, Pacific cod, and walleye pollock consisted of the following members: from the Northwest Fisheries Science Center, Tonya L. Builder, Dr. W. Stewart Grant, Dr. Richard G. Gustafson, Lyndal L. Johnson, Dr. Bruce B. McCain, Dr. Richard D. Methot, Cyreis Schmitt, Dr. Thomas C. Wainwright, and Dr. Robin Waples; and from the Alaska Fisheries Science Center, Dr. Kevin M. Bailey, Michael Canino, Dr. Martin W. Dorn, Dr. Charles Fowler, and Dr. Anne Hollowed.

INTRODUCTION

The National Marine Fisheries Service (NMFS) received a petition on February 8, 1999 to list 18 species of marine fishes in Puget Sound under the U.S. Endangered Species Act (ESA) (Wright 1999). The ESA allows the listing of "distinct population segments" of vertebrate species or subspecies as threatened or endangered, if severe declines in abundance are indicated or substantial risks are facing the species. NMFS evaluated the petition for each species to determine whether the petitioner provided "substantial information" as required by the ESA to list a species. The agency also reviewed other readily available information and consulted with state and tribal biologists to determine whether general agreement existed on the uniqueness, distribution, abundance, and threats to the petitioned species/populations. Additionally, NMFS evaluated whether available information might support the identification of distinct population segments that might warrant listing under the ESA. NMFS (1999) concluded that the petitioner provided substantial information, or cited such information in other sources, to initiate a status review for Pacific hake, *Merluccius productus* (Ayres, 1855); Pacific cod, *Gadus macrocephalus* Tilesius, 1810; walleye pollock, *Theragra chalcogramma* (Pallas, 1815); and Pacific herring, *Clupea pallasi* Valenciennes, 1847. NMFS (1999) further concluded that the information provided in the petition on Puget Sound rockfish species was insubstantial for most of the species petitioned, but that compelling reasons existed to believe some Puget Sound rockfishes may warrant ESA protection. Information appeared to be sufficient to conduct a status review that could provide the basis for an ESA determination for three species: brown rockfish, *Sebastes auriculatus* Girard, 1854; copper rockfish, *S. caurinus* Richardson, 1845; and quillback rockfish, *S. maliger* Jordan and Gilbert, 1880. NMFS (1999) decided, therefore, to also initiate status reviews for these three species of Puget Sound rockfish. NMFS determined that it would be most efficient to conduct these status reviews along taxonomic lines, and therefore three BRTs were formed, one for the gadiforms, one for rockfish, and one for Pacific herring.

Scope and Intent of Present Document

This document reports the results of a comprehensive ESA status review of three gadiform species in Puget Sound: Pacific hake, Pacific cod, and walleye pollock. Hake species in the genus *Merluccius* are variously placed by different authorities in the Family Merluccidae (Cohen et al. 1990, Eschmeyer 1998) or the Family Gadidae (Robins et al. 1991) (together with Pacific cod and walleye pollock). In either taxonomic arrangement, the three species are members of the Order Gadiformes (Cohen et al. 1990, Robins et al. 1991, Eschmeyer 1998), and for the purposes of this document will hereafter be jointly referred to as gadiforms. Biological and ecological information for populations throughout the range of the three gadiform species were also considered in order to provide a context for evaluating information on these species within Puget Sound.

In order to meet the provision in the ESA that listing determinations be made with the best available scientific and commercial information, NMFS formed a team of scientists with diverse backgrounds in marine fish biology and marine habitats to conduct this review. This Biological Review Team (BRT)[1] reviewed and evaluated scientific information compiled by NMFS staff from published literature and unpublished data. Information presented at public meetings in 1999 in Seattle, Washington was also considered. The BRT also reviewed additional information submitted to the ESA administrative record.

Key Questions in ESA Evaluations

Two key questions must be addressed in determining whether a listing under the ESA is warranted: 1) Is the entity in question a "species" as defined by the ESA? and 2) If so, is the "species" in danger of extinction (endangered) or likely to become so (threatened)? These questions are addressed for each of the three species in the following separate sections. If it is determined that a listing(s) is warranted, then NMFS is required by law (1973 ESA Sec. 4(a)(1)) to identify one or more of the following factors responsible for the species' threatened or endangered status: 1) destruction or modification of habitat, 2) over-utilization by humans, 3) disease or predation, 4) inadequacy of existing regulatory mechanisms, or 5) other natural or human factors. This status review does not formally address factors for decline, except as they provide information about the degree of risk faced by the species in the future, if present conditions prevail.

The "Species" Question

The ESA, as originally enacted, defined "species" to include "any subspecies of fish or wildlife or plants and any other group of fish or wildlife of the same species or smaller taxa in common spatial arrangement that interbreed when mature." As amended in 1978, the ESA defined "species" as "any subspecies of fish or wildlife or plants, and any distinct population segment of any species of vertebrate fish or wildlife which interbreeds when mature." Thus the ability to list distinct population segments (DPSs) is restricted to vertebrate animals, and specifically excludes plants and invertebrates. Furthermore, Congress has stated that the authority to list DPSs should be used "sparingly and only when the biological evidence indicates that such action is warranted" (Senate Report 151, 96th Congress, 1st Session, 1979). Listing of vertebrate DPSs has occurred relatively rarely, for example, USFWS-NMFS (1996) stated that "of over 300 native vertebrate species listed under the Act, only about 30 are given separate status as DPS's." Wilcove et al. (1993) examined listings under the ESA between 1985 and 1991 and found that only 8.5% of the 94 vertebrate "species" listed or proposed for listing were classified as DPSs.

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[1] A list of the Biological Review Team members for Pacific hake, Pacific cod, and walleye pollock is included in the acknowledgments section.

Guidance on what constitutes a "distinct population segment" is provided by the joint U.S. Fish and Wildlife Service (USFWS) and NMFS interagency policy on vertebrate populations (USFWS-NMFS 1996). To be considered "distinct," a population, or group of populations, must be "discrete" from other populations and "significant" to the species as a whole. A population segment of a vertebrate species may be considered discrete if it is markedly separated from other populations of the same taxon as a consequence of physical, physiological, ecological, or behavioral factors. The policy states that quantitative measures of genetic or morphological discontinuity may provide evidence of this separation. If a population segment is considered discrete, considerations that can be used to determine its significance to the taxon as a whole include: 1) persistence of the discrete population segment in an ecological setting unusual or unique for the taxon, 2) evidence that loss of the discrete population segment would result in a significant gap in the range of the taxon, 3) evidence that the discrete population segment represents the only surviving natural occurrence of a taxon that may be more abundant elsewhere as an introduced population outside its historic range, and 4) evidence that the discrete population segment differs markedly from other populations of the species in its genetic characteristics.

This joint policy applies to all vertebrate species, but does not elaborate on the information that can be used to assess distinctiveness in species of marine fishes. The types of evidence that can be considered to evaluate distinctiveness of populations in Pacific salmon species have been extensively reviewed (Waples 1991a, b, 1995), and similar kinds of evidence can be used to assess distinctiveness of populations or groups of populations of marine fishes. NMFS Pacific salmon framework advocates a holistic approach in which all available information is considered, as well as a consideration of the strengths and limitations of such information in delineating distinct population segments. Important information includes natural rates of migration and recolonization, evaluations of the efficacy of natural barriers to migration, phenotypic and life history traits that reflect local adaptation, and measurements of genetic differences between populations. NMFS's Pacific salmon policy states that (Waples 1995, p. 9):

> A vertebrate population will be considered distinct (and hence a "species") for purposes of conservation under the Act if the population represents an evolutionarily significant unit (ESU) of the biological species. An ESU is a population (or group of populations) that (1) is substantially reproductively isolated from other conspecific population units, and (2) represents an important component in the evolutionary legacy of the species.

To date, NMFS has used the Pacific salmon policy to identify over 50 ESUs among seven biological species of anadromous Pacific salmonids (Busby et al. 1993, 1994, 1996; Gustafson et al. 1997; Hard et al. 1996; Johnson et al. 1991, 1994, 1997, 1999; Matthews and Waples 1991; Myers et al. 1998; Waknitz et al. 1995; Waples et al. 1991a, b; Weitkamp et al. 1995). Approximately half of these ESUs have been listed as threatened or endangered species (see http://www.nwr.noaa.gov/1salmon/salmesa/index.htm for a complete list, and the current status of Pacific salmon ESUs). Although the joint DPS policy does not specifically identify evolutionary significance as a criterion for distinctness, "the first criterion (discreteness) is similar to the reproductive isolation criterion in the NMFS [Pacific] salmon policy, and the second (significance to the biological species) is roughly analogous to the contribution to ecological-genetic diversity criterion of the NMFS [Pacific] salmon policy" (Waples 1995, p. 25).

The Natural Resource Council, in a report entitled "Science and the Endangered Species Act" (NRC 1995), developed the concept of an evolutionary unit (EU) to assist in identifying DPSs. This report defined an EU as "a group of organisms that represents a segment of biological diversity that shares evolutionary lineage and contains the potential for a unique evolutionary future" (NRC 1995). NRC (1995) stated that evidence of uniqueness of an EU can be found through analysis of morphology, behavior, physiology, and biochemistry, and that, in most cases, an EU will occupy a particular geographical area. NRC (1995) suggested that a DPS can be thought of as "an evolutionarily distinct population segment that is geographically or otherwise isolated from other population segments." The DPS, in some cases, may be a group of populations (metapopulation, i.e., "a larger population made up of smaller, local breeding populations that have some genetic and ecological interactions among them") (NRC 1995). The considerations identified by the NRC (1995) are very similar to those identified and used by the NMFSs ESU policy.

The "Extinction Risk" Question

The ESA (section 3) defines the term "endangered species" as "any species which is in danger of extinction throughout all or a significant portion of its range." The term "threatened species" is defined as "any species which is likely to become an endangered species within the foreseeable future throughout all or a significant portion of its range." NMFS considers a variety of information in evaluating the level of risk faced by a DPS. Important considerations include 1) absolute numbers of fish and their spatial and temporal distribution, 2) current abundance in relation to historical abundance and carrying capacity of the habitat, 3) trends in abundance, based on catch-per-unit effort (CPUE) or on estimates of spawner-recruit ratios, 4) possible threats to genetic integrity, 5) recent events (e.g., climate variability or change in management) that have predictable short-term consequences for the abundance of the DPS. Additional risk factors, such as disease prevalence or changes in life-history traits, may also be considered in evaluating risk to populations.

The determination of whether a species is threatened or endangered should be made according to the ESA on the basis of the best scientific information available on its current status, after taking into consideration conservation measures that are proposed or are in place. We did not evaluate likely or possible effects of conservation measures in this review. Therefore, we did not recommend whether identified DPSs should be listed as threatened or endangered species, because that determination requires evaluation of additional factors not considered by the BRT. Instead, the BRT drew scientific conclusions about the risk of extinction faced by identified DPSs under the assumption that present conditions would continue and with the recognition that natural demographic and environmental variability is an inherent feature of "present conditions." Conservation measures will be considered by the NMFS Northwest Regional Office in making ESA listing recommendations.

Summary of Information Presented by the Petitioner

NMFS received on February 8, 1999 a petition from Sam Wright, a biologist retired from the Washington State Department of Fish and Wildlife, to list as threatened or endangered 18 species/populations of marine fishes in Puget Sound, Washington and to designate critical habitat (Wright 1999). NMFS evaluated the petition to determine whether it presented substantial scientific or commercial information indicating that the petitioned action may be warranted. Section 424.14(b)(1) of NMFS' ESA implementation regulations defines "substantial" information" as the amount of information that would lead a reasonable person to believe that the measure proposed in the petition may be warranted. Section 424.14(b)(2) of these regulations lists factors to be considered in evaluating the petition, including whether the petition contains detailed narrative justification for the recommended measure, a description of past and present numbers, of geographical distributions of the species and of threats facing the species.

Stock Structure

The petitioner defined a stock as a "population of fish which is reproductively isolated, or partially isolated, from other such populations of the same species." Most of the petitioner's arguments dealt with evidence for reproductive isolation between populations within Puget Sound, and between populations in Puget Sound and those along the outer coast. Three kinds of information were presented to indicate that significant differences among populations may exist.

First, the petitioner argued that genetic differences between northern and southern regions of Puget Sound may be present, because reduced gene flow in some species may result from the physical isolation of north- and south-sound basins by a shallow sill in Admiralty Inlet and by the narrow passage through Deception Pass. The petitioner stated that the northern portion of Puget Sound is "exposed to storms, receives more oceanic water, and contains abundant, often contiguous, rocky reef habitat." The petitioner also stated that the southern portion of Puget Sound is protected from the action of storms, is more influenced by freshwater, and contains fewer rocky reefs than the northern portion. According to the petitioner, complex current patterns in both segments of the sound may also limit dispersal between localities by the entrainment of planktonic larvae in local gyres. Second, the petitioner presented information on genetic population subdivision for some species. Allele-frequency differences between populations provide evidence for reproductive isolation between some populations.

Third, the petitioner noted the presence of life-history differences between populations or the occurrence of discrete spawning areas for some species. Life-history differences between areas may reflect genetic differences between populations or may be the result of environmental influences on development and growth in the absence of genetic differentiation. The occurrence of discrete spawning areas is a necessary, but not sufficient criterion for the development of reproductive isolation between populations.

Risk of Extinction

Most of the petitioner's assessment of abundances was based on fishery statistics and sporadic stock assessments by the Washington State fishery management agencies. In addition to harvests, the petitioner listed marine mammal predation as a possible threat to populations of marine fishes in Puget Sound.

Pacific Hake

Distinct population segments

Populations of Pacific hake in Puget Sound lie in the northern part of the geographical range of this species. Outer coastal populations appear to consist of a single large population that migrates annually from winter spawning grounds off California to northern feeding areas in summer. According to the petitioner, a comparison of Pacific hake from Puget Sound, Strait of Juan de Fuca, and coastal Washington demonstrated allele-frequency differences between coastal populations and populations in the Strait of Juan de Fuca and Puget Sound.

Extinction risk

According to the petitioner, two major stocks of Pacific hake occur in Puget Sound–a northern spawning aggregation in the Bellingham area, and a southern stock with spawning aggregations in Port Susan. The petitioner stated that as much as 15 million pounds of spawning Pacific hake were once harvested in southern Puget Sound, but the catch declined rapidly after a peak catch in 1983. By 1991, the fishery was closed because of low abundances. According to the petitioner, at peak abundances, acoustic and midwater trawl surveys in winter indicated a spawner biomass of over 40 million pounds, which declined to about one million pounds between 1982 and 1993. The annual exploitation rate in the 1980s was as high as 40% of the adult population. Parallel to the decline in biomass, the average size of individual fish declined so that the stock could not be used commercially. According to the petitioner, predation from marine mammals now appears to be preventing the recovery of this stock.

Pacific Cod

Distinct population segments

Pacific cod in Puget Sound lie at the southern margin of the geographical range of this species. The petitioner noted that life-history data for Pacific cod may distinguish coastal populations from populations in Puget Sound and may also distinguish populations within Puget Sound. Puget Sound populations appear to have higher rates of growth and egg production than do other populations along the Pacific Coast. The petitioner stated that within Puget Sound, fishery patterns, the locations of spawning, parasite markers, and tagging studies indicate the existence of three population groups: 1) one located in the Strait of Georgia and the area around Bellingham, 2) one in eastern Strait of Juan de Fuca and Port Townsend Bay, and 3) one in the area south of Admiralty Inlet, including Hood Canal, Agate Passage, and Dalco Passage.

Extinction risk

The petitioner noted that the Pacific cod fishery in northern Puget Sound (Kilisut Harbor and Port Townsend Bay spawning stocks) expanded in the late 1970s and early 1980s, but declined in the mid 1980s. The fishery in this area was closed in 1987. However, trawling for Pacific cod in Admiralty Inlet continued until 1994. Experimental trawling in Port Townsend Bay in 1988 failed to find appreciable numbers of Pacific cod. A second spawning Pacific cod population in Agate Passage was the target of a recreational fishery in the 1970s and early 1980s, but declined in the mid 1980s. Few fish were harvested by 1988, and the area was closed to fishing in winter, beginning in 1991. In 1991, this fishery was closed throughout the year. According to the petitioner, acoustic surveys have failed to detect Pacific cod aggregations in surveys of Agate Passage after 1988.

Walleye Pollock

Distinct population segments

Populations of walleye pollock in Puget Sound lie at the southern margin of the geographical range of this species in the Eastern North Pacific. The petitioner stated that individual walleye pollock grow at different rates in northern and southern areas in Puget Sound, and spawning populations in these two areas are spatially separated.

Extinction risk

According to the petitioner, walleye pollock stocks in southern Puget Sound are most at risk of extinction. The petitioner stated that the sports fishery represented the largest catches of walleye pollock in the southern Puget Sound with an average catch exceeding 400,000 pounds per year from 1977 to 1986. Catches declined severely after 1986, and the fishery disappeared by 1989. Trawl surveys were conducted in 1987, 1989, and 1991, and biomasses in these years were estimated to be 3,537, 172, and 99 mt, respectively. The petitioner stated that recent surveys indicate that this stock is severely depressed or may be extinct.

APPROACHES TO THE SPECIES QUESTION AND TO DETERMINING RISK

The Species Question

The joint policy of the U.S. Fish and Wildlife Service and the National Marine Fisheries Service provides guidelines for defining distinct population segments below the taxonomic level of species (USFWS-NMFS 1996). The first of two elements to be considered is the discreteness of a population segment with respect to the rest of the populations within the species. Discreteness may result from physical factors that isolate the population segment and may be reflected as life-history differences in physiology, ecology, or behavior between the DPS and other populations. Genetic or morphological differences between the population segment being considered, and other populations, may also be used to evaluate discreteness. The policy also states that international boundaries within the geographical range of the species may be used to delimit a distinct population segment in the United States. This criterion is applicable if differences in the control of exploitation of the species, the management of the species' habitat, the conservation status of the species, or regulatory mechanisms differ between countries that would influence the conservation status of the population segment in the United States. In past assessments of evolutionarily significant units (ESUs) in Pacific salmon, however, NMFS has placed the emphasis on biological information in defining DPSs and has considered political boundaries only at the implementation of ESA listings.

A second element in defining distinct population segments is that the segment must be biologically or ecologically significant. Significance is evaluated in terms of the importance of the population segment to the overall welfare of the species and may be considered in the light of, but not limited to, the following factors. The population segment may be considered significant if it persists in an unusual or unique ecological setting for the species. A population segment may also be considered significant, if its loss would result in a significant gap in the geographical range of the species. Such a gap may disrupt the normal connectivity between populations. A segment also meets the significance guideline, if it represents the only surviving natural occurrence of the species that may be more abundant elsewhere as an introduced population outside its historical range. Another guideline is that the population segment differs markedly in its genetic characteristics from other populations of the species. Genetic differences may be detected by molecular genetic methods or may be reflected in unique adaptations to habitats not found in other parts of the species' geographical range. Other classes of information may also bear on the biological or ecological importance of a distinct population segment.

We considered several kinds of information in this status review to attempt to delineate DPSs of Pacific hake, Pacific cod, and walleye pollock in Puget Sound. The first kind of information was habitat characteristics that might indicate the population segment occupies an unusual or unique ecological setting for the species as a whole. The second kind of information was to consider geographical variability in phenotypic and life-history traits that may reflect local adaptation. Such traits may have an underlying genetic basis, but are often strongly influenced by environmental factors from one locality to another. The third kind of information consisted of mark-recapture studies, which give insight into the physical movement of individuals between areas. The fourth kind of information consisted of traits that are inherited in a predictable way and remain unchanged throughout the life of an individual. Differences among populations in the frequencies of these genetically-determined traits may reflect isolation between the populations.

In order to properly evaluate data and information on fish populations in Puget Sound, similar information was gathered for each biological species, as a whole, to provide a context in which to determine whether Puget Sound populations are distinct. Therefore, reference data were gathered on Pacific hake, Pacific cod, and walleye pollock from throughout their ranges. Not all types of biological data were available for each of the three species under review but an effort was made to utilize the best scientific information available at the time. The kinds of information analyzed and the relative usefulness of this information in delineating DPSs for marine fish in general are discussed briefly in the following sections.

Habitat Characteristics

The analysis of habitat characteristics may indicate that a population segment occupies an unusual or distinctive habitat, relative to the biological species as a whole. The persistence of a discrete population segment in an ecological setting unusual or unique for the taxon is one factor identified in the joint DPS policy (USFWS-NMFS 1996) that may provide evidence of the population's significance. However, Waples (1991a, p. 15) cautioned against "drawing inferences based on physical characteristics of the habitat without supporting biological information linking the habitat differences to adaptations."

Conversely, the continuous distribution of a population segment within a region possessing similar habitat and ecological characteristics makes it less likely that unique adaptations have arisen in local populations. Without associated compelling phenetic or genetic evidence for a finer population structure, marine fish continuously distributed throughout similar habitat and lacking physical or behavioral barriers to migration are not likely to be composed of multiple DPSs.

Phenotypic and Life History Traits

Isolation between populations may be reflected in several life history variables, including differences in behavior (e.g., spawning timing, migration) and demography (e.g., growth rate, fecundity, age structure), among others. Although some of these traits may have a broad genetic basis and may reflect local adaptations of evolutionary importance, they are usually strongly influenced by environmental factors over the life time of an individual or over a few generations. Differences can arise among populations in response to environmental variability among areas and they can sometimes be used to infer the degree of independence among populations. However, differences in phenotypic and life-history traits among populations do not provide definitive information on reproductive isolation between populations, because the genetic basis of many phenotypic and life-history traits is weak or unknown. Likewise, elemental profiles present in otoliths, and other structures, reflect local environmental conditions or diets and although they may indicate that different areas or environments are occupied, they also provide little definitive information on the degree of reproductive isolation between populations.

Variation in reproductive behavior within a species of marine fish is an important factor to consider because it may provide the isolating mechanism required for differentiation. The presence of geographically-discrete and temporally-persistent spawning aggregations in a species indicates that reproductive isolation may be occurring. However, it is necessary to evaluate the degree of reproductive isolation by addressing the questions of migration rate, gene flow, and recolonization rate. These later considerations are dependent on the degree of homing ability and natal-site fidelity of adults.

Studies of parasite incidence can provide important information about the degree of intermingling of marine fish stocks, particularly when a parasite is present in one area and totally absent in an adjoining area. However, parasite studies have some inherent interpretation problems: 1) in most cases parasite incidences exhibit clinal trends with latitude, and the degree to which parasite occurrence is due to environmental differences, acting on the parasite, or to a lack of host stock intermingling, is unknown, 2) the lack of a parasite in an area may be due to a regional absence of an alternate host organism, independent of host distribution, and 3) parasites may not be permanent natural tags in that parasites may be lost during the lifetime of the host.

Mark/Recapture Studies

The analysis of applied or acquired tags can indicate the degree of migration between localities. These tags consist of physical tags that are attached to a fish and later recovered. These tags provide evidence of movement of individuals from one place to another, but not necessarily of population connectivity through gene flow. Since these kinds of population markers largely lack a genetic basis and are not inherited, they must be applied each generation or must arise naturally anew each generation.

The application and recovery of physical tags on adult marine fish on spawning grounds can answer the question of whether fish return to the same locality to spawn in subsequent years, but these studies lack the direct evidence of parent-offspring linkage. In other words, these studies do not provide direct evidence that fish return to their natal area for spawning; however, they may provide evidence of straying and thus, the potential for gene flow between spawning aggregations.

Morphological Differentiation

Two problems inherent in the use of morphometric and meristic characteristics to separate marine fish populations are that: 1) the characteristics are often under strong environmental influence and are not inherited in a simple Mendelian fashion, and 2) the characteristics are continuously variable and exhibit clinal trends and a high variance about the mean. A further drawback of using morphometric and meristic characteristics to detect population structure in fish is that few of these characteristics have been examined from a genetic standpoint. As shown by studies on several species, environmental parameters such as temperature, salinity, pH, and oxygen concentration can modify the expression of genes responsible for meristic characters (see references in Ihssen et al. 1981).

Genetic Differentiation

The BRT considered molecular genetic evidence that might be used to define reproductively isolated populations or groups of populations of Pacific hake, Pacific cod, and walleye pollock in Puget Sound, as well as throughout their respective ranges. Molecular genetic markers appear to be largely unaffected by natural selection, so that geographical differences in gene frequencies can be interpreted in terms of genetic flow and genetic drift. The analysis of the geographical distributions of these markers may reveal historical dispersals, equilibrium levels of migration (gene flow), and past isolation. Evidence for genetic population structure is based on the analysis of protein variants (allozymes), microsatellite loci (variable numbers of short tandem DNA repeats), and mitochondrial DNA (mtDNA).

Evidence of substantial genetic divergence between populations, as shown through analysis of these neutral molecular markers, is an important aspect of distinctiveness because even a small amount of interbreeding between populations will reduce the genetic differentiation between them. Although these molecular genetic methods "provide valuable insight into the process of genetic differentiation among populations" they offer "little direct information regarding the extent of adaptive genetic differences" (Waples 1995).

One widely used method of population analysis is sequence or RFLP (restriction fragment length polymorphism) analysis of mtDNA, which codes for several genes that are not found in the cell nucleus. Mitochondrial DNA differs from nuclear DNA (nDNA) in two important ways. One way is that recombination is lacking in mtDNA, so that gene combinations (haplotypes) are passed unaltered from one generation to the next, except for new mutations. A second way is that mtDNA is inherited from only the maternal parent in most fishes, so that gene phylogenies correspond to female lineages. A greater amount of random genetic drift among populations is expected for mtDNA genes, because the effective population size for mtDNA is about one-fourth of that for nuclear genes. These characteristics permit phylogeographical analyses of mtDNA haplotypes, which can potentially indicate dispersal pathways for females and the extent of gene flow between populations (Avise et al. 1987).

Microsatellite DNA markers can potentially detect stock structure on finer spatial and temporal scales than can other DNA or protein markers, because of higher levels of polymorphism found in microsatellite DNA (reflecting a high mutation rate). When populations are at least partially isolated, genetic markers at loci with high mutation rates may accumulate more rapidly in some areas than in others.

Statistical methods

Several standard statistical methods have been used to analyze molecular genetic data to detect reproductive isolation between populations. Comparisons of genotypic frequencies in a sample with frequencies expected under random mating (Hardy-Weinberg proportions) may be used to infer the breeding structure of a population or to detect population mixing (Wahlund's effect). Contingency-table comparisons of allozyme or microsatellite allele frequencies among population samples with chi-square or *G* (log-likelihood ratio) test statistics, or with randomization tests, can be used to detect significant differences between populations, which may be evidence of reproductive isolation.

A complementary way of assessing genetic isolation between populations is to analyze genetic distances based on allele-frequency estimates. Several genetic distance measures (e.g., Cavalli-Sforza and Edwards 1967; Nei 1972, 1978) have been used to study the population genetic structure of anadromous salmonids. It is unclear, however, which measure is most appropriate in a particular case or whether there is one measure that is always most appropriate. Discussions of the features of genetic distances appear in Nei (1978), Rogers (1991), and Hillis et al. (1996). Most of this discussion has focused on the merits of the various measures for phylogenetic reconstruction among species or higher taxa.

Sample sizes and heterozygosity may also influence the power of the genetic distance approach to resolving genetic population structure. When sample sizes used to estimate allelic frequencies are 50 individuals or more, the difference between Nei's genetic distance, *D*, (Nei 1972) and Nei's unbiased genetic distance (Nei 1978) is small in absolute terms, but still might be a substantial proportion of *D*, if *D* is small. When genetic distances between populations are also small, as they often are between populations of marine fishes, low but significant levels of genetic differentiation may not be detected by an unbiased distance measure because sample size corrections may reduce estimates of genetic distance to zero. These measures range from 0.0 (identity) to infinity (complete dissimilarity). In most cases, the different genetic-distance measures yield highly-correlated results.

The degree of reproductive isolation between populations can be inferred from an analysis of the pattern of genetic distances between populations. Clustering methods, such as the unweighted pair group method with averages (UPGMA, Sneath and Sokal 1973) and the neighbor-joining method (Saitou and Nei 1987), find hierarchical groupings of genetically similar populations. Multivariate methods, such as multidimensional scaling (MDS, Kruskal 1964) or principal components analysis (PCA), find groupings of genetically-similar populations in several dimensions, which are depicted here in two or three dimensions.

Various studies have estimated levels of genetic variability within populations, because the level of within-population variability may reflect evolutionary or historical differences in population size and in migration patterns between populations. Within-population gene diversity was measured by the expected proportion of heterozygous genotypes in a population of randomly mating individuals averaged over the number of loci examined (*H*). Estimates of *H* based on a small number of individuals are usually accurate, as long as a large number of loci (>30) are surveyed for variability (Nei 1978).

Genetic differentiation between populations at various hierarchical levels has been estimated in many studies with a gene diversity analysis (Nei 1973, Chakraborty 1980), which apportions allele-frequency variability among populations into its geographical or ecological components. For example, the proportion of the total genetic variability in a set of samples that is due to differences among populations may be estimated with F_{ST} or the multiallelic equivalent statistics, G_{ST}. These variables range from 0.0 (no difference among populations) to 1.0 (fixed allele-frequency differences). The range 0.05-0.15 for F_{ST} indicates moderate differentiation, and the range 0.15-0.25 indicates strong genetic differentiation among populations (Wright 1978). These statistics facilitate comparisons among groups of populations that may reveal regional differences in gene flow between populations.

Relationship of DPS and Stock Concepts

The term "stock" has been used rather loosely in fisheries management and no single definition has been accepted by all fisheries biologists. Stock may be used to refer to groups of fish being harvested in a particular area, whether these fish are genetically related or not. However, in most cases, identification of a group of fish as a stock implies that these fish are in some way different or distinct from those in another stock, and generally implies some genetic relatedness among its members (Ihssen et al. 1981). Evidence of stock structure may be shown through differences in demographic population statistics (age composition, growth rate, fecundity, etc.), morphology (morphometrics and meristics), or genetics (differentiation at allozyme or DNA loci).

Ricker (1972, p. 28) defined a salmon stock as "the fish spawning in a particular lake or stream (or portion of it) at a particular season, which fish to a substantial degree do not interbreed with any group spawning in a different place, or in the same place at a different season." Larkin (1972) defined a stock as "a population of organisms, which, sharing a common environment and participating in a common gene pool, is sufficiently discrete to warrant consideration as a self-perpetuating system which can be managed." Booke (1981) provided a general definition of a stock as "a species group, or population, of fish that maintains and sustains itself over time in a definable area." Ihssen et al. (1981) defined a stock as "an intraspecific group of randomly mating individuals with temporal or spatial integrity." In none of these definitions is it implied that a fish stock is ecologically or biologically significant in relation to the biological species as a whole.

By contrast, not only must a marine fish DPS be "markedly separated from other populations of the same taxon," it must also exhibit ecological or biological significance in comparison to other population segments of the biological species. Thus, following the guidance supplied by the joint policy statement (USFWS-NMFS 1996), a distinct population segment of marine fish may be viewed as a group of related stocks (or in some cases, if the evidence warrants, a single stock) that form(s) a discrete population and are(is) significant to the biological species as a whole. As stated previously, considerations that can be used to determine a discrete population's significance to the taxon as a whole include: 1) persistence of the population segment in an ecological setting unusual or unique for the taxon, 2) evidence that loss of the population segment would result in a significant gap in the range of the taxon, 3) evidence that the population segment represents the only surviving natural occurrence of a taxon that may be more abundant elsewhere as an introduced population outside its historic range, and 4) evidence that the population segment differs markedly from other populations of the species in its genetic characteristics.

Evaluating Risk of Extinction

The ESA (Section 3) defines "endangered species" as "any species which is in danger of extinction throughout all or a significant portion of its range." "Threatened species" is defined as "any species which is likely to become an endangered species within the foreseeable future throughout all or a significant portion of its range." NMFS considers a variety of information in evaluating the level of risk faced by a DPS, including: 1) absolute numbers of fish and their spatial and temporal distributions, 2) current abundance in relation to historical abundance and carrying capacity of the habitat, 3) trends in abundance, based on indices such as catch statistics, CPUE, and spawner-recruit ratios, 4) natural and human-influenced factors that cause variability in survival and abundance, 5) possible threats to genetic integrity (e.g., selective fisheries and interactions between cultured and natural populations), and 6) recent events (e.g., climate change and changes in management) that have predictable short-term consequences for the abundance of a DPS. Additional risk factors, such as disease prevalence or changes in life-history traits, also may be considered in the evaluation of risk to a population.

The determination of whether a species is threatened or endangered, according to the ESA, should be based on the best scientific information available, after taking into consideration conservation measures that are proposed or in place. The BRT did not evaluate likely or possible effects of conservation measures. Therefore, they did not make recommendations on whether DPSs should be listed as threatened or endangered species, because that determination requires evaluation of factors not considered by the BRT. However, the BRT did draw scientific conclusions about the risk of extinction faced by DPSs, under the assumption that present conditions will continue, and recognizing that natural demographical and environmental variability is an inherent feature of present conditions. Conservation measures will be taken into account by the NMFS's Northwest Regional Office in making listing recommendations. The following sections summarize the kinds of information the BRT considered in evaluating the potential effects of risk factors on the each of the DPSs identified by the BRT.

Absolute Numbers

The absolute number of individuals in a population is important in assessing two aspects of extinction risk. First, population sizes of small populations that are stable or increasing can be an indicator of whether the population can sustain itself in the face of environmental fluctuations and small-population stochasticity. This conclusion follows from the theory of minimum viable populations (see Gilpin and Soulé 1986, Thompson 1991). Second, present abundance in a declining population is an indicator of the time expected until the population reaches critically low numbers. This follows from the idea of "driven extinction" (Caughley 1994). In addition to absolute numbers, the spatial and temporal distributions of adults are important in assessing risk to a DPS. Spatial distribution is important, both at the scale of the spawning population and the metapopulation.

Assessments of marine fish populations have focused on the biomass or numbers of adults harvested by commercial and sports fishing. Catch records, CPUE, and biomass estimates from research cruises constitute most of the data available to estimate abundance trends. However, the numbers of reproductive adults is the most important measure of abundance in assessing the status of a population. Data on other life-history stages can be used as a supplemental indicator of abundance.

Historical Abundances and Carrying Capacity

The relationship of present abundance to present carrying capacity is important for evaluating the health of a population, but a population with abundance near the carrying capacity of the habitat it occupies does not necessarily indicate that the population is healthy. Populations abundances near carrying capacity imply that the effectiveness of short-term management actions is limited in increasing population abundance. The relationship between current abundance and habitat capacity to the historical relationship between these variables is an important consideration in evaluating risk. An understanding of historical conditions provides a perspective of the conditions under which present populations evolved. Estimates of historical abundances also provide the basis for establishing long-term abundance trends. Comparisons of past and present habitat capacity can also indicate long-term population trends and potential problems stemming from population fragmentation.

Trends in Abundance

Short- and long-term trends in abundance are primary indicators of risk in natural populations. Trends may be calculated with a variety of quantitative data, including catch, CPUE, and survey data. Trend analyses for the three species considered in this review is greatly limited by the lack of long time series of abundances in Puget Sound. The times series of abundance estimates that are available are limited in their usefulness by the lack of regular sampling, by use of different survey methods for a species, and, for harvest data, by the imposition of harvest regulations. The influence of environmental variability on population abundances also limits the use of short-term trends, because the climate changes in the late 1970s and 1980s coincided with apparent declines in population abundances for each of the three species being considered in this review.

Factors Influencing Abundance

Several natural and anthropogenic factors influence the degrees of risk facing populations of marine fish in Puget Sound. Recent changes in these factors may influence the degree of risk of a population without apparent changes in abundance, because of time lags between the events and the effects on the population. Thus, a consideration of these effects extends beyond the examination of recent trends in abundance. The BRT considered documented physical and climatic changes, but did not consider possible effects of recent or proposed conservation measures. Population variability in itself may not be an indication of risk, because populations in Puget Sound for two of the species considered in this review are at the margins of the geographical distribution of the species, and thus have evolved in a variable environment. Habitat degradation and harvest have most likely weakened the resilience of populations in Puget Sound to climate variability. However, these effects are not easily quantified.

Threats to Genetic Integrity

Artificial propagation and enhancement of populations in Puget Sound does not presently appear to be a risk factor for the species considered here. However, mariculture of some species is under development, and the effects of hatchery releases on natural populations may be important in the future. The interbreeding of cultured and natural fish can potentially lead to a loss in fitness of naturally-spawning populations. The genetic effects of artificially propagated releases of species with high fecundities, as is common for many marine fishes, could be substantial. Ryman and Lairkre (1991), Waples and Do (1994), and Ryman et al. (1995) discussed possible risks associated with enhancement of marine populations, but these risks are difficult to quantify and to incorporate into risk analysis. The chief concern is that the release of propagated fish, which may be inadvertently modified by breeding practices and novel rearing environments, may lead to the erosion of genetic diversity and fitness in natural populations.

Human activities other than population enhancement can also influence the genetic characteristics of natural populations. These include size-selective harvest methods (Nelson and Soulé 1987), introductions of non-native species, and alterations of marine habitats by shoreline development, by increased siltation in river runoff, and by pollution. At the present time, empirical information documenting the genetic effects of these kinds of changes is largely lacking.

Climate Variability

Coupled changes in climate and ocean conditions have occurred on several different time scales and have influenced the geographical distributions, and hence local abundances, of marine fishes. On time scales of hundreds of millennia, periodic cooling produced several glaciations in the Pleistocene Epoch (Imbrie et al. 1984, Bond et al. 1993). The central part of Puget Sound was covered with ice about 1 km thick during the last glacial maximum about 14,000 years ago (Thorson 1980). Since the end of this major period of cooling, several population oscillations of pelagic fishes, such as anchovies and sardines, have been noted on the west coast of North America (Baumgartner et al. 1992). These oscillations, with periods of about 100 years, have presumably occurred in response to climatic variability. On decadal time scales, climatic variability in the North Pacific and North Atlantic Oceans has influenced the abundances and distributions of widespread species, including several species of Pacific salmon (Francis et al. 1998, Mantua et al. 1997) in the North Pacific, and Atlantic herring (Alheit and Hagen 1997) and Atlantic cod (Swain 1999) in the North Atlantic. Recent declines in marine fish populations in Puget Sound may reflect recent climatic shifts. However, we do not know whether these climatic shifts represent long-term changes or short-term fluctuations that may reverse in the near future. Although recent climatic conditions appear to be within the range of historical conditions, the risks associated with climatic changes may be exacerbated by human activities (Lawson 1993).

ENVIRONMENTAL HISTORY AND FEATURES OF PUGET SOUND

Introduction

This section describes physical, oceanographic, and climatic features in Puget Sound that may contribute to isolation between populations of the three gadiform species considered in this review. This section further provides a basis for identifying climatic and biological factors that may contribute to extinction risk for these species. The following summary primarily considers the marine waters north and west of Puget Sound that lie south of the boundary between Canada and the United States; however, because the three gadiform species are also found in the Strait of Georgia, a brief description the of this system will also be presented. Puget Sound is a fjord-like estuary located in northwest Washington state and covers an area of about 2,330 km^2, including 3,700 km of coastline. It is subdivided into five basins or regions: 1) North Puget Sound, 2) Main Basin, 3) Whidbey Basin, 4) South Puget Sound, and 5) Hood Canal (Figs. 4, 5). The average depth of Puget Sound is 62.5 m at mean low tide, the average surface water temperature is 12.8°C in summer and 7.2°C in winter (Staubitz et al. 1997). Estuarine circulation in Puget Sound is driven by tides, gravitational forces, and freshwater inflows. For example, the average daily difference between high and low tide varies from 2.4 m at the northern end of Puget Sound to 4.6 m at its southern end. Tidal oscillations substantially reduce the flushing rate of nutrients and contaminants. Concentrations of nutrients (i.e., nitrates and phosphates) are consistently high throughout most of the Sound, largely due to the flux of oceanic water into the basin (Harrison et al. 1994). The freshwater inflow into Puget Sound is about 900 million gallons/day (gpd) (3.4 trillion liters /day). The major sources of freshwater are the Skagit and Snohomish Rivers located in Whidbey Basin (Table 1); however the annual amount of freshwater entering Puget Sound is only 10 to 20% of the amount entering the Strait of Georgia, primarily through the Fraser River. The Fraser River has a drainage area of 234,000 km^2 (Bocking 1997). The rate of flow in the Fraser River ranges from an average of 750 m^3/sec in the winter to an average of 11,500 m^3/sec during the spring freshet, although, flows of 20,000 m^3/sec are not uncommon during the spring floods (Bocking 1997).

Eight major habitats occur in Puget Sound; kelps beds and eelgrass meadows cover the largest area, almost 1000 km^2. Other major habitats include subaerial and intertidal wetlands (176 km^2), and mudflats and sandflats (246 km^2). The extent of some of these habitats have markedly declined over the last century. Hutchinson (1988) indicated that overall losses since European settlement, by area, of intertidal habitat were 58% for Puget Sound in general and 18% for the Strait of Georgia. Four river deltas (the Duwamish, Lummi, Puyallup, and Samish) have lost greater than 92% of their intertidal marshes (Simenstad et al. 1982, Schmitt et al. 1994). At least 76% of the wetlands around Puget Sound have been eliminated, especially in urbanized estuaries. Substantial declines of mudflats and sandflats have also occurred in the deltas of these estuaries (Levings and Thom 1994). The human population in the Puget Sound region is estimated to be about 3.6 million.

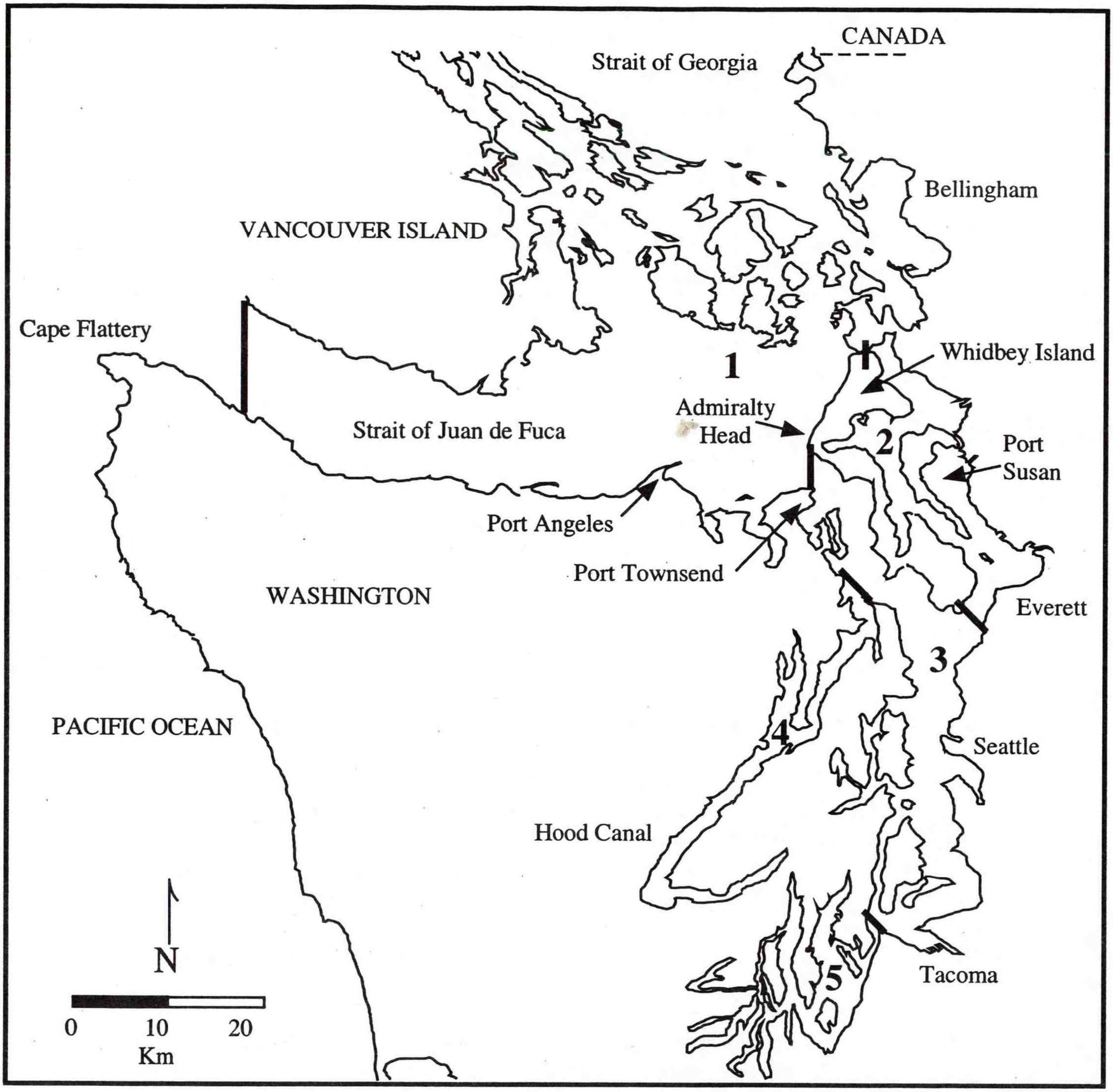

Figure 4. Regional water masses and subareas of Puget Sound: 1) Northern Puget Sound, 2) Whidbey Basin, 3) Main Basin, 4) Hood Canal, and 5) Southern Puget Sound.

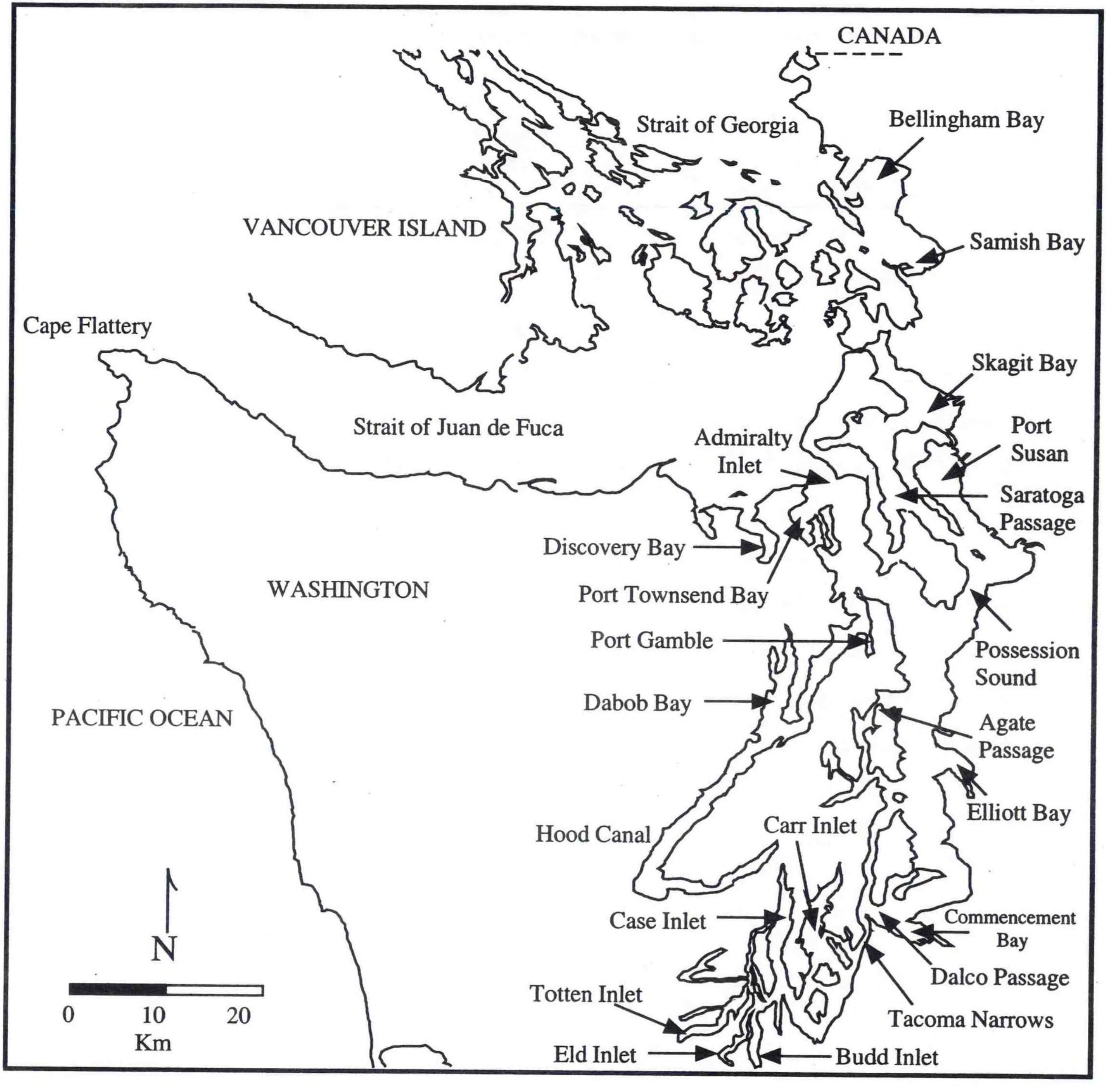

Figure 5. Geographical locations and important water bodies in Puget Sound mentioned in the text.

Table 1. Mean annual streamflow of major Puget Sound streams (from Staubitz et al. 1997). Data converted from U.S. Customary to metric units.

Gaging Station Name	Drainage area (km²)	Mean annual flow (m³/sec)	Mean annual runoff (cm)	Period of record (years)
Nooksack River at Ferndale	2,036	87.3	168	27
Samish River near Burlington	228	6.9	96	28
Skagit River near Mt. Vernon	8,011	469.9	185	53
N. F. Stillaguamish River at Arlington	679	53.5	249	65
Snohomish River near Monroe	3,981	270.1	214	30
Cedar River at Renton	477	18.9	125	48
Green River at Tukwila	1,140	42.2	117	27
Puyallup River at Puyallup	2,455	94.3	121	79
Nisqually River at McKenna	1,339	36.5	86	39
Deschutes River at Tumwater	420	9.3	70	6
Skokomish River near Potlatch	588	33.4	76	52
Dosewallips River near Brinnon	244	10.7	305	20
Dungeness River near Sequim	404	10.7	83	67
Elwha River near Port Angeles	697	42.5	192	83

Geological and Climatic History

Geological History

The Puget Sound Basin falls within the Puget Lowland, a portion of a low lying area extending from the lower Fraser River Valley southward to the Willamette Lowland (Burns 1985). In the distant past, the Puget Lowland was drained by numerous small rivers that flowed northward from the Cascade and Olympic mountains and emptied into an earlier configuration of the Strait of Juan de Fuca. During the Pleistocene, massive Piedmont glaciers, as much as 1,100 m thick, moved southward from the Coast Mountains of British Columbia and carved out the Strait of Juan de Fuca and Puget Sound. The deepest basins were created in northern Puget Sound in and around the San Juan Islands. About 15,000 years ago, the southern tongue of the last glacier receded rapidly leaving the lowland covered with glacial deposits and glacial lakes, and revealing the Puget Sound Basin (Burns 1985). The large glacially formed troughs of Puget Sound were initially occupied by large proglacial lakes that drained southward (Thorson 1980). Almost two dozen deltas were developed in these lakes as the result of streams flowing from the melting ice margins.

Climatic History

Considerable evidence indicates that climate in the Puget Sound region is cyclical, with maxima (warm, dry periods) and minima (cold, wet periods) occurring at decadal intervals. For example, according to the Pacific Northwest Index (PNI), since 1893 there have been about five minima and four maxima (Fig. 6) (Ebbesmeyer and Strickland 1995). Three minima occurred between 1893 and 1920, one between the mid 1940s and 1960, and one between the mid 1960s and mid 1970s. Two maxima occurred between the early 1920s and the early 1940s, and two more occurred between the late 1970s and 1997.

Mantua et al. (1997) and Hare and Mantua (2000) evaluated relationships between interdecadal climate variability and fluctuations in the abundance and distribution of marine biota. These authors used statistical methods to identify the Pacific Decadal Oscillation (PDO). The PDO shows predominantly positive epochs between 1925 and 1946 and following 1977, and a negative epoch between 1947 and 1976 (Fig. 7). For Washington State, positive epochs are characterized by increased flow of relatively warm humid air and less than normal precipitation, and the negative epochs correspond to a cool-wet climate. Mantua et al. (1997) reported connections between the PDO and indicators of populations of Alaskan sockeye and pink salmon and Washington-Oregon-California coho and chinook salmon, although the coho and chinook populations were highest during the negative epochs. Hare and Mantua (2000) found evidence for major ecological and climate changes for the decade following 1977 (a positive epoch) (Fig. 8). They also found less powerful evidence of a climate regime shift (a negative epoch) following 1989, demonstrated primarily by ecological changes. Examples of ecological

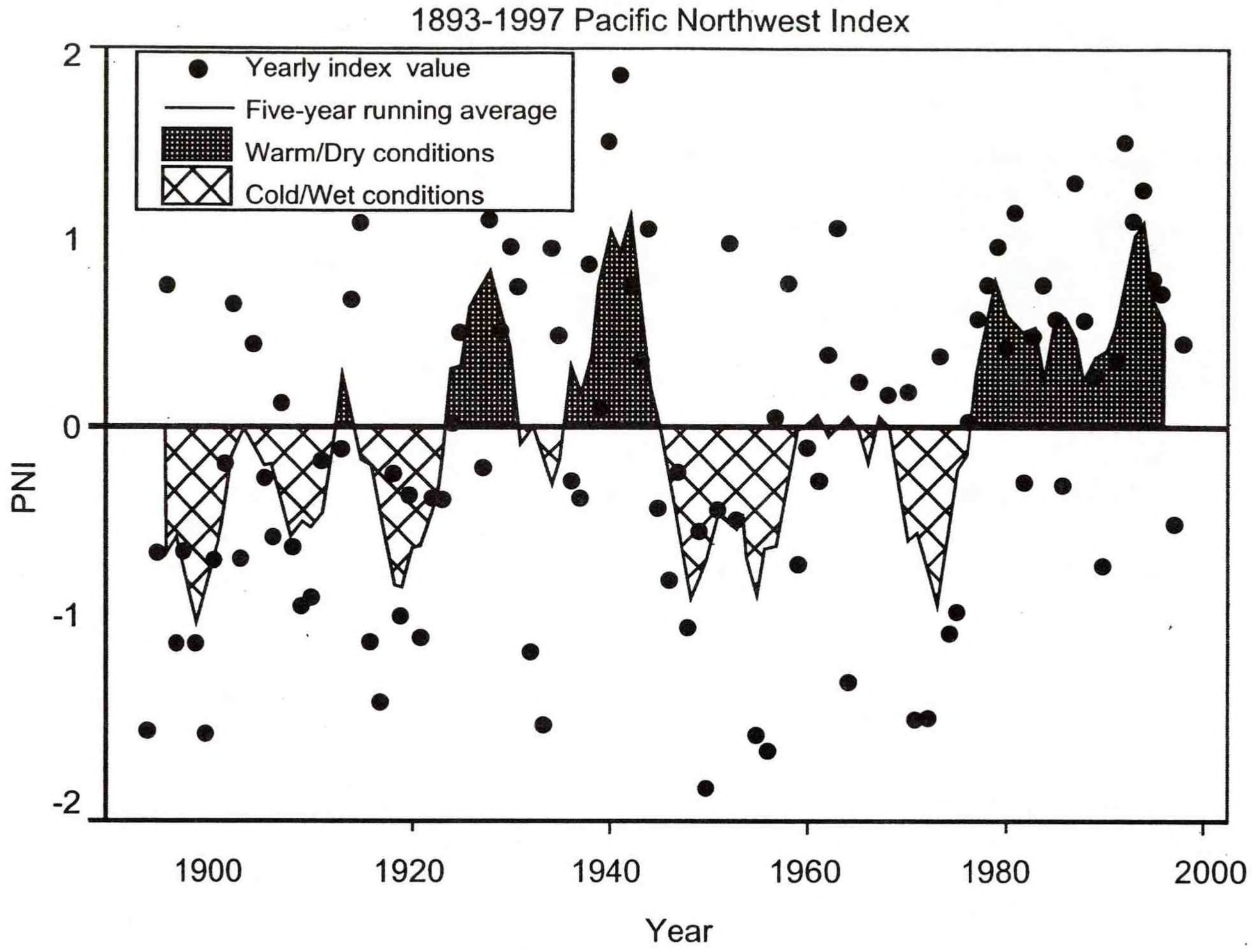

Figure 6. The Pacific Northwest Index (PNI) is a terrestrial climate index that characterizes Pacific Northwest climate patterns in both coastal waters and freshwater habitats. The PNI uses three parameters: 1) air temperature at Olga in the San Juan Islands, averaged annually from daily data; 2) total precipitation at Cedar Lake in the Cascade Mountains; and 3) snowpack depth at Paradise on Mount Rainier on March 15th of each year. Modified after Ebbesmeyer and Strickland (1995).

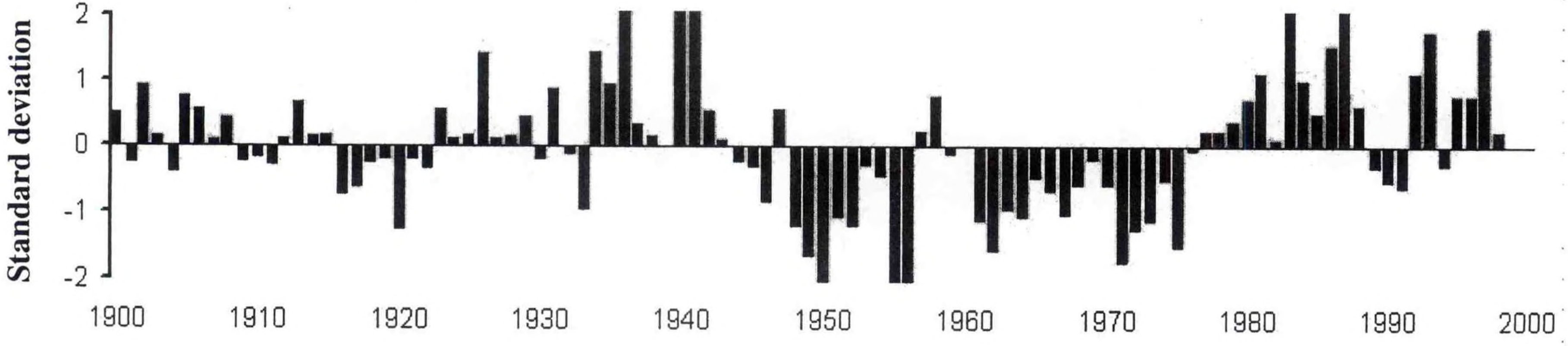

Figure 7. Pacific decadal oscillation index (PDO), annual averages from 1900-98. Positive values indicate warm phases of PDO and negative values indicate cool phases of PDO.

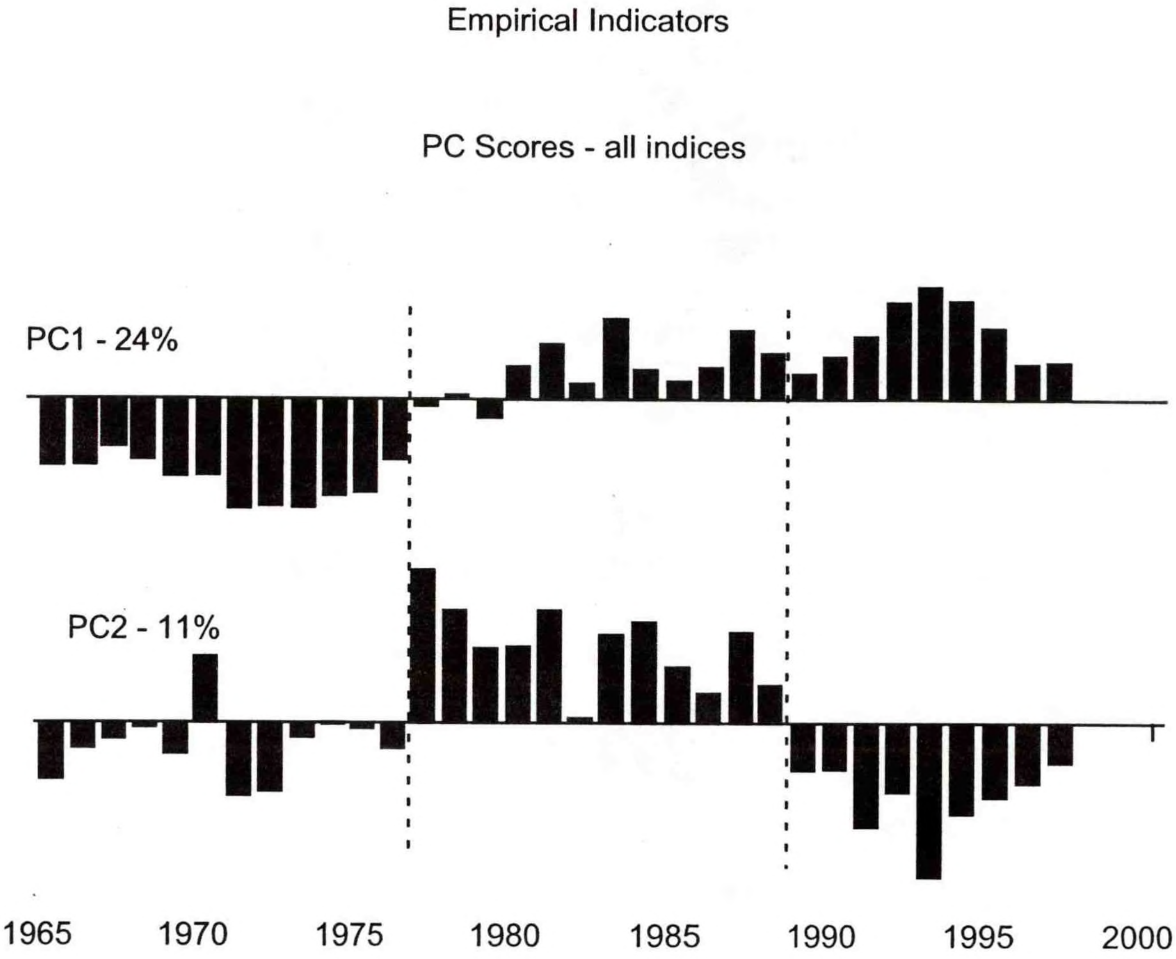

Figure 8. The first two principal component scores from a principal component analysis of 100 environmental time series. Examples of these time series included the Pacific Decadal Oscillation index (PDO); the El Niño/Southern Oscillation index; Arctic Oscillation index; six Alaskan and west coast air temperature records; Bering Sea ice cover; 60 records of biomass, recruitment, and catch data for selected Alaskan and west coast marine and anadromous species; and streamflow records for rivers in Alaska and the Pacific Northwest. Modified after Hare and Mantua (2000).

parameters that were correlated with these decadal changes included annual catches of Alaskan coho and sockeye salmon, annual catches of Washington and Oregon coho and chinook salmon, biomass of zooplankton in the California Current, and the Oyster Condition Index for oysters in Willapa Bay, Washington (Hare and Mantua 2000).

Few climatological records are available prior to the 1890s. Proxy measures of climatic variation have been used to reconstruct temperature fluctuations in the Pacific Northwest. Graumlich and Brubaker (1986) reported correlations between annual growth records for larch and hemlock trees located near Mt. Rainier and temperature and snow depth. A regression model was used to reconstruct temperatures from 1590 to 1913. Their major findings were that temperatures prior to 1900 were approximately 1°C lower than those of the 1900s, and that only the temperature pattern in the late 1600s resembled that of the 1900s.

Oceanographic and Geomorphological Features

Northern Puget Sound

Bathymetry and geomorphology

The North Puget Sound region is demarcated to the north by the U.S.-Canadian border, to the west by a line due north of the Sekiu River, to the south by the Olympic Peninsula, and to the east by a line between Point Wilson (near Port Townsend) and Partridge Point on Whidbey Island and the mainland between Anacortes and Blaine, WA (Fig. 4). The predominant feature of the North Sound is the Strait of Juan de Fuca, which is 160 km long, and 22 km wide at its western end to over 40 km at its eastern end (Thomson 1994).

One of the deepest sections of this region is near the western mouth (about 200 m) (Holbrook et al. 1980), whereas the deepest sections of eastern portions are located northwest of the San Juan Islands (340-380 m) (PSWQA 1987). Subtidal depths range from 20 to 60 m in most of the northwest part of the region. Deeper areas near the entrance to the Main Basin north of Admiralty Inlet range from 120 to 180 m in depth (PSWQA 1987).

Most of the rocky-reef habitat in Puget Sound is located in this region. Pacunski and Palsson (1998) estimated that about 200 km^2 of rocky-reef habitat was present in this region, whereas only about 14 km^2 was found in the remaining Puget Sound basins. Several rockfish species, including copper and quillback rockfish prefer rocky-reef habitats (Pacunski and Palsson 1998).

Sediment characteristics

The surface sediment of the Strait of Juan de Fuca is composed primarily of sand, which tends to be coarser, including some gravel, toward the eastern portion of North Sound and gradually becomes finer towards the mouth (Anderson 1968). Many of the bays and sounds in the eastern portion of the North Sound have subtidal surface sediments consisting of mud or mixtures of mud and sand (PSWQA 1987, WDOE 1998). The area just north of Admiralty Inlet is primarily gravel in its deeper portions, and a mixture of sand and gravel in its shallower portions, whereas the shallow areas north of the inlet on the western side of Whidbey Island and east of Protection Island consist of muddy-sand (Roberts 1979). The majority of the subtidal surface sediments among the San Juan Islands consist of mixtures of mud and sand. Within the intertidal zone, 61.2 ± 49.7% of the area also has mixed fine sediment and 22.6 ± 27.5% has sandy sediment (Bailey et al. 1998).

Currents and tidal activity

The Strait of Juan de Fuca is a weakly stratified, positive estuary with strong tidal currents (Thomson 1994). The western end of the Strait is strongly influenced by ocean processes, whereas the eastern end is influenced by intense tidal action occurring through and near the entrances to numerous narrow passages. Seasonal variability in temperature and salinity is small because the waters are vertically well mixed (Thomson 1994). On average, freshwater runoff makes up about 7% of the water by volume in the Strait and is derived primarily from the Fraser River. Generally, the circulation in the Strait consists of seaward surface flow of diluted seawater (< 30.0‰) in the upper layer and an inshore flow of saline oceanic water (> 33.0‰) at depth (Thomson 1994, Collias et al. 1974). Exceptions include an easterly flow of surface waters near the shoreline between Port Angeles and Dungeness Spit, landward flows of surface waters in many of the embayments and passages, and flows of surface water southward toward the Main Basin near Admiralty Inlet (PSWQA 1987).

Water quality

Temperatures generally range between 7° and 11°C, although occasionally surface temperatures reach as high as 14°C (WDOE 1999). In the eastern portion of North Sound, temperature and salinity vary from north to south, with the waters in the Strait of Georgia being slightly warmer than the waters near Admiralty Inlet. Waters near Admiralty Inlet also tended to have a higher salinities than waters to the north (WDOE 1999). Dissolved oxygen levels vary seasonally, with lowest levels of about 4 mg/L at depth during the summer months, and highest levels of about 8 mg/L near the surface.

Macro vegetation

Eelgrass is the primary vegetation in the intertidal areas of the Strait of Juan de Fuca, covering 42.2 ± 27.2% of the intertidal area (Fig. 9), and green algae is the second most common covering 4.4 ± 3.7% of the intertidal area (Bailey et al. 1998). About 45% of the shoreline of this region consists of kelp habitat, compared to only 11% of the shoreline of the four Puget Sound Basins (Shaffer 1998). Nevertheless, both areas each have approximately 50% of the total kelp resource. Most species of kelp are associated with shoreline exposed to wave action, whereas eelgrass is found in protected areas, such as Samish and Padilla Bays (Fig. 10). Some of the densest kelp beds in Puget Sound are found in the Strait of Juan de Fuca. Kelp beds at the north end of Protection Island declined drastically between 1989 and 1997, decreasing from about 181 acres to "nothing" (Sewell 1999). The cause of this decline is currently unknown.

Urban, industrial, and agricultural development

The North Puget Sound Basin is bordered primarily by rural areas with a few localized industrial developments (PSWQA 1988). About 71% of the area draining into North Sound is forested, 6% is urbanized, and 15% is used for agriculture. This area, among the five Puget Sound basins, is used most heavily for agriculture. The main human population in this area centers around Port Angeles (1996 population census 19,200), Port Townsend (7,000), Anacortes (11,500), and Bellingham (58,300). About 10% of the total amount of wastes discharged from point-sources into Puget Sound comes from urban and industrial sources in this basin (PSWQA 1988). About 17% of the nutrients (in the form of inorganic nitrogen) entering Puget Sound originate from rivers carrying runoff from areas of agricultural and forest production (Embrey and Inkpen 1998). The Washington State Department of Natural Resources (WDNR 1998) estimated that 21% of the shoreline in this area has been modified by human activities.

Main Basin

Bathymetry and geomorphology

The 75 km-long Main Basin is delimited to the north by a line between Point Wilson (near Port Townsend) and Partridge Point on Whidbey Island, to the south by Tacoma Narrows, and to the east by a line between Possession Point on Whidbey Island and Meadow Point (near Everett) (Fig. 4). The western portion of the Main Basin includes such water bodies as Sinclair and Dyes inlets, and Colvos and Dalco passages. Large embayments on the east side include Elliott and Commencement bays.

Among of the most important bathymetric features of the Main Basin are the sills at its northern and southern ends. The sill at the north end of Admiralty Inlet is 30 km wide and is 65 m deep at its shallowest point. The sill at Tacoma Narrows is 45 m deep (Burns 1985). South of Admiralty Inlet, depths generally range from 100 to 140 m in the central part of the basin, and 10 to 100 m in the waterways west of Bainbridge and Vashon islands. The central basin consists of five sub-basins: 1) one near the southern end of Admiralty Inlet, west of Marrowstone Island, with depths to 190 m, 2) one near the southern tip of Whidbey Island with depths to 250 m, 3) one west of Port Madison, north of Seattle with depths to 290 m, and 4) one south of Seattle, near Point Pulley, with depths to about 250 m (Burns 1985). Elliott and Commencement bays, associated with Seattle and Tacoma, respectively, are relatively deep, with depths in excess of 150 m. Freshwater flows into Elliott Bay through the Duwamish-Green River System, and into Commencement Bay through the Puyallup River.

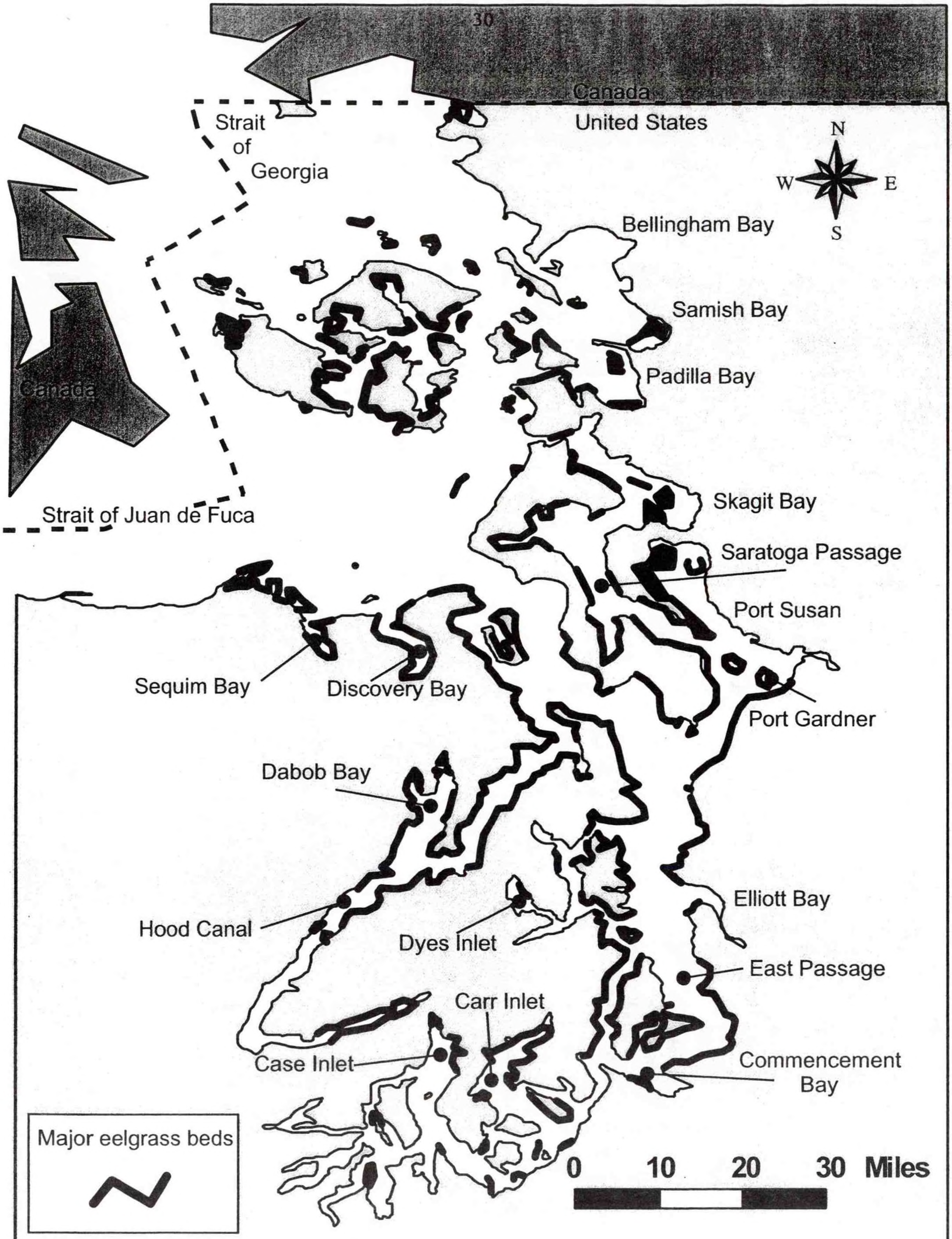

Figure 9. Locations of major eelgrass beds in Puget Sound (PSWQA 1987).

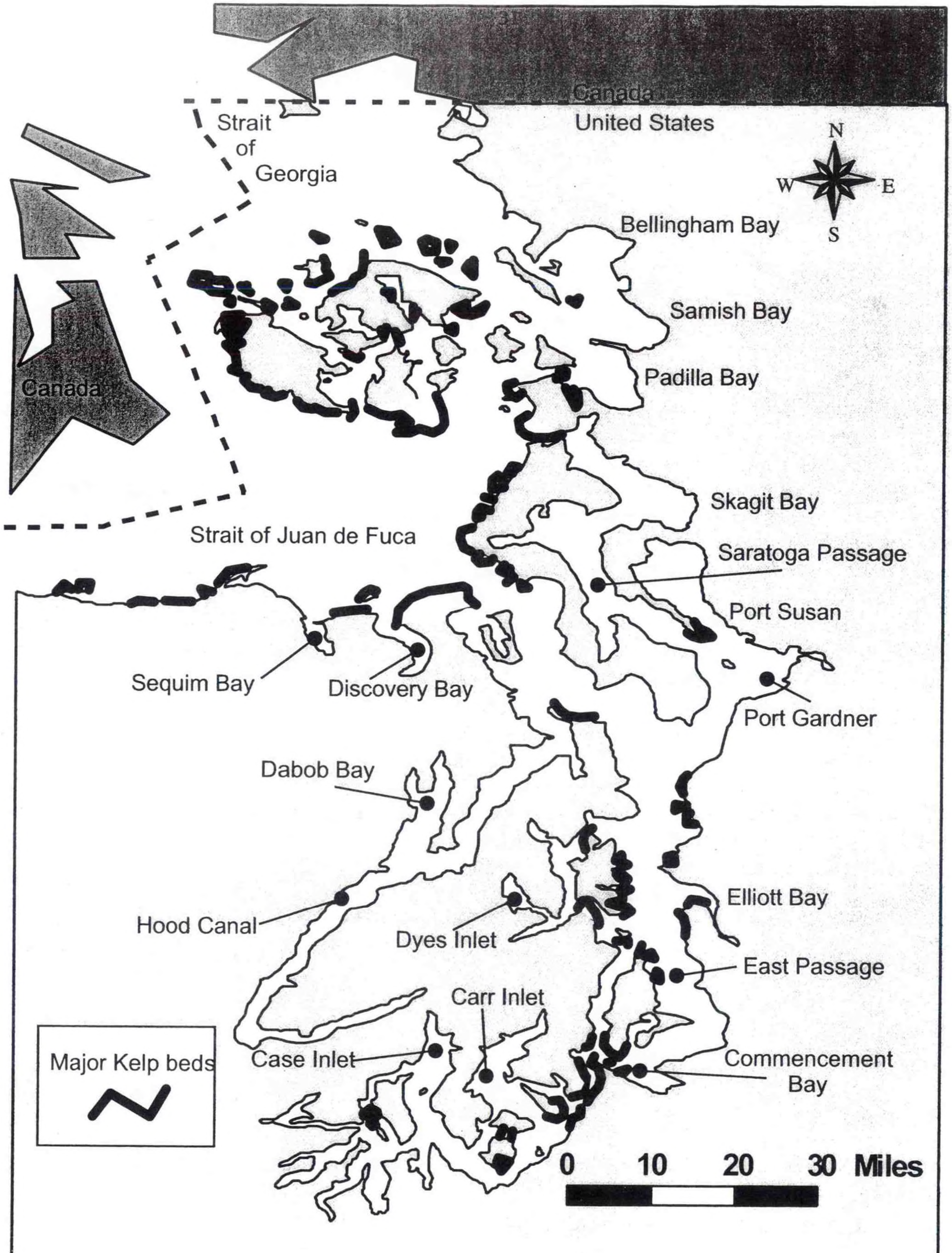

Figure 10. Locations of major kelp beds in Puget Sound (PSWQA 1987).

Sediment characteristics

Subtidal surface sediments in Admiralty Inlet tend to consist largely of sand and gravel, whereas sediments just south of the inlet and southwest of Whidbey Island are primarily sand (PSWQA 1987). Sediments in the deeper areas of the central portion of the Main Basin generally consist of mud or sandy mud (PSWQA 1987, WDOE 1998). Sediments in the shallower and intertidal areas of the Main Basin are mixed mud, sand, and gravel. Bailey et al. (1998) reported that 92% of the intertidal area of the Main Basin consisted of mixed sand and gravel. A similar pattern is also found in the bays and inlets bordering this basin.

Currents and tidal activity

About 30% of the freshwater flow into the Main Basin is derived from the Skagit River. The Main Basin is generally stratified in the summer, due to river discharge and solar heating, and is often well mixed in the winter due to winter cooling and increased mixing by wind. Circulation in the central and northern sections of the Main Basin consists largely of outflow through Admiralty Inlet in the upper layer and inflow of marine waters at depth (below approximately 50 m) (Figs. 11A, 11B) (Strickland 1983, Thomson 1994). Oceanic waters from the Strait of Juan de Fuca flow over the northern sill at Admiralty Inlet into the Main Basin at about two-week intervals (Cannon 1983). In the southern section, currents generally flow northward along the west side of Vashon Island and southward on the east side through Colvos Passage. The sill at Tacoma Narrows also causes an upwelling process that reduces the seawater/freshwater stratification in this basin. With freshwater inflow, comes sediment deposits at an estimated rate of 0.18 to 1.2 grams/cm²/year (Staubitz et al. 1997).

Major circulation patterns in the Main Basin are greatly influenced by decadal climate regimes (Ebbesmeyer et al. 1998). During cool periods with strong oceanic upwellings and heavy precipitation, the strongest oceanic currents entering from the Strait of Juan de Fuca flow near mid-depth when the basin is cooler than 9.7°C. However, the strongest oceanic currents move toward the bottom of the basin, during warmer, dryer periods when waters are warmer than 9.7°C.

Water quality

Water temperature, salinity, and concentration of dissolved oxygen in waters of the Main Basin are routinely measured by the WDOE at six sites (WDOE 1999). Subsurface temperatures are usually between 8° and 12°C; however, surface temperatures can reach 15 to 18°C in summer, and temperatures at depth can get as low as 7.5°C in winter. Salinities in the deeper portions of the Main Basin are generally about 30‰ in summer and fall, but decrease to about 29‰ during the rainier months. Surface waters are also usually about 29‰, but occasionally have salinities as low as 25-27‰ during the rainy season (WDOE 1999).

The mid-basin site had consistently higher temperatures and lower salinity values compared to the water quality parameters at the site near the northern entrance to Admiralty Inlet (WDOE 1999). To demonstrate this trend, values from near mid-basin at West Point in Seattle, considered to be representative of this basin, were compared to values from the northern end of Admiralty Inlet. Values measured on the same dates (a summer month and a winter month) and depths at each site for two different years (1993 and 1996) were compared. For the summer month, the mean temperature at mid-basin site was 12.25°C vs. 9.19°C for the entrance site. The mean salinities for this same month were 29.65‰ and 31.43‰, respectively. For the winter month, the mean temperature at mid basin site was 9.71°C and 8.11°C for the entrance site. The mean salinity values for this same month were 30.24‰ and 30.84‰, respectively.

Dissolved oxygen varies seasonally, with lowest levels of about 5.5 mg/L occurring at depth in summer months, and highest levels of about 7.5 mg/L near the surface. Occasionally summertime highs reach 13-14 mg/L at the surface.
Figures 11A and 11B.

Macro vegetation

The Main Basin has a relatively small amount of intertidal vegetation, with 28.3 ± 10.4% of the intertidal area containing vegetation (Bailey et al. 1998). The predominant types are green algae (12.0 ± 4.4%) and eelgrass (11.4 ± 6.6%). Most eelgrass is located on the western shores of Whidbey Island and the eastern shores of the Kitsap Peninsula (Fig. 9) (PSWQA 1987). Although Figure 9 suggests a continuous distribution of eel grass on the eastern shores of the Main Basin, a recent report by the Puget Sound Water Quality Action Team (PSWQAT 2000) indicates that only 8% of the shoreline has a continuous distribution of eelgrass beds and 40% of the shoreline has a patchy distribution.

Urban, industrial, and agricultural development

Areas bordering the Main Basin include the major urban and industrial areas of Puget Sound: Seattle, Tacoma, and Bremerton. Human population sizes for these cities are about 522,500, 182,900, and 44,000, respectively (1996 census). Approximately 70% of the drainage area in this basin is forested, 23% is urbanized, and 4% is used for agriculture (Staubitz et al. 1997). About 80% of the total amount of waste discharged from point-sources into Puget Sound comes from urban and industrial sources in this region (PSWQA 1988). Moreover, about 16% of the waste entering Puget Sound, overall, enters this basin through its major river systems, in the form of inorganic nitrogen (Embrey and Inkpen 1998). The Washington State DNR (1998) estimates that 52% of the shoreline in this area has been modified by human activities.

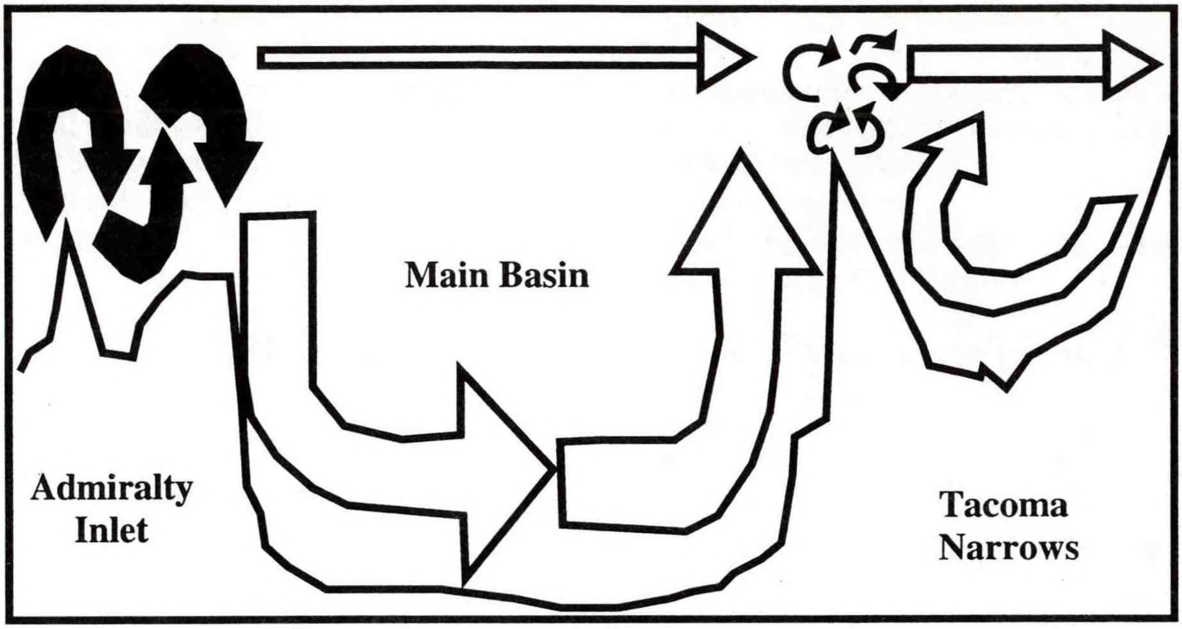

Figure 11A. Schematic of Puget Sound circulation during flood tide. Gray arrows represent strong vertical mixing. Light arrows represent horizontal currents. Modified after Strickland (1983).

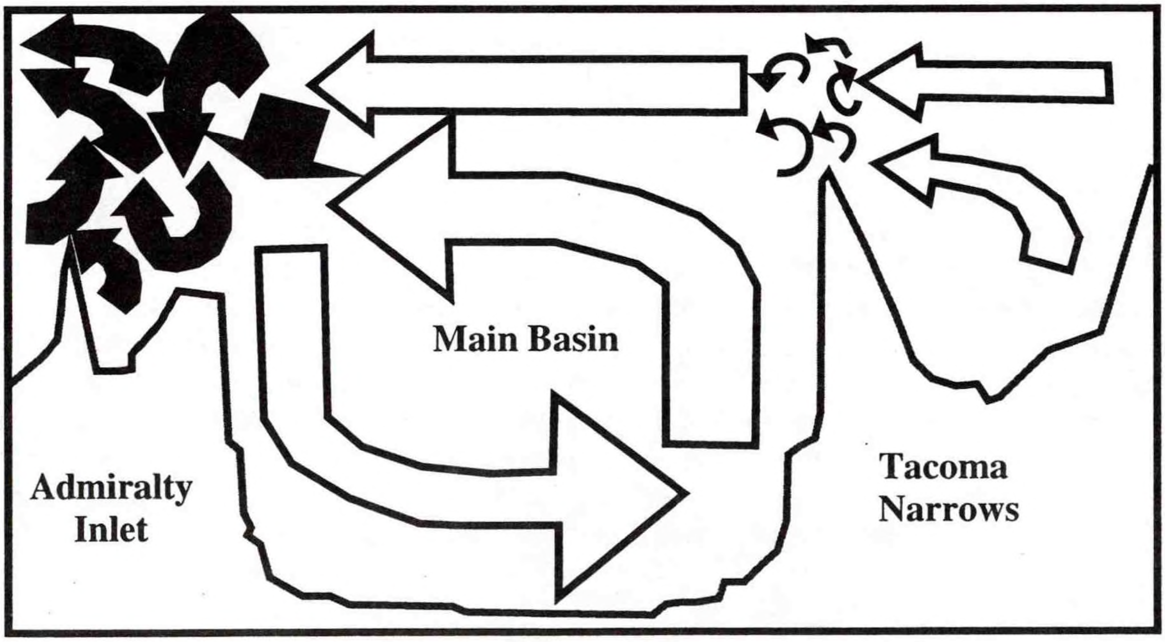

Figure 11B. Schematic of Puget Sound circulation during ebb tide. Gray arrows represent strong vertical mixing. Light arrows represent horizontal currents. Modified after Strickland (1983).

Whidbey Basin

Bathymetry and geomorphology

The Whidbey Basin includes the marine waters east of Whidbey Island and is delimited to the south by a line between Possession Point on Whidbey Island and Meadowdale, west of Everett. The northern boundary is Deception Pass at the northern tip of Whidbey Island (Fig. 4). The Skagit River (the largest single source of freshwater in Puget Sound) enters the northeastern corner of the Basin, forming a delta and the shallow waters (< 20 m) of Skagit Bay. Saratoga Passage, just south of Skagit Bay, separates Whidbey Island from Camano Island. This passage is 100 to 200 m deep, with the deepest section (200 m) located near Camano Head (Burns 1985). Port Susan is located east of Camano Island and receives freshwater from the Stillaguamish River at the northern end and from the Snohomish River (the second largest of Puget Sound's rivers) at southeastern corner. Port Susan also contains a deep area (120 m) near Camano Head. The deepest section of the basin is located near its southern boundary in Possession Sound (220 m).

Sediment characteristics

The most common sediment type in the intertidal zone of the Whidbey Basin is sand, representing 61.4 ± 65.5% of the intertidal area. Mixed fine sediments is the next most common sediment type covering 25.6 ± 18.9% of the intertidal area (Bailey et al. 1998). Similarly, subtidal areas near the mouths of the three major river systems are largely sand; however, the deeper areas of Port Susan, Port Gardner, and Saratoga Passage have surface sediments composed of mixtures of mud and sand (PSWQA 1987, WDOE 1998). Deception Pass sediments consist largely of gravel.

Currents and tidal activity

Although only a few water circulation studies have been performed in the Whidbey Basin, some general observations are possible. Current profiles in the northern portion of this basin are typical of a close-ended fjord. For example, currents during the summer tend to occur in the top 40 m, moving at low velocities in a northerly direction (Cannon 1983). Currents through Saratoga Passage tend to move at moderate rates in a southerly direction. Due to the influences of the Stillaguamish and Snohomish River systems, surface currents in Port Susan and Port Gardner tend to flow toward the Main Basin, although there is some evidence of a recirculating pattern in Port Susan (PSWQA 1987).

Water quality

The waters in this basin are generally stratified, with surface waters being warmer in summer (generally 10-13°C) and cooler in winter (generally 7-10°C) (Collias et al. 1974, WDOE 1999).

Salinities in the southern section of the Whidbey Basin in Possession Sound are similar to those of the Main Basin. In Port Susan and Saratoga Passage, salinities of surface waters (27.0-29.5‰) are generally lower than in the Main Basin, due to runoff from the two major rivers; moreover, after heavy rain these salinities range from 10-15‰. However, salinities in deeper areas often parallel those of the Main Basin (WDOE 1999).

Concentrations of dissolved oxygen in the waters of the Whidbey Basin are routinely measured by the WDOE in Saratoga Passage and in Port Gardner (WDOE 1999). Concentrations were highest in surface waters (up to 15 mg/L) and tended to be inversely proportional to salinity. Samples collected during spring run-off had the highest concentrations of dissolved oxygen. The lowest values (3.5 to 4.0 mg/L) were generally found at the greatest depths in fall.

Macro vegetation

Vegetation covers 23.6 ± 8.8% of the intertidal area of the Whidbey Basin (Bailey et al. 1998). The three predominant types of cover include green algae (6.8 ± 6.2%), eelgrass (6.5 ± 5.8%), and salt marsh (9.0 ± 9.4%). Eelgrass beds are most abundant in Skagit Bay and in the northern portion of Port Susan (Fig. 9) (PSWQA 1987).

Urban, industrial, agricultural, and development

Most of the Whidbey Basin is surrounded by rural areas with low human population densities. About 85% of the drainage area of this Basin is forested, 3% is urbanized, and 4% is in agricultural production. The primary urban and industrial center is Everett, with a population of 78,000. Most waste includes discharges from municipal and agricultural activities and from a paper mill. About 60% of the nutrients (as inorganic nitrogen) entering Puget Sound, enter through the Whidbey Basin by way of its three major river systems (Embrey and Inkpen 1998). The Washington State DNR (WDNR 1998) estimated that 36% of the shoreline in this area has been modified by human activities.

Southern Puget Sound

Bathymetry and geomorphology

The Southern Basin includes all waterways south of Tacoma Narrows (Fig. 4). This basin is characterized by numerous islands and shallow (generally < 20 m) inlets with extensive shoreline areas. The mean depth of this basin is 37 m, and the deepest area (190 m) is located east of McNeil Island, just south of the sill (45 m) at Tacoma Narrows (Burns 1985). The largest river entering the basin is the Nisqually River which enters just south of Anderson Island.

Sediment characteristics

A wide assortment of sediments are found in the intertidal areas of this basin (Bailey et al. 1998). The most common sediments and the percent of the intertidal area they cover are as follows: mud, 38.3 ± 29.3%; sand, 21.7 ± 23.9%; mixed fine, 22.9 ± 16.1%; and gravel, 11.1 ± 4.9%. Subtidal areas have a similar diversity of surface sediments, with shallower areas consisting of mixtures of mud and sand, and deeper areas consisting of mud (PSWQA 1987). Sediments in Tacoma Narrows and Dana Passage consists primarily of gravel and sand.

Currents and tidal activity

Currents in the Southern Basin are strongly influenced by tides, due largely to the shallowness of this area. Currents tend to be strongest in narrow channels (Burns 1985). In general, surface waters flow north and deeper waters flow south. Among the five most western inlets, Case, Budd, Eld, Totten, and Hammersley, the circulation patterns of Budd and Eld inlets are largely independent of those in Totten and Hammersley inlets due largely to the shallowness of Squaxin Passage (Ebbesmeyer et al. 1998). These current patterns are characterized by flows of high salinity waters from Budd and Eld inlets into the south end of Case Inlet, and from Totten and Hammersley inlets into the north end of Case Inlet. Flows of freshwater into the north and sound ends of Case Inlet originate from surface water runoff and the Nisqually River, respectively.

Water quality

The major channels of the Southern Basin are moderately stratified compared to most other Puget Sound basins, because no major river systems flow into this basin. Salinities generally range from 27-29‰, and, although surface temperatures reach 14-15°C in summer, the temperatures of subsurface waters generally range from 10-13°C in summer and 8-10°C in winter (WDOE 1999). Dissolved oxygen levels generally range from 6.5 to 9.5 mg/L. Whereas salinities in the inlets tend to be similar to those of the major channels, temperatures and dissolved oxygen levels in the inlets are frequently much higher in summer. Two of the principal inlets, Carr and Case inlets, have surface salinities ranging from 28-30‰ in the inlet mouths and main bodies, but lower salinities ranging from 27-28‰ at the heads of the inlets (Collias et al. 1974). Summertime surface waters in Budd, Carr and Case Inlets commonly have temperatures that range from 15-19°C and dissolved oxygen values of 10-15 mg/L. Temperature of subsurface water tends to be elevated in the summer (14-15°C); however, temperatures are similar to those of the main channels in other seasons of the year (WDOE 1999).

Macro vegetation

Among the five basins of Puget Sound, the Southern Basin has the least amount of vegetation in its intertidal area (12.7 ± 15.5% coverage), with salt marsh (9.7 ± 14.7% coverage) and green algae (2.1 ± 1.9% coverage) being the most common types (Bailey et al. 1998).

Urban, industrial, and agricultural development

About 85% of the area draining into this basin is forested, 4% is urbanized, and 7% is in agricultural production. The major urban areas around the South Sound Basin are found in the western portions of Pierce County. These communities include west Tacoma, University Place, Steilacoom, and Fircrest, with a combined population of about 100,000. Other urban centers in the South Sound Basin include Olympia with a population of 41,000 and Shelton with a population of 7,200 (PSRC 1998). Important point sources of wastes include sewage treatment facilities in these cities and a paper mill in Steilacoom. Furthermore, about 5% of the nutrients (as inorganic nitrogen) entering Puget Sound, enter into this basin through non-point sources (Embrey and Inkpen 1998). The Washington State DNR (WDNR 1998) estimated that 34% of the shoreline in this area has been modified by human activities.

Hood Canal

Bathymetry and geomorphology

Hood Canal branches off the northwest part of the Main Basin near Admiralty Inlet and is the smallest of the Puget Sound basins, being 90 km long and 1-2 km wide (Fig. 4). Like many of the other basins, it is partially isolated by a sill (50 m deep) near its entrance that limits the transport of deep marine waters in and out of Hood Canal (Burns 1985). The major components of this basin consist of its Entrance, Dabob Bay, the central region, and The Great Bend at the southern end. Dabob Bay and the central region are the deepest sub basins (200 and 180 m, respectively), whereas other areas are relatively shallow, < 40 m for The Great Bend and 50-100 m at the entrance (Collias et al. 1974).

Sediment characteristics

Sediment in the intertidal zone consists mostly of mud (53.4 ± 89.3% of the intertidal area), with similar amounts of mixed fine sediment and sand (18.0 ± 18.5% and 16.7 ± 13.7%, respectively) (Bailey et al. 1998). Surface sediments in the subtidal areas also consist primarily of mud, with the exception of the entrance, which consists of mixed sand and mud, and The Great Bend and Lynch Cove, which have patchy distributions of sand, gravelly sand, and mud (PSWQA 1987, WDOE 1998).

Currents and tidal activity

Aside from tidal currents, currents in Hood Canal are slow, perhaps because the basin is a closed-ended fjord without large-volume rivers. The strongest currents tend to occur near the entrance and generally involve a northerly flow of surface waters.

Water quality

Water temperature, salinity, and concentration of dissolved oxygen in Hood Canal are routinely measured by the WDOE at two sites, near The Great Bend and near the Entrance (WDOE 1999). Salinities generally range from 29-31‰ and tend to be similar at both sites. In contrast, temperature and dissolved oxygen values are often markedly different between the two sites. Values measured on the same dates (a summer month and a winter month) and at the same depths at each site for 1993 and 1996 demonstrate these differences. Mean temperature in the summer month at The Great Bend site was 9.9°C, but 12.1°C at the Entrance site. Mean dissolved oxygen values for this same month were 3.24 mg/L and 6.67 mg/L at the Great Bend and Entrance sites, respectively. For the winter month, the mean temperature at The Great Bend site was 10.6°C, but 9.1°C for the Entrance site. Mean dissolved oxygen for this same month were 4.22 mg/L and 6.78 mg/L at the Great Bend and Entrance sites, respectively.

Macro vegetation

Vegetation covers 27.8 ± 22.3% of the intertidal areas of the Hood Canal Basin. Salt marsh (18.0 ± 8.8%) and eelgrass (5.4 ± 6.3%) are the two most abundant plants (Bailey et al. 1998). Eelgrass is found in most of Hood Canal, especially in the Great Bend and Dabob Bay (Fig. 9).

Urban, industrial, and agricultural development

The Hood Canal Basin is one of the least developed areas in Puget Sound and lacks large centers of urban and industrial development. About 90% of the drainage area in this basin is forested (the highest percentage of forested areas of the five Puget Sound basins), 2% is urbanized, and 1% is in agricultural production (Staubitz et al. 1997). However, the shoreline is well developed with summer homes and year-around residences (PSWQA 1988). A small amount of waste is generated by forestry practices and agriculture. Nutrients (as inorganic nitrogen) from non-point sources in this basin represent only 3% of the total flowing into Puget Sound annually (Embrey and Inkpen 1998). The Washington State DNR (WDNR 1998) estimated that 33% of the shoreline in this area has been modified by human activities.

Marine Species in Puget Sound

Algal productivity in the open waters of the central basin of Puget Sound is dominated by intense blooms of microalgae beginning in late April or May and recurring through the summer. Annual primary productivity in the central basin of the Sound is about 465 g C/m^2. This high productivity is due to intensive upward transport of nitrate by the estuarine mechanism and tidal mixing. Chlorophyll concentrations rarely exceed 15 μg/L. Frequently, there is more chlorophyll below the photic zone than within it. Winter et al. (1975) concluded that phytoplankton growth was limited by a combination of factors, including vertical advection and turbulence, light, sinking and occasional rapid horizontal advection of the phytoplankton from the area by sustained winds. Summer winds from the northwest would be expected to transport phytoplankton to the south end of the Sound which could exacerbate the anthropogenic effects that are already evident in some of these inlets and bays (Harrison et al. 1994).

The abundance and distribution of zooplankton in Puget Sound is not well understood. A few field surveys have been conducted in selected inlets and waterways, but reports on Sound-wide surveys are lacking. In general, the most numerically abundant zooplankton throughout the Puget Sound region are the calanoid copepods, especially *Pseudocalanus* spp. (Giles and Cordell 1998, Dumbauld 1985, Chester et al. 1980, Ohman 1990). Giles and Cordell (1998) reported that crustaceans (primarily calanoid copepods) were most abundant in Budd Inlet in South Puget Sound, although larvae of larvaceans, cnidarians, and polychaetes in varying numbers were also abundant during the year. Likewise, in a study conducted by Dumbauld (1985) at two locations in the Main Basin (a site near downtown Seattle and a cluster of sites in the East Passage near Seattle) covering a variety of depths from 12 to 220 m, he found that calanoid copepods and cyclopoid copepods, and two species of larvaceans were dominant numerically. Dominant copepods at deeper sites were *Pseudocalanus* spp. and *Corycaeus anglicus*. The larvacean, *Oikopleura dioica*, was also relatively common at the shallow sites. Similarly, the most abundant zooplankton in the Strait of Juan de Fuca were reported by Chester et al. (1980) to be calanoid copepods, including *Pseudocalanus* spp. and *Acartia longiremis*, and the cyclopoid copepod, *Oithona similis*.

It is likely that zooplankton assemblages vary both seasonally and annually. Evidence of depth-specific differences was reported by Ohman (1990). In studies conducted in Dabob Bay near Hood Canal, he compared the abundance of certain zooplankton species at a shallow and deep site. He found one species of copepod (*Pseudocalanus newmani*) was common at both sites, whereas species (e.g., *Euchaeta elongata* and *Euphausia pacifica*) that prey upon *P. newmani* were abundant at the deep site, but virtually absent from the shallow site. An example of seasonal variability was reported by Bollens et al. (1992b). In Dabob Bay, *E. pacifica* larvae were abundant in the spring and absent in the winter, and juveniles and adults were most abundant in the summer and early fall, with their numbers declining in the winter (Bollens et al. 1992b).

A few Sound-wide surveys of abundance and distribution of benthic invertebrates have been performed (Lie 1974, Llansó et al. 1998). A common finding among these surveys is that certain species prefer specific sediment types. For example, in areas with predominantly sandy sediments, among the most common species are *Axinopsida serricata* (a bivalve) and *Prionospio jubata* (a polychaete); in muddy, clayey areas of mean to average depth, *Amphiodia urtica-periercta* (a echinoderm) and *Eudorella pacifica* (a cumacean) are among the most common species; in areas with mixed mud and sand, *Axinopsida serricata* and *Aphelochaeta* sp. (a polychaete) are commonly found; and lastly, in deep muddy, clayey areas, predominant species tend to be *Macoma carlottensis* (a bivalve) and *Pectinaria californiensis* (a polychaete). In general, areas with sandy sediments tend to have the most species (Llansó et al. 1998), but the lowest biomass (Lie 1974). Areas with mixed sediments tend to have the highest biomass (Lie 1974).

As with zooplankton, assemblages of benthic invertebrates vary both seasonally and annually. Lie (1968) reported seasonal variations in the abundance of species, with the maxima taking place during July-August, and the minima occurring in January to February. However, there were no significant variations in the number of species during different seasons. Annual variation was examined by Nichols (1988) at three Puget Sound sites in the Main Basin: two deep sites (200-250 m) and one shallow site (35 m). For one of the deep sites, he reported that *M. carlottensis* generally dominated the benthic community from 1963 through the mid-1970s. Subsequently, these species were largely replaced by *A. serricata*, *E. pacifica*, *P. californensis*, *Ampharete acutifrons* (a polychaete), and *Euphiomedes producta* (an ostracod). A similar dominance by *P. californensis* and *A. acutifrons* was reported for the other deep site over approximately the same time period.

Several macroinvertebrate species are widely distributed in Puget Sound. Among the crustacean species, Dungeness crab (*Cancer magister*) and several species of shrimp [e.g., sidestripe (*Pandalopsis dispar*) and pink (*Pandalus borealis*)] are the most commonly harvested species (Bourne and Chew 1994). The non-indigenous Pacific oyster (*Crassostrea gigas*) accounts for approximately 90% of the landings of bivalves. Other abundant bivalves are the Pacific littleneck clam (*Protothaca staminea*), Pacific geoduck (*Panopea abrupta*), Pacific gaper (*Tresus nuttalii*), and the non-indigenous Japanese littleneck clam (*Tapes philippinarum*) and softshell clam (*Mya arenaria*) (Kozloff 1987, Turgeon et al. 1988).

The most common Pacific salmon species utilizing Puget Sound during some portion of their life cycle include chinook (*Oncorhynchus tshawytscha*), coho (*O. kisutch*), chum (*O. keta*), pink (*O. gorbuscha*), and sockeye salmon (*O. nerka*). Anadromous steelhead (*O. mykiss*) and cutthroat trout (*O. clarki clarki*) also utilize Puget Sound habitats.

Palsson et al. (1997) identified about 221 species of fish in Puget Sound. The marine species are generally categorized as bottomfish, forage fish, non-game fishes, and other groundfish species. In addition to Pacific hake, Pacific cod, and walleye pollock, other important commercial marine fish species in Puget Sound are Pacific herring, spiny dogfish (*Squalus acanthias*), lingcod (*Ophiodon elongatus*), various rockfish species (*Sebastes* spp.), and English sole (*Pleuronectes vetulus*). English sole are thought to be relatively healthy in the central portions of Puget Sound; however, significant declines have been recorded in localized embayments, such as Bellingham Bay and Discovery Bay. Other species of bottomfish species found throughout Puget Sound include skates (*Raja rhina* and *R. binoculata*), spotted ratfish (*Hydrolagus cooliei*), sablefish (*Anoplopoma fimbria*), greenlings (*Hexagrammos decagrammus* and *H. stelleri*), sculpins [e.g., cabezon (*Scorpaenichthys marmoratus*), Pacific staghorn sculpin (*Leptocottus armatus*), and roughback sculpin (*Chitonotus pugetensis*)], surfperches [e.g., pile perch (*Rhacochilus vacca*) and striped seaperch (*Embiotoca lateralis*)], wolf-eel (*Anarrhichthys ocellatus*), Pacific sanddab (*Citharichthys sordidus*), butter sole (*Pleuronectes isolepis*), rock sole (*Pleuronectes bilineatus*), Dover sole (*Microstomus pacificus*), starry flounder (*Platichthys stellatus*), sand sole (*Psettichthys melanostictus*), and over one dozen rockfish species [e.g., brown rockfish (*Sebastes auriculatus*), copper rockfish (*S. caurinus*), greenstriped rockfish (*S. elongatus*), yellowtail rockfish (*S. flavidus*), quillback rockfish (*S. maliger*), black rockfish, (*S. melanops*) and yelloweye rockfish (*S. ruberrimus*)] (DeLacy et al. 1972, Robins et al. 1991). Additional fish species that are less known, but widely distributed in Puget Sound, include surf smelt (*Hypomesus pretiosus*), plainfin midshipman (*Porichthys notatus*), eelpouts [e.g., blackbelly eelpout (*Lycodopsis pacifica*)], pricklebacks [e.g., snake prickleback, (*Lumpenus sagitta*)], gunnels [e.g., penpoint gunnel (*Apodichthys flavidus*)], Pacific sand lance (*Ammodytes hexapterus*), bay goby (*Lepidogobius lepidus*), and poachers [e.g., sturgeon poacher (*Podothecus acipenserinus*)] (DeLacy et al. 1972, Robins et al. 1991).

About 66,000 marine birds breed in or near Puget Sound. About 70% of them breed on Protection Island, located just outside of the northern entrance to the Sound. The most abundant species are rhinoceros auklet (*Cerorhinca monocerata*), glaucous-winged gull (*Larus glaucescens*), pigeon guillemot (*Cepphus columba*), cormorants (*Phalacrocorax* spp.), marbled murrelet (*Brachyramphus marmoratus*), and the Canada goose (*Branta canadensis*). Examples of less abundant species include common murre (*Uria aalge*) and tufted puffins (*Fratercula cirrhata*).

Populations of rhinoceros auklet and pigeon guillemot appear to be stable, whereas populations of glaucous-winged gull have increased slightly in recent years, especially in urban areas (Mahaffy et al. 1994). Accurate estimates of current populations of marbled murrelet and the Canada goose are not available, but the population of marbled murrelet has been greatly reduced and this species has been listed as threatened. Thirty years ago, year-around resident Canada geese were rare, but current anecdotal evidence from observations in waterfront parks suggests that their population is growing rapidly. The common murre and tufted puffin populations have declined drastically during the last two decades.

Nine primary marine mammal species occur in Puget Sound including (listed in order of abundance): harbor seal (*Phoca vitulina*), California sea lion (*Zalophus californianus*), Steller sea lion (*Eumetopias jubatus*), Northern elephant seal (*Mirounga angustirostris*), harbor porpoise (*Phocoena phocoena*), Dall's porpoise (*Phocoenoides dalli*), killer whale (*Orcinus orca*), gray whale (*Eschrichtius robustus*), and minke whale (*Balaenoptera acutorostrata*). Harbor seals are year-round residents, and their abundance has been increasing in Puget Sound by 5 to 15% annually at most sites (Calambokidis and Baird 1994).

California sea lions, primarily males, reside in Puget Sound between late summer and late spring, and spend the remainder of the year at their breeding grounds in southern California and Baja California. Sea lion populations are growing at approximately 5% annually. Populations of the remaining species are quite low in Puget Sound. Steller sea lions and elephant seals are transitory residents, whereas the Steller sea lion is currently listed as threatened in the U.S., the elephant seal is abundant in the eastern North Pacific but has few haul-out areas in Puget Sound.

Although harbor porpoises are also abundant in the eastern North Pacific and were common in Puget Sound 50 or more years ago, they are now rarely seen in the Sound (Calambokidis and Baird 1994). Low numbers of Dall's porpoise are observed in Puget Sound throughout the year, but little is known about their population size—they are also abundant in the North Pacific. A pod of resident fish-feeding killer whales, numbering about 100, resides just north of the entrance to Puget Sound, and the size of this group is increasing about 2.0% each year. Minke whales are also primarily observed in this same northern area, but their population size is unknown. Gray whales migrate past the Georgia Basin en route to or from their feeding or breeding grounds; a few of them enter Puget Sound during the spring through fall to feed.

Marine Statistical Areas

Marine groundfish fishery statistics, including those from Puget Sound, are typically reported by geographically delimited fishery management regions. Major groundfish statistical areas as established by the Pacific Marine Fisheries Commission (PFMC) for the west coast of the lower 48 states and British Columbia are illustrated in Figure 12. Puget Sound constitutes Area 4A in the PFMC designation. Minor Statistical Areas (MSA) in the Strait of Georgia and the Strait of Juan de Fuca used by the Canadian Department of Fisheries and Oceans for fishery statistical purposes are illustrated in Figure 13. The Washington Department of Fish and Wildlife reports groundfish statistics in the U.S portion of the Strait of Georgia and in Puget Sound by Marine Fish Management Regions as illustrated in Figure 14.

Georgia Basin

The Georgia Basin is an international waterbody that encompasses the marine waters of Puget Sound, the Strait of Georgia, and the Strait of Juan de Fuca (Fig. 15). The coastal drainage of the Georgia Basin is bounded to the west and south by the Olympic and Vancouver Island mountains and to the north and east by the Cascade and Coast mountains. At sea level, the Basin has a mild maritime climate and is dryer than other parts of the coast due to the rain shadow of the Olympic and Vancouver Island mountains. At sea level, air temperatures range from 0° to 5°C in January and 12° to 22°C in July, and winds are typically channeled by the local topography and blow along longitudinal axes of the straits and sounds. Winds are predominantly from the southeast in winter and the northwest in summer.

Physical Features of the Strait of Georgia

The Strait of Georgia (Fig. 15) has a mean depth of 156 m (420 m maximum) and is bounded by narrow passages (Johnstone Strait and Cordero Channel to the north and Haro and Rosario straits to the south) and shallow submerged sills (minimum depth of 68 m to the north and 90 m to the south). The Strait of Georgia covers an area of approximately 6,800 km^2 (Thomson 1994) and is approximately 220 km long and varies from 18.5 to 55 km in width (Tully and Dodimead 1957, Waldichuck 1957). Both southern and northern approaches to the Strait of Georgia are

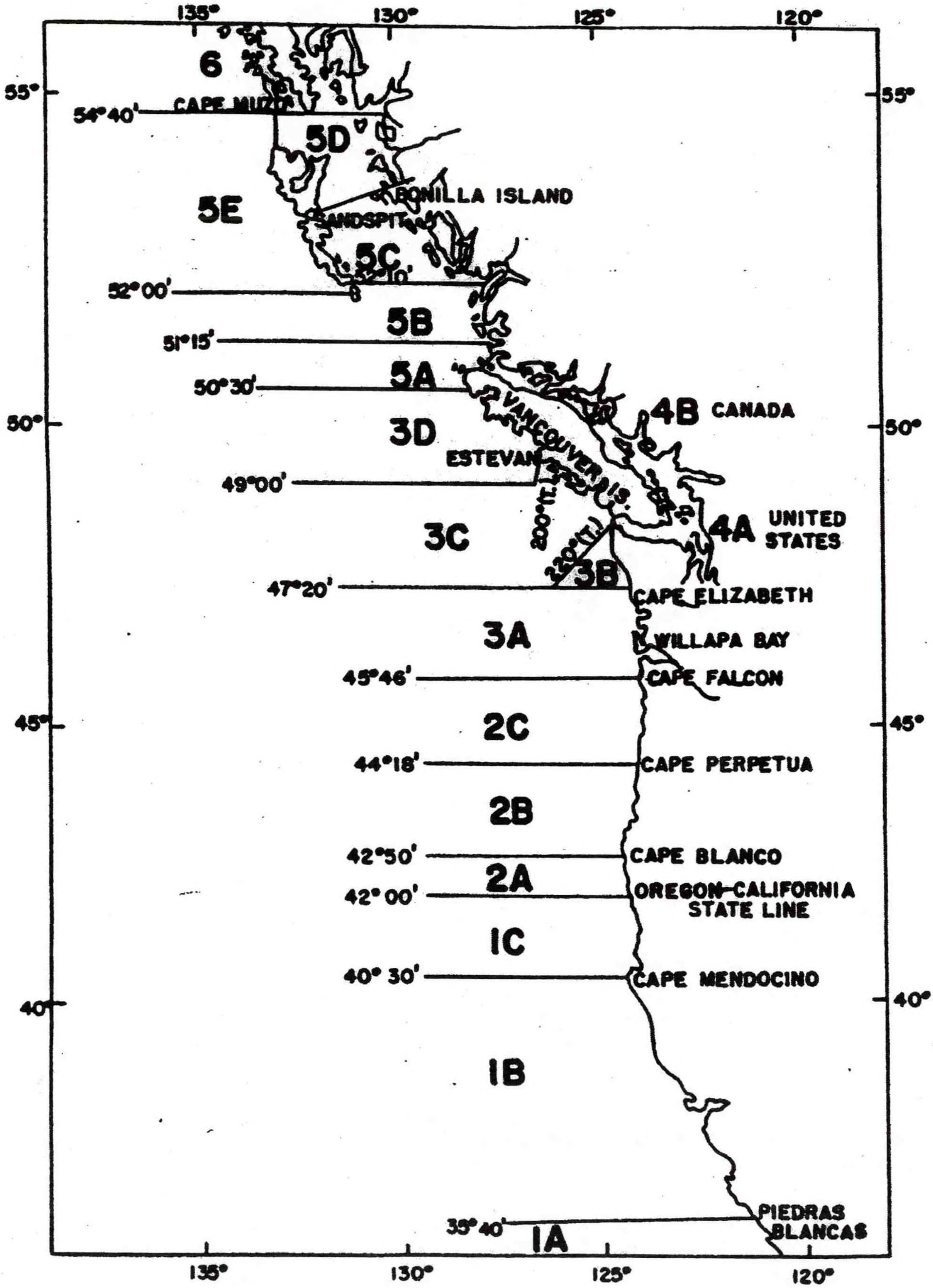

Figure 12. International marine fisheries statistical areas as established by the Pacific Marine Fisheries Commission in the California to British Columbia region.

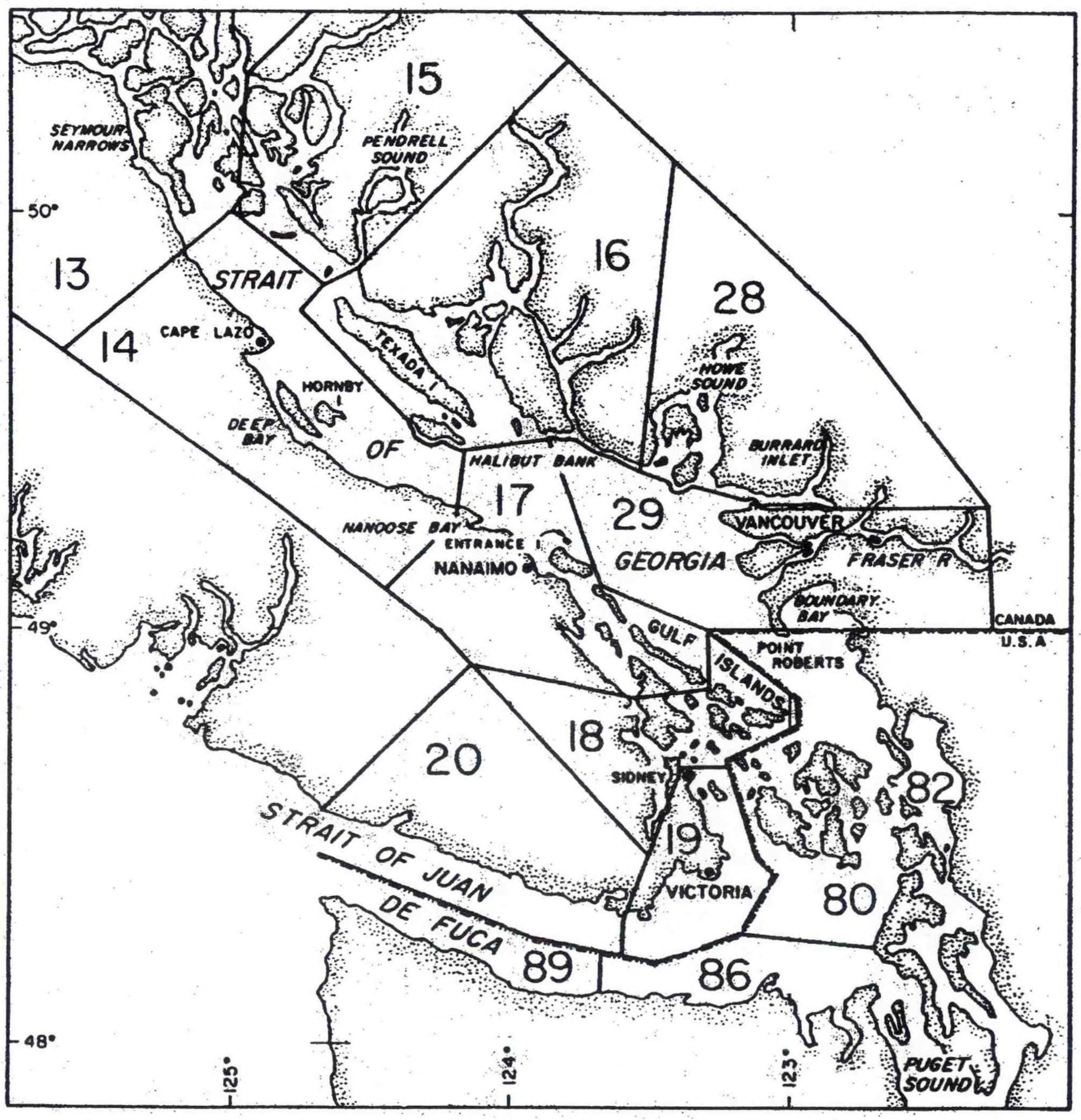

Figure 13. Canadian Department of Fisheries and Oceans Minor Statistical Areas (MSA) in the Strait of Georgia and Strait of Juan de Fuca.

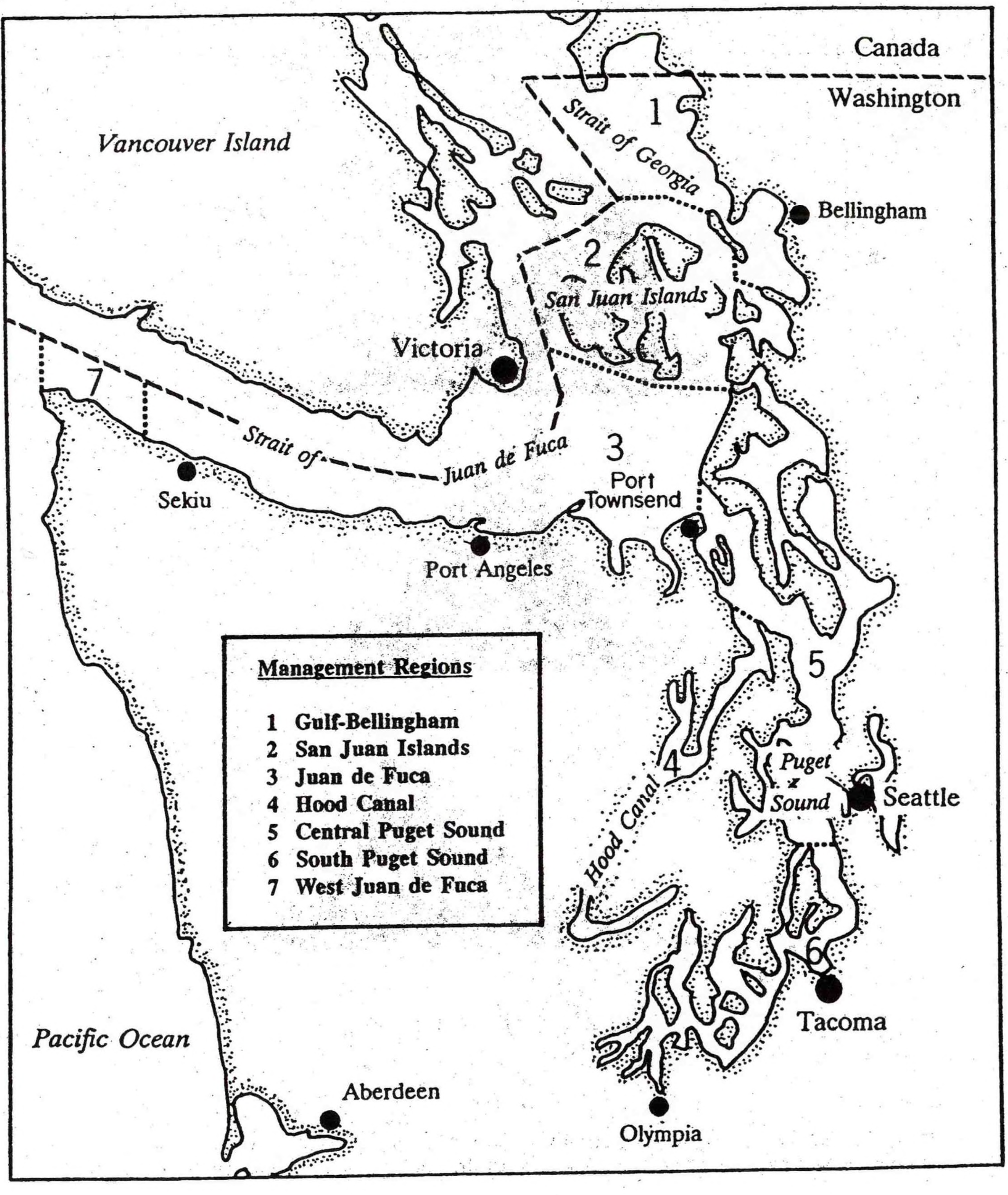

Figure 14. Washington Department of Fish and Wildlife Marine Fish Management Regions of Puget Sound.

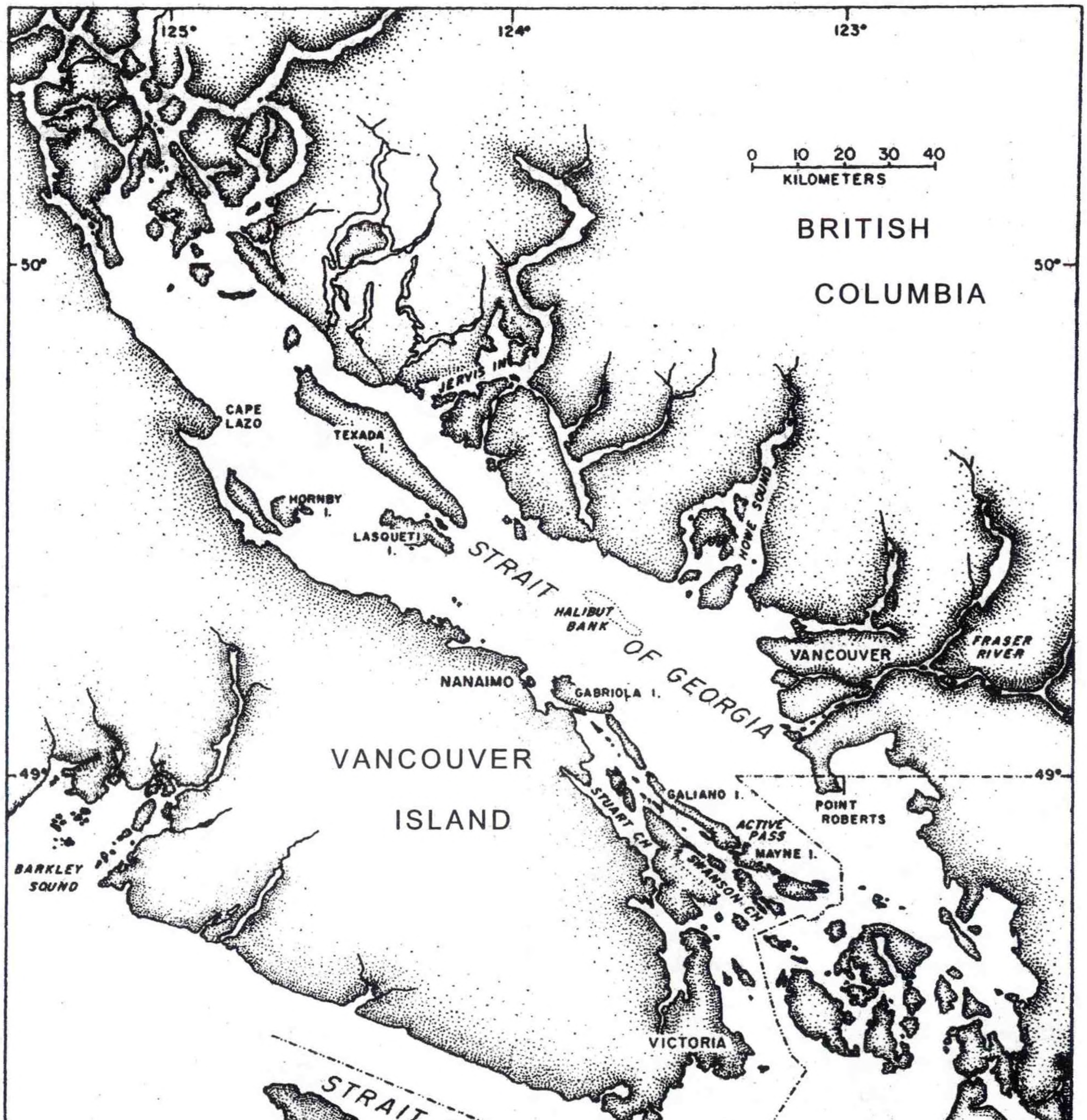

Figure 15. Geographical locations in the Strait of Georgia and on the southern coast of British Columbia considered in this manuscript.

through a maze of islands and channels, the San Juan and Gulf islands to the south and a series of islands to the north that extend for 240 km to Queen Charlotte Strait (Tully and Dodimead 1957). Both northern channels (Johnstone Strait and Cordero Channel) are from 1.5 to 3 km wide and are effectively two-way tidal falls, in which currents of 12-15 knots occur at peak flood (Tully and Dodimead 1957). However, both lateral and vertical constriction of water flow at the narrowest points in these northern channels are even more severe. Constrictions occur at Arran Rapids, Yuculta Rapids, Okisollo Channel, and to a lesser degree at Seymour Narrows (0.74 km wide, minimum depth of 90 m) in Discovery Passage (Waldichuck 1957). Overall, these narrow northern channels have only about 7% of the cross-sectional area as do the combined southern entrances into the Strait of Georgia (Waldichuck 1957).

Freshwater inflows are dominated by the Fraser River, which accounts for roughly 80% of the freshwater entering the Strait of Georgia. Fraser River run-off and that of other large rivers on the mainland side of the Strait are driven by snow and glacier melt and their peak discharge period is generally in June and July. Rivers that drain into the Strait of Georgia off Vancouver Island (such as the Chemainus, Cowichan, Campbell, and Puntledge rivers) peak during periods of intense precipitation, generally in November (Waldichuck 1957).

Circulation in the Strait of Georgia occurs in a general counter-clockwise direction (Waldichuck 1957). Tides, winds, and freshwater run-off are the primary forces for mixing, water exchange, and circulation. Tidal flow enters the Strait of Georgia predominantly from the south creating vigorous mixing in the narrow, shallow straits and passes of the Strait of Georgia. The upper, brackish water layer in the Strait of Georgia is influenced by large freshwater run-off and salinity in this layer varies from 5 to 25‰. Deep, high-salinity (33.5 to 34‰), oceanic water enters the Strait of Georgia from the Strait of Juan de Fuca. The surface outflowing and deep inflowing water layers mix in the vicinity of the sills, creating the deep bottom layer in the Strait of Georgia, where salinity is maintained at about 31‰ (Waldichuck 1957). The basic circulation pattern in the summer is the southerly outflow of relatively warm, low salinity surface, with the northerly inflow of high salinity oceanic water from the Strait of Juan de Fuca at the lowest depths. In the winter, cool, low salinity near surface water mixes with the intermediate depth high salinity waters; however, oceanic inflow is generally confined to the intermediate depths. Crean et al. (1988) reported that "the freshwater discharge finds primary egress through the southern boundary openings into the Strait of Juan de Fuca" and that subsurface waters (5 to 20 m below the region of the Fraser River discharge) also have "a predominantly southerly flow." Since surface water run-off peaks near the time of peak salinity of inflowing source water, the salinity of the deepwater in the Strait of Georgia undergoes only a small seasonal change in salinity (Waldichuck 1957).

Marine Zoogeographic Provinces

Ekman (1953), Hedgpeth (1957), and Briggs (1974) summarized the distribution patterns of coastal marine fishes and invertebrates and defined major worldwide marine zoogeographic zones or provinces. Along the coastline of the boreal Eastern Pacific, which extends roughly from Point Conception, California to the Eastern Bering Sea, numerous schemes have been proposed for grouping the faunas into zones or provinces. A number of authors (Ekman 1953, Hedgpeth 1957, Briggs 1974, Allen and Smith 1988) have recognized a zoogeographic zone within the lower boreal Eastern Pacific that has been termed the Oregonian Province. Another zone in the upper boreal Eastern Pacific has been termed the Aleutian Province (Briggs 1974). However, exact boundaries of zoogeographic provinces in the Eastern boreal Pacific are in dispute (Allen and Smith 1988). Briggs (1974) and Allen and Smith (1988) reviewed previous literature from a variety of taxa and from fishes, respectively, and found the coastal region from Puget Sound to Sitka, Alaska to be a "gray zone" or transition zone that could be classified as part of either of two provinces: Aleutian or Oregonian (see Fig. 16). The southern boundary of the Oregonian Province is generally recognized as Point Conception, California and the northern boundary of the Aleutian Province is similarly recognized as Nunivak in the Bering Sea or the Aleutian Islands (Allen and Smith 1988).

Briggs (1974) placed the boundary between the Oregonian and Aleutian Provinces at Dixon Entrance, based on the well-studied distribution of mollusks, but indicated that distributions of fishes, echinoderms, and marine algae gave evidence for placement of this boundary in the vicinity of Sitka, Alaska. Briggs (1974) placed strong emphasis on the distribution of littoral mollusks (due to the more thorough treatment this group has received) in placing a major faunal break at Dixon Entrance. The authoritative work by Valentine (1966) on distribution of marine mollusks of the northeastern Pacific shelf showed that the Oregonian molluscan assemblage extended to Dixon Entrance with the Aleutian fauna extending northward from that area. Valentine (1966) erected the term Columbian Sub-Province to define the zone from Puget Sound to Dixon Entrance.

Several lines of evidence suggest that an important zoogeographic break for marine fishes occurs in the vicinity of Southeast Alaska. Peden and Wilson (1976) investigated the distributions of inshore fishes in British Columbia, and found Dixon Entrance to be of minor importance as a barrier to fish distribution. A more likely boundary between these fish faunas was variously suggested to occur near Sitka, Alaska, off northern Vancouver Island, or off Cape Flattery, Washington (Peden and Wilson 1976, Allen and Smith 1988). Chen (1971, as cited in Briggs 1974) stated that of the more than 50 or more rockfish species belonging to the genus *Sebastes* occurring in northern California, more than two-thirds do not extend north of British Columbia or Southeast Alaska. Briggs (1974) further stated that "about 50 percent of the entire shore fish fauna of western Canada does not extend north of the Alaskan Panhandle." In addition, many marine fish species common to the Bering Sea, extend southward into the Gulf of Alaska but apparently occur no further south (Briggs 1974). Allen and Smith (1988, p. 144) stated that "the relative abundance of some geographically-displacing [marine fish] species suggest that the boundary between these provinces [Aleutian and Oregonian] occurs off northern Vancouver Island."

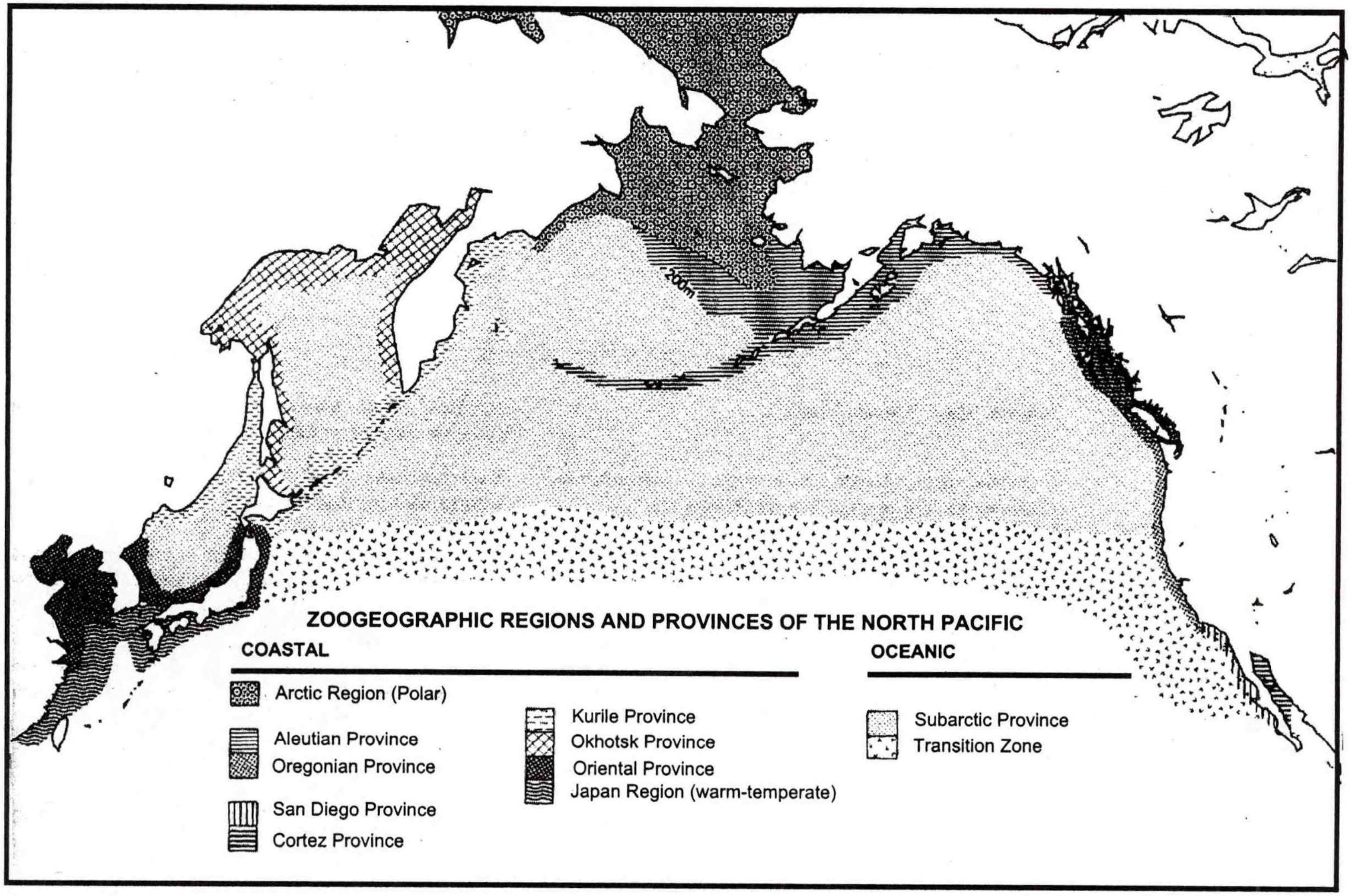

Figure 16. Marine zoogeographic provinces of the North Pacific Ocean. Modified after Allen and Smith (1988).

PACIFIC HAKE

General Biology

Geographical distribution

Pacific hake, *Merluccius productus* (Ayres, 1855), of the offshore stock range from Sanak Island in the western Gulf of Alaska to Magdalena Bay, Baja California Sur. They are most abundant in the California Current System (Bailey 1982, Hart 1973, Love 1991, NOAA 1990). There are three much smaller stocks with much smaller ranges: a Puget Sound stock, a Strait of Georgia stock, and a dwarf stock limited to waters off Baja California (Bailey et al. 1982, Stauffer 1985). The offshore stock of Pacific hake is migratory and inhabits the continental slope and shelf within the California current system from Baja California to British Columbia (Quirollo 1992). All life stages are found in euhaline waters at 9-15°C (NOAA 1990).

Eggs and larvae of the offshore stock are pelagic in 40-140 m of water (Smith 1995), with eggs in the earlier stages being at the deeper depths (Moser et al. 1997). Pacific hake larvae tend to aggregate near the base of the thermocline or mixed layer (Stauffer 1985). This association with the thermocline or mixed layer may partially explain why Pacific hake in the Strait of Georgia and Puget Sound spawn near major sources of freshwater which would cause a stratified layer of low-salinity water on top of the well mixed marine waters common during the winter. Juveniles reside in shallow coastal waters, bays, and estuaries (Bailey 1981, Bailey et al. 1982, Dark 1975, Dark and Wilkins 1994, Dorn 1995, NOAA 1990, Sakuma and Ralston 1995, Smith 1995), and move to deeper water as they get older (NOAA 1990). Pacific hake school at depth during the day, then move to the surface and disband at night for feeding (McFarlane and Beamish 1986, Sumida and Moser 1980, Tanasich et al. 1991).

Adults are epi-mesopelagic (Bailey et al. 1982, NOAA 1990, Sumida and Moser 1980). Highest densities of Pacific hake are usually found between 50 and 500 m, but adults occur as deep as 920 m and as far offshore as 400 km (Bailey 1982, Bailey et al. 1982, Dark and Wilkins 1994, Dorn 1995, Hart 1973, NOAA 1990, Stauffer 1985). Spawning is greatest at depths between 130 and 500 m (Bailey et al. 1982, NOAA 1990, Smith 1995).

Smith (1995) recognized three habitats utilized by the offshore stock of Pacific hake: 1) a narrow 30,000 km^2 feeding habitat near the shelf break of British Columbia, Washington, Oregon, and California, populated 6-8 months per year, 2) a broad 300,000 km^2 open-sea area of California and Baja California populated by spawning adults in the winter and embryos and larvae for 4-6 months, and 3) a continental shelf juvenile rearing area of unknown size off California and Baja California.

Migrations

Offshore stocks spawn off Baja California in the winter, then mature adults begin moving northward and inshore, following the food supply and Davidson currents (Fig. 17) (NOAA 1990). Pacific hake reach as far north as southern British Columbia by fall. By early late fall, they begin the southern migration to southern spawning grounds and further offshore (Bailey et al. 1982, Dorn 1995, Smith 1995, Stauffer 1985) (see Fig. 17).

Stocks in the Strait of Georgia and Puget Sound undergo similar migration patterns, but on a greatly reduced scale (McFarlane and Beamish 1986, Shaw et al. 1990). In both areas, spawning occurs in locations proximate to major sources of freshwater inflow: near the Frazer River in the Strait of Georgia, and near the Skagit and Snohomish Rivers in Port Susan (McFarlane and Beamish 1985, Pedersen 1985). The Puget Sound and Strait of Georgia stocks spend their entire lives in these estuaries (McFarlane and Beamish 1986, Shaw et al. 1990).

Reproduction and development

Pacific hake may spawn more than once per season, so absolute fecundity is difficult to determine. Pacific hake are oviparous with external fertilization. Offshore stocks have 180-232 eggs/g body weight, but Puget Sound and Strait of Georgia stocks have only 50-165 eggs/g body weight (Mason 1986). Bailey (1982) estimated that a 28-cm female had 39,000 eggs, while a 60-cm female had 496,000 eggs.

Eggs are spherical, 1.14 to 1.26 mm in diameter with a single oil droplet, and are neritic and float to neutral buoyancy (Bailey 1981, Bailey et al. 1982, NOAA 1990). The pelagic eggs of Pacific hake off California are found at depths between 50 and 75 m over a bottom depth of at least 300 m (Moser et al. 1997). Pelagic eggs of Puget Sound Pacific hake are found at approximately the same depth, but Pacific hake eggs in Puget Sound are in the bottom 25 m of the water column over a bottom depth of about 110 m (Bailey 1982, Moser et al. 1997).

Embryonic development is indirect and external (NOAA 1990). Hatching occurs in 5-6 days at 9-10°C and 4-5 days at 11-13°C (Bailey 1982, Hollowed 1992). Larvae hatch at 2-3 mm total length (Stauffer 1985, Sumida and Moser 1984) with a yolk sac that is gone in 5-7 days (Bailey 1982). Larvae metamorphose into juveniles at 35 mm, typically in 3-4 months (Hollowed 1992). Juveniles range from 35 mm to 40 cm depending on sex (Bailey et al. 1982, Beamish and McFarlane 1986, Hollowed 1992).

In Puget Sound and the Strait of Georgia, female Pacific hake mature at 37 cm and 4-5 years of age (McFarlane and Beamish 1986). Females of the offshore stock mature at 3-4 years and 34-40 cm, and nearly all males are mature by age 3 and as small as 28 cm. Females grow more rapidly than males after 4 years; growth ceases for both sexes at 10-13 years (Bailey et al. 1982).

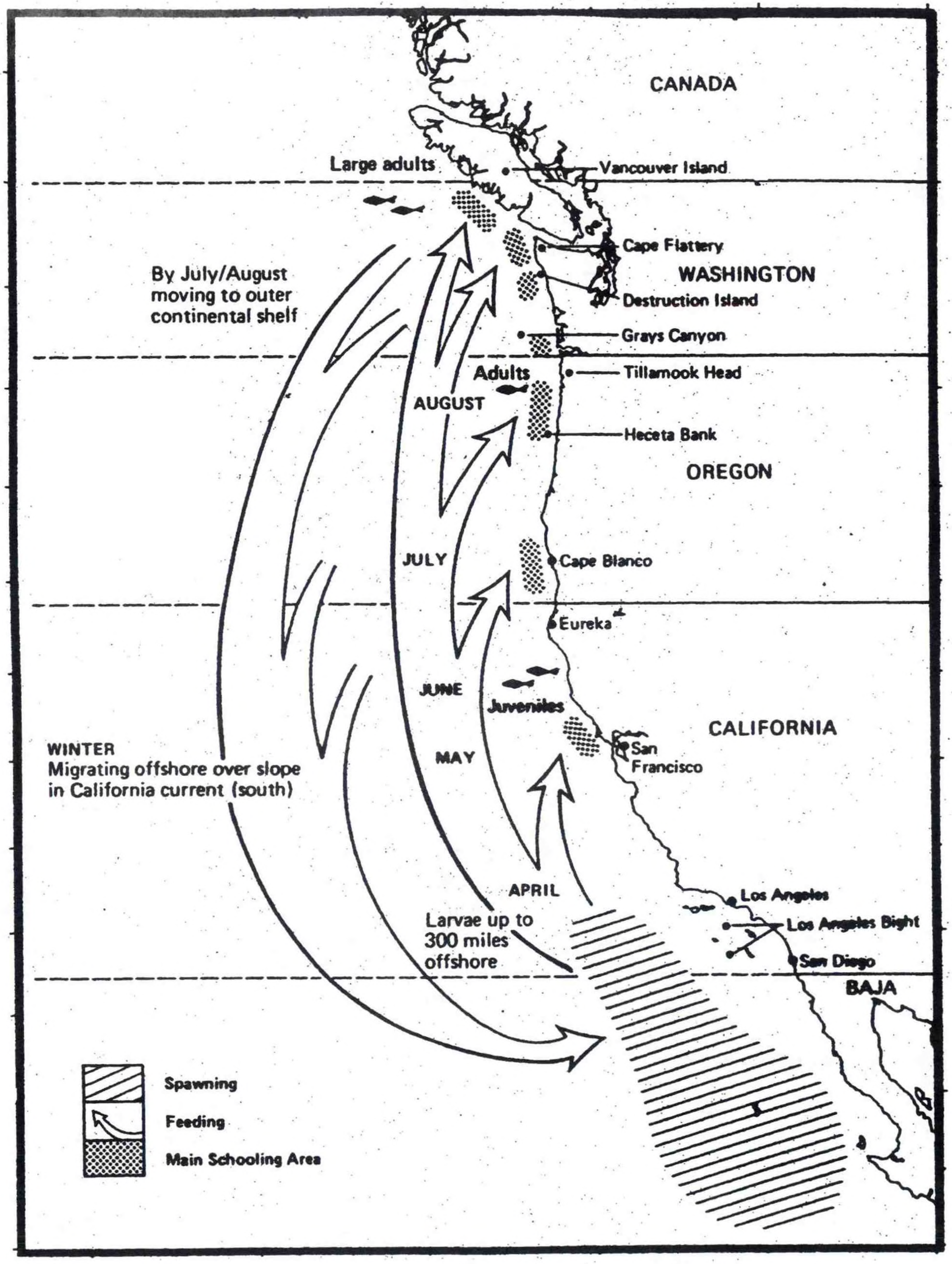

Figure 17. Migratory patterns of the offshore stock of Pacific hake, *Merluccius productus*. Modified from Bailey et al. (1982, their fig. 1).

By age 3, most Pacific hake become available to the mid-water trawl fishery, although Pacific hake between ages 6 and 11 are most commonly caught. The maximum age of Pacific hake is about 20 years, but Pacific hake over age 12 are rare (Methot and Dorn 1995). The size-at-age of offshore Pacific hake has been declining since the 1960s (Methot and Dorn 1995). By the early 1990s, age-10 males were 47 cm, and age-10 females were 48 cm. McFarlane and Beamish (1985) reported a more rapid growth rate in Pacific hake from the Strait of Georgia compared to Pacific hake from offshore up to age 4, after which time their growth rate levels off. Moreover, the Strait of Georgia Pacific hake reach maximum mean lengths (approximately 44 cm) that are approximately 10 cm shorter than the length at maximum age for offshore Pacific hake. In Puget Sound, male Pacific hake rarely exceed a length of 40 cm, whereas females tend to be about 4 cm longer than males (Pedersen 1985).

MacGregor (1971) noted a marked cline in size at maturity with latitude for Pacific hake. According to MacGregor (1971) Pacific hake grow to a larger size and mature at a larger size in the northern part of their range, when comparing Pacific hake from southern Baja California to Puget Sound. MacGregor (1971) noted that this same growth pattern is apparent in European hake (*M. merluccius*) with larger hake occurring in the north and smaller hake in the south.

Trophic interactions

Pacific hake larvae eat calanoid copepod eggs, nauplii, and adults (McFarlane and Beamish 1986, Sumida and Moser 1984). Juveniles and small adults feed chiefly on euphausiids (NOAA 1990). Large adults also eat amphipods, squid, Pacific herring, smelt, crabs, shrimp, and sometimes juvenile Pacific hake (Bailey 1981, Dark and Wilkins 1994, McFarlane and Beamish 1986, NOAA 1990).

Eggs and larvae of Pacific hake are eaten by walleye pollock, herring, invertebrates, and sometimes Pacific hake. Juveniles are eaten by lingcod, Pacific cod, and rockfish species. Adults are preyed on by sablefish, albacore, walleye pollock, Pacific cod, soupfin sharks, and spiny dogfish (Fiscus 1979, McFarlane and Beamish 1986, NOAA 1990). Another important group on predators of adult Pacific hake are marine mammals, including the northern elephant seal (*Mirounga angustirostris*), northern fur seal (*Callorhinus ursinus*), California sea lion (*Zalophus californianus*), and several species of dolphins and whales (Methot and Dorn 1995).

Size and age distributions

As was mentioned above in the "Reproduction and development section," Pacific hake in the Strait of Georgia tend to be shorter at age than Pacific hake in the offshore populations; in some cases up to 10 cm (McFarlane and Beamish 1985). In addition, Pacific hake from central Puget Sound appear to be 2 to 4 cm shorter at age than Pacific hake from the Strait of Georgia. Quinnell and Schmitt (1991) presented length/frequency data for Pacific hake from Puget Sound (Fig. 18) which demonstrated a trimodal length distribution, with most Pacific hake being 33 to 50 cm, and approximately similar numbers of Pacific hake being either 22 to 28 cm or 9 to 14 cm (see Table 2).

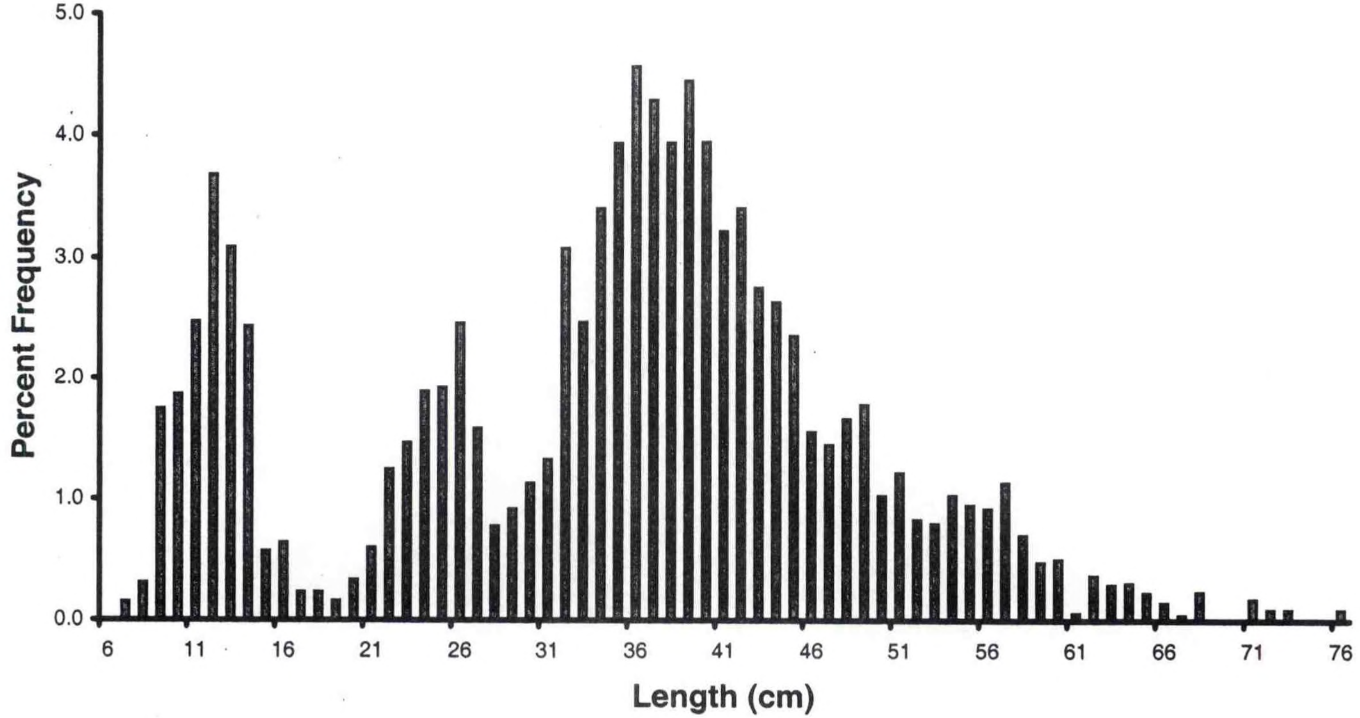

Figure 18. Proportion at length of Puget Sound Pacific hake in 1987 research trawl survey. Modified after Quinnell and Schmitt (1991, fig. 1).

Table 2. Estimated body size of Pacific hake sampled during research trawling in major regions of Puget Sound in 1987 (from Quinnell and Schmitt 1991).

	No. of tows	No. of tows with catch	Mean length (cm)	No. of fish measured
Gulf of Bellingham	11	8	40	112
Strait of Juan de Fuca	30	5	52	102
Hood Canal	7	6	27	91
Central Puget Sound	28	19	34	876
South Puget Sound	17	6	28	54

Phenetic and Genetic Information Relating to the Species Question

Phenetic and genetic information examined for evidence of DPS delineations of Pacific hake included presence of geographically-discrete and temporally-persistent spawning aggregations, and variation in seasonal migration patterns, year-class strength, parasite incidence, growth rate, size- and age-at-maturity, length frequency, fecundity, meristics and morphometrics, and genetic population structure.

Life History Information

In addition to the abundant migratory population of Pacific hake, that spawns offshore from Cape Mendocino, California to southern Baja California, several other stocks of Pacific hake have been identified including at least two that spawn in Puget Sound, several in the Strait of Georgia, several in the west coast inlets of Vancouver Island, and a small-bodied ("dwarf hake") off the west coast of southern Baja California (Nelson 1969, Bailey et al. 1982, Ermakov 1982, Bailey and Yen 1983, Beamish and McFarlane 1985, Pedersen 1985, Bollens et al. 1992a, Alados et al. 1993, Methot and Dorn 1995, Fox 1997).

The Pacific hake stocks from offshore (Baja California to the west coast of Vancouver Island), Strait of Georgia, and Puget Sound have been considered discrete from one another on the basis of differences either in: 1) allozyme frequencies (Utter 1969a, b; Utter and Hodgins 1969, 1971; Utter et al. 1970), 2) spawning locality (Alverson and Larkins 1969), 3) size- and age-at-maturity (Goñi 1988), 4) growth (Nelson 1969, Beamish et al. 1982, McFarlane and Beamish 1985), 5) year-class strength (McFarlane and Beamish 1985, Goñi 1988), 6) effective fecundity (McFarlane and Saunders 1997), 7) otolith morphology and annuli formation (McFarlane and Beamish 1985), or 8) the degree of infestation with the protozoan parasite *Kudoa paniformis* Kabata and Whitaker, 1981 (Kabata and Whitaker 1981, 1985; McFarlane and Beamish 1985).

Pre-historical and historical persistence in Puget Sound

Tunnicliffe et al. (in press) examined fish remains in a complete Holocene sediment core sequence from Saanich Inlet, Vancouver Island, British Columbia. Pacific hake were one of the first fish species to occur in Saanich Inlet following glacial retreat from the region, after approximately 12,000 years before present (BP) (Tunnicliffe et al. in press). Fish abundance and species diversity peaked in Saanich Inlet between 7,500 and 6,000 BP, and the last 1,000 years have seen some of the lowest abundances of fishes in Saanich Inlet's marine history (Tunnicliffe et al. in press). The close proximity of Saanich Inlet to Puget Sound would suggest that Pacific hake were also likely established in Puget Sound by about 12,000 BP.

Pacific hake were identified in prehistoric fish skeletal remains from the Duwamish No. 1 archeological site (45-KI-23), located 3.8 km upstream from Elliott Bay on the Duwamish River, utilized by aboriginal humans between A.D. 15 and A.D. 1654 (Butler 1987). Gadiforms were present throughout the occupational history of this site, and were third and fourth in rank order of taxonomic abundance in two separate studies of fish bones performed at this site (following Salmonidae, Pleuronectiformes, and in one case Squalidae) (Butler 1987). Conversely, archaeological investigations of the West Point site on the north side of Discovery Park in Seattle (utilized by hunter-fisher-gatherers between 4,250 and 200 BP) found few remains of gadiforms, although some Pacific cod bones were identified at this site (Wigen 1995). Wigen (1995) postulated that differences in the frequency of gadiform remains found between the Duwamish and West Point sites may be related to the possible use of fish traps at West Point versus hook and line methods at the Duwamish site, or perhaps to differences in the season of human occupation between the two sites. In historic times, Pacific hake were reported as abundant in Puget Sound by Jordan and Starks (1895).

Spawning location and spawn timing

Within Puget Sound (including Hood Canal) Pacific hake are known to spawn in Port Susan (Nelson 1969, Pedersen 1985, WDFHMD 1992) and in Dabob Bay (Bailey and Yen 1983, Bollens et al. 1992a, Fox 1997) and there may be other spawning aggregations of Pacific hake in Puget Sound (Fig. 19) but only the Port Susan-Saratoga Passage population has been commercially exploited (Thorne et al. 1971, Kimura and Millikan 1977, Pedersen 1985). Smith (1936) stated that spawning Pacific hake of both sexes were taken in Hale Passage near Carr Inlet in southern Puget Sound in March of 1936. WDFHMD (1992) also lists Carr Inlet as a known Pacific hake spawning location. According to Nelson (1969) large numbers of Pacific hake eggs and larvae have been found in Puget Sound only at Port Susan, with small numbers of eggs and larvae occurring in southern Puget Sound, Hood Canal, and near Possession Sound. Miller and Borton (1980) summarized distribution records of Pacific hake in Puget Sound as found in published records, museum collections, and various boat logs. Centers of collection of Pacific hake in Puget Sound were heavily influenced by fishing effort and ease of access, and centered around Port Susan, Saratoga Passage, Possession Sound, the central Sound from Shilshole Bay to Port Madison, Port Orchard, Carr Inlet, Penn Cove and Holmes Harbor on Whidbey Island, and Dabob Bay in Hood Canal (Miller and Borton 1980). Pedersen (1985) stated that small groups of Pacific hake occur in other areas of Puget Sound, in addition to Port Susan, but he did not identify the areas specifically. Historically, commercial fisheries for Pacific hake in Puget Sound centered around the Port Susan, Saratoga Passage, Port Gardner, and southern Carr Inlet areas (Fig. 20, Pedersen and DiDonato 1982).

Table A-1 summarizes available data on spawn timing in various locations for Pacific hake. In Puget Sound, spawning occurs primarily during February through April, peaking in March (W. Palsson[2]).

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[2] W. Palsson, WDFW, 16018 Mill Creek Blvd., Mill Creek, WA 98012-1296. Pers. commun. to B. McCain.

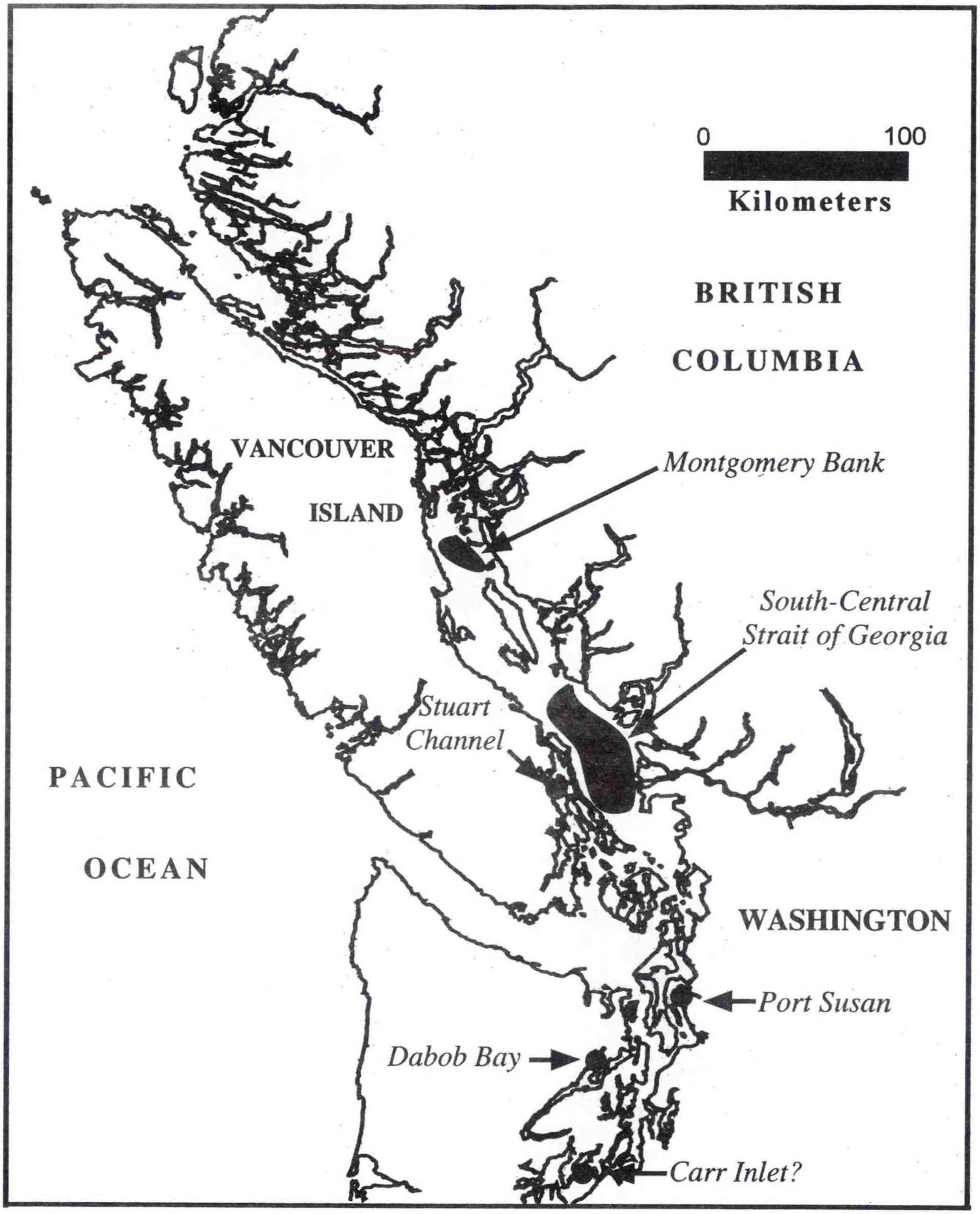

Figure 19. Known spawning locations (*in italics*) of Pacific hake in Puget Sound and southern British Columbia.

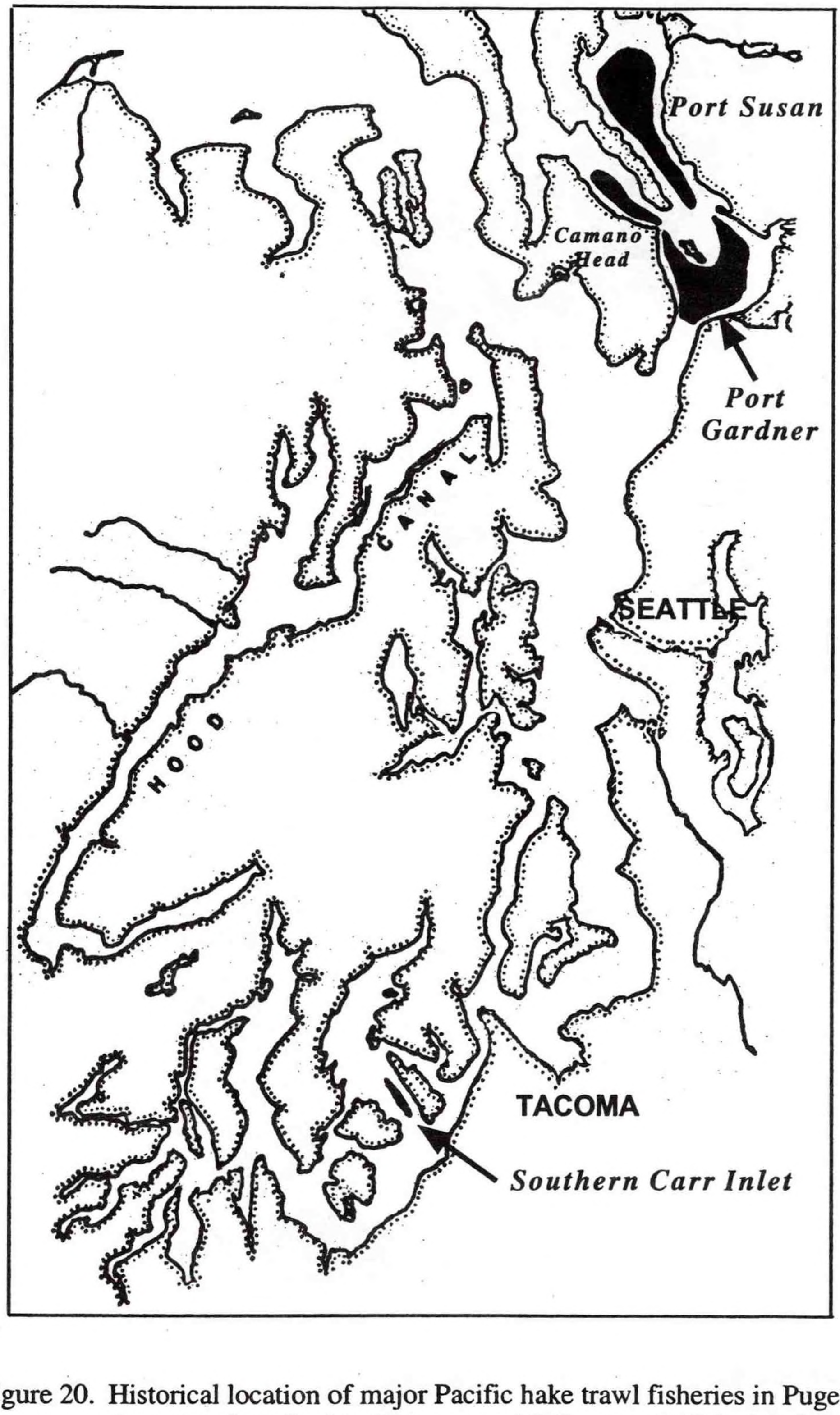

Figure 20. Historical location of major Pacific hake trawl fisheries in Puget Sound as described in Pedersen and DiDonato (1982). Modified from Pedersen and DiDonato (1982, their Appendix I, fig. 2).

Spawning aggregations begin to form up to a month before actual spawning. Within Puget Sound, peak spawning of Pacific hake occurs in mid-late-March in the Central Puget Sound population in Port Susan (Goñi 1988). Spawn timing of the Dabob Bay stock ranged from the beginning of February to the end of April in 1990 and from mid-January to the beginning of April in 1991 (Fox 1997). The mean back-calculated spawn date for Pacific hake in Dabob Bay was 14 March, in 1990, and February 20, in 1991 (Table A-1) (Fox 1997).

The main Pacific hake stock in the Strait of Georgia aggregates to spawn in the deep basins of the south-central Strait of Georgia (Fig. 19), with peak spawning occurring from March to May (Table A-1) (Goñi 1988, Shaw et al. 1990, Kieser et al. 1999). This area is bound by Halibut Bank and Gabriola Island, to the east and west, and Texada Island and Galiano Island to the north and south. Spawning aggregations of Pacific hake in south-central Strait of Georgia occur in two depth strata between 50-120 m and 150-330 m (Shaw et al. 1990). Beamish et al. (1976b) and McFarlane and Beamish (1985) stated that there is a second discrete stock of Pacific hake in the Strait of Georgia that has been found spawning northwest of Texada Island near Montgomery Bank (Fig. 19).

Foucher and Beamish (1980) reported that a third small stock of large Pacific hake has been observed spawning, 4-6 months prior to the main Strait of Georgia stock, in the Gulf Islands near Yellow Point in Stuart Channel (Fig. 19, Table A-1), suggesting this group is an additional discrete spawning stock (McFarlane and Beamish 1985). Likewise, Beamish et al. (1976a, c, 1978a) speculated that a stock of large Pacific hake may occur in Stuart Channel in the Gulf Islands that mature and spawn earlier than do Pacific hake in the open Strait of Georgia (Shaw et al. 1985a). Beamish et al. (1976c) stated that a small percentage of the presumed Stuart Channel stock appear to be in spawning condition year-round. An additional stock of Pacific hake was suggested to occur in Saanich Inlet by Beamish et al. (1978b) based on apparent different rates of growth and presence of larger than normal Pacific hake in this area.

Palsson et al. (1997) stated that the South Puget Sound Pacific hake, which spawn in the Port Susan area are distinct from the offshore migratory stock and probably distinct from the resident transboundary stock shared with Canada that spawns in the Strait of Georgia. This resident transboundary population is also considered distinct from the offshore migratory stock (Palsson et al. 1997). Although spawning of the stocks occurs in well separated areas, it is not clear to what degree precise homing to the spawning grounds occurs in the Strait of Georgia and Puget Sound (Goñi 1988). Alverson (1969) stated that the migration pattern and distribution of eggs and larvae indicate that the offshore migratory Pacific hake population is homogeneous. Alverson (1969) also stated that the evidence is good that Pacific hake in inshore waters of Puget Sound, and perhaps the Strait of Georgia, are distinct from the offshore migratory population.

Various Canadian publications provide evidence that two types of Pacific hake occur off the southwest coast of Vancouver Island. These two types consist of: 1) small numbers of resident Pacific hake that remain in the region year round, spending the summer in coastal inlets along the west coast of Vancouver Island, and 2) the much larger stock of migratory offshore Pacific hake that spawn off southern California and migrate north to feed in the spring and summer (Beamish and McFarlane 1985, Shaw et al. 1985b, Ware and McFarlane 1995). Separate resident stocks of Pacific hake apparently occur in Nootka Sound, Barkley Sound (Trevor Channel), Sydney Inlet, and Tahsis Inlet on Vancouver Island (Beamish and McFarlane 1985; Shaw et al. 1985b, 1989a, b; Ware and McFarlane 1995). Shaw et al. (1985b) stated that "it appears that each inlet contains a "resident" stock of hake which may have different spawning times assuming similar growth rates." Beamish and McFarlane (1985) cited unpublished data indicating that eggs and larvae of Pacific hake have been found in samples from January to April in the vicinity of Barkley Sound and Sydney Inlet "clearly indicating the presence of resident spawning stocks." Beamish (1981a) and Beamish and McFarlane (1985) also stated that since few Pacific hake have been observed in this region in winter, the putative resident stocks of Pacific hake off the west coast of Vancouver Island are likely small in size. Smith et al. (1990) speculated that as resident west coast Vancouver Island inlet Pacific hake mature, they may eventually mix with the offshore migratory population during summer months off southwest Vancouver Island. In addition, McFarlane and Beamish (1985) reported that small distinct local stocks of Pacific hake are suspected to occur in mainland inlets of the British Columbia coast north of the Strait of Georgia.

The offshore stock spawns off southern California, primarily from December to April, with peak activity occurring in January and February (Bailey 1981, Smith 1995)—although sometimes heavy spawning occurs in March (Fig. 17, Table A-1) (Bailey et al. 1982). Woodbury et al. (1995) provided evidence, based on back-calculated spawn dates of young-of-the-year Pacific hake collected in central California, that spawning occurred in some years from September to March but that the majority of survivors were spawned in January-February. Hirschberger and Smith (1983) reported on an anomalous group of over 180 Pacific hake collected in spawning condition in August 1980 along the coast of Oregon; a time of year and region where spawning Pacific hake had not been previously, or subsequently, reported.

Doyle (1992) and Hollowed (1992) reported the presence of Pacific hake eggs and larvae in ichthyoplankton samples collected offshore of Northern California, Oregon, and Washington in the spring of 1983 and 1984, but not in the spring of 1980, 1981, 1982, or 1985. Hollowed (1992) speculated that the 1983-84 El Niño may have caused a shift in Pacific hake spawner distribution to the north in the winter of 1983 and 1984, accounting for the finding of most eggs in those years between 40° and 44° N.

A stock of Pacific hake off the west coast of southern Baja California was identified as distinct from the main offshore stock by Vrooman and Paloma (1976) based on morphometry, meristics, and general protein electrophoresis. Vrooman and Paloma (1976) called this population "dwarf hake" and suggested that it does not interbreed with *M. productus* and may therefore be a separate species. Ermakov (1982) also differentiated between an "oceanic" and a "dwarf" Pacific hake off southern California and Baja California based on morphometrics and disjunct spawning localities. Bailey et al. (1982) regarded the separation of the dwarf and offshore stocks to be controversial and suggested the differences between the two units may not be genetic, but "are not inconsistent with changes caused by environmental effects in the different habitats."

Mathews (1985) described the "dwarf hake" of Vrooman and Paloma (1976) off Baja California as *M. hernandezi*; however, the taxonomic status of this species is still uncertain (Cohen et al. 1990).

Tagging and distribution

In general, species in the Genus *Merluccius* do not survive capture and release well and therefore no tagging studies exist to infer patterns of migration (Fritz 1959). This generality also holds for Pacific hake, which are difficult to tag externally due to their fragility (MacLellan and Saunders 1995). Despite the lack of tagging data, Mason et al. (1984) and Mason (1986) thought it unlikely that offshore and Strait of Georgia Pacific hake stocks intermingle to any large degree, based on their distributional patterns; although, according to Mason (1986), there may be some interchange between the Strait of Georgia and Puget Sound stocks due to surface transport of larvae produced in the central Strait of Georgia. However, WDFW (2000) pointed out that since water leaves the Strait of Georgia primarily "through and west of the San Juans into the northern Strait of Juan de Fuca," direct exchange of larvae between the Strait of Georgia and Puget Sound would not be expected.

Seasonal migrations

In autumn, the offshore stock of Pacific hake migrate from summertime feeding grounds (located between Queen Charlotte Sound in British Columbia and central California) to winter spawning areas (located between Cape Mendocino on the California coast and northern Baja California) (see Fig. 17). Spawning occurs from 60-1,655 km offshore at depths of from 120-400 m over bottom depths exceeding 1,000 m (Saunders and McFarlane 1997). Some Pacific hake may spawn as far south as off the southern tip of Baja California (Bailey 1982). The distribution of eggs and larvae and the migration pattern suggests that there is a single large offshore Pacific hake stock (Alverson and Larkins 1969). Adults migrate northward in the spring while juveniles remain off central and northern California (Bailey et al. 1982). The extent of northward migration is age-dependent, with older and larger fish migrating furthest north (Richards and Saunders 1990, Dark and Wilkins 1994, Saunders and McFarlane 1997). In warm years a greater proportion of the offshore Pacific hake stock moves into the Canadian fishery zone (Richards and Saunders 1990) and spawner distribution may shift further north as well (Hollowed 1992, Saunders and McFarlane 1997). Saunders and McFarlane (1997) summarized observations of latitudinal trends in biological characteristics such as age composition, sex ratio, mean size, and parasite prevalence for both summer-feeding and winter-spawning aggregations of offshore Pacific hake and propose processes that may explain these patterns.

Inshore Pacific hake that spawn in the Strait of Georgia, in Puget Sound at Port Susan and Dabob Bay, and in Nootka Sound, Barkley Sound, and Sydney Inlet on Vancouver Island are essentially resident stocks, although they may have relatively short spawning migrations (Ware and McFarlane 1995).

Year class strength

Strong year classes in offshore Pacific hake are not synchronous with those in Strait of Georgia Pacific hake (Beamish 1981a, McFarlane and Beamish 1985). According to Beamish et al. (1982), the dominant age-groups of Pacific hake in the Strait of Juan de Fuca and off the west coast of Vancouver Island were identical, and differed from Pacific hake in the Strait of Georgia. Analysis of age composition suggests that the differences between offshore Pacific hake and the inshore populations probably would be better characterized as differences in year-class variability rather than in year-class syncronicity (M. Dorn[3]).

Goñi (1988) found "strong inequalities" between indices of year-class strength (YCI, calculated by adding up percent contributions of each particular year class at ages 4, 5, and 6) for Port Susan (Puget Sound) and Strait of Georgia Pacific hake. Although discrepancies between ageing methods employed for these two populations may have confounded correlations between year classes in this study, Goñi (1988) stated that the differing relative importance and lack of correlation between strong year-class abundances in Port Susan and Strait of Georgia Pacific hake could be interpreted as evidence of their physical isolation. However, the fact that ageing procedures for Pacific hake differed by agency for these two groups of fish (Goñi 1988) and that the YCI used by Goñi (1988) was sensitive to the exploitation level, suggests that apparent differences in the YCI can't be used as reliable evidence of stock separation. At the time that Goñi (1988) did her study, the exploitation level for Puget Sound Pacific hake was high, whereas Strait of Georgia Pacific hake had a low exploitation rate. A high exploitation rate would accentuate the variability in the YCI even with the same variability in year class strength. The observation that recruitment (as evident by strong year classes) is more variable in Puget Sound Pacific hake relative to Strait of Georgia Pacific hake isn't supportable (M. Dorn[4]).

Parasite incidence

The softness and rapid deterioration of Pacific hake flesh following capture is generally considered to be due to two species of *Kudoa*, a genus of myxosporean protozoan parasites that infect the Pacific hake muscle fibers (Kabata and Whitaker 1981, 1985, 1986). The myxosporean parasite *Kudoa paniformis* was absent from Strait of Georgia Pacific hake (Kabata and Whitaker 1981, McFarlane and Beamish 1985) but was found in 57% of the large offshore migratory Pacific hake population (Kabata and Whitaker 1985). *Kudoa paniformis* was also absent in the putative resident Pacific hake stock in Tahsis Inlet on Vancouver Island, and was found in only one fish (11%) from the putative resident Pacific hake stock in Barkley Sound (Trevor Channel)

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[3] M. Dorn, NMFS, F/AKC3, 7600 Sandpoint Way NE, Seattle, WA 98115-6349. Pers. commun. to R. Gustafson.

[4] M. Dorn, NMFS, F/AKC3, 7600 Sandpoint Way NE, Seattle, WA 98115-6349. Pers. commun. to R. Gustafson.

(Shaw et al. 1989b). Another less harmful but more widespread myxosporean parasite *K. thyrsitis* (Gilchrist, 1924) is found in Pacific hake from the Strait of Georgia, west coast Vancouver Island inlets, and offshore locations. This parasite is also prevalent in walleye pollock, some flatfish, and in several fish from Australia and South Africa (Kabata and Whitaker 1985). The presence of *K. paniformis* in the offshore stock but not in the Strait of Georgia or in Tahsis Inlet stocks indicates that this parasite likely infected the offshore Pacific hake stock subsequent to the separation of the inshore stocks (Kabata and Whitaker 1981, 1985). Distribution of parasites in the Genus *Kudoa* is further indication that resident Pacific hake stocks do not substantially intermingle with offshore migratory Pacific hake; *Kudoa* infection is spread either by release of spores from dead fish or via cannibalism.

Growth rate and body size

Due to the difficulty of visualizing scale annuli in Pacific hake, ageing of this species has typically occurred through analysis of the surface or internal annuli of otoliths (Etchevers 1971, Chilton and Beamish 1982). Due to difficulties in detecting growth zones in older, slower growing fish in the Strait of Georgia, Pacific hake in this area are aged by the "break and burn" method where the otolith is broken or sectioned through the nucleus and exposed to an alcohol flame, which enhances the contrast between the translucent and opaque zones (Chilton and Beamish 1982). Beamish (1979) stated that "age determinations using whole otoliths will not accurately determine the age of most older Pacific hake in some stocks." Puget Sound Pacific hake have routinely been aged by counting annuli on the surface of the otolith (Goñi 1988). Since growth zones on the otolith surface are difficult to identify in older, slower growing fish (Etchevers 1971), Beamish (1979) suggested that ages assigned to Pacific hake in the Puget Sound population by Kimura and Millikan (1977) may have underestimated the actual ages of older fish. Attempts to compare growth rates between stocks of Pacific hake are further compounded by apparent temporal changes in mean length-at-age and consequent interannual variations in mean growth rates within the offshore stock (Woodbury et al. 1995). Hollowed et al. (1988) reported recent declines in mean length-at-age of offshore Pacific hake that may have been associated with the 1983 El Niño event or a density-dependent growth response to increased population abundance (Hollowed et al. 1988, Dorn 1992, Dark and Wilkins 1994). Despite differences in ageing methods applied to different stocks of Pacific hake, comparisons of growth parameters between stocks are routinely made.

Puget Sound Pacific hake have been reported to have a substantially slower growth rate than offshore Pacific hake (Alverson and Larkins 1969, Nelson and Larkins 1970). Likewise, Beamish et al. (1982) and McFarlane and Beamish (1985) noted that Pacific hake in the Strait of Georgia were considerably smaller than similar aged Pacific hake in the Strait of Juan de Fuca and off the west coast of Vancouver Island. Beamish et al. (1982) concluded that these differences supported the contention that Pacific hake in the Strait of Georgia are a separate stock from Pacific hake found in the western Strait of Juan de Fuca and offshore of Vancouver Island. The size of offshore and Strait of Georgia Pacific hake is reportedly similar up to the age at which they first mature, but offshore Pacific hake continue to increase in length, and reach larger sizes (Beamish 1979).

Goñi (1988) compared growth rate parameters from the literature for Puget Sound and Strait of Georgia Pacific hake and found between-stock differences in mean length-at-age that were significant for all cohorts examined. Comparison of growth plots of the two stocks revealed a consistent between-stock difference of about 5 cm in size-at-age. Puget Sound Pacific hake do not seem to grow as large overall as do Strait of Georgia Pacific hake (Goñi 1988).

Alverson et al. (1964) reported that mature Pacific hake taken off the Oregon-Washington coast averaged 52 cm in length with a range of from 22 to 71 cm. In the Strait of Georgia, the mean size of males was 52 cm and 54.5 cm for females between 1977 and 1981 (Beamish and McFarlane 1985). Between 1977 and 1981, the largest male and female Pacific hake reported from the Strait of Georgia were 77 and 84 cm, respectively, although very small percentages of either sex were greater than 60 cm in length (Beamish and McFarlane 1985). Most of the Pacific hake that occurred in the fishery in Port Susan in Puget Sound were from 32-45 cm in length (Pedersen 1985). Maximum lengths recorded by Pedersen (1985) for Puget Sound Pacific hake were 45 cm for males and 73 cm for females.

Nelson (1969) stated that for any given age, Pacific hake from inshore waters of Puget Sound and the Strait of Georgia are substantially smaller than the offshore migratory Pacific hake. For instance, the mean lengths of inshore Pacific hake at age 3 and 4 are 15 to 20 cm shorter than offshore Pacific hake of the same age (Nelson 1969). Pedersen (1985) stated that Puget Sound Pacific hake appear to be 2-4 cm larger at age 2 and 2-4 cm shorter at age 3 and older, than Strait of Georgia Pacific hake. Pedersen (1985) suggested that this relationship (and the fact that Puget Sound Pacific hake mature at a smaller size than do Strait of Georgia Pacific hake) may have been due to the intense commercial Pacific hake fishery in Puget Sound. The average sizes of Pacific hake in both Puget Sound and the Strait of Georgia are substantially smaller at the present time than they were in the 1980s. For example, very few Pacific hake larger than 30 cm are currently present in the Port Susan Pacific hake population (Figs. 21, 22).
Kautsky (1989) stated that "the coastal stock consistently attains larger sizes at age than the Puget Sound stock suggesting that the maximum attainable size for the Puget Sound stock is less than that for the coastal stock."

Shaw et al. (1989a) reported that mean length-at-age of Pacific hake in Trevor Channel in Barkley Sound on the west coast of Vancouver Island was significantly smaller than that for the migratory offshore Pacific hake from La Perouse Bank and Triangle Island off Vancouver Island.

Length and age at maturity

Table A-2 summarizes length at first maturity, at 50% maturity, and at 100% maturity for selected Pacific hake populations. Puget Sound and Strait of Georgia Pacific hake stocks appear to mature at a smaller size than the offshore migratory stock (McFarlane and Saunders 1997).

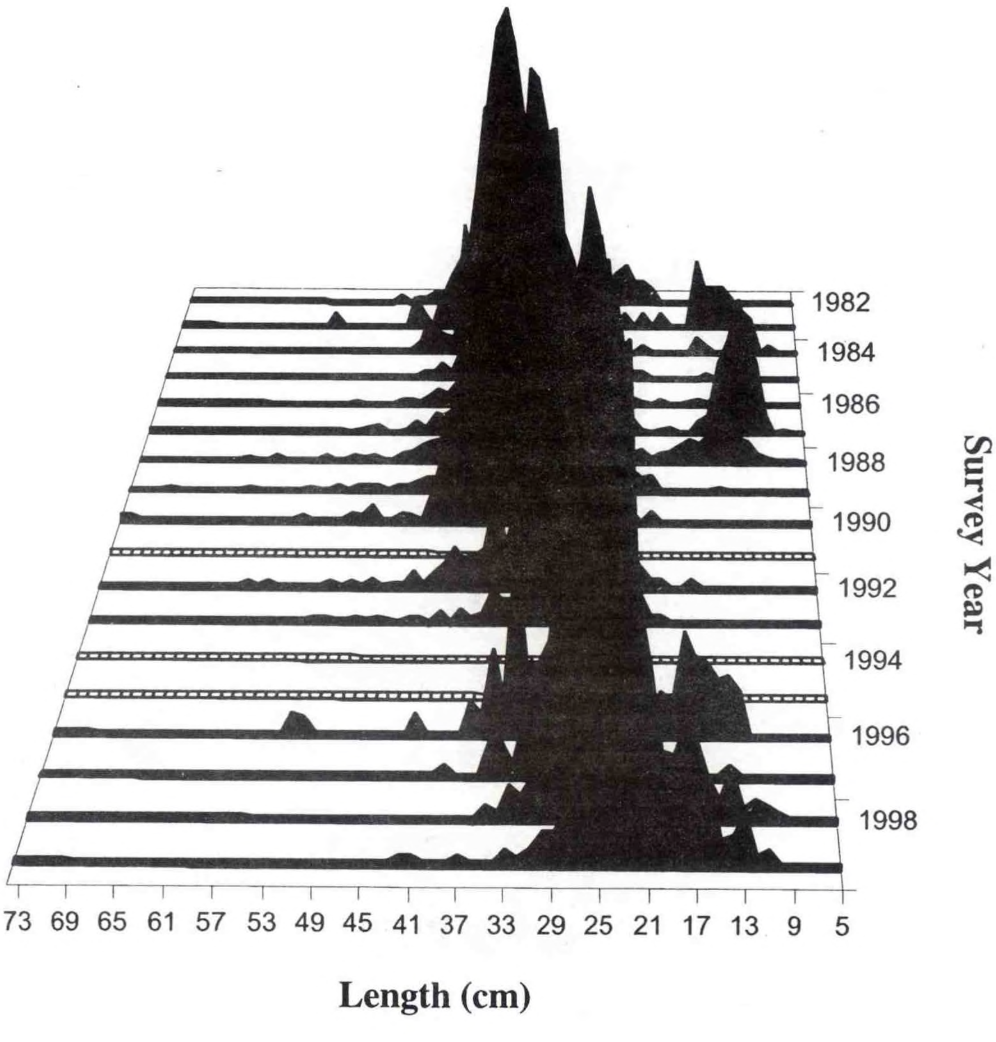

Figure 21. Port Susan Pacific hake length frequency composition from 1982 to 1999 in spring acoustic survey trawl samples. Data from W. Palsson (WDFW, 16018 Mill Creek Blvd., Mill Creek, WA 98012-1296, pers. commun. to W. Lenarz).

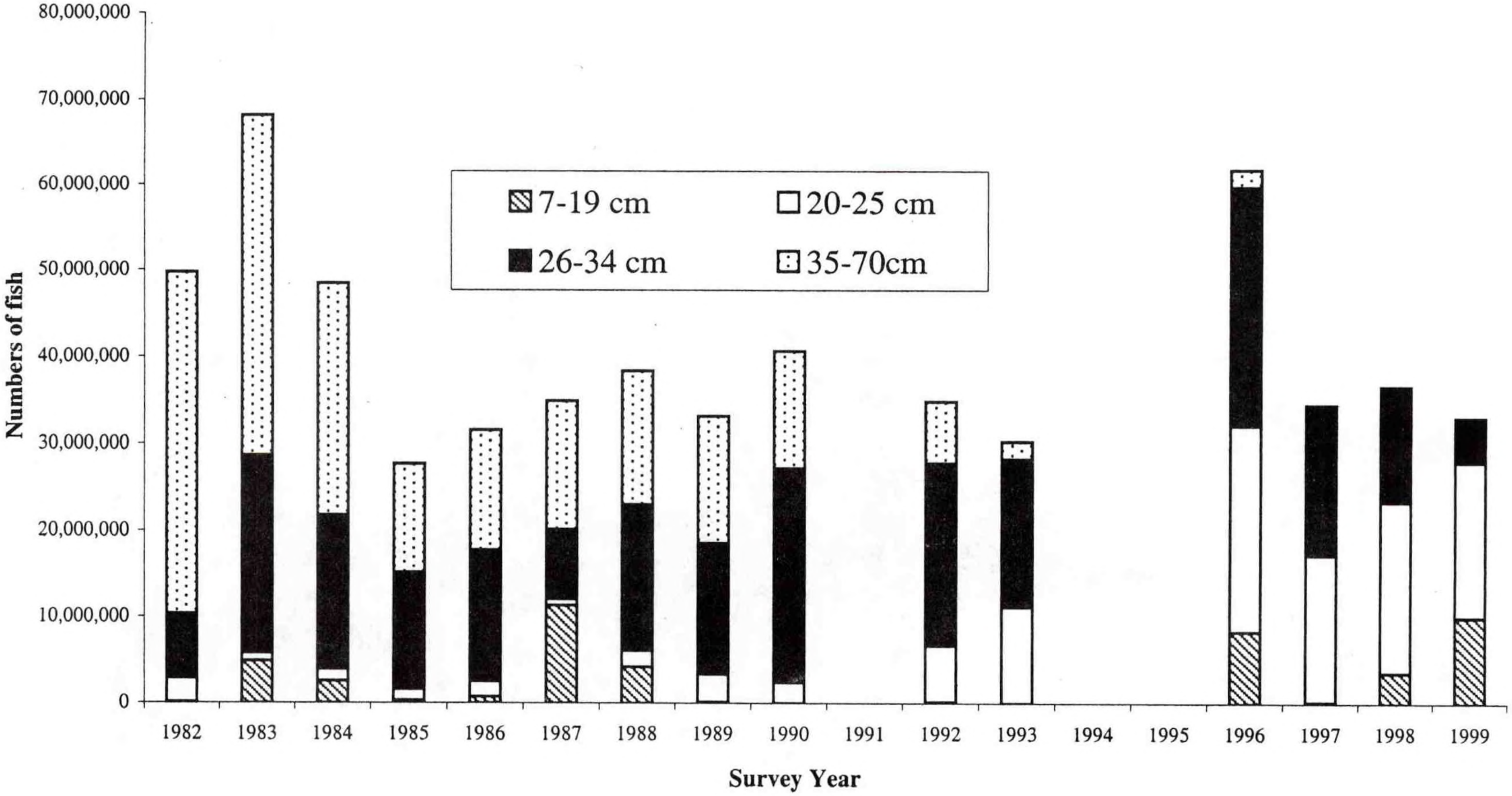

Figure 22. Estimated size composition (numbers by length category) of Pacific hake in the Port Susan population, based on acoustic-trawl surveys during 1982-99. Data from W. Palsson (WDFW, 16018 Mill Creek Blvd., Mill Creek, WA 98012-1296, pers. commun. to W. Lenarz).

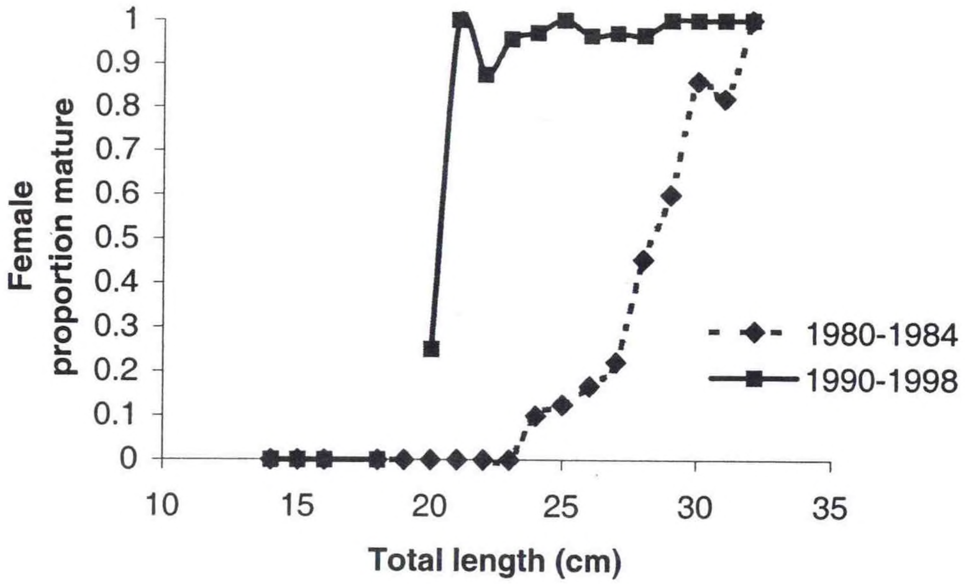

Figure 23. Maturity schedule for female Pacific hake caught during WDFW hydro-acoustic surveys in the Port Susan area. Data provided by W. Palsson (WDFW, 16018 Mill Creek Blvd., Mill Creek, WA 98012-1296, pers. commun. to W. Lenarz).

Historically, both male and female offshore Pacific hake matured at a length of about 40 cm (Best 1963), whereas male and female Pacific hake in the Port Susan population in Puget Sound matured at a length of about 30 cm (Kimura and Millikan 1977). Currently, length at 50% maturity for females in the Port Susan Pacific hake population is approximately 21.5 cm, compared to 29.8 cm in the 1980s (Fig. 23, Table A-2).

Length frequencies

Figures 21 and 22 illustrate the temporal decline in the size of survey-caught Pacific hake in the Port Susan spawning population from the late 1980s to the present. A large proportion of the Pacific hake in Puget Sound sampled in the 1987 research-trawl survey (Quinnell and Schmitt 1991) were greater than 30 cm length (Fig. 18), indicating that this decline in average length and shift to smaller size frequencies occurred after this period of time. In the latter half of the 1990s, few Pacific hake larger than 35 cm were caught in the Port Susan acoustic-trawl surveys and by 1999 the majority were less than 25 cm in length (Figs. 21, 22).

Fecundity

Like hake species elsewhere, the Strait of Georgia Pacific hake stock shows evidence of resorption of unreleased oocytes following spawning (Foucher and Beamish 1980, Mason 1986, McFarlane and Saunders 1997). MacGregor (1966, 1971) also noted that small-yoked oocytes were resorbed following spawning of larger eggs in a sample of female Pacific hake collected off California in March and April.

The presence of oocytes of different maturity stages in pre-spawning Pacific hake and the retention of small-sized yoked oocytes in spent or partially spent Pacific hake have been interpreted differently by various researchers. In the case of *Merluccius hubbsi*, *M. gayi*, *M. merluccius*, *M. capensis*, and *M. paradoxus* multiple size classes of oocytes in different maturity states and retention of yoked oocytes in post spawners have been interpreted as evidence for serial or batch spawning (Osborne et al. 1999, and references therein). Similarly, Ermakov (1974) interpreted multi-modal oocyte diameters in Pacific hake as evidence for multiple spawning events in a single year. However, other researchers (MacGregor 1966, 1971; Foucher and Beamish 1980; McFarlane and Saunders 1997) reported that smaller yoked oocytes that remain after spawning in *M. productus* were completely resorbed and that a second spawning did not occur. Although other species of *Merluccius* may be batch spawners, it is currently assumed that Pacific hake spawn only once per year. The retention of some oocytes after spawning in Pacific hake suggests that traditional methods of estimating fecundity are not applicable to Pacific hake. Therefore, McFarlane and Saunders (1997) have defined "effective fecundity" in Pacific hake "as the number of yoked oocytes that are actually released to be fertilized."

McFarlane and Saunders (1997) reported that although total fecundity does not differ among Pacific hake stocks, effective fecundity differs between the migratory offshore stock and the smaller discrete stocks of Pacific hake in Puget Sound and the Strait of Georgia. All three stocks of Pacific hake retained and resorbed a portion of their oocytes (10-12% for the offshore stock, 32-44% for the Puget Sound stock, and 38-58% for the Strait of Georgia stock), but the Strait of Georgia stock retained a considerably higher percentage of eggs than the other stocks, ranging from 38% for the largest fish to 58% for the smallest (McFarlane and Saunders 1997).

Morphological Differentiation

Morphometric discrimination

Ehrich and Rempe (1980) examined morphometric differences (diameter of bony orbit, head length, precaudal length, and distances from the tip of snout to end of the pectoral and 2nd dorsal fin) between four groups of Pacific hake found in the northern and southern regions of the Gulf of California, offshore of Baja California to Alaska, and in nearshore regions of the west coast of Baja California. The greatest differences were found between the offshore population and the southern Gulf of California population, while the offshore population was most similar to the southern nearshore population off the west coast of Baja California (Ehrich and Rempe 1980).

Shape and size of the otolith

McFarlane and Beamish (1985) reported that sagittal otoliths from offshore Pacific hake were more elongate and less concave in section than otoliths from Strait of Georgia Pacific hake, although no statistical analyses were published to test these observations. Anonymous (1968) also reported that otoliths from Puget Sound Pacific hake "vary" from offshore Pacific hake otoliths.

A number of studies have attempted to utilize interspecific and intraspecific size and shape variation in otoliths to identify species, populations and stocks of various hake species in the genus *Merluccius* (Lombarte and Castellón 1991, Torres et al. 2000, Bolles and Begg 2000). Lombarte and Castellón (1991) applied multivariate analysis to a numerical description of otolith outlines for four size classes of fish in six species of *Merluccius*. Analysis of otoliths from fish greater than 20 cm in length correctly classified individuals into a Euro-African group (*M. merluccius*, *M. capensis,* and *M. paradoxus*) and an American group (*M. bilinearis*, *M. productus*, and *M. gayi*). Lombarte and Castellón (1991) concluded that these morphological differences "are a reflection of genetic distance between species." Within Pacific hake (*M. productus)*, "otoliths taken from individuals from different geographical areas [presumably from off west coast Vancouver Island and California] had no influence on otolith shape." Lombarte and Castellón (1991) did not apparently make a comparison of otoliths in offshore Pacific hake with otoliths from inshore Pacific hake.

Torres et al. (2000) demonstrated clear geographical differentiation between two groups of *M. gayi* (from Chile and Peru) and between Atlantic and Mediterranean samples of *M. merluccius* in morphometric measurements of otoliths. In both species, all otoliths could be correctly assigned to the appropriate geographical sample based on otolith analysis. However, two groups of *M. hubbsi* from off the southeast coast of South America could not be differentiated on the basis of otolith morphometrics. Likewise, Bolles and Begg (2000) successfully used whole sagittal otolith morphometrics, specific to fish age, to differentiate silver hake (*M. bilinearis*) stocks from the east coast of North America into a northern stock from the Gulf of Maine to Georges Bank and a southern stock from southern Georges Bank to the Middle Atlantic.

Otolith morphometrics related to length and width can be expected to reflect localized environmental variables. Although variation in otolith morphometrics can be used to differentiate stocks or management units of fish, the usefulness of these differences in the delineation of a DPS in a marine fish species is dependent on the degree to which otolith variability reflects environmental or genetic differences between groups of fish.

Genetic Information

Genetic population structure of hake species

Inada (1981) recognized 12 species of hake in the Genus *Merluccius:* 1) European hake *M. merluccius*, 2) Senegalese hake *M. senegalensis*, 3) Bengualean hake *M. polli*, 4) shallow-water Cape hake *M. capensis*, 5) deep-water Cape hake *M. paradoxus*, 6) silver hake *M. bilinearis*, 7) offshore hake *M. albidus*, 8) Pacific hake *M. productus*, 9) Panamanian hake *M. angustimanus*, 10) Chilean hake *M. gayi*, 11) Argentinian hake *M. hubbsi*, and 12) New Zealand hake *M. australis*.

Interspecific allozymic variation of hake has been investigated by Stepien and Rosenblatt (1996), Roldan et al. (1999), and Galleguillos et al. (1999), while Becker et al. (1988) and Quinteiro et al. (2000) examined between-species genetic divergence using mtDNA RFLP variation and comparison of sequence divergence in the control region of mtDNA, respectively (see "Glossary" for definitions). Intraspecific relationships have been studied using allozyme electrophoresis in *M. merluccius* (Pla et al. 1991, Lo Brutto et al. 1998, Roldan et al. 1998), *M. capensis* and *M. paradoxus* (Grant et al. 1987b, and references therein), *M. hubbsi* (Roldan 1991), and *M. productus* (Anonymous 1968; Utter 1969a, b; Utter and Hodgins 1969, 1971; Utter et al. 1970). Lundy et al. (1999) have investigated population structure in European hake through variation at six microsatellite loci.

The European hake, *M. merluccius,* is distributed along the eastern Atlantic coast from Norway to Morocco and throughout the Mediterranean Sea. Early efforts at detecting genetic population structure in European hake with protein electrophoresis revealed no significant variation at three allozyme loci among twelve samples ranging from Norway to the Bay of Biscay

(Mangaly and Jamieson 1978). More recent genetic studies, using up to 21 polymorphic allozyme loci, have indicated a clear genetic difference between European hake in the Atlantic Ocean and the Mediterranean Sea, with the Straits of Gibralter acting as a geographic barrier (Pla et al. 1991, Roldan et al. 1998). Lo Brutto et al. (1998) detected insignificant levels of allozyme variation at four polymorphic loci among populations of *M. merluccius* along the coasts of Italy and Sicily. Despite the reported genetic homogeneity among Italian populations, Roldan et al. (1998) found significant allozyme genetic evidence of population substructuring in both Atlantic and western Mediterranean *M. merluccius*. Similarly, Lundy et al. (1999) found significant population subdivisions between Mediterranean and Atlantic European hake, but no substructure within the Mediterranean, using six polymorphic microsatellite loci. However, Lundy et al. (1999) did find significant differentiation in the same microsatellite loci between Bay of Biscay and Portuguese populations, which are currently managed as one stock, but no differentiation between southern Bay of Biscay and Celtic Sea populations, which are managed as separate stocks.

Grant et al. (1987b) detected only small amounts of genetic divergence by allozyme electrophoresis between stocks of both *M. capensis* and *M. paradoxus* off Namibia and South Africa. More than 98% of the total genetic diversity in these species was found to occur within sampling locations for both species. Nei's genetic distances (D) between samples were generally less than 0.001. Although three widely separated spawning grounds have been identified for *M. australis* in New Zealand waters (Colman 1995), Smith et al. (1979) were unable to detect significant differences in allele frequencies at two polymorphic allozyme loci among four New Zealand sampling locations. Roldan (1991) found a complex structure to occur among *M. hubbsi* populations on the Argentinian continental shelf upon analysis of 4 polymorphic allozyme loci sampled at 10 locations. However, genetic heterogeneity among samples was primarily due to variation at a single locus (*EST-1**) and sample sizes were relatively small (Roldan 1991). In general, species of *Merluccius* that have been investigated tend to show subdivided population structure around geographically complex coastlines (Roldan et al. 1998, Lundy et al. 1999), but not along linear coastlines (Smith et al. 1979, Grant et al. 1987b).

Pacific hake genetics

In a series of publications, Utter and coauthors (Utter 1969a, b; Utter and Hodgins 1969, 1971; Utter et al. 1970) compared protein electrophoretic variation in Pacific hake from various locations in Puget Sound, off the Oregon-Washington coast, and off southern California at four polymorphic loci (lactate dehydrogenase (LDH), transferrin, muscle protein, and esterase). Two alleles were detected at both the muscle protein and LDH loci, four at the transferrin locus, and five at the esterase locus (Utter and Hodgins 1971). No evidence of heterogeneity was found at LDH or esterase within or between the two sampling locales for offshore Pacific hake (off Oregon/Washington and southern California) (Utter and Hodgins 1969, 1971; Utter et al. 1970). Comparison between multiple samples of Pacific hake taken off the outer coasts of Oregon and Washington also revealed no heterogeneity at the transferrin or muscle protein loci (Utter 1969b, Utter and Hodgins 1971).

However, Utter and Hodgins (1971) stated that allelic frequencies of all four polymorphic loci differed significantly between offshore and Puget Sound Pacific hake and indicated that these populations were reproductively isolated. The average and range of frequencies of the most common allele for the four loci for the two regions were as follows: 1) esterase, 0.603 (range 0.577-0.655) in offshore samples (n=358) and 0.828 (range 0.733-0.904) in Puget Sound (n=903); 2) transferrin, 0.564 (range 0.536-0.583) in offshore (n=203) and 0.696 (range 0.672-0.750) in Puget Sound (n=115); 3) skeletal muscle protein, 0.982 (range 0.969-0.992) for offshore samples (n=225) and 0.730 (range 0.705-0.823) for Puget Sound (n=250); and 4) LDH, 0.980 in offshore samples (n=355) and 0.745 (range 0.695-0.794) in Puget Sound (n=762) (Utter 1969b; Utter and Hodgins 1969, 1971; Utter et al. 1970). Many of the Pacific hake samples used in the above allozyme studies of Utter and coauthors were collected in Puget Sound outside of the spawning season and distant from known spawning grounds; however, several collections (particularly for esterase and LDH) were made of fish in or near the spawning grounds (Port Susan) and during the spawning season and these samples did not differ significantly from any of the other Puget Sound samples (Utter 1969b; Utter and Hodgins 1969, 1971; Utter et al. 1970).

Utter et al. (1970) included analysis of esterase variation of one sample of 80 Pacific hake juveniles collected in Hood Canal (Dabob Bay in Hood Canal is a known Pacific hake spawning ground). The frequency of the most common allele in this sample (0.831) did not differ significantly from that of other samples taken in Puget Sound (average frequency of 0.828 for 12 samples) (Utter et al. 1970).

Prior to the recent decrease in body size of inshore Pacific hake (see "Length and age-at-maturity" section), Puget Sound fish averaged approximately 35 cm and offshore fish averaged about 50 cm. However, observations of large-sized (greater than 60 cm) Pacific hake have been made in both Puget Sound and the Strait of Georgia and speculation as to whether these large fish are from the offshore population has been made. Anonymous (1968) addressed this question and stated that:

> Hake of oceanic size have occasionally been caught in Puget Sound, which raised the question of whether the larger fish were migratory or indigenous. ... The gene frequencies of the large and normal fish in Puget Sound agreed with those of smaller fish from the same area. This indicated that the larger fish are indigenous to Puget Sound.

Goñi (1988) examined restriction fragment length polymorphism (RFLP) variation of mitochondrial DNA (mtDNA) in Pacific hake collected from California (four individuals pooled, collected off Cape Mendocino, California in August), Puget Sound (four individuals pooled, collected off West Point, Washington in August), and the Strait of Georgia (two separate individuals, collected in the central Strait of Georgia in November). Goñi (1988) observed four composite mtDNA haplotypes amongst these samples and stated that "The geographical distribution of these genotypes seems to reveal a certain degree of mixture between populations." Goñi (1988) also stated that "The apparent absence of high diversity in the mtDNA molecules might indicate that the three stocks either intermingle to a certain extent, or are units that have recently formed." However, several factors make the interpretation of Goñi's (1988) mtDNA study difficult. Homogenization of both the California and Puget Sound samples was done by Goñi (1988) with the assumption that within-sample variation was nonexistent. However, within-sample variation was found in pooled California and separate Strait of Georgia samples, leading Goñi (1988) to conclude that homogenization was inappropriate and may have masked the true results. Another factor that complicates the interpretation of Goñi's (1988) results is that all samples were collected outside of the spawning season and a considerable distance away from known spawning grounds of Pacific hake. The small sample sizes used in this study would also indicate that Goñi's (1988) study should be considered inconclusive.

Information Relevant to the Pacific Hake DPS Question

As stated in the previous "Approaches to the Species Question and to Determining Risk" section, four broad types of information were analyzed by the BRT in its determinations of whether Pacific hake in Puget Sound represent a "discrete" and "significant" population and therefore qualifies as a DPS under the ESA. These are: habitat characteristics, phenotypic and life-history traits, mark-recapture studies, and analysis of neutral genetic markers. As such data can only be properly evaluated in relation to similar information for the biological species as a whole, Puget Sound Pacific hake data were compared with data from Pacific hake from throughout the species' range.

As detailed in the previous sections on "Environmental History and Features of Puget Sound" and "Phenetic and Genetic Information Relating to the Species Question," specific information in the following categories was available for Puget Sound Pacific hake: physical habitat, spawning time and location, year-class strength, growth rate and body size, size and age at maturity, length frequency, fecundity, and protein electrophoretic variation. Data on migration patterns, tagging, parasite incidence, meristics and morphometrics, and genetic population structure using contemporary techniques were largely unavailable for Pacific hake in Puget Sound. A similar assemblage of data was available for Pacific hake from the Strait of Georgia, although protein electrophoretic data were lacking and studies on the incidence of the parasite *Kudoa paniformis* were available. With the exception of tagging and a contemporary study of genetic population structure, all categories of information mentioned above were available for offshore Pacific hake. The previous section on "Approaches to the Species Question and to Determining Risk" should be consulted for a general discussion of the relative usefulness of the various categories of data for DPS delineation. Issues of biological data quality for Pacific hake are addressed for each category in the preceding section on "Phenetic and Genetic Information Relating to the Species Question."

Discussion and Conclusions for Pacific Hake DPS Determinations

The BRT considered several possible DPS configurations for populations of Pacific hake in the northeastern Pacific Ocean in its attempt to identify a "discrete" and "significant" segment of the biological species that incorporates Puget Sound Pacific hake. After careful consideration of the available information, the BRT concluded that inshore resident Pacific hake from Puget Sound and the Strait of Georgia are part of a separate DPS from offshore (coastal) migratory Pacific hake that are seasonally distributed from southern California to as far north as southeastern Alaska. These inshore Pacific hake will hereafter be identified as the Georgia Basin Pacific hake DPS (Fig. 1). Pacific hake that spawn occasionally off the west coasts of Oregon, Washington and Vancouver Island were considered to be opportunistic spawners belonging to the offshore Pacific hake stock and not part of the Georgia Basin DPS. Lack of biological information precluded the BRT from drawing any firm conclusions about the affinities of Pacific hake from west coast Vancouver Island inlets. At the present time, Pacif hake from west coast Vancouver Island inlets are not considered to be part of the Georgia Basin DPS.

The BRT identified a variety of evidence to support their conclusion that Georgia Basin Pacific hake constitute a separate DPS relative to offshore Pacific hake: 1) Differences in annual migration behavior; 2) significant allozyme frequency differences between Puget Sound and offshore Pacific hake; 3) absence of the protozoan parasite *Kudoa paniformis* in inshore populations compared to its common occurrence in offshore Pacific hake; 4) differences in otolith morphology between Strait of Georgia and offshore Pacific hake; 5) distinctiveness of the habitats of inshore Pacific hake (they spawn in deep, inshore basins that receive large freshwater inputs and are the only populations of Pacific hake that inhabit fjord-like environments); 6) wide geographic separation of inshore and offshore spawning locales; and 7) demographic data showing inshore Pacific hake are generally smaller for a given age, mature at a smaller size, and reach a smaller maximum length than offshore fish.

The BRT expressed several concerns about the available data; for example: 1) it is not clear to what degree demographic differences between Georgia Basin and offshore Pacific hake are driven by environmental or genetic differences, 2) some of the allozyme loci that show differences between the Puget Sound and offshore Pacific hake have been shown to be under selection in other animals, and 3) there is no obvious physical barrier preventing mixing of offshore and Georgia Basin Pacific hake, especially during the June-August period when offshore Pacific hake may occur near the mouth of the Strait of Juan de Fuca.

The Georgia Basin DPS encompasses at least five geographically-discrete spawning aggregations in deep-water basins, including Dabob Bay and Port Susan in Puget Sound and south-central Strait of Georgia, Stuart Channel, and Montgomery Bank in the Strait of Georgia (Figs. 1, 19). Therefore, the BRT considered whether there is evidence for multiple populations or stocks of Pacific hake within this DPS and, perhaps, multiple DPSs within the Puget Sound/Strait of Georgia area. Such information is limited. The majority of the BRT felt that good evidence that stock structure may exist within the Georgia Basin DPS includes: 1) the presence of geographically-discrete and temporally-persistent spawning aggregations, and 2) demographic differences between Strait of Georgia and Puget Sound fish. Tagging and genetic data for within Georgia Basin comparisons are unavailable or incomplete. Data showing apparent asynchronous year class strength between Puget Sound and Strait of Georgia Pacific hake were viewed as technically flawed (see above "Year class strength" section). Although the BRT could not with any certainty identify multiple populations or DPSs of Pacific hake within the Georgia Basin, the majority of the BRT acknowledged the possibility that significant structuring may exist within the proposed DPS and that such structure might be revealed by new information in the future.

Offshore Pacific hake migrate annually between summer feeding areas in waters off Oregon, Washington, British Columbia, and occasionally as far north as south central Alaska to spawning areas off southern California. The BRT did not attempt to determine whether offshore Pacific hake are composed of more than one DPS.

Assessment of Extinction Risk

Introduction

The petition discussed decline in abundance (Palsson et al. 1997), decline in average size, and predation by marine mammals (Schmitt et al. 1995) in its proposal to list Pacific hake in South Puget Sound. South Puget Sound was defined in the petition as the Sound east of Deception Pass and to the south of and east of Admiralty Point and south of Point Wilson on the Quimper Peninsula. Although the petition only discussed the spawning population of Pacific hake in the Port Susan area, it is known that Pacific hake also spawn in Dabob Bay (Fox 1997). The BRT concluded that Puget Sound populations of Pacific hake are part of the Georgia Basin DPS.

This section presents results of review and analysis of available information on abundance, evaluation of risk of extinction of the Port Susan population, and evaluation of the risk of extinction of the DPS as a whole. Hydro-acoustic estimates of the Port Susan population were revised under assumptions that are more appropriate for the risk analysis than those originally used. Also, new target strength estimates based on recent developments in hydro-acoustic technology were used for the revision. Risk assessment of the Port Susan population used two models to analyze the impact of pinniped predation under a wide range of assumed levels of predation. There were insufficient data available to evaluate the status of the Dabob Bay population. There were also insufficient data to perform more than a semi-quantitative analysis of the risk of extinction of the Canada portion of the DPS or of the DPS as a whole.

Information on Abundance and Composition

Port Susan

Biomass estimates of Pacific hake in Port Susan were given by Palsson et al. (1997) (Table 3). The Washington Department of Fish and Wildlife (WDFW) produced the estimates from annual hydro-acoustic surveys (Lemberg et al. 1990). After examination of available data and consultations with Wayne Palsson (W. Palsson[5]) and Martin Dorn (M. Dorn[6]) it was decided that analysis of the data shown in Table 3 could be improved in several ways for the risk analysis.

WDFW designed the surveys to produce estimates of biomass available to the fishery in each year. Their information indicated that peak abundance usually occurs in March. Since the fishing season often began in the preceding fall, WDFW usually added catches up to the time of the survey to the survey results to obtain a biomass estimate at the beginning of the fishing season. The fishery ceased in 1991. WDFW used one to three surveys taken in late February through mid March. Also WDFW and the industry desired that immature fish not be harvested. Pacific hake matured at about 30 cm during the early years of the survey. In most years WDFW used catch compositions of trawl surveys to first convert acoustic biomass estimates to estimates of Pacific hake biomass and then to convert Pacific hake biomass estimates to estimates of biomass of greater than 29 cm. However, WDFW included smaller Pacific hake in estimates for the earlier years. WDFW did not conduct trawl surveys in 1994 or 1995, but made biomass estimates from hydro-acoustic surveys (biomass estimates not in Table 3).

Wayne Palsson (W. Palsson[7]) provided biomass estimates from 1982 through 1999 (data for the year 2000 were received subsequent to the analyses) and information about the quality of the surveys. It was decided not to use the 1994 and 1995 estimates, because WDFW did not conduct trawl surveys, and their1995 acoustic survey was in early February which is before the time of normal peak abundance. While WDFW's decision to add catch to the survey estimates and estimating biomass of Pacific hake greater than 29 cm were appropriate for fishery management, it was decided to use estimates of biomass of all Pacific hake in the Port Susan area at the time of surveys for risk assessment. The surveys occurred during the spawning season, which seemed the appropriate season for examination of productivity of the population. Catch was not added to the

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[5] W. Palsson, WDFW, 16018 Mill Creek Blvd., Mill Creek, WA 98012-1296. Pers. commun. to W. Lenarz.

[6] M. Dorn, NMFS, F/AKC3, 7600 Sandpoint Way NE, Seattle, WA 98115-6349. Pers. commun. to W. Lenarz.

[7] W. Palsson, WDFW, 16018 Mill Creek Blvd., Mill Creek, WA 98012-1296. Pers. commun. to W. Lenarz.

Table 3. Hydro-acoustic estimates of biomass of Pacific hake in the Port Susan area, 1983-1994 (Palsson et al. 1997). Estimates were converted from million lbs to metric tons.

Year	Biomass (mt)
1983	20,457
1984	12,292
1985	7,258
1986	7,258
1987	5,398
1988	5,806
1989	5,489
1990	6,124
1991	5,307
1992	4,037
1993	499
1994	590

survey estimates. Examination of data provided by WDFW (W. Palsson[8]) revealed that size of maturity decreased since the early 1980s (Fig. 23). Recent surveys captured Pacific hake that were smaller than Pacific hake captured in earlier years, but mature fish comprised most of the biomass in both time periods. In addition, fish less than 30 cm comprise a significant proportion of Pacific hake consumed by pinnipeds (P. Gearin[9]).

Martin Dorn (M. Dorn[10]) reviewed the first draft of this document and noted that both NMFS (Traynor 1996) and Canada Department of Fisheries and Oceans (DFO) (Kieser et al. 1999) now use target strength relationships dependent on length for hydro-acoustic estimates of Pacific hake biomass rather than the constant target strength procedure used by WDFW. The length-dependent target strength method is considered more accurate and after consultation with WDFW (W. Palsson[11]), the biomass estimates for Port Susan were revised (M. Dorn[12]) Average weights and Pacific hake length frequency data needed for the revision were compiled from data supplied by WDFW. Length-frequency samples from trawls taken during the surveys (Fig. 21) were weighted equally in terms of weight rather than numbers of sampled fish to avoid bias towards larger fish. There were changes in trawls used for the surveys during the time span. These changes were assumed to not have significant impacts on the composition of the catch. Data from Kautsky (1989) were used to estimate that target strength = 20 log length - 73.5 (M. Dorn[13]). New estimates of Pacific hake biomass under both the constant and length-dependent target strength models are shown in Table 4. Estimates made under the length-dependent target strength model were used for the following analyses.

Biomass estimates (Table 4) made under the length-dependant target strength assumption were higher than estimates made under the constant target strength assumption until 1997. The 1999 biomass declined to 12% of the 1983 estimate under the length-dependent target strength assumption compared to 19% under the constant target strength assumption (Fig. 24). Although

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[8] W. Palsson, WDFW, 16018 Mill Creek Blvd., Mill Creek, WA 98012-1296. Pers. commun. to W. Lenarz.

[9] P. Gearin, NMFS, F/AKC4, National Marine Mammal Laboratory, 7600 Sandpoint Way NE, Seattle, WA 98115-6349. Pers. commun. to W. Lenarz.

[10] M. Dorn, NMFS, F/AKC3, 7600 Sandpoint Way NE, Seattle, WA 98115-6349. Pers. commun. to W. Lenarz.

[11] W. Palsson, WDFW, 16018 Mill Creek Blvd., Mill Creek, WA 98012-1296. Pers. commun. to W. Lenarz.

[12] M. Dorn, NMFS, F/AKC3, 7600 Sandpoint Way NE, Seattle, WA 98115-6349. Pers. commun. to W. Lenarz.

[13] M. Dorn, NMFS, F/AKC3, 7600 Sandpoint Way NE, Seattle, WA 98115-6349. Pers. commun. to W. Lenarz.

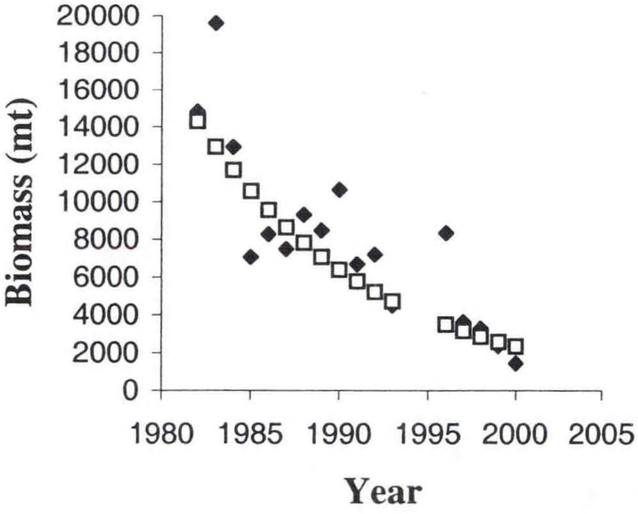

Figure 24. Biomass of Pacific hake in Port Susan as a function of year from 1982-2000. Biomass = 14794*Exp(-0.088*(year-1982)), R = -0.86. Expected values were not adjusted for bias due to log transformation. See text for source of observations.

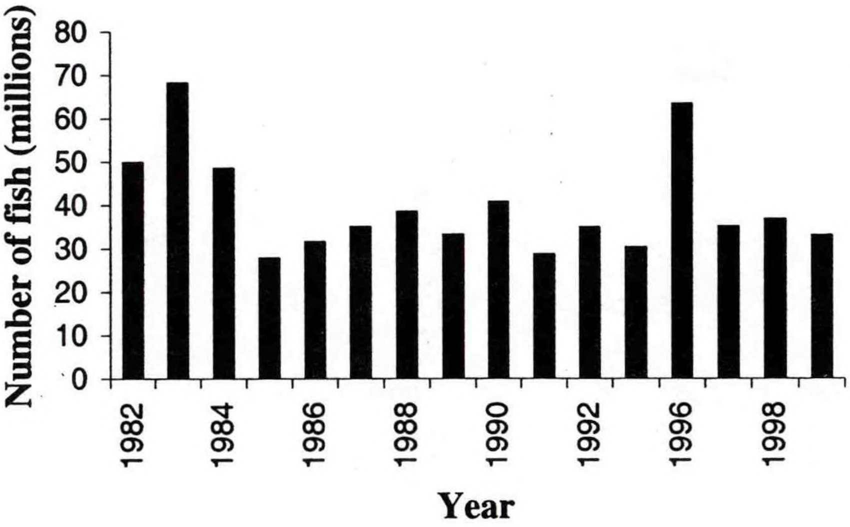

Figure 25. Estimate of total number of Pacific hake in Port Susan from 1982-1999. Data derived from estimates of total biomass and average weight of individual Pacific hake provided by W. Palsson (WDFW).

catches were not added to survey biomass estimates, the new estimates (Table 4) were similar to or higher than the old estimates during the 1983-1993 period (Table 3). Average weight decreased from 0.298 kg in 1982 to 0.072 kg in 1999. There does not appear to be a trend in numbers of Pacific hake in the survey area (Fig. 25).

Preliminary results from the March 7, 2000 WDFW Port Susan Pacific hake survey were received subsequent to the above analyses (W. Palsson[14]). Pacific hake biomass estimates were calculated using the length dependent target strength methodology described above (M. Dorn[15]). Results are shown in Table 4. Reliable acoustic data were not available for the Possession Sound portion of the 2000 survey, because of equipment problems, and WDFW estimates that 15-20% of the total stock may have been missed (M. Dorn[16]). The new estimates indicate that both biomass and numbers are at the lowest level since the surveys were started in 1982. If the survey missed 20% of the total biomass, the corrected biomass would be 1,240 mt, which would be the lowest on record, 52% of the 1999 biomass, 6% of the peak biomass in 1983, and represent an 85% decrease during the past 15 years. Average weight increased from 0.072 kg in 1999 to 0.091 kg in 2000. Compared to recent years there were relatively few fish smaller than 20 cm and relatively more fish larger than 30 cm.

Palsson et al. (1997) presented estimates of mid-water trawl catch per effort (Table 5) and Pacific hake biomass estimates from bottom trawl surveys (Table 6). Catch-per-effort data were not used in this analysis because of the difficulties in adjusting the data for undocumented changes in gear and fishing strategies. Bottom-trawl survey estimates were not used because there were not enough to serve as an index, and bottom-trawl surveys are not suitable for estimates of absolute abundance of Pacific hake because of the semi-pelagic behavior of Pacific hake.

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[14] W. Palsson, WDFW, 16018 Mill Creek Blvd., Mill Creek, WA 98012-1296. Pers. commun. to BRT, July 26, 2000.

[15] M. Dorn, NMFS, F/AKC3, 7600 Sandpoint Way NE, Seattle, WA 98115-6349. Pers. commun. to W. Lenarz.

[16] M. Dorn, NMFS, F/AKC3, 7600 Sandpoint Way NE, Seattle, WA 98115-6349. Pers. commun. to W. Lenarz.

Table 4. Estimates of total Pacific hake biomass, average weight, and numbers of fish in the Port Susan area during the spawning season. Data provided by Wayne Palsson (WDFW) and converted from million lbs to metric tons. Trawl surveys were not made in 1994 and 1995. Biomass estimates using length dependent target strength were made by Martin Dorn (NMFS, AFSC), these data are utilized in the remainder of the document, and are emphasized by being put in **bold**. Length frequencies were not available from 1991, therefore length data from adjacent years were used. Data for 2000 provided by Wayne Palsson (WDFW) after analysis was completed.

Year	Biomass (mt) (target strength, constant)	Biomass (mt) (target strength, length dependent)	Average weight (kg)	Number of Pacific hake
1982	11,975	**14,826**	0.298	49,746,267
1983	14,946	**19,612**	0.288	68,129,922
1984	10,168	**12,925**	0.267	48,470,006
1985	5,690	**7,066**	0.255	27,725,137
1986	6,332	**8,277**	0.263	31,508,611
1987	5,638	**7,501**	0.215	34,893,521
1988	7,031	**9,322**	0.243	38,362,214
1989	6,683	**8,483**	0.256	33,127,174
1990	8,087	**10,648**	0.262	40,654,512
1991	5,262	**6,701**	0.235	28,575,429
1992	5,897	**7,211**	0.207	34,817,610
1993	4,218	**4,506**	0.149	30,226,033
1996	7,847	**8,343**	0.132	63,384,421
1997	4,264	**3,636**	0.104	35,026,849
1998	3,992	**3,289**	0.090	36,750,409
1999	2,858	**2,365**	0.072	32,930,666
2000	1,227	992	0.091	10,890,255

Table 5. Fishery trends for Pacific hake in Southern Puget Sound (modified from Palsson et al. 1997). Dashes indicate data were not available.

Year	Trawl catch rate (1000 kg/hr)
1970	2.7
1971	1.5
1972	1.4
1973	1.6
1974	2.9
1975	3.5
1976	7.7
1977	4.8
1978	8.2
1979	10.3
1980	9.9
1981	5.5
1982	4.4
1983	2.9
1984	2.1
1985	2.5
1986	1.5
1987	3.3
1988	4.2
1989	1.1
1990	0.1
1991	4.5
1992	----
1993	----
1994	----

Table 6. Area-swept-estimates of biomass, number and size of Pacific hake in the Puget Sound population from WDFW trawl surveys (source: W. Palsson, WDFW, 16018 Mill Creek Blvd., Mill Creek, WA 98012-1296. Pers. commun. to W. Lenarz.). Dashes indicate data were not available.

Biomass (mt)

Year	Gulf-Bellingham	Strait of Juan de Fuca	North Sound	Hood Canal	Central Sound	South Sound	Southern areas combined
1987	103.93	233.34	337.27	34.21	1,421.65	90.97	1,546.83
1989	182.46	0.00	182.46	172.58	397.19	27.46	597.23
1991	76.85	0.18	77.03	129.92	837.33	51.40	1,018.65
1994	424.47	--	--	--	--	--	--
1995	--	--	--	--	4713.78	--	--
1996	--	--	--	70.88	--	40.89	--
1995-1996	--	--	--	--	--	--	4,825.55
1997	355.87	--	--	--	--	--	--

Numbers (thousands of fish)

Year	Gulf-Bellingham	Strait of Juan de Fuca	North Sound	Hood Canal	Central Sound	South Sound	Southern areas combined
1987	240.90	243.74	484.64	227.03	3,887.18	311.40	4,425.61
1989	203.02	0.00	203.02	3,215.55	1,794.40	172.18	5,181.73
1991	142.08	12.42	154.50	3,471.12	18,997.54	348.85	22,817.51
1994	969.82	--	--	--	--	--	--
1995	--	--	--	--	85,220.29	--	--
1996	--	--	--	472.39	--	536.59	--
1995-1996	--	--	--	--	--	--	86,229.27
1997	883.38	--	--	--	--	--	--

Table 6. (Continued).

	Size (kg/ fish)						
Year	Gulf-Bellingham	Strait of Juan de Fuca	North Sound	Hood Canal	Central Sound	South Sound	Southern areas combined
1987	0.43	0.96	0.70	0.15	0.37	0.29	0.35
1989	0.90	--	0.90	0.05	0.22	0.16	0.12
1991	0.54	--	0.54	0.04	0.04	0.15	0.04
1994	0.44	--	--	--	--	--	--
1995	--	--	--	--	0.06	--	--
1996	--	--	--	0.15	--	0.08	--
1995-1996	--	--	--	--	--	--	0.06
1997	0.40	--	--	--	--	--	–

Canadian portion of the Strait of Georgia

The DFO conducts periodic hydro-acoustic estimates of biomass of Pacific hake in the Canadian portion of the Strait of Georgia using length-dependent target strength (Saunders and McFarlane 1999). Timing of the surveys has changed. There was concern that March-April estimates included signal from the spring plankton bloom, particularly in 1981 and 1993 (Saunders and McFarlane 1999, Kieser et al. 1999). Since 1993, the surveys have been conducted in February. There was concern that February surveys occurred before peak in spawning and may have underestimated the biomass (Saunders and McFarlane 1999, Kieser et al. 1999). The estimates are shown in Table 7. Saunders and McFarlane (1999) stated that

> "At the present time we do not have an adequate absolute or relative index of stock size and the recent biomass estimates should be considered a conservative minimum. Based on the information briefly stated above and reported in detail in Kieser er al. (1999) we believe the biomass of Pacific hake in the 1990's to be stable at approximately 50-60,000t."

Data in Saunders and McFarlane (1999) also revealed that, as in Puget Sound, average size of Pacific hake in the Strait of Georgia has decreased. Size-at-age data indicated that growth between ages 2 and 3 years considerably decreased between 1976 and 1999. Age-composition data indicated that the 1991-1992 year classes were strong and persisted in the samples through 1999. The 1995 and 1998 year classes were also strong compared to adjacent year classes, but do not appear to be as strong as the 1991-1992 year classes.

Risk Assessment

Port Susan

Introduction–The BRT concluded that the Port Susan Pacific hake population is a component of the Georgia Basin DPS, the interactions of the Port Susan population with other components of the DPS are not known. Two models were developed for evaluation of risk to the Port Susan population. The models are similar to models used by Mohn and Bowen (1996) to study grey seal predation on Atlantic cod. Both models include a variable, relative productivity or population growth rate, that includes the impact of migration to or from other components of the DPS. Otherwise, it is assumed that the dynamics of the Port Susan population are independent of the other components. Hollowed et al. (2000) and Livingston and Methot (1998) developed age-based models of fish population dynamics that incorporated predation mortality. Insufficient data were available for use of their models in this study.

Table 7. Hydro-acoustic estimates of Pacific hake biomass in the Canadian portion of the Strait of Georgia. (Saunders and McFarlane 1999).

Year	Date of survey	Biomass (mt)
1981	Jan 12-23	53,387
1981	Feb 09-20	80,525
1981	April 13-24	126,240
1981	April 13-24 (adjusted)	71,542
1988	March 18-28	66,174
1993	March 8-25	105,008
1996	Feb 20-March 5	60,266
1997	Feb 17-28	46,524
1998	Feb 16-26	33,681

Pacific hake removals by humans and pinnipeds--Pacific hake commercial catch and pinniped predation were used in the models. Commercial catches were compiled from monthly catch data (W. Palsson[17]) (Table 8). Fishing year was defined as March through February of the following year to correspond with Pacific hake biomass estimates assumed to be for March 1. Catches were different than shown in Palsson et al. (1997), because they defined the fishing year to begin in the fall of the preceding year and include recreational catches. Recreational landings of Pacific hake were minor.

It was more difficult to estimate Pacific hake exploitation by pinnipeds than by humans. California sea lions and harbor seals are known to consume Pacific hake (Olesiuk 1993, Schmitt et al. 1995). Schmitt et al. (1995) estimated Pacific hake consumption by California sea lions in Puget Sound for the 1986-1994 period. However consultation with knowledgeable marine mammal experts, including the two junior authors of Schmitt et al. (1995) (S. Jeffries[18] and P. Gearin[19]), revealed that these estimates were not acceptable to the marine mammal research community. In addition, researchers have not estimated Pacific hake consumption by harbor seals in Puget Sound. Also, researchers have not attempted to understand functional relationships between Pacific hake consumption by pinnipeds and the abundance of Pacific hake and other potential prey.

Because of the uncertainty, Pacific hake consumption by pinnipeds in Puget Sound was treated as hypothetical values in what-if risk assessments of the Port Susan Pacific hake population. After consultation with experts at the NMFS's National Marine Mammal Laboratory (NMML), ranges of values were used that were consistent with published and unpublished information in the sense that the ranges were likely to include the real levels of consumption. There was insufficient knowledge to conclude that the actual levels were likely to be close to the center of the ranges.

Patrick Gearin (P. Gearin[20]) indicated that estimates of consumption of all food items in Puget Sound by California sea lions and harbor seals given in NMFS (1997) are consensus estimates by the marine mammal research community and thus acceptable to them as the best

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[17] W. Palsson, WDFW, 16018 Mill Creek Blvd., Mill Creek, WA 98012-1296. Pers. commun. to W. Lenarz.

[18] S. Jeffries, WDFW, 600 Capitol Way N., Olympia, WA 98501-1091. Pers. commun. to W. Lenarz.

[19] P. Gearin, NMFS, F/AKC4, National Marine Mammal Laboratory, 7600 Sandpoint Way NE, Seattle, WA 98115-6349. Pers. commun. to W. Lenarz.

[20] P. Gearin, NMFS, F/AKC4, National Marine Mammal Laboratory, 7600 Sandpoint Way NE, Seattle, WA 98115-6349. Pers. commun. to W. Lenarz.

available. They estimated that California sea lions on the average consumed 830 mt per year between 1986 and 1994, which is close to the lower estimate of Schmitt et al. (1995). They did not use the upper estimate of Schmitt et al.(1995), because they believed that it was not justified by research information. NMFS (1997) estimated that in 1993 harbor seals consumed 3,209 mt in Eastern Bays and 1,649 mt in Puget Sound proper (Fig. 26). They also provided an estimate for Hood Canal, but it was assumed that harbor seals in Hood Canal prey on the Dabob Bay rather than the Port Susan population. The peak count of sea lions in Puget Sound was 444. Population abundances of harbor seals were 3,479 in Eastern Bays, and 1,787 in Puget Sound proper.

Jeff Laake (J. Laake[21]) provided estimates of predicted annual monthly counts of sea lions at Everett, Washington for 1986-1998. Year was defined in the same manner as for fishing year, which is March through February of the following year. Actual counts were available for about half of the possible year-month combinations. He used a generalized additive model containing spline-smoothed functions for year, season, and year-season to predict the average monthly counts. A Poisson error structure with over dispersion was assumed. Patrick Gearin (P. Gearin[22]) provided peak count data for 1982-1999. Peak counts usually occurred in about March. A regression between peak count and average monthly count was used to estimate average monthly count for 1982-1985 and 1999. Average counts were then doubled because Schmitt et al. (1995) indicated that counts probably represented about 50% of the total Puget Sound population as was done for consumption estimates in NMFS(1997). Sea lion counts increased from 1982 to 1986, decreased from 1986 to 1989, increased from 1989 to 1995, and decreased from 1995 to 1999 (Table 9).

The literature details difficulties in estimation of pinniped diet composition (see Olesiuk 1990). These difficulties center around questions concerning prey specific digestion and retention rates. Variation in digestion and retention rates are also a source of uncertainty in studies of diet composition of fish, but compositions of stomach contents are usually used for fish studies, while compositions of scat contents are the predominant data source for pinniped studies. Different rates of digestion and retention are likely to produce less severe problems for stomach contents than for scat contents.

Schmitt et al. (1995) estimated that Pacific hake comprised 32% of the diet of California sea lions in Puget Sound during the 1986-1994 period. Their estimates were based on the estimated mass of individual prey items. Estimates in Schmitt et al. (1995) seem consistent with a more recent unpublished summary (Gearin et al. 1999), which showed that about 82% of sea lion scats contained Pacific hake parts, while the next two important items were dogfish parts, at about

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[21] J. Laake, NMFS, F/AKC4, National Marine Mammal Laboratory, 7600 Sandpoint Way NE, Seattle, WA 98115-6349. Pers. commun. to W. Lenarz.

[22] P. Gearin, NMFS, F/AKC4, National Marine Mammal Laboratory, 7600 Sandpoint Way NE, Seattle, WA 98115-6349. Pers. commun. to W. Lenarz.

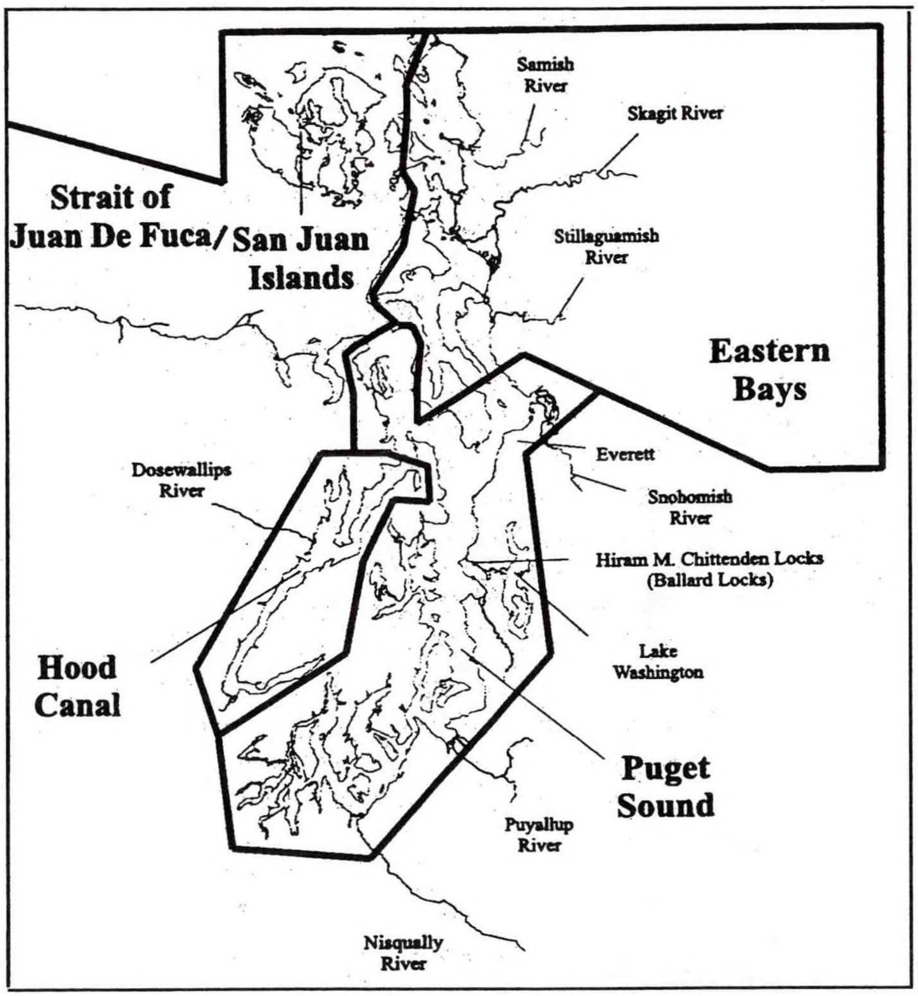

Figure 26. Regional designations for inside waters of Washington, for analysis of the status of pinniped populations, as defined in NMFS (1997). Modified from NMFS (1997, their fig.2).

22%, and salmon parts, at about 15%. Pacific hake parts are more likely to resist destruction by digestion than either spiny dogfish parts or salmon parts. However, since the major concentration of sea lions in Puget Sound overlaps both spatially and temporally with the major Pacific hake spawning activity, it would seem likely that Pacific hake comprise a significant portion of sea lion diets. Olesiuk et al. (1990) estimated boundaries on their point estimates of diet composition of harbor seals in the Canadian portion of the Strait of Georgia. Their gadiform contribution to the diet was 45.1%. Their lower limit was 28.0% (62% of point estimate) and upper limit was 60.9% (135% of point estimate). Schmitt et al. (1995) did not provide boundaries and used different methodologies in their study of California sea lions. It seemed reasonable to use a range that is broader than that used by Olesiuk et al. (1990) and to set the bounds at 50% and 200% of the Schmitt et al. (1995) estimates in an attempt to include the true value. The hypothetical range of consumption of Pacific hake by California sea lions in Puget Sound was calculated by multiplying total consumption by 0.16 (0.5 x 0.32) and 0.64 (2 x 0.32). Hypothetical estimates of Pacific hake consumption by California sea lions are shown for 10 levels within the above range in Table 9. The hypothetical estimates assume that consumption per sea lion was independent of Pacific hake abundance, and constant during the 1982-1999 time period.

Robert DeLong (R. DeLong[23]) provided information on annual rates of change of populations of harbor seals based on WDFW/NMML data. Harbor seals were estimated to have increased by 3.3% annually in Puget Sound between 1985 and 1997. They were estimated to have increased by 2.7% annually in Eastern Bays between 1983 and 1998. It was assumed that the expansion rates applied to the entire 1982-1999 period for estimation of consumption of Pacific hake rates. The estimates of harbor seal abundance in 1993 by NMFS (1997) were used for the baseline population.

Researchers have developed less information on composition of the diet of harbor seals in Puget Sound than in the Canadian portion of Strait of Georgia or for California sea lions in Puget Sound. Pacific hake parts frequently occur in harbor seal scat samples (79%-Skokomish River, 84% - Hamma Hamma River, 100% - Duckabush River, 85% - Dosewallips River and 88% - Quilcene Bay) (S. Jeffries[24]). These estimates are for the Hood Canal area and are shown here only to illustrate that Pacific hake apparently can comprise a significant portion of harbor seals in the general Puget Sound area. Pacific hake parts were estimated to occur in 32% of scat samples and Pacific hake comprised 5% of the diet by weight of harbor seals at Gertrude Island (South Puget Sound) from June 24, 1994 to October 23, 1995 (P. Gearin[25]). Pacific hake also occurred

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[23] R. DeLong, NMFS, F/AKC4, National Marine Mammal Laboratory, 7600 Sandpoint Way NE, Seattle, WA 98115-6349. Pers. commun. to W. Lenarz.

[24] S. Jeffries, WDFW, 600 Capitol Way N., Olympia, WA 98501-1091. Pers. commun. to T. Builder. September 17, 1999.

[25] P. Gearin, NMFS, F/AKC4, National Marine Mammal Laboratory, 7600 Sandpoint Way NE, Seattle, WA 98115-6349. Pers. commun. to W. Lenarz.

in 80% of scat samples and comprised 83% of the diet by weight of harbor seals at Everett from January-April, 1989 and October-November, 1995. Olesiuk et al. (1990) estimated that Pacific hake comprised 42.6% of the diet of harbor seals in the Strait of Georgia. Since harbor seals are not as concentrated in the Port Susan area as sea lions are, it seems reasonable to set the bounds of Pacific hake contribution to harbor seal diet lower than used for sea lions. In the Eastern Bays, which includes Port Susan, it was set at 10-40%, a four-fold change from low to high as for sea lions. The low bound seemed reasonable, although it is two times higher than the estimate for Gertrude Island, which appears to be an extreme location. The high bound is about half of the Everett estimate, which also probably is an extreme location. At the suggestion of Robert DeLong (R. DeLong[26]), the hypothetical Pacific hake contribution in the diet of harbor seals in Puget Sound was set at 5%, which is the estimate for Gertrude Island. The estimates are shown in Table 10. The hypothetical estimates assume that consumption per harbor seal was independent of Pacific hake abundance and constant during the 1982-1999 time period.

Population productivity–Two models were used to estimate the productivity of the Pacific hake population during the 1982-1999 period. The first model assumes that the annual consumption of Pacific hake by an individual pinniped is independent of Pacific hake abundance. The second model assumes that annual consumption of Pacific hake by an individual pinniped is described by the catch equation usually used to describe fish population dynamics, (i.e. it is dependent on abundance of Pacific hake, rate of natural mortality for Pacific hake, human generated fishing mortality, and number of pinnipeds). Both models assume that all estimated human and pinniped consumption is from the Port Susan population. While the commercial fishery and most observed sea lions occur in the Port Susan area, there are substantial occurrences of harbor seals in other areas of Puget Sound. The portion of Pacific hake from other populations consumed by pinnipeds is unknown. It is also not known if Hood Canal harbor seals or harbor seals west and/or north of Eastern Bays consume Pacific hake from the Port Susan population.

Under the first model, productivity in year i is

$$\mathrm{Prod}(i) = (\mathrm{Bio}(i+1) - \mathrm{Bio}(i) + C_h(i) + C_{sl}(i) + C_{hs}(i))/\mathrm{Bio}(i) \qquad (1)$$

Where,

$\mathrm{Bio}(i)$ = Biomass of Pacific hake in year i,
$C_h(i)$ = Catch by humans in year i,
$C_{sl}(i)$ = Consumption by California sea lions in year i, and
$C_{hs}(i)$ = Consumption by harbor seals in year i.

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[26] R. DeLong, NMFS, F/AKC4, National Marine Mammal Laboratory, 7600 Sandpoint Way NE, Seattle, WA 98115-6349. Pers. commun. to W. Lenarz.

Pacific hake biomass was estimated to increase considerably between 1993 and 1996 (Table 4). However missing biomass estimates for 1994 and 1995 preclude estimation of annual productivity estimates for 1993, 1994, and 1995. The missing data were approximated by assuming that productivity was constant for those three years and using iteration to estimate Prod(1993), Prod(1994), Prod(1995), Bio(1994), and Bio(1995).

Estimates of average annual productivity during the 1982-1998 period increased with pinniped consumption and ranged from 0.13 to 0.38 (Table 11). There was no obvious temporal trend in productivity at the higher assumed levels of predation, but productivity tended to decline over time (nonsignificant, $r = -0.33$) when pinniped predation was assumed to be low (Fig. 27). The lowest estimated annual value was -0.46 in 1996 under the hypothetical minimum pinniped predation. The highest value was 1.03 in 1982 under the hypothetical maximum pinniped predation. Estimates of productivity include impacts of migration to and from other populations of the DPS. It is not known what proportion of the estimated productivity is the result of migrations.

Under the second model biomass in year i+1 is

$$\mathrm{Bio}(i+1) = \mathrm{Bio}(i)e^{-Z(i)} \qquad (2)$$

Where,

$Z(i) = M + F(i) - G(i)$,

M = Constant instantaneous rate of natural mortality,

$F(i)$ = Instantaneous rate of exploitation mortality from all causes in year i,

$F(i) = F_h(i) + F_{sl}(i) + F_{hs}(i)$,

$F_h(i)$ = Instantaneous rate of mortality caused by exploitation by humans in year i,

$F_{sl}(i)$ = Instantaneous rate of mortality caused by exploitation by sea lions in year i,

$F_{hs}(i)$ = Instantaneous rate of mortality caused by exploitation by harbor seals in year i, and

$G(i)$ = Instantaneous rate of productivity in year i. It includes migration to and from other populations.

M was assumed to be 0.23, which is the value used in Dorn et al. (1999a) to assess the offshore stock of Pacific hake. The offshore stock estimate included impacts of predation by pinnipeds, which are probably of minor importance compared to the Port Susan population, and was used to describe changes in numbers rather than biomass. The Port Susan population appears to be shorter lived than the offshore stock and thus probably has a higher value of M. However, M as used in the model does not include the impact of predation by pinnipeds.

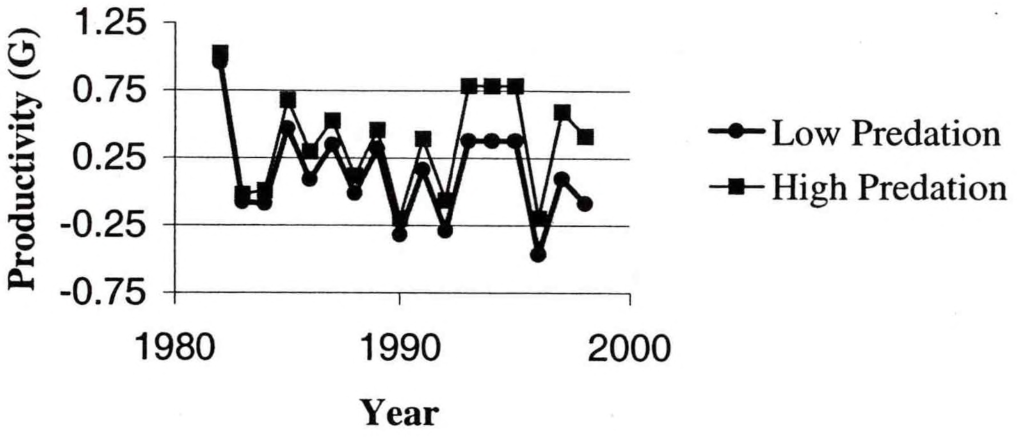


Figure 27. Estimates of Pacific hake productivity (G) under Model 1 and lowest and highest levels of pinniped predation on Pacific hake.

The following constraints and relationships were used to solve iteratively for G(t). It was assumed that G(t) was approximately constant between 1993 and 1995 for middle levels of pinniped predation.

Total consumption in year i is
$C(i) = Bio(i)F(i)(1-e^{-z(i)})/Z(i)$ and
$C(i) = C_h(i) + C_{sl}(i) + C_{hs}(i)$.

Where
$C_h(i)$ = human consumption in year i,
$C_{sl}(i)$ = sea lion consumption in year i, and
$C_{hs}(i)$ = harbor seal consumption in year i.

It follows from (2) that
$Z(i) = -\ln(Bio(i+1)/(Bio(i))$.

Catchability coefficients q were estimated for sea lions and harbor seals where,

$F_{sl}(i) = q_{sl}N_{sl}(i)$,
$N_{sl(}(i)$ = number of sea lions in year i,
$F_{hs}(i) = q_{hs}N_{hs}(i)$, and
$N_{hs}(i)$ = number of harbor seals in year i.

The productivity estimates (Table 12) are similar to the results obtained using Model 1. Average productivity was greater than natural mortality, increased with increased hypothetical level of predation by pinnipeds, and ranged from 0.30 to 0.51. There was no obvious temporal trend in productivity at the higher assumed levels of predation, but productivity tended to decline over time (nonsignificant, $r = -0.42$) when pinniped predation was assumed to be low (Fig. 28). The lowest estimated annual value was -0.49 in 1996 under the hypothetical minimum pinniped predation. The highest value was 1.23 in 1982 under the hypothetical maximum pinniped predation.

Results of both models suggest that the Port Susan Pacific hake population would have increased between 1982 and 1999, if there had been no commercial exploitation and no pinniped predation, and either model held. It is likely that productivity would be lower if the population were approaching the carrying capacity of its habitat. Since the results did not indicate a positive trend in productivity as the population decreased, we are not able to estimate the carrying capacity. Population dynamics theory predicts that productivity would increase as biomass decreases. The lack of such a response for Port Susan Pacific hake suggests that productivity may have been impacted by natural or human related factors. One possible factor is the relatively warm climate conditions experienced since 1976. Average weight of Pacific hake decreased from 0.298 kg in 1982 to 0.072 kg in 1999. The decrease may have been partially caused by decreased growth as occurred for Pacific hake in the Canadian portion of the Georgia Basin (Saunders and McFarlane 1999). The possible decrease in growth may have been related to the relatively warm conditions or smaller size-at-maturity (Fig. 23) and may have had a negative

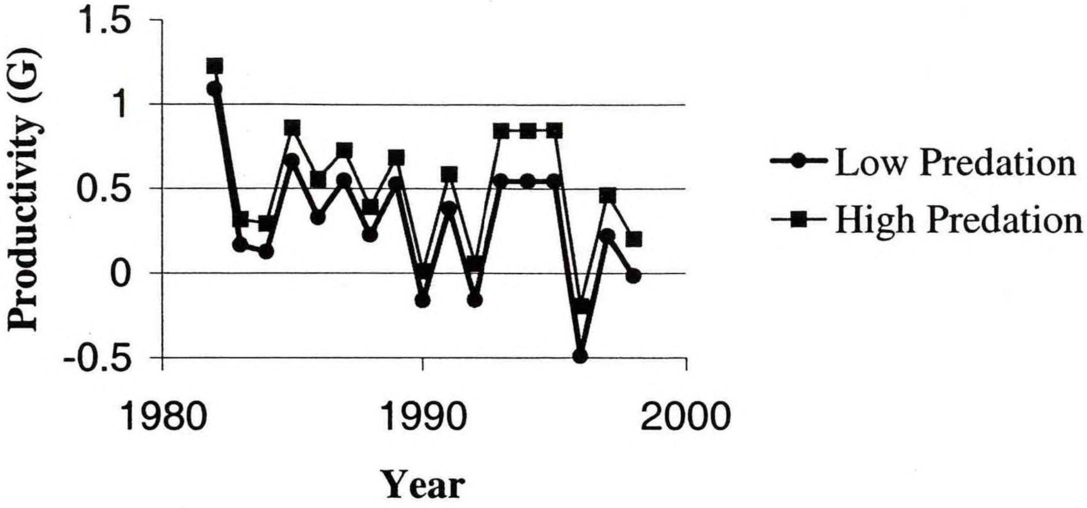


Figure 28. Estimates of Pacific hake productivity (G) under Model 2 and lowest and highest levels of pinniped predation on Pacific hake.

impact on productivity. It is possible that the theoretically expected negative relationship between biomass and productivity would have been strong enough to significantly reduce the observed decline in Pacific hake biomass, if unknown factors had not affected the ability of the population to respond to decreased levels.

Both models have theoretical deficiencies in the description of predation by pinnipeds. For example, under the first model the consumption of Pacific hake per pinniped is constant until extinction of the Pacific hake population, and under the second model Pacific hake consumption per pinniped increases without bounds as the Pacific hake population increases. Both models ignore the effect of varying abundances of other prey.

There was a non-significant (r = -0.03) negative relationship between Pacific hake abundance and average sea lion count between 1986 and 1999, not including 1994 and 1995. Since California sea lion aggregations did not regularly occur in Puget Sound until 1979 (Schmitt et al. 1995), and sea lion abundance tended to increase until 1986, the year 1986 was chosen as the first year to examine the sea lion-Pacific hake relationship. There is no apparent trend in sea lion abundance in Puget Sound since 1986, although the coast-wide stock has continued to increase (NMFS 1997).

d) Projections –

Hypothetical projections (see Appendix B) indicated that uncertainty about rates of predation of Pacific hake by pinnipeds and the form of the relationships between Pacific hake predation by pinnipeds and commercial fishing precludes definitive conclusions concerning the risk of extinction of the Port Susan Pacific hake population.

Table 8. Commercial catches of Pacific hake in the Port Susan area. Fishing year defined as March to February of the following year. Data were converted from million lbs to metric tons. Data provided by Wayne Palsson (W. Palsson, WDFW, 16018 Mill Creek Blvd., Mill Creek, WA 98012-1296. Pers. commun. to W. Lenarz.).

Year	Commercial catch (mt)
1982	8,986
1983	4,749
1984	4,232
1985	1,538
1986	880
1987	268
1988	231
1989	64
1990	41
1991	0
1992	0
1993	0
1994	0
1995	0
1996	0
1997	0
1998	0
1999	0
2000	0

Table 9. California sea lion counts and hypothetical consumption of Pacific hake in Puget Sound. California sea lion count data for 1986-1998 and estimates of ten levels of consumption of Pacific hake by California sea lions based on information provided by Jeff Laake (NMFS, F/AKC4, National Marine Mammal Laboratory, 7600 Sandpoint Way NE, Seattle, WA 98115-6349. Pers. commun. to W. Lenarz.). California sea lion count data for 1982-1985 and 1999 data estimated from regression of mean counts and peak counts. Peak count data provided by Patrick Gearin (NMFS, F/AKC4, National Marine Mammal Laboratory, 7600 Sandpoint Way NE, Seattle, WA 98115-6349. Pers. commun. to W. Lenarz.).

Year	Mean sea lion count	Ten levels of Pacific hake consumption (mt) by California sea lions									
1982	135	110	147	184	221	257	294	331	368	404	441
1983	164	134	179	224	269	313	358	403	448	493	537
1984	207	170	226	283	339	396	452	509	565	622	679
1985	290	237	316	395	474	554	633	712	791	870	949
1986	378	309	412	515	618	721	824	927	1,030	1,133	1,236
1987	218	178	237	297	356	415	474	534	593	652	712
1988	168	137	183	229	274	320	366	411	457	503	548
1989	138	113	151	188	226	264	301	339	377	414	452
1990	168	138	184	230	276	323	369	415	461	507	553
1991	258	212	283	353	424	495	565	636	707	777	848
1992	282	231	308	385	461	538	615	692	769	846	923
1993	352	288	384	481	577	673	769	865	961	1,057	1,153
1994	546	448	598	747	897	1,046	1,196	1,345	1,494	1,644	1,793
1995	664	545	726	908	1,089	1,271	1,452	1,634	1,815	1,997	2,179
1996	488	399	532	665	798	931	1,065	1,198	1,331	1,464	1,597
1997	304	249	333	416	499	582	665	748	831	915	998
1998	222	182	242	303	364	424	485	545	606	666	727
1999	210	172	230	287	345	402	459	517	574	632	689

Table 10. Hypothetical estimates of consumption of Pacific hake in Puget Sound and Eastern Bays by harbor seals. The base line year is 1993. Consumption in other years is based on estimate that abundance of harbor seals increased 3.3% per year in Puget Sound, and 2.7% per year in Eastern Bays. Estimates based on information provided by Robert DeLong (NMFS, F/AKC4, National Marine Mammal Laboratory, 7600 Sandpoint Way NE, Seattle, WA 98115-6349. Pers. commun. to W. Lenarz.). One level estimated for Puget Sound and ten levels estimated for Eastern Bays. Methodology is detailed in text.

	Pacific hake consumption by harbor seals (mt)										
Year	Puget Sound	Eastern Bays									
1982	57	237	317	396	475	554	633	712	792	871	950
1983	59	244	325	407	488	569	651	732	814	895	976
1984	61	251	334	418	502	585	669	753	836	920	1,003
1985	63	258	344	430	516	602	687	773	859	945	1,031
1986	65	265	353	442	530	618	707	795	883	971	1,060
1987	67	272	363	454	545	635	726	817	908	998	1,089
1988	70	280	373	466	560	653	746	840	933	1,026	1,119
1989	72	288	383	479	575	671	767	863	959	1,055	1,150
1990	75	296	394	493	591	690	788	887	985	1,084	1,182
1991	77	304	405	506	608	709	810	911	1,013	1,114	1,215
1992	80	312	416	520	624	729	833	937	1,041	1,145	1,249
1993	82	321	428	535	642	749	856	963	1,070	1,177	1,284
1994	85	330	439	549	659	769	879	989	1,099	1,208	1,318
1995	88	338	451	564	677	790	903	1,015	1,128	1,241	1,354
1996	91	348	463	579	695	811	927	1,043	1,159	1,275	1,390
1997	94	357	476	595	714	833	952	1,071	1,190	1,309	1,428
1998	97	367	489	611	733	855	978	1,100	1,222	1,344	1,466
1999	100	377	502	628	753	879	1,004	1,130	1,255	1,381	1,506

Table 11. Estimates of productivity (G) of the Port Susan population of Pacific hake at 10 levels of pinniped consumption using equation 1.

Year	Productivity									
1982	0.96	0.96	0.97	0.98	0.99	1.00	1.00	1.01	1.02	1.03
1983	-0.08	-0.07	-0.06	-0.06	-0.05	-0.04	-0.04	-0.03	-0.03	-0.02
1984	-0.09	-0.08	-0.07	-0.06	-0.05	-0.03	-0.02	-0.01	0.00	0.01
1985	0.47	0.49	0.51	0.54	0.56	0.58	0.61	0.63	0.65	0.68
1986	0.09	0.11	0.14	0.16	0.18	0.21	0.23	0.25	0.27	0.30
1987	0.35	0.37	0.39	0.41	0.43	0.45	0.47	0.49	0.51	0.53
1988	-0.01	0.00	0.02	0.03	0.05	0.06	0.08	0.09	0.11	0.12
1989	0.32	0.33	0.35	0.37	0.38	0.40	0.41	0.43	0.44	0.46
1990	-0.32	-0.31	-0.29	-0.28	-0.26	-0.25	-0.24	-0.22	-0.21	-0.20
1991	0.16	0.19	0.22	0.24	0.27	0.29	0.32	0.34	0.37	0.40
1992	-0.29	-0.26	-0.24	-0.21	-0.19	-0.16	-0.14	-0.11	-0.09	-0.06
1993	0.38	0.42	0.47	0.52	0.56	0.61	0.65	0.70	0.74	0.79
1994	0.38	0.42	0.47	0.52	0.56	0.61	0.65	0.70	0.74	0.79
1995	0.38	0.42	0.47	0.52	0.56	0.61	0.65	0.70	0.74	0.79
1996	-0.46	-0.43	-0.40	-0.37	-0.34	-0.31	-0.28	-0.25	-0.23	-0.20
1997	0.10	0.15	0.21	0.26	0.32	0.38	0.43	0.49	0. 54	0.60
1998	-0.08	-0.03	0.03	0.08	0.14	0.19	0.25	0.30	0.36	0.42
Mean	0.13	0.16	0.19	0.21	0.24	0.27	0.30	0.32	0.35	0.38

Table 12. Estimates of productivity (G) of the Port Susan population of Pacific hake at 10 levels of pinniped consumption using equation 2.

Year	Productivity (G)									
1982	1.09	1.10	1.12	1.13	1.15	1.17	1.18	1.19	1.21	1.23
1983	0.17	0.18	0.20	0.22	0.23	0.25	0.27	0.28	0.30	0.32
1984	0.13	0.14	0.16	0.18	0.20	0.22	0.24	0.25	0.27	0.29
1985	0.66	0.68	0.71	0.73	0.75	0.77	0.79	0.81	0.83	0.86
1986	0.33	0.35	0.38	0.40	0.43	0.46	0.48	0.50	0.52	0.56
1987	0.55	0.56	0.59	0.61	0.62	0.65	0.67	0.68	0.70	0.73
1988	0.23	0.24	0.26	0.28	0.30	0.32	0.34	0.35	0.37	0.39
1989	0.53	0.54	0.56	0.58	0.60	0.62	0.63	0.65	0.66	0.69
1990	-0.16	-0.14	-0.12	-0.10	-0.09	-0.06	-0.05	-0.03	-0.01	0.01
1991	0.38	0.40	0.43	0.45	0.47	0.50	0.52	0.54	0.56	0.59
1992	-0.16	-0.14	-0.11	-0.09	-0.07	-0.03	-0.01	0.01	0.03	0.06
1993	0.55	0.58	0.62	0.65	0.68	0.72	0.75	0.78	0.81	0.85
1994	0.55	0.58	0.62	0.65	0.68	0.72	0.75	0.78	0.81	0.85
1995	0.55	0.58	0.62	0.65	0.68	0.72	0.75	0.78	0.81	0.85
1996	-0.49	-0.46	-0.42	-0.39	-0.36	-0.32	-0.29	-0.26	-0.23	-0.19
1997	0.22	0.24	0.28	0.30	0.33	0.36	0.38	0.41	0.43	0.46
1998	-0.02	0.01	0.04	0.06	0.08	0.11	0.13	0.15	0.17	0.20
Mean	0.30	0.32	0.35	0.37	0.39	0.42	0.44	0.46	0.48	0.51

Georgia Basin DPS

Saunders and McFarlane (1999) indicated that a conservative estimate of the biomass of Pacific hake in the Canadian portion of the Strait of Georgia during the 1990's was about 50,000 to 60,000 mt and that biomass was stable during this time. Biomass estimates for the Port Susan population ranged from 10,648 mt in 1990 to 2,365 mt in 1999 (Table 4). Using these estimates, the Port Susan Pacific hake population comprised from 3.8-17.6% of the combined Port Susan-Strait of Georgia population during the 1990's. If the Canadian portion of the Strait of Georgia population is maintained, extinction of the Port Susan population does not appear to pose a serious risk of extinction for the entire Georgia Basin DPS. However, the Canadian portion of the DPS has shown some signs of decline in the late 1990s so the situation warrants continued close monitoring.

Saunders and McFarlane (1999) did not recommend formal changes in the range of yield recommended for the Canadian population. However, because of concern about factors such as decreasing size-at-age and increasing predation by pinnipeds they suggested "that managers choose from the lower half of the yield range," which was 7,554 to 14,687 mt. Saunders and McFarlane (1999) also estimated that harbor seals consumed 11,000 mt of Pacific hake in the Strait of Georgia in 1996, ranging from 4,400 to 21,000 mt. They qualified the consumption estimate by observing that age composition and distribution of harbor seals had changed considerably since composition of the diet estimates were made in the 1980's. Thus the estimate and ranges may not be accurate.

If harbor seals consumed 11,000 mt and commercial catch was 7,554 mt of Pacific hake and the biomass was 60,000 mt, then the total rate of exploitation would have been 0.31. Average estimated total rate of predation of the Port Susan Pacific hake population was lower under low hypothetical values of predation by pinnipeds during the time that the population declined from 14,826 mt in 1982 to 2,365 mt in 1999 (Table 13).

Environmental risks to the Georgia Basin Pacific hake DPS

The above analyses examined the possible effects of human and pinniped predation on the population of Pacific hake in the Georgia Basin DPS. As previously mentioned, environmental factors could have been very important factors in the observed decreases in biomass and size.

Changes in migratory behavior and location specific size at age of the offshore population of Pacific hake appear to be related to environmental factors (Dorn 1995). In the discussion that follows, temperature is referred to with the understanding that temperature is just one parameter of what is probably a complex suite of environmental factors that fish encounter. During warm years, a greater portion of the offshore Pacific hake population is found off Canada during the summer feeding season (Dorn 1995), and during the very warm period of the late 1990's some Pacific hake apparently spawned off Washington and Canada, which is much further north than

Table 13. Estimates of total rate of exploitation of Port Susan Pacific hake by humans and pinnipeds under 10 hypothetical levels of pinniped predation.

Year	Rate of total exploitation under 10 hypothetical levels of pinniped predation									
1982	0.63	0.64	0.65	0.66	0.66	0.67	0.68	0.69	0.70	0.70
1983	0.26	0.27	0.28	0.28	0.29	0.30	0.30	0.31	0.32	0.32
1984	0.36	0.38	0.39	0.40	0.41	0.42	0.43	0.44	0.45	0.46
1985	0.30	0.32	0.34	0.37	0.39	0.41	0.44	0.46	0.48	0.51
1986	0.18	0.21	0.23	0.25	0.28	0.30	0.32	0.35	0.37	0.39
1987	0.10	0.12	0.14	0.16	0.18	0.20	0.22	0.24	0.26	0.28
1988	0.08	0.09	0.11	0.12	0.14	0.15	0.17	0.18	0.20	0.21
1989	0.06	0.08	0.09	0.11	0.13	0.14	0.16	0.17	0.19	0.20
1990	0.05	0.07	0.08	0.09	0.11	0.12	0.13	0.15	0.16	0.17
1991	0.09	0.11	0.14	0.17	0.19	0.22	0.24	0.27	0.29	0.32
1992	0.09	0.11	0.14	0.16	0.19	0.21	0.24	0.26	0.29	0.31
1993	0.15	0.20	0.24	0.29	0.33	0.38	0.42	0.47	0.51	0.56
1994	0.16	0.20	0.25	0.30	0.34	0.39	0.44	0.48	0.53	0.58
1995	0.14	0.19	0.23	0.27	0.32	0.36	0.40	0.45	0.49	0.53
1996	0.10	0.13	0.16	0.19	0.22	0.25	0.28	0.31	0.34	0.37
1997	0.19	0.25	0.30	0.36	0.41	0.47	0.53	0.58	0.64	0.69
1998	0.20	0.25	0.31	0.36	0.42	0.47	0.53	0.59	0.64	0.70
Mean	0.19	0.21	0.24	0.27	0.29	0.32	0.35	0.38	0.40	0.43

the typical spawning area off California and Mexico (Dorn et al. 1999a). The Port Susan population apparently has changed more than the Canadian portion of the DPS. It is possible that warm environmental conditions have caused the Port Susan area to be relatively less favorable for Pacific hake spawning than the Canadian portion of the Strait of Georgia. Some of the Port Susan population may have migrated to Canadian waters, or perhaps there has been less movement from Canadian waters than before. The warm period may be part of global warming that has occurred during the last century. There is evidence that anthropogenic increases in atmospheric CO_2 may cause global warming. However there is still considerable scientific debate on whether or not the observed increases have natural or anthropogenic causes. Continuation or perhaps even enhancement of the warm conditions observed in the Pacific Northwest could preclude improvement in the condition of the Port Susan population of Pacific hake unless the fish eventually adapt to these conditions.

There may be other anthropogenic changes in the environment that have adversely affected Pacific hake. As previously noted (see "Environmental History and Features of Puget Sound" section) there have been changes in kelp and eel grass beds. While kelp and eel grass beds are not an important habitat for Pacific hake, it is possible that reduced beds result in reduced detritus for detrital feeders which may be important sources of food for Pacific hake in Puget Sound. Anthropogenic changes in river flow patterns and increased turbidity could possibly cause changes in the ecosystem that are adverse to Pacific hake. There have been insufficient studies to determine if there have been impacts from anthropogenic sources of toxic chemicals.

Summary and Conclusions of Georgia Basin Pacific Hake Risk Assessment

In its deliberations concerning ESA risk assessment for Pacific hake in the Georgia Basin DPS, the BRT considered the status of the Port Susan and Strait of Georgia stocks, the relationships among stocks, and effects of potential risk factors.

The BRT identified several concerns about the status of the Port Susan stock. Biomass and numbers of fish surveyed during the spawning period in Port Susan are the lowest since the surveys began in 1992. Estimated biomass in 2000 was 992 mt, about half the biomass in 1999 and represents an 85% decrease in the past 15 years. The size composition of the stock also showed a marked shift to smaller fish. Consequently, recruitment appeared to be maintained through 1999 despite declines in spawning biomass. Numbers of Pacific hake fluctuated around 30 million fish between 1985 and 1999, except in 1996 when estimated numbers exceeded 60 million fish. However in 2000, estimated numbers fell below 11 million. The size, and presumably age, at maturity has also dropped substantially. Nearly all female Pacific hake over 20 cm sampled during the 1990s were mature, whereas in the early 1980s, none were mature until 24 cm and about half of the sampled females were mature by 30 cm.

In addition to concerns about the status of the Port Susan stock, the BRT identified several areas of uncertainty. The extent of any mixing of spawners or spawning products among stocks within Puget Sound or between Puget Sound and Strait of Georgia stocks is not known. Unlike in Port Susan, the abundance of Pacific hake in the Strait of Georgia has not markedly declined over the past 15 years, and recruitment of young fish to the Port Susan stock may be the result of migration from the Strait of Georgia and other areas. If so, the Port Susan stock measured during the spawning period may be a variable portion of a larger stock and its size may not be indicative of the size of the larger stock. Under this hypothesis, the BRT's concerns about the low abundance of Pacific hake observed in Port Susan may be considerably reduced, but the BRT did not reach a consensus on the likelihood or extent of potential mixing among stocks.

The effects of potential risk factors, such as pinniped predation, habitat alteration or loss, and environmental changes, are also poorly known. Environmental changes could contribute to the observed changes in the status of Port Susan stocks, such as decreased growth, size at maturity, and reduced survival. The effect of pinniped predation or other risk factors that may be contributing to the decline in Port Susan Pacific hake abundance is also inconclusive. For two hypothetical models of pinniped predation that were considered, uncertainties about predation rates and behaviors precluded definitive conclusions about the risk of extinction of the Port Susan stock. Predation by other fish on Pacific hake or reductions in prey abundance have not been evaluated. The potential effects of habitat loss or degradation are not known, although West (1997) speculated that juvenile survival could be reduced through loss or degradation of nearshore nursery habitats.

In contrast to Port Susan, Pacific hake abundance in the Canadian portion of the Strait of Georgia apparently has been stable during the 1990s. Estimated biomass ranged between 50,000-60,000 mt, much larger than the Port Susan stock. The status of the Pacific hake in Dabob Bay, its relation to stocks in other areas, or the potential existence of undetected stocks are all unknown. Similarly, it is not known if the factors contributing to the decline in Port Susan could similarly affect the Strait of Georgia stocks in the near future.

These uncertainties and the differences in stock status between Strait of Georgia and Port Susan Pacific hake made evaluation of the status of the DPS difficult. The BRT concluded that the Georgia Basin Pacific hake DPS was not presently in danger of extinction, but could with nearly equal likelihood fall into either of two categories: 1) not in danger of extinction, nor likely to become so in the foreseeable future, or 2) not presently in danger of extinction, but likely to become so in the foreseeable future. As a whole, the BRT gave slightly higher support to the first category. Over the next year much new information is expected to become available that will likely resolve many of the uncertainties about the status and relationship of stocks of Pacific hake within the Georgia Basin DPS. When it is available, the BRT urges that this new information be considered and extinction risk be reevaluated.

PACIFIC COD

General Biology

Geographical distribution

Pacific cod are found in continental shelf and upper continental slope waters of the North Pacific Ocean from off Port Arthur, China in the northern Yellow Sea, north around the North Pacific Rim, into the Bering Sea as far north as the Chukchi Sea, and south along the North America coast to Santa Monica Bay, California (Fig. 29) (Pinkas 1967, Hart 1973, Bakkala et al. 1984, Allen and Smith 1988, Love 1991, Stepanenko 1995, Westrheim 1996). Pacific cod are also found off the east coast of Japan from Tokyo Bay to northern Hokkaido, on the west coast of Japan in the Sea of Japan, and off the coasts of the Sakhalin and Kurile Islands (Bakkala et al. 1984, Fredin 1985). Off North America, the southern limit of specific commercial Pacific cod fishing occurs between Cape Flattery and Destruction Island on the Washington outer coast (Ketchen 1961).

Pacific cod in Puget Sound are generally categorized into three components: the North Sound component (located in U.S. waters north of Deception Pass, including the San Juan Islands, Strait of Georgia, and Bellingham Bay), the West Sound component (located west of Admiralty Inlet and Whidbey Island, and in the U.S. section of the Strait of Juan de Fuca, including Port Townsend), and the South Sound component (located south of Admiralty Inlet). The primary densities of numerous populations have historically been in the North Pacific, including the Bering Sea and the waters near northern Japan, suggesting that Pacific cod populations in Puget Sound are relatively isolated and distant (Table 14) (Westrheim 1996, Bakkala et al. 1984).

Adult Pacific cod are a member of the inner shelf-mesobenthal community (NOAA 1990). Adults occur as deep as 875 m (Allen and Smith 1988), but the vast majority occur between 50 and 300 m (Allen and Smith 1988, Hart 1973, Love 1991, NOAA 1990). Spawning occurs at depths of from 40 to 265 m (NOAA 1990, Palsson 1990).

Eggs are demersal and are found sublittorally (Palsson 1990). Larvae and small juveniles are pelagic; large juveniles and adults are parademersal (Dunn and Matarese 1987, NOAA 1990). Larvae are found in the upper 45 m of the water column; highest abundances are between 15 and 30 m (Garrison and Miller 1982, Matarese et al. 1981, NOAA 1990, Palsson 1990). Eggs and larvae are found over the continental shelf between Washington and central California from winter through summer (Dunn and Matarese 1987, Palsson 1990). Small juveniles (between 60 and 150 mm in length) usually settle into intertidal/subtidal habitats, commonly associated with sand and eel grass, and gradually move into deeper water with increasing age (NOAA 1990, Miller et al. 1976).

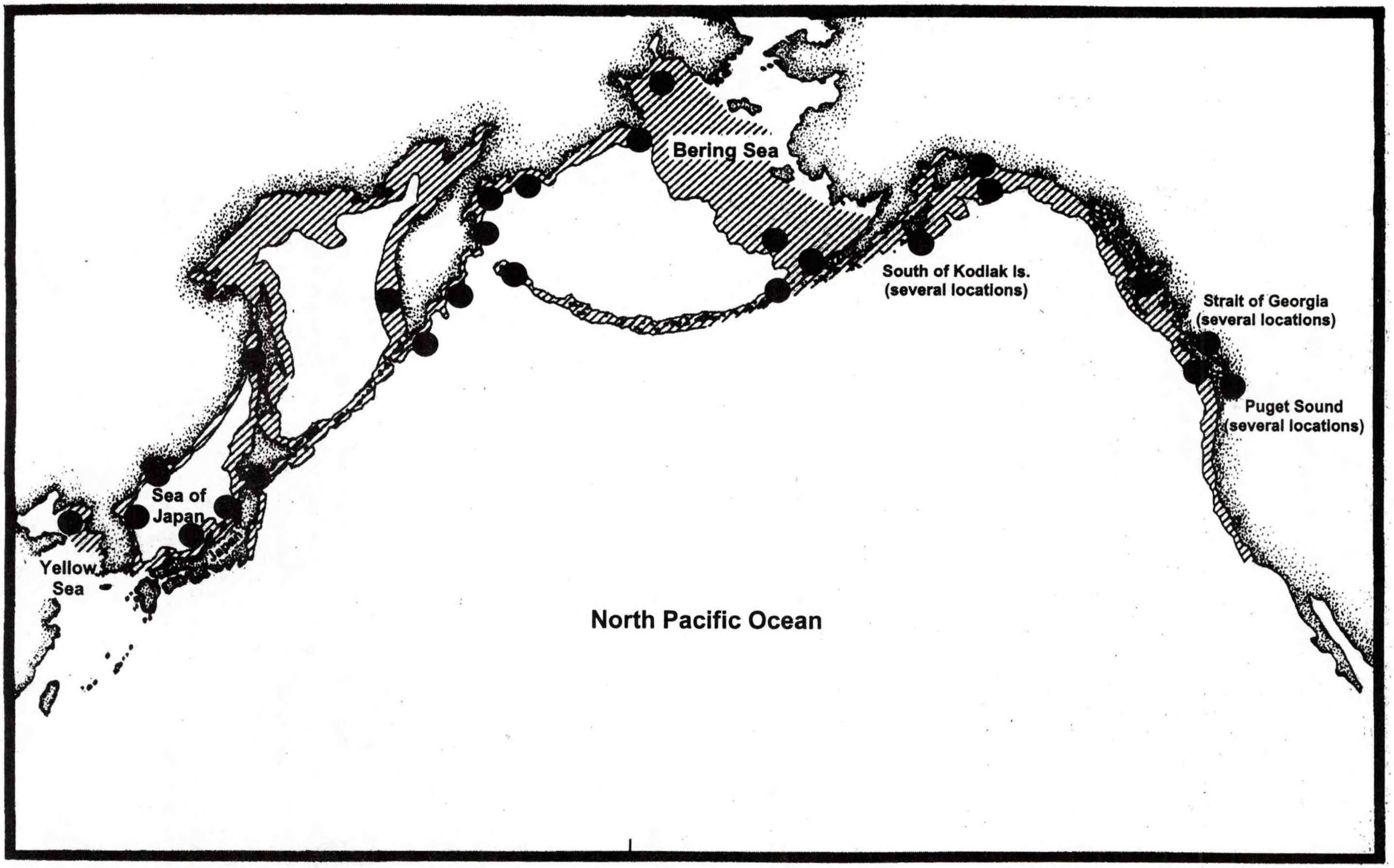


Figure 29. Geographic distribution (cross hatching) and major known spawning locations (●) of Pacific cod. Modified from Bakkala et al. 1984, their fig. 1).

Pacific cod are historically an important groundfish of shallow, soft-bottom habitats in marine and estuarine environments along the west coast (Garrison and Miller 1982). Garrison and Miller (1982) reported that all life stages of Pacific cod occur in various bays in Puget Sound and in the Strait of Juan de Fuca. Adults and large juveniles prefer mud, sand and clay, although Palsson (1990) and Garrison and Miller (1982) found adults associated with coarse sand and gravel substrates.

Migrations

Although they are not considered to be a migratory species, individual adult Pacific cod have been found to move more than 1,000 km (NOAA 1990, Shimada and Kimura 1994). In the northern extent of the range, there exists a seasonal bathymetric movement from deep spawning areas of the outer shelf and upper slope in fall and winter to shallow middle-upper shelf feeding grounds in the spring and early summer (Dunn and Matarese 1987, Hart 1973, NOAA 1990, Shimada and Kimura 1994, Stepanenko 1995).

Larvae may be transported by tidal current to nursery areas (Garrison and Miller 1982). Juveniles are found in polyhaline to euhaline waters, whereas adults are found in marine waters. There is some evidence to suggest that the fish move to deeper water with growth (Hart 1973, NOAA 1990), but they are not found exclusively in deeper water (Brodeur et al. 1995, Palsson 1990).

Reproduction and development

In British Columbia waters, 50% of the male Pacific cod have been reported to be sexually mature at 41-53 cm, and 50% of the females have been reported to be mature at 47-56 cm (Westrheim 1996). For Pacific cod spawning near Port Townsend, both sexes mature by 2 years and 45 cm (NOAA 1990). A 60-cm female (3-4 years) may produce 1.2 million eggs. A 78-cm female (5-7 years) may have up to 3.3 million eggs. In general, fecundity in Pacific cod has been estimated between 225,000 and 5 million eggs per spawning female (Alderdice and Forrester 1971, Forrester 1969, Hart 1973, Palsson 1990, NOAA 1990).

Pacific cod are oviparous and have external fertilization (Hart 1973, NOAA 1990). They are single-batch spawners, releasing all ripe eggs in a single spawning event in a few minutes time (Sakurai 1989, Sakurai and Hattori 1996). Spawning occurs from late fall to early spring in Puget Sound (Garrison and Miller 1982); stocks further north in the Gulf of Alaska and the Bering Sea spawn in winter through spring (Klovach et al. 1995). Pacific cod in northern areas spawn at lower temperature (1-5°C in the Bering Sea) than do fish in southern areas (7-9°C around Japan; 6-9°C in the Strait of Georgia). Eggs are demersal, weakly adhesive, and are found in polyhaline to euhaline waters between 1°C and 10°C (Thomson 1963, Alderdice and Forrester 1971, Dunn and Matarese 1987, Forrester 1969, Hart 1973, Sakurai 1989, Palsson 1990). Fertilized eggs are spherical, 0.98-1.08 mm in diameter (Forrester 1969, Hart 1973, Palsson 1990). Pacific cod eggs have been found associated with coarse sand and cobble bottoms (Phillips and Mason 1986), and because most winter concentration areas have bottom sediments consisting of coarse sand and cobble, it is inferred that Pacific cod preferentially spawn near these bottom types (Palsson 1990).

Conditions for optimal hatching were found to be in the range of 3-6°C, salinities of 12.7-24.6‰, and dissolved oxygen levels from three ppm to saturation (Alderdice and Forrester 1971, Forrester 1969). Alderdice and Forrester (1971) found that no spawning occurs below 0°C or above 10-13°C, speculating that eggs may experience high mortality or very decreased development at these temperatures. Embryonic development is indirect and external. Eggs hatch in 8-9 days at 11°C, 20 days at 5°C, and 28 days at 2°C (Alderdice and Forrester 1971, Forrester 1969, Hart 1973, NOAA 1990). Larvae hatch at about 3-4 mm (Dunn and Matarese 1987, Palsson 1990) with a yolk sac that is absorbed in about 10 days. Larvae metamorphose at 20-25 mm (Alderdice and Forrester 1971, Dunn and Matarese 1987, Palsson 1990) and settle into the benthic community by 35 mm (Palsson 1990).

Karp (1982) reported that juvenile and adult Pacific cod in Hecate Strait, Strait of Georgia, and Puget Sound had growth rates that were similar, and that these rates were faster than those for Pacific cod in the Bering Sea and Gulf of Alaska. He also suggested that Georgia Basin Pacific cod had shorter life spans than subarctic Pacific cod stocks. Even though Pacific cod in Alaskan waters grow more slowly, their greater longevity allows them to reach a greater size (Table 15).

Trophic interactions

Larval feeding is poorly understood. It is known that at about 20 mm, larvae eat copepods (Hart 1973), but it is not known what they eat between yolk absorption and this size. Juveniles and adults are carnivorous, and feed at night (Allen and Smith 1988, Palsson 1990). Young juveniles in the Bering Sea eat copepods, small shrimps and amphipods, and switch to more crabs with increased size (Tokranov and Vinnikov 1991).

Adult Pacific cod have been described as euryphages because the main part of their diet is whatever prey species is most abundant (Kihara and Shimada 1988, Klovach et al. 1995). Klovach et al. (1995) found that 20-40 cm Pacific cod in the Bering Sea eat shrimp, mysids and amphipods; 40-50 cm Pacific cod eat crabs and amphipods; 50-70 cm Pacific cod prefer mainly sandlance; and 70+ cm Pacific cod consume almost exclusively walleye pollock when available.

Larval Pacific cod are eaten by pelagic fishes and sea birds. Juveniles are eaten by larger demersal fishes, including Pacific cod. Adults are preyed upon by toothed whales, Pacific halibut, salmon shark, and larger Pacific cod (Hart 1973, Love 1991, Stepanenko 1995, NOAA 1990, Palsson 1990). The closest competitor of Pacific cod for resources is the sablefish (Allen 1982).

Size and age distributions

Quinnell and Schmitt (1991) presented length distribution information for Pacific cod from Puget Sound. With the exception of Pacific cod from the Gulf of Bellingham (mean length of 54 cm), mean lengths of Pacific cod collected in the sampling areas of Puget Sound were relatively similar, ranging from 38 to 44 cm (Table 16). The authors also presented length/frequency data (Fig. 30), which indicated that the length distribution was bimodal, with most of Pacific cod being 30 to 46 cm, and a smaller number being 11 to 16 cm. Length/frequency distributions for Pacific cod collected from British Columbia waters are also frequently multi-modal; however, the length ranges are generally larger (Westrheim 1996). Alverson et al. (1964) presented length frequencies for Pacific cod in the Bering Sea, Gulf of Alaska, and British Columbia/Southeast Alaska. Few fish larger than 50 cm were reported in the Gulf of Alaska, although these large fish were common in the Bering Sea and British Columbia/Southeast Alaska samples (Alverson et al. 1964).

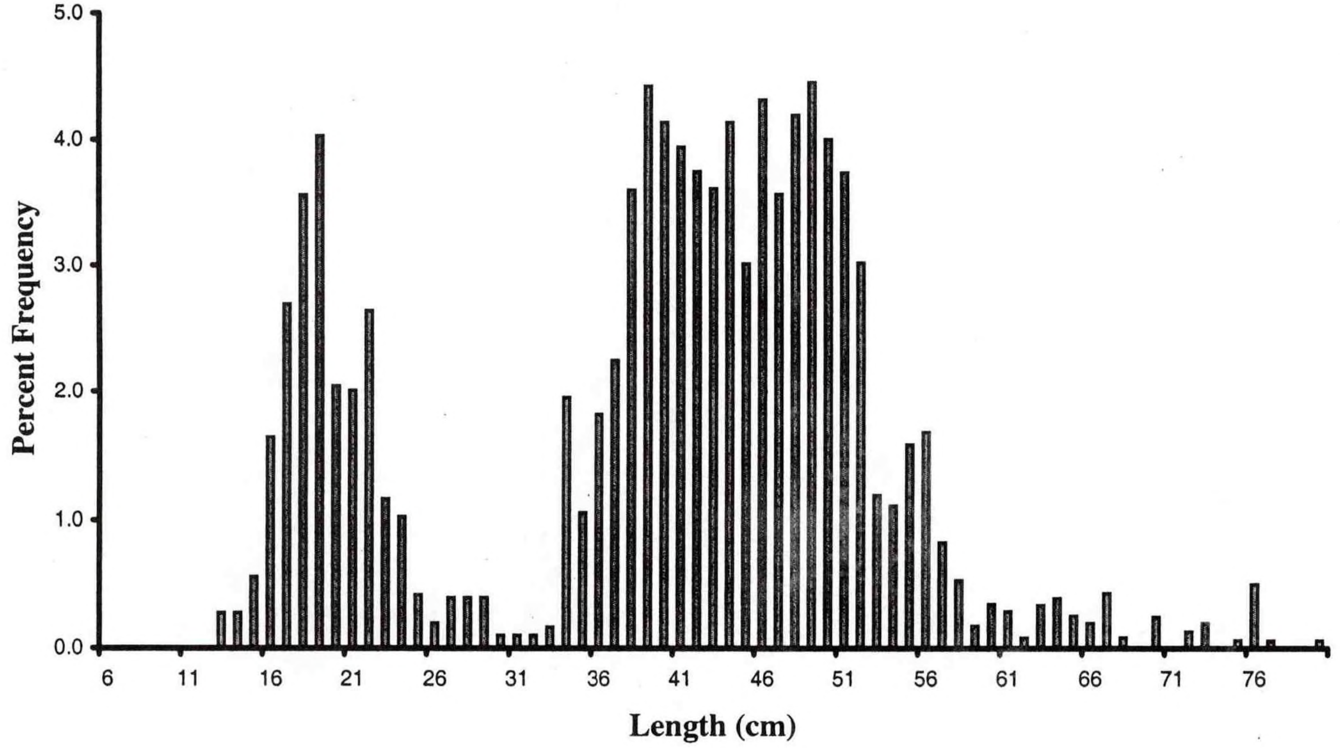


Figure 30. Proportion at length of Puget Sound Pacific cod in 1987 research trawl survey. Modified after Quinnell and Schmitt (1991, fig. 1).

Table 14. Mean annual catches of Pacific cod from selected major geographical regions of the north Pacific for the years 1960 to 1977. Data from Bakkala et al. (1984).

Region	Catch (t)	Percent (%)
Korea	1,690	1.3
Japan (principally Hokkaido)	40,700	31.9
USSR	18,667	14.6
Aleutian Islands	1,485	1.2
East Bering Sea	51,563	40.4
Gulf of Alaska	3,447	2.7
British Columbia	9,059	7.4
Washington-California	1,056	0.8
Total	127,667	100.0

Table 15. Comparison of mean lengths (cm) at age for Pacific cod from selected sites in the Georgia Basin, Hecate Strait, and the Bering Sea (data from Karp 1982).

	Age								
Location	1	2	3	4	5	6	7	8	Source
Hecate Strait	26.0	43.5	55.2	64.2	71.1	76.4	80.5	83.6	Ketchen (1964)
Strait of Georgia	26.1	49.9	61.4	67.3	72.6	76.2	--	--	Ketchen (1961)
Port Townsend	--	25.0	42.1	54.5	63.4	69.9	--	--	Karp (1982)
Bering Sea	18.1	30.7	41.3	49.9	57.3	63.4	68.4	73.9	Moiseev (1953)
Bering Sea	15.1	26.6	33.0	45.6	57.9	67.4	69.4	73.3	Mosher (1954)

Table 16. Estimated body size of Pacific cod sampled during research trawling in major regions of Puget Sound in 1987 (from Quinnell and Schmitt 1991).

	No. of tows	No. of tows with catch	Mean length (cm)	No. of fish measured
Gulf of Bellingham	11	9	54	32
Strait of Juan de Fuca	30	25	40	460
Hood Canal	7	4	41	7
Central Puget Sound	28	19	38	192
South Puget Sound	17	6	44	56

Phenetic and Genetic Information Relating to the Species Question

Phenetic and genetic information examined for evidence of DPS delineations of Pacific cod included presence of geographically-discrete and temporally-persistent spawning aggregations, stock structure, tagging studies, and variation in seasonal migrations, parasite incidence, growth rate, length and age-at-maturity, length frequency, fecundity, meristics and morphometrics, and genetic population structure.

Life History Information

Pre-historical and historical persistence in Puget Sound

Tunnicliffe et al. (in press) examined fish remains in a complete Holocene sediment core sequence from Saanich Inlet, Vancouver Island, British Columbia. Pacific cod first appear in the sediment record of Saanich Inlet around 6,000 BP (Tunnicliffe et al. in press). Fish abundance and species diversity peaked in Saanich Inlet between 7,500 and 6,000 BP, and the last 1,000 years have seen some of the lowest abundances of fishes in Saanich Inlet's marine history (Tunnicliffe et al. in press). The close proximity of Saanich Inlet to Puget Sound would suggest that Pacific cod were also likely established in Puget Sound by approximately 6,000 BP.

Gadiform remains were identified in prehistoric fish skeletal remains from the Duwamish No. 1 archeological site (45-KI-23), located 3.8 km upstream from Elliott Bay on the Duwamish River, utilized by aboriginal humans between A.D. 15 and A.D. 1654 (Butler 1987). Gadiforms were present throughout the occupational history of this site, and were third and fourth in rank order of taxonomic abundance in two separate studies of fish bones performed at this site (following Salmonidae, Pleuronectiformes, and in one case Squalidae) (Butler 1987). Conversely, archaeological investigations of the West Point site on the north side of Discovery Park in Seattle (utilized by hunter-fisher-gatherers between 4,250 and 200 BP) found few remains of gadiforms, although some Pacific cod bones were identified at this site (Wigen 1995). Wigen (1995) postulated that differences in the frequency of gadiform remains found between the Duwamish and West Point sites may be related to the possible use of fish traps at West Point versus hook and line methods at the Duwamish site, or perhaps to differences in the season of human occupation between the two sites.

Pacific cod remains were also reported from the early component of the Bear Cove archaeological site on northeastern Vancouver Island that was occupied 6,500 to 5,000 years ago (Carlson 1979, Hebda and Frederick 1990) and from Namu, on the central coast of British Columbia from the same time period (Carlson 1979, Hebda and Frederick 1990).

Spawning location and spawn timing

Puget Sound to Dixon Entrance–Spawning locations of Pacific cod have been identified in Washington and British Columbia waters primarily on the basis of wintertime aggregations (Figs. 31, 32, Table A-3) (Palsson 1990). Spawning aggregations (several of these may no longer be viable) have been reported in Agate Passage northwest of Bainbridge Island (Bargmann 1980, Palsson 1991, WDFHMD 1992), Port Townsend Bay (Karp and Miller 1977, Karp 1982, WDFHMD 1992), Port Gamble (WDFHMD 1992), Dalco Passage near Tacoma, and Eliza Island off Bellingham, all in Puget Sound (Palsson 1990); Protection Island and Port Angeles in the Strait of Juan de Fuca (WDFHMD 1992); Nanoose Bay, Hornby Island/Cape Lazo in Minor Statistical Area (MSA) 14, and in the vicinity of Swanson Channel in the Gulf Islands in MSA 17s+18, all in the Strait of Georgia (Ketchen 1961, Westrheim 1996); Amphitrite and Clo-oose Banks off southwest Vancouver Island (Ware and McFarlane 1986); and White Rocks (Foucher and Westrheim 1990) and Bonilla Island in eastern Hecate Strait (Tyler and Westrheim 1986). In addition, Phillips and Mason (1986) identified Baynes Sound (in MSA 14) on eastern Vancouver Island as a Pacific cod spawning location by direct sampling of demersal Pacific cod eggs. This later area is in the vicinity of Hornby Island in MSA 14 (Figs. 13 and 15).

Puget Sound is near the southern limit of the range of Pacific cod (Pedersen and DiDonato 1982). Miller and Borton (1980) summarized distribution records of Pacific cod in Puget Sound as found in published records, museum collections, and various boat logs. Centers of collection of Pacific cod in Puget Sound were heavily influenced by fishing effort and ease of access, and centered around Point Roberts to Semiahmoo Bay, Bellingham Bay, west of Orcas Island in President Channel, in East Sound on Orcas Island, off the west side of Whidbey Island near Deception Pass and Point Partridge, Port Townsend, off Discovery Bay, Holmes Harbor, northern Hood Canal, the central Sound from Shilshole Bay to Port Madison, Elliott Bay, off Alki Point, Port Orchard, in the Tacoma Narrows, and between Fox and Anderson Islands at the mouth of Carr Inlet (Miller and Borton 1980). Historically, commercial and recreational fisheries for Pacific cod occurred throughout much of Puget Sound (see Figs. 33, 34) (Pedersen and DiDonato 1982).

Over the North Pacific Ocean as a whole, Pacific cod spawn within the period from December to May (see Table A-3). Spawning seasons appear to be somewhat earlier for Pacific cod in higher latitudes and earlier in lower latitudes. Within British Columbia the Pacific cod spawning season occurs from February to March (Foucher and Westrheim 1990). Principal spawning occurs off southwest Vancouver Island in February and in Hecate Strait in March (Foucher and Westrheim 1990). Within northern Hecate Strait (Area 5D), Pacific cod spawn later than elsewhere in British Columbia, while Pacific cod in southern Hecate Strait (Area 5C) spawn substantially earlier, possibly indicating that two separate stocks exist within Hecate Strait (Fig. 12) (Foucher and Westrheim 1990). Spawning is completed by April in most areas of British Columbia but not until May in northern Hecate Strait (Foucher and Westrheim 1990).

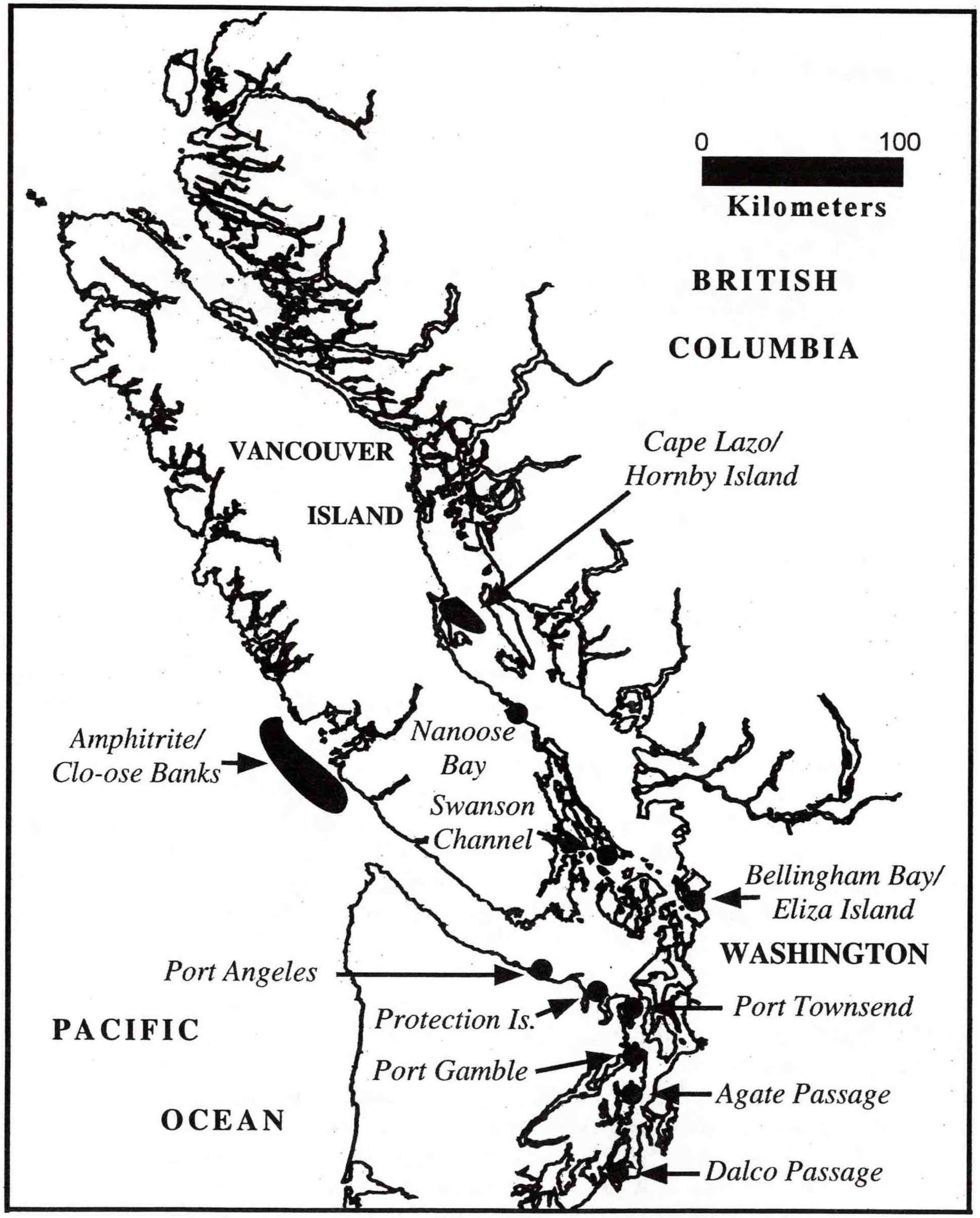


Figure 31. Current and historical spawning locations (*in italics*) of Pacific cod in Puget Sound and southern British Columbia.

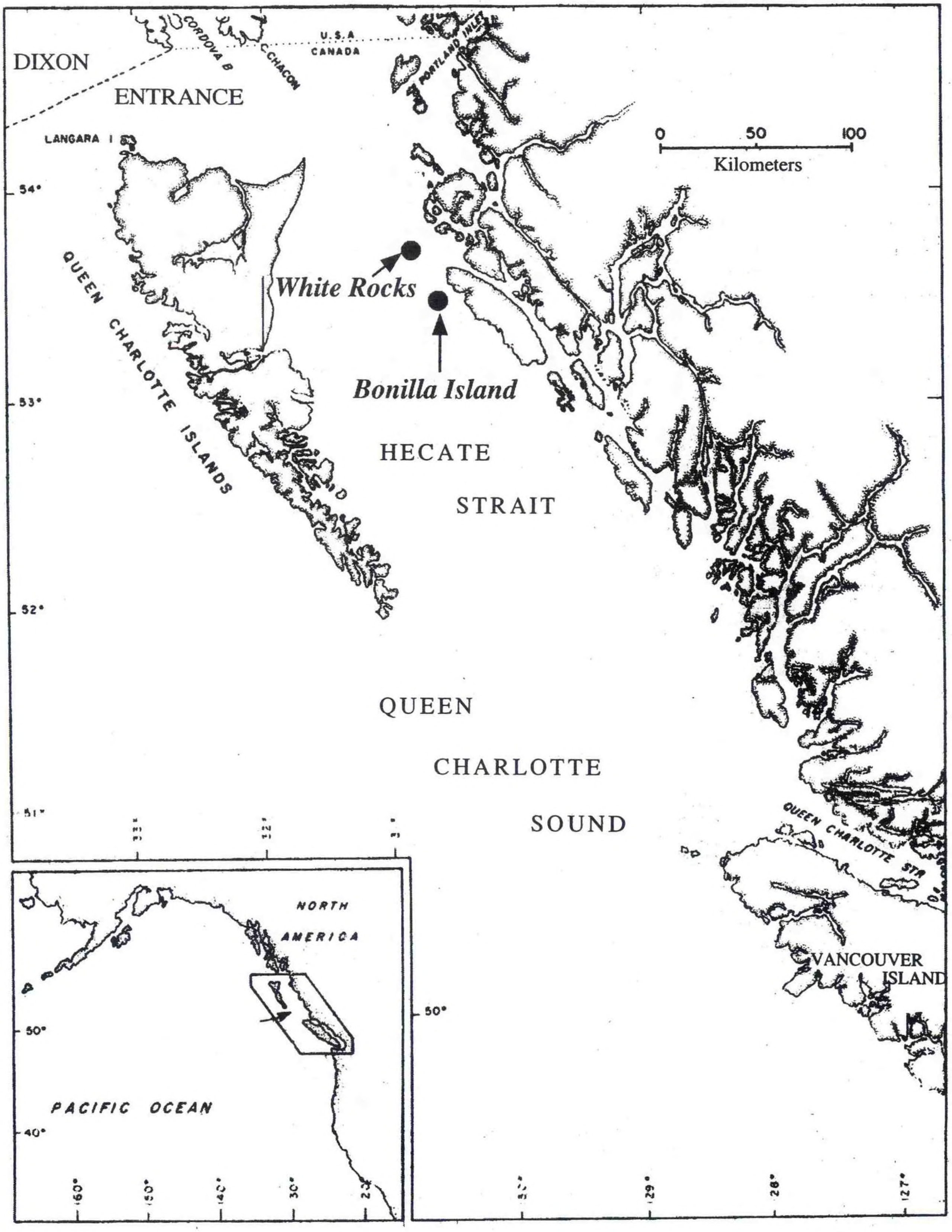


Figure 32. Known spawning locations (*in italics*) of Pacific cod in northern British Columbia.

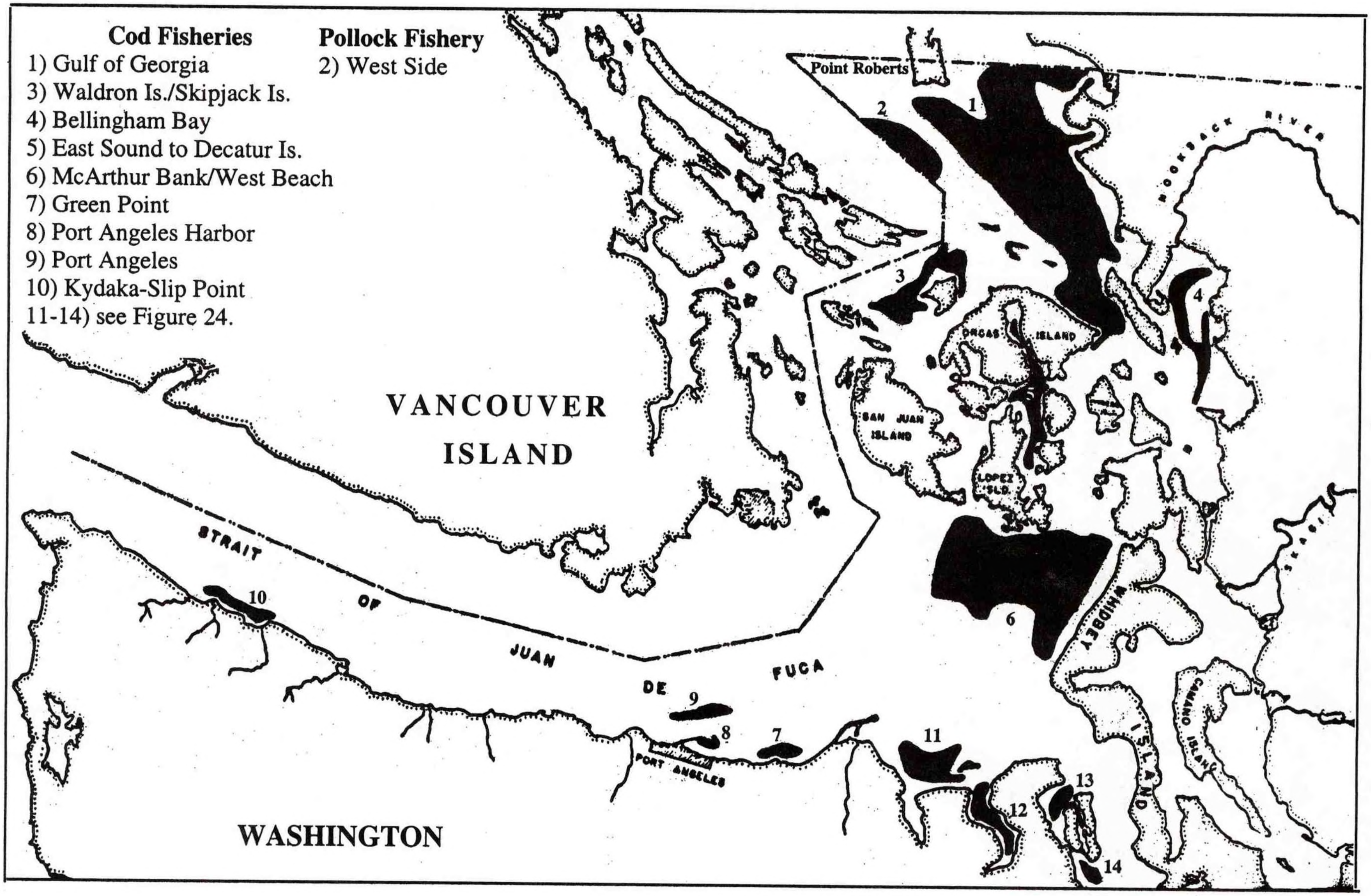
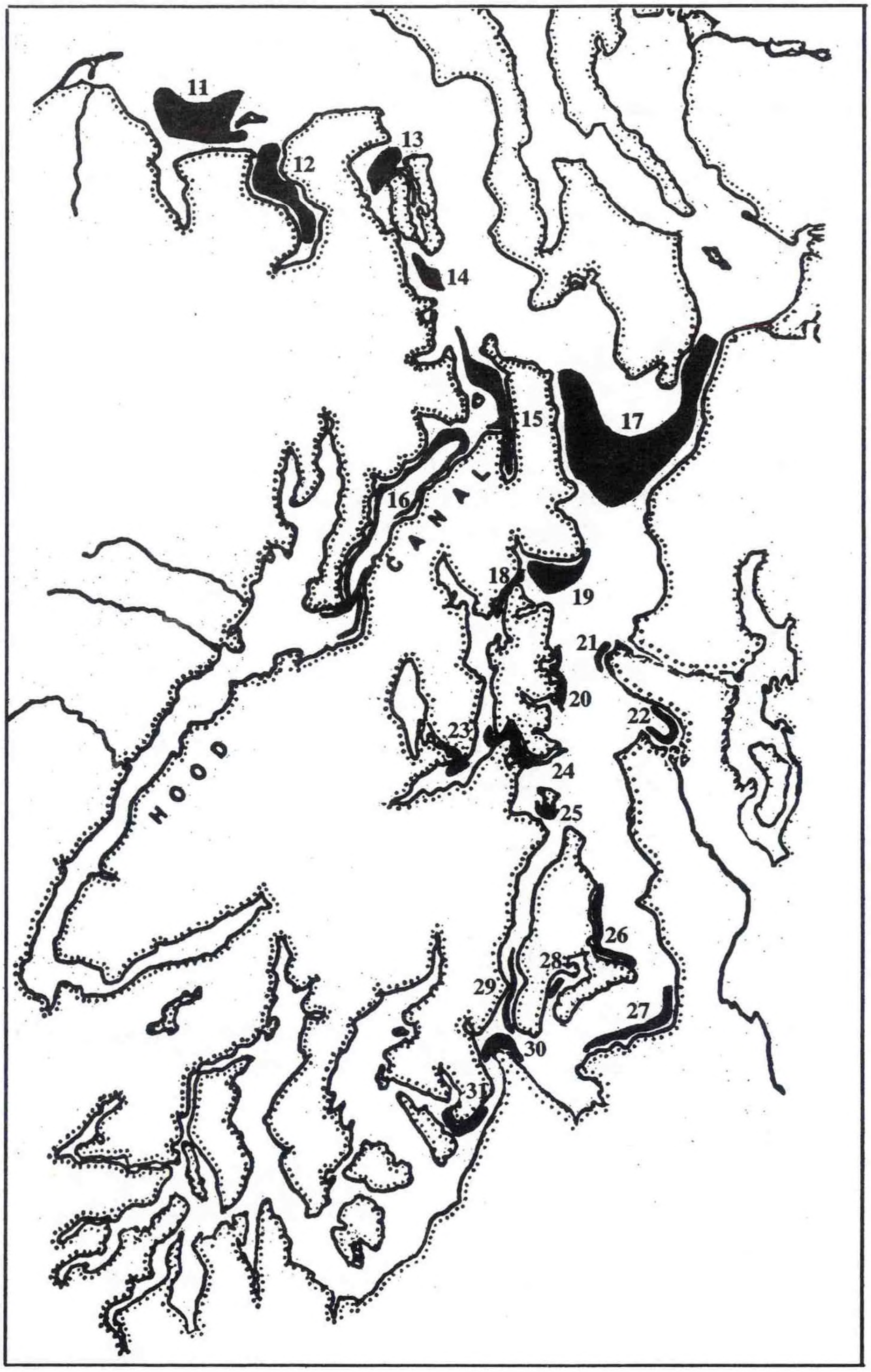


Figure 33. Historical location of major Pacific cod sport, trawl and set-net fisheries and walleye pollock trawl fishery in northern Puget Sound and Strait of Juan de Fuca as described in Pedersen and DiDonato (1982). Modified from Pedersen and DiDonato (1982, their Appendix I, fig. 1).



11) Protection Island
12) Discovery Bay
13) Port Townsend
14) Oak Bay
15) Port Gamble
16) N. Hood Canal
17) Possession Sound
18) Agate Passage
19) Port Madison
20) Skiff Point
21) West Point
22) Elliot Bay
23) Bremerton
24) Rich Passage
25) Blake Island
26) East Vashon Is.
27) Redondo
28) Quartermaster
29) Colvos Passage
30) Pt. Defiance
31) Pt. Fosdick

Figure 34. Historical location of major Pacific cod sport, trawl and set-net fisheries in Puget Sound as described in Pedersen and DiDonato (1982). Modified from Pedersen and DiDonato (1982, their Appendix I, fig. 2).

Gulf of Alaska–Hirschberger and Smith (1983) and Dunn and Matarese (1987) reported on observations of spawning Pacific cod in the Gulf of Alaska at Shelikof Strait, on the outer edge of the continental shelf from Yakutat Bay to Chirikof Island, and especially south of Kodiak Island in the Chirikof Island and outer Albatross Bank areas (Fig. 29). Spawning fish were most prevalent from February to May, and occurred between 73 and 265 m depth and in water of 4.5-5.9°C (Hirschberger and Smith 1983). Young-of-the-year Pacific cod ($\geq$80 mm) are the dominate fish in nearshore eelgrass communities in Prince William Sound (Laur and Haldorson 1996, Dean et al. 2000) indicating significant Pacific cod spawning is occurring in, or near, Prince William Sound.

Bering Sea–Within the eastern Bering Sea, spawning Pacific cod have been taken in fisheries along the continental slope south of the Pribilof Islands in late January through March and in bays and nearshore waters in the eastern Aleutians and along the north side of Unimak Island to False Pass, from late December to April (Fredin 1985). In the western Bering Sea, Pacific cod spawn from January to May in various locations from Anadyr Bay southwesterly to the Commander Islands (Fig. 29, Table A-3) (Moiseev 1953, Musienko 1970, Vinnikov 1996)

Sea of Okhotsk to Korea–In the eastern part of the Sea of Okhotsk, off western Kamchatka, Pacific cod spawn from the end of February to the end of May in depths of 170 to 280 m (Rovnina et al. 1997). In Japanese coastal waters Pacific cod spawn along the coasts of Hokkaido and northern Honshu primarily from December to March (Fig. 29, Table A-3) over bottom areas consisting of hard or gravelly mud (Mishima 1984). Off the east coast of Korea in the Sea of Japan, Pacific cod spawn in a number of locations, particularly in Yeongil and Chinhoe Bays from late December to late January in water temperatures of 5-9°C (Zhang 1984). In the Yellow Sea, Pacific cod do not concentrate in any given spawning areas but instead spawn over broad areas along the west coast of the Korean Peninsula (Zhang 1984) (Fig. 29, Table A-3).

Pacific cod management stocks

Palsson (1990) identified three Pacific cod stocks in Puget Sound (North, West, and South), based on tagging studies and spawning ground location. The North stock included Pacific cod in the Gulf-Bellingham and San Juan Marine Fish Management Regions (Fig. 14). Pacific cod in the Juan de Fuca and West Juan de Fuca Management Regions comprised the West stock, which included Pacific cod that spawn in Port Townsend Bay. The South stock was comprised of Pacific cod in Hood Canal, Central Puget Sound, and South Sound Management Regions (Palsson 1990). Tagging studies indicated that some of the fish in the North stock spawn at Nanoose Bay in the Strait of Georgia, north of Nanaimo on Vancouver Island (Palsson 1990).

Nine Pacific cod stocks have been provisionally identified in British Columbia waters; four in the Strait of Georgia (Nanoose Bay, Gulf Islands, MSA 14, and MSA 19), one off the southwest coast of Vancouver Island (La Perouse Bank/Amphitrite Bank), two in Queen Charlotte Sound (Areas 5A and 5B); and two in Hecate Strait (a northern and a southern stock) (Figs. 12, 13, 15) (Westrheim 1996). The itinerant MSA 19 stock has been identified as a transitory grouping of

Pacific cod apparently lured inshore by spawning Pacific herring and is not associated with a particular Pacific cod spawning ground (Westrheim and Foucher 1987). The stocks in the Gulf Islands and MSA 14 are considered to consist of year-round residents in the Strait of Georgia (Westrheim and Foucher 1987). Pacific cod that spawn in Nanoose Bay, north of Nanaimo on the east coast of Vancouver Island, are considered an itinerant stock that disperses widely beyond Nanoose Bay into the southeast Strait of Georgia, Gulf Islands, and MSA 14 (Figs. 13, 15) (Westrheim and Foucher 1987).

Definitive stock structure analysis of Pacific cod in Alaska has not occurred, although separate Gulf of Alaska and Aleutian Islands/East Bering Sea stocks are recognized for management purposes (Westrheim 1996). Wilimovsky et al. (1967) tentatively identified four separate stocks, based on meristic measurements: southern British Columbia, southeastern Alaska/northern British Columbia, eastern Aleutian Islands/Bering Sea, and western Aleutian Islands.

Numerous stocks of Pacific cod have been identified by researchers in the northwestern Pacific. Moiseev (1960) concluded, based on length frequency differences, that at least 10 local stocks of Pacific cod exist off the Asian coast, but he did not identify them. Zhang (1984) reviewed size at first spawning and morphological differences between the two recognized Korean Pacific cod stocks; an east coast and a west coast stock, which are presumably isolated from one another by warm water at the southern end of the Korean Peninsula. Pacific cod in Japanese waters are differentiated as either "bank cod" or "offshore cod" on the basis of differences in age composition and condition factors (Matsubara 1938, 1939; Mishima 1984). Mishima (1984) noted that Pacific cod in various regions of Japan obtain sexual maturity at different sizes, but he also postulated that these differences were likely due to variable rates of growth affected by biotic and abiotic factors, and by implication not indicative of genetic differences between stocks. Hattori et al. (1992b) cited diverging catch rates between Pacific cod in the Sea of Japan and Pacific cod off the east coast of Japan as evidence of separate stocks occurring in these regions. According to Moiseev (1960), Pacific cod stocks off Asia are believed to have resulted following isolation during the quaternary period when island chains and deep-sea canyons were forming. This resulted in many individual stocks that do not mix, undergo short spawning migrations, and occupy relatively small areas.

Tagging and distribution

Unlike Pacific hake and walleye pollock, numerous tagging studies of adult Pacific cod have occurred in the Northwest Pacific Ocean, including within Puget Sound (Gosho 1976, Bargmann 1980, Westrheim 1982, Karp 1982, Palsson 1990); however, few of these studies have tagged Pacific cod during the spawning season and on the spawning grounds. In the context of delineation of Pacific cod population structure, key questions that tagging studies may help answer are: 1) To what degree do the same fish return to spawn on the same grounds year after year? and 2) How much interchange (gene flow) occurs between spawning populations? Unfortunately, adult tagging studies cannot help answer another important question: do adult Pacific cod return to the same spawning grounds where they were hatched?

Westrheim (1982) reviewed results of Pacific cod tagging studies in British Columbia from 1944 to 1968 that tagged and released over 6,800 Pacific cod in the Strait of Georgia, over 1,600 off southwest Vancouver Island, and over 13,000 in Hecate Strait, with respective area recapture rates of 16%, 18%, and 27%. For the Strait of Georgia releases, 90.8% of recoveries occurred in the Strait of Georgia, 8.5% in Puget Sound, 0.6% off Southwest Vancouver Island, and 0.2% off the outer coast of Washington. For the southwest Vancouver Island releases, 97.9% of recaptures occurred in the area of release, 1.8% in the Strait of Georgia, and 0.4% in Hecate Strait. For Hecate Strait releases, 99.7% of recaptures occurred in Hecate Strait, 0.2% in Queen Charlotte Sound, and 0.1% off northwest Vancouver Island. Pacific cod tagged on the Nanoose Bay spawning grounds appeared to disperse more widely than other stocks: 45% of Nanoose Bay releases were recaptured at Nanoose Bay, 26% in the southeast Strait of Georgia and north Puget Sound, 13% in the Gulf Islands, 7% in MSA 14, and 4% from offshore waters (Westrheim 1982). Westrheim (1982) stated that "Overall, there was little migration of tagged cod among the three tagging regions."

Gosho (1976) summarized Pacific cod tagging in Washington waters from 1955 to 1970. The majority of tagged fish in these studies were recovered in or near the area of release in the fishery that was underway during tagging operations. Palsson (1990) reanalyzed the results of Washington tagging studies of 1955 to 1979 and the Canadian Nanoose Bay tagging by eliminating all recoveries that occurred in the season of tagging. Results of tagging recoveries on apparent spawning aggregations, as reported in Palsson (1990), are reproduced in Table A-4. Palsson (1990) concluded that tagging results suggested that most Pacific cod remained in the area of spawning after tagging, although some out of area movements did occur. Palsson (1990) pointed out problems with interpretation of these tagging studies due to the unquantified and non-uniform recovery efforts among areas and that significant recoveries of tagged fish occurred immediately after tagging in the same areas.

Bargmann (1980) reported on tagging of Pacific cod aggregated for spawning in Agate Passage. Overall recoveries of tags during the year after tagging indicated dispersion of this stock throughout Puget Sound. Figure 35 illustrates tag recoveries as reported in Bargmann (1980) from fish tagged in February and March 1977 in Agate Passage that occurred one or two years later during the months of February and March when spawning aggregations occur. Most spawning season recoveries occurred in or near Agate Passage (74%), although recoveries during February or March also occurred at Port Townsend and in Dalco Passage, known spawning areas of Pacific cod. Shimada and Kimura (1994) reported on tagging studies of Pacific cod between 1982 and 1990 in the eastern Bering Sea and adjacent waters and found "sufficient migration to explain Grant et al.'s (1987a) findings of genetic homogeneity in Pacific cod over broad areas of the North Pacific." Direct evidence was found that Pacific cod migrate from the eastern Bering Sea into the Gulf of Alaska during winter. Shimada and Kimura (1994) stated that tag-recapture data and inferred seasonally directed movements suggest a single winter spawning population of Pacific cod occurs in the eastern Bering Sea, nearby Aleutian Island waters, and in the Western Gulf of Alaska between 157°W and 170°W.

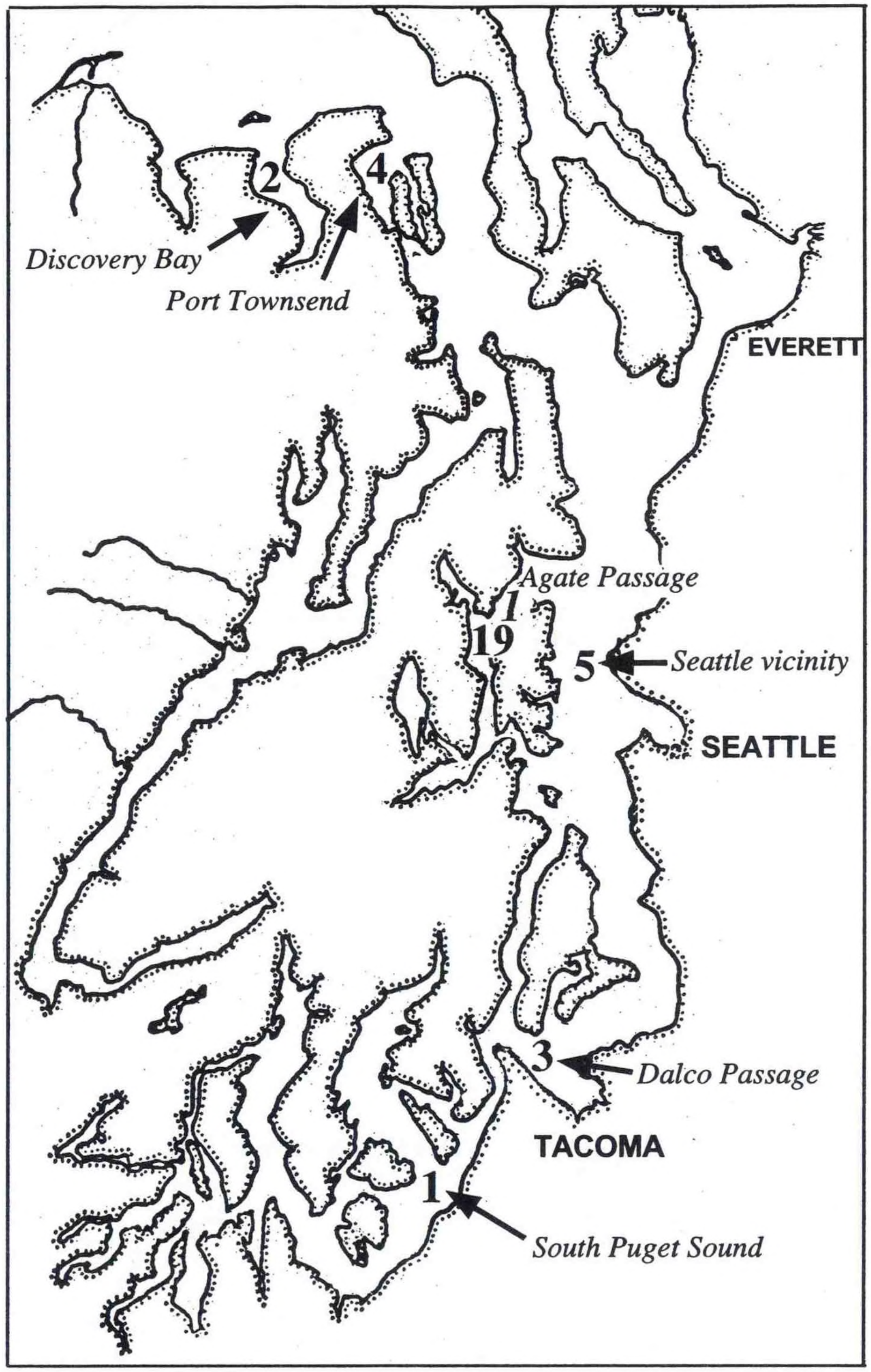


Figure 35. Recovery locations in February and March of 1978 and 1979 of Pacific cod tagged in Agate Passage in February and March of 1977. A total of 642 adults were tagged in 1977. Of the 121 recovered fish, 34 were recovered in the spawning months of February and March 1978 and 1 was recovered in March 1979 (data from Bargmann 1980).

Seasonal migrations

The spawning migrations of Pacific cod in offshore waters of Washington and southwest Vancouver Island and in Puget Sound differ from the migration pattern of Pacific cod in northern British Columbia (Palsson 1990). In all cases, Pacific cod migrate from areas where they feed during most of the year to winter spawning areas, where the water is between 6°-7° C. At the southern extent of its range, off Korea, Japan, Washington, Vancouver Island, and in Puget Sound, Pacific cod move from deep water to cool shallow water to spawn in the winter and then return to deeper offshore waters to feed when the shallower coastal waters warm (Bargmann 1980, Westrheim and Tagart 1984). In northern British Columbia, Pacific cod follow a reverse pattern, migrating to deeper waters to spawn during the winter and returning to shallower waters to feed at other times of the year (Ketchen 1961, Palsson 1990).

Likewise, Pacific cod in the eastern Bering Sea appear to conduct seasonal migrations to deeper warmer water in the winter to avoid cooling of inshore waters (Bakkala 1984). Spring feeding migrations are shoreward in the Bering Sea towards the coastal shelf environment. The southern coastal stocks of Pacific cod can achieve these seasonal migrations with short inshore-offshore depth migrations; however, in the Bering Sea, seasonal migrations are necessarily much longer due to the extensive area covered by the Bering Sea shelf (Shimada and Kimura 1994).

Juvenile Pacific cod are found in nearshore kelp and sand-eelgrass habitats in Puget Sound (Miller et al. 1976, WDFHMD 1992). Laur and Haldorson (1996) and Dean et al. (2000) reported that juvenile Pacific cod were utilizing inshore eelgrass habitat in Prince William Sound. These observations indicate that there is a migration of juvenile Pacific cod to inshore nursery habitats at least in fjord-like environments like Puget and Prince William Sounds, followed by migration to deeper waters as fish mature.

Parasite incidence

A protistan parasite, tentatively placed in the Family Hartmannelidae has been identified as the cause of parabranchial X-cell lesions in Pacific cod (Westrheim 1996). Palsson (1990) reported that the incidence of parabranchial lesions in Pacific cod in all Marine Fish Management Regions in Puget Sound was 0%, except in the San Juan (0.04%; n=2,374) and Juan de Fuca (0.86%; n=700) Regions. Since Westrheim (1987) reported a parabranchial lesion frequency of 3.4% for trawl-caught Pacific cod off southwest Vancouver Island and incidence of lesions was 0% in Puget Sound, Palsson (1990) concluded that little intermingling of Puget Sound and southwest Vancouver Island Pacific cod occurred.

Growth rate

Westrheim (1996) presented an historical review of age determination studies in Pacific cod and stated that although numerous structures have been investigated for age determination of Pacific cod no validated method currently exists. Age determination of Pacific cod has been attempted through examination of otoliths (Ketchen 1970, LaLanne 1975, Lai et al. 1987, Kimura and Lyons 1990, Hattori et al. 1992a, Tok 1994), scales (Kennedy 1970, Lai et al. 1987, Kimura and Lyons 1990), fin rays (Beamish 1981b, Chilton and Beamish 1982, Lai et al. 1987, Beamish et al. 1990, Tok 1994), and length frequency analysis (Foucher and Fournier 1982, Lai et al. 1987, Beamish et al. 1990). Ketchen (1984) indicated that age of Pacific cod cannot be reliably estimated from either scales or otoliths in Canadian waters. Fish age calculated from scales often disagrees with age computed from otoliths (Tok 1994). In Canada, ageing of Pacific cod is currently done by computerized analysis of length-frequencies (Foucher and Fournier 1982, Foucher et al. 1984, Westrheim 1996).

Ketchen (1961) suggested that the initial high growth rate, early sexual maturity, and short life span exhibited by Pacific cod along the Canadian coast was a result of the species being at the southern limit of its range where it is subject to relatively high water temperatures and consequent environmental stress. Karp's (1982) analysis of age and growth data for Port Townsend Bay Pacific cod indicated that this stock was short lived and fast growing compared to other populations further north. Karp (1982) presented mean length-at-age data for several stocks of Pacific cod (Table 15, Fig. 36). Although ageing errors, as discussed above, may occur and selective behavior of different trawl gear may confound the results, the data presented in Table 15 and Figure 36 and discussed in Karp (1982) indicate that Port Townsend, Hecate Strait, and Strait of Georgia Pacific cod are relatively fast growing compared to Pacific cod from the Bering Sea, especially. Karp (1982) suggested that rapid growth rates evident in Washington and British Columbia Pacific cod stocks may be "a function of increased metabolic activity and longer growing seasons in warmer waters of these southernmost limits of Pacific cod distribution."

Length and age at maturity

Table A-5 summarizes length at first maturity, at 50% maturity, and at 100% maturity for selected Pacific cod populations. Thomson (1962) stated that length at 50% maturity for male and female Pacific cod in Hecate Strait in 1960-61 was 50 and 55 cm, respectively. This was compared to Pacific cod from West Kamchatka (Sea of Okhotsk) where males and females reach 50% maturity at 69 and 73 cm, respectively. Similar lengths at 50% maturity in Strait of Georgia Pacific cod were reported to be 48-49 cm and 55 cm for male and females, respectively (Ketchen 1961). Males appear to mature at an earlier age, as well as a smaller size, with 50% of males mature at age-2 and all mature by age-3 in the Strait of Georgia (Ketchen 1961). By comparison, only 15-25% of females are mature at age-2, although almost all are mature by 3-years-of-age (Ketchen 1961). Moiseev (1953) stated that Pacific cod in the Sea of Okhotsk reach sexual maturity at age-5, and some are still immature age-9. By contrast, Pacific cod off the east coast of Korea are more comparable to Pacific cod in the Strait of Georgia, reaching maturity at age-3, with all mature by age-5 (Ketchen 1961).

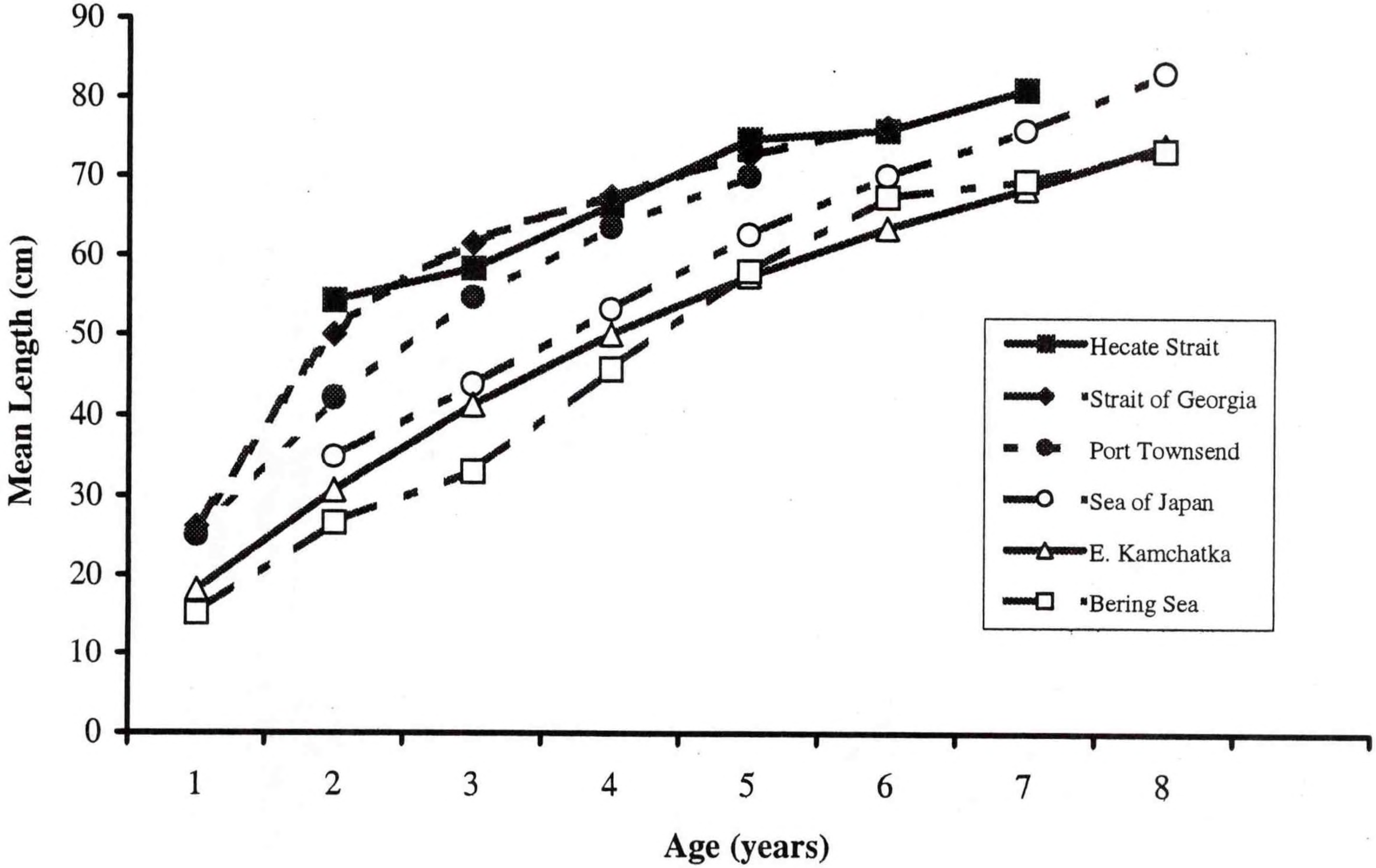


Figure 36. Mean length (cm) at age for Pacific cod from selected locations. Data from Karp (1982).

Fredin (1985) reported that both male and female Pacific cod in the eastern Bering Sea first reach maturity at slightly greater than 50 cm and that 50% of the fish are mature at a length of 60 cm for males and 62 cm for females. By comparison, Pacific cod from Hecate Strait mature at a smaller size and Pacific cod from the west coast of Kamchatka mature at a greater size than eastern Bering Sea Pacific cod (Fredin 1985).

Length frequencies

Westrheim (1996) examined length-frequency samples from both research and commercial catches of Pacific cod in British Columbia and Puget Sound, as well as elsewhere. Palsson (1990) also presented length-frequency data for trawl (Gulf-Bellingham, Juan de Fuca, Port Townsend), setnet (Port Townsend), and recreational (Juan de Fuca, Central Puget Sound, South Puget Sound) Pacific cod fisheries in Puget Sound in the 1970s and 1980s. Length frequencies were usually multi-modal but "revealed that fisheries depend upon one or two year classes" for most of the catch (Palsson 1990). Palsson (1990) examined mean lengths of Pacific cod in these fisheries since 1970 but did not find long term patterns. Figure 37 presents a comparison of length frequencies for Pacific cod from Canadian commercial catches near known spawning grounds at White Rocks-Bonilla Island (Hecate Strait), Amphitrite Bank (off southwest Vancouver Island), Nanoose Bay, and MSA 14 (Strait of Georgia) (Figs. 13, 31, 32) during the spawning months of January-March (data from Foucher [1987]). Although these data are from commercial catch records and not survey cruises they suggest little intermingling of White Rocks-Bonilla Island and Amphitrite Bank Pacific cod with each other or with the two Strait of Georgia stocks occurred during the years analyzed (Fig. 37).

Fecundity and egg size

Thomson (1962) concluded that since there was no apparent difference in fecundity at similar body lengths between Pacific cod in Hecate Strait and West Kamchatka, the Pacific cod stocks in Hecate Strait had reduced reproductive potential compared to other populations in the North Pacific. Foucher and Tyler (1990) examined fecundity in Pacific cod from the west coast of Vancouver Island and Hecate Strait and found that Hecate Strait fish showed a slightly higher fecundity at length than did Pacific cod from the west coast of Vancouver island. Hecate Strait Pacific cod, in this later study, also showed a higher fecundity at length than was reported by Thomson (1962).

Karp (1982) found the fecundity-length relationship in Pacific cod in Port Townsend Bay to be represented by the relationship $F=12.024L^{2.959}$, which results in 40, 50, and 60 cm female Pacific cod producing 661,000, 1,280,000, and 2,195,000 eggs, respectively. Karp (1982) compared fecundity in Port Townsend Pacific cod to stocks from Kamchatka and Hecate Strait (Fig. 38) and suggested that southern locations have higher size-specific fecundities than northern stocks and this could provide some compensation for southern populations that appear to grow and mature at faster rates and die at a younger age than do Pacific cod from northern areas (Ketchen 1961).

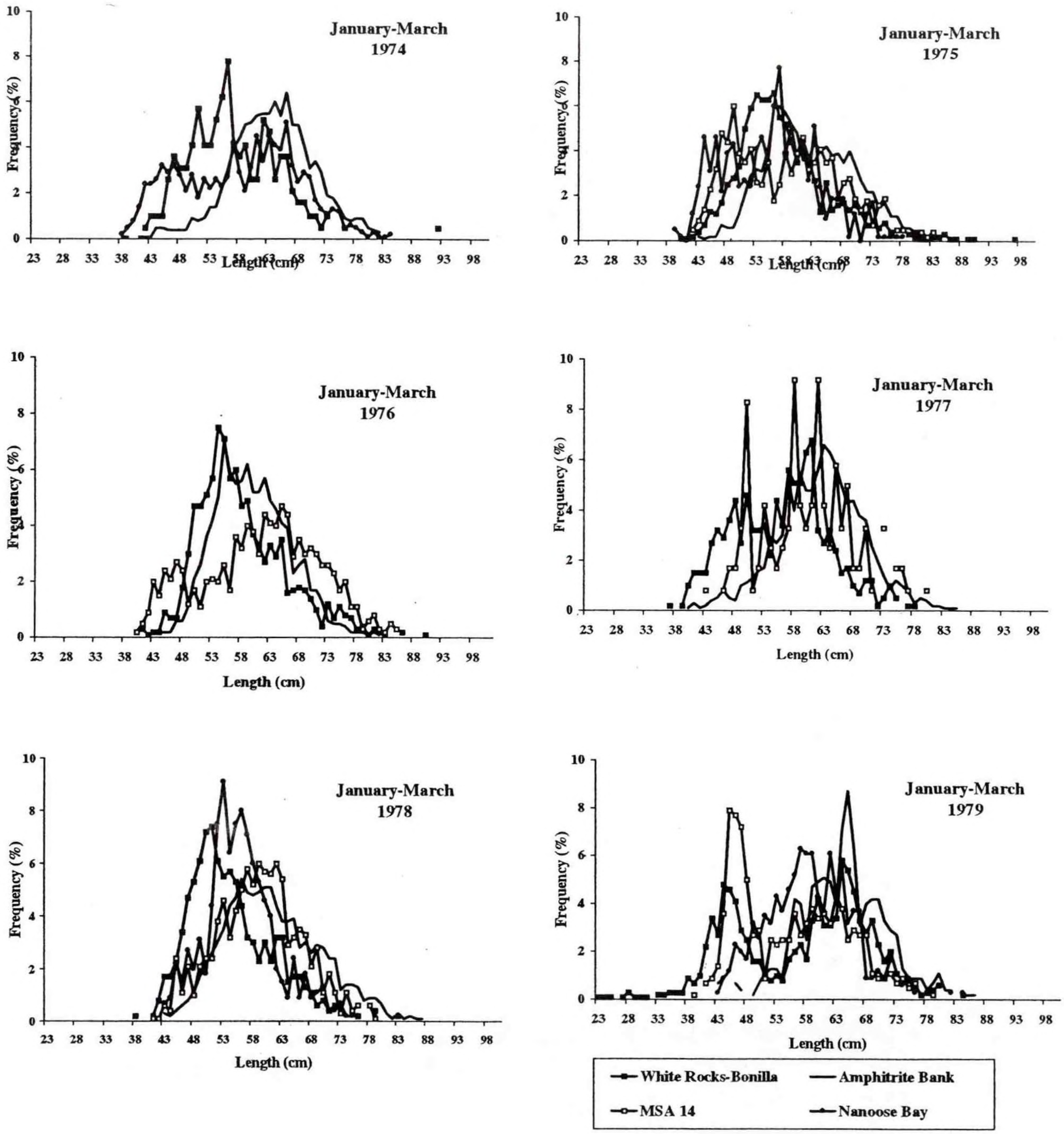


Figure 37. Length composition of Pacific cod from commercial catch during the spawning months of January to March in Canadian fisheries between 1974 and 1979 at White Rocks-Bonilla, Amphitrite Bank, Nanoose Bay, and MSA 14 fishing grounds. Data from Foucher (1987).

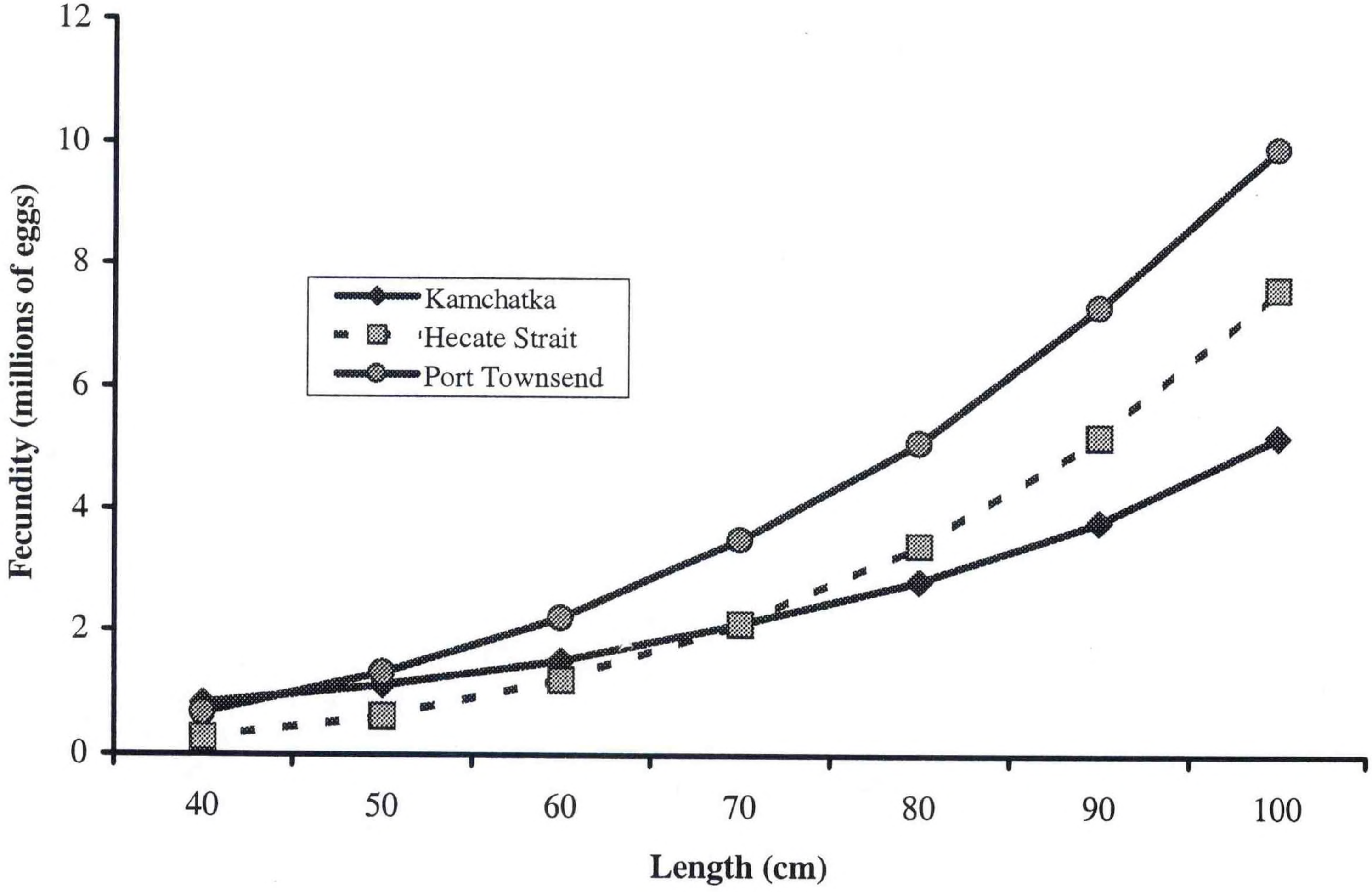


Figure 38. Estimates of fecundity of Pacific cod at length in selected locations. Data from Karp(1982).

Tyler (1995) compared reproductive biology between Pacific cod stocks from Hecate Strait and Amphitrite Bank (off southwestern Vancouver Island) and found that Hecate Strait fish had greater fecundity at the same size than did Amphitrite Bank fish (Foucher and Tyler 1990). A larger proportion of mature female Pacific cod from the Amphitrite Bank stock (14%) go through a resting stage (failing to spawn in any one year), than do female Pacific cod from the Hecate Strait stock (0.2%) (Tyler 1995). Tyler (1995) hypothesized that these stock differences could be due to the warmer water temperatures interfering with reproductive activity at Amphitrite Bank or to differences in feeding opportunity between the two stocks. Tyler (1995) did not consider the possibility that genetic differences in reproductive capacity may exist between these two stocks.

Morphological Differentiation

Morphometric discrimination

Wilimovsky et al. (1967) analyzed Pacific cod from Alaska and British Columbia for morphometric and meristic characters, and initially subdivided specimens into four geographic areas: British Columbia, Southeast Alaska, Aleutian Islands, and Bering Sea. Morphometric characters (interorbital width, depth of caudal peduncle, length of barbel, length of first dorsal fin, and body depth at the pelvic and anal fins) showed no consistent clinal trends and did not serve to differentiate stocks of Pacific cod from British Columbia to the Bering Sea (Wilimovsky et al. 1967). However, meristic counts of dorsal and anal fin rays, left pectoral fin, gill rakers, and total vertebrae showed varying degrees of an irregular clinal trend that suggested separate stocks of Pacific cod in southern British Columbia, Southeast Alaska, and the Bering Sea (Wilimovsky et al. 1967). Wilimovsky et al. (1967) were unable to delimit the stocks precisely due to insufficient sample sizes.

Genetic Information

Pacific cod

Grant et al. (1987a) examined ocean-wide genetic variation at 40 allozyme loci (seven of which were polymorphic) in Pacific cod collected at 11 locations, ranging from Puget Sound to the Yellow Sea. Two genetically distinct groupings were revealed, a North American group (including the eastern Bering Sea, Aleutian Islands, Gulf of Alaska, Southeast Alaska, and Puget Sound) and a western north Pacific (Asian) group. Nei's genetic distance, D, between the North American and Asian groups was 0.025, and it was suggested that this level of differentiation reflects isolation of these two groups during coastal Pleistocene glaciation (Grant et al. 1987a). Among the North American samples, Nei's D averaged 0.0007 (± 0.0006) among pairs of North American samples. Nei's D for the two Asian samples, Yellow Sea and Sea of Japan, averaged 0.0041 (± 0.0026).

There was "a highly significant amount of allele-frequency heterogeneity between western (Asia) and eastern (North America including the Bering Sea) North Pacific samples"; however, comparisons of the amount of genetic heterogeneity between "regions" in the North American samples (Puget Sound/Gulf of Alaska compared to Bering Sea/Aleutian Islands) were not significant (Grant et al. 1987a). Comparisons of the amount of genetic heterogeneity between Gulf of Alaska and eastern North Pacific samples and between Bering Sea and Aleutian Islands samples were also not significant. At the population level, significant allele-frequency differences were detected between Yellow Sea and Sea of Japan Pacific cod at three loci, *GDA**, *ME2**, and *PEPA**; between Bering Sea samples for *ADA-2**; and among Gulf of Alaska samples for *PEPA**.

In summary, Grant et al. (1987a) stated that, in contrast to the two Asian samples, "there was virtually no regional genetic differentiation among North American stocks of Pacific cod." The small average genetic distance between samples (0.0007) and the small fraction of total gene diversity due to all sources of population subdivision serve to illustrate this lack of differentiation among North American stocks (Grant et al. 1987a). One factor that complicates the interpretation of this study is that all samples were collected outside of the spawning season and some samples have the potential to represent mixed populations (Grant et al. 1987a).

Gong et al. (1991) examined genetic variation for 21 polymorphic loci in Pacific cod sampled at various times and subsequently pooled (some collections occurred on spawning aggregations and others did not) from five localities; Yellow Sea, Sea of Japan off Korea, Sea of Japan off Hokkaido, Pacific Ocean off Hokkaido, and Bering Sea. Significant allele frequency differences were detected between all population pairs except for the comparison between Pacific cod on the Pacific and Sea of Japan coasts of Hokkaido (Gong et al. 1991). Two major clusters were revealed from this analysis corresponding to the Hokkaido/Bering Sea and the Yellow Sea/Korean coast of the Sea of Japan. Gong et al. (1991) stated that the large genetic distance (Roger's *D* of 0.020) between samples from the Yellow Sea and Sea of Japan indicate a divergence time between these populations of about 110,000 years ago. The Yellow Sea population is currently isolated from other Pacific cod populations by a high temperature barrier that exists in shallow waters around the southern tip of the Korean Peninsula (Zhang 1984).

Saitoh (1998) analyzed RAPD markers and haplotype diversity at the mtDNA control region using RFLP and SSCP techniques (see "Glossary" for description) in Pacific cod from the Bering Sea and 3 putative Japanese spawning sites; Noto-shima (Ishikawa Prefecture), Wakinosawa (Aomori Prefecture), and Joban (Fukushima Prefecture). Samples from the first two Japanese sites were of individuals extruding gametes when collected. The Joban and Bering Sea collections were of juveniles (possible descendants of spawning in nearby Sendai Bay) and adults, respectively (Saitoh 1998). The mtDNA analysis revealed low variability and no local differentiation among Japanese samples, but did show genetic divergence between Japanese coastal areas and the Bering Sea. Saitoh (1998) concluded that "this study gives no evidence for genetic identity among the Japanese localities analyzed."

Comparative genetic information for Atlantic cod

Although Atlantic cod spawn pelagic eggs, in contrast to the demersal eggs released by Pacific cod, the comparison of genetic population structure studies from Atlantic cod (with what little is known concerning population structure in Pacific cod) is thought to be informative due to these species' close systematic relationship and more comprehensive treatment Atlantic cod have received. Grant et al. (1999) recently reviewed studies of genetic variability in Atlantic cod. Surveys of genetic population structure of Atlantic cod across the North Atlantic using allozymes, mtDNA, and anonymous nuclear DNA loci showed differing results. Fine scale population structure in Atlantic cod has not been detected in allozyme (Mork et al. 1985) or mtDNA (Carr and Marshall 1991, Arnason and Rand 1992, Carr et al. 1995) studies. However, analyzes of nuclear DNA have revealed greater levels of genetic differentiation between regional populations (Pogson et al. 1995, Galvin et al. 1995). Analysis of microsatellite loci have revealed even finer scale population structure of Atlantic cod in the northwest Atlantic Ocean (Bentzen et al. 1996; Ruzzante et al. 1996, 1997, 1998). Bentzen et al. (1996) stated that rather than comprised of a "single, panmictic assemblage," northern cod "are composed of genetically distinguishable subunits, each of which appear to be geographically affiliated with spawning area."

Information Relevant to the Pacific Cod DPS Question

As stated in the previous "Approaches to the Species Question and to Determining Risk" section, four broad types of information were analyzed by the BRT in its determinations of whether Pacific cod in Puget Sound represent a "discrete" and "significant" population and therefore qualifies as a DPS under the ESA; habitat characteristics, phenotypic and life-history traits, mark-recapture studies, and analysis of neutral genetic markers. As such data can only be properly evaluated in relation to similar information for the biological species as a whole, Puget Sound Pacific cod data were compared with data from Pacific cod from throughout the species' range.

As detailed in the previous sections on "Environmental Features..." and "Phenetic and Genetic Information Relating to the Species Question," specific information for Puget Sound Pacific cod was available in the following categories; physical habitat, spawning time and location, migration patterns, tagging, parasite incidence, growth rate and body size, size and age at maturity, length frequency, fecundity, and very limited data on genetic population structure. Data on year-class strength, meristics and morphometrics, and local genetic population structure were largely unavailable for Pacific cod in Puget Sound. Specific information on Pacific cod in the Strait of Georgia was available for physical habitat, spawning time and location, migration patterns, tagging, parasite incidence, growth rate and body size, size and age at maturity, length frequency, and meristics and morphometrics. No data on year-class strength, fecundity, or genetic population structure were available for Strait of Georgia Pacific cod. Within the region from southwest Vancouver Island north to Dixon Entrance, specific information for Pacific cod was available on physical habitat, spawning time and location, migration patterns, tagging, parasite incidence, growth rate and body size, size and age at maturity, length frequency, fecundity, and meristics and morphometrics. No data on year-class strength or genetic population structure were available for Pacific cod in this region. Only very limited data on meristics and morphometrics and genetic population structure were available for Pacific cod in Southeast Alaska. The previous section on "Approaches to the Species Question and to Determining Risk" should be consulted for a general discussion of the relative usefulness of the various categories of data for DPS delineation. Issues of data quality are addressed for each category of biological data for Pacific cod in the preceding section on "Phenetic and Genetic Information Relating to the Species Question."

Discussion and Conclusions on Pacific Cod DPS Determinations

The BRT considered several possible DPS configurations for populations of Pacific cod in the northeastern Pacific Ocean in its attempt to identify a "discrete" and "significant" segment of the biological species that incorporates Puget Sound fish. It is the majority opinion of the BRT that Pacific cod from Puget Sound are part of a DPS that extends well beyond Puget Sound and north to at least Dixon Entrance, although many BRT members were unable to rule out the possibility that the northern boundary of the Pacific cod DPS occurs at the level of the Georgia Basin, or at the other extreme, Southeast Alaska. A high level of uncertainty concerning the northern boundary of the DPS was expressed in the decision-making process, and the BRT agreed that there is insufficient information available at present to identify DPSs of Pacific cod with any certainty. The BRT struggled with this decision and noted that the lack of suitable data to answer the DPS question for Pacific cod was a cause for concern.

The conclusion that the Pacific cod DPS is larger than Puget Sound was supported by the following considerations: 1) Genetic data that show a lack of significant heterogeneity among Pacific cod sampled, largely during summer and fall, at various locations in the northeastern Pacific Ocean (although it is possible that if collections had been of spawning fish the data might have shown greater population structure); 2) results of adult tagging studies in the Strait of Georgia and Puget Sound that show movement amongst inshore locations and some limited movement between inshore and coastal areas (although rare tagging studies on spawning fish do show some level of spawning site fidelity); and 3) the ecological similarity of fjord-type marine habitat in Puget Sound to habitats along the coasts of British Columbia and southern Alaska. In particular, the BRT noted that ecosystems where Pacific cod spawn north of the Georgia Basin are similar to Puget Sound and that the physical habitat is similar from Washington to Southeast Alaska. The BRT did not preclude the possibility that further information on the behavior, ecology, and genetic population structure of Pacific cod might provide a basis for delineating smaller DPSs.

The BRT examined several scenarios as to where the northern boundary for a Pacific cod DPS may occur, including: 1) the Georgia Basin, 2) the north end of Vancouver Island (encompassing the Georgia Basin and Amphitrite Bank spawning aggregations), 3) Dixon Entrance, and 4) Southeast Alaska (Fig. 2). Although many BRT members expressed some level of support for each of these scenarios, the BRT had the greatest overall support for scenarios 3 and 4. Therefore, the majority opinion of the BRT was that the northern boundary of the Pacific cod DPS extends at least as far north as Dixon Entrance. In addition, the BRT recognized that the DPS that includes Puget Sound Pacific cod may represent fish that are uniquely adapted to survive at the southern end of the species' range.

Within the area south of Dixon Entrance, Pacific cod encompass several geographically-discrete, current and historical spawning aggregations, including (but not necessarily limited to): Agate Passage, Port Townsend Bay, Port Gamble, Dalco Passage, and Bellingham Bay/Eliza Island in Puget Sound; Nanoose Bay, Hornby Island/Cape Lazo, and Swanson Channel in the Strait of Georgia; off southwest Vancouver Island; and in Hecate Strait (Figs. 2, 31, 32). Therefore, the BRT considered whether there is evidence for multiple populations or stocks of Pacific cod within this area and, perhaps, multiple DPSs within Puget Sound, Georgia Basin, or the area south of Dixon Entrance. Such evidence included: 1) the persistence of geographically and temporally discrete spawning aggregations of Pacific cod, 2) the Pacific cod reproductive traits of demersal spawning and adhesive eggs that would tend to concentrate eggs in the vicinity of the spawning grounds, 3) results of limited adult tagging studies indicating some degree of spawning site fidelity, and 4) demographic differences amongst Pacific cod sampled from discrete spawning locations. Although the BRT could not with any certainty identify multiple populations or DPSs of Pacific cod within the region south of Dixon Entrance, they acknowledged the possibility that significant structuring does exist within the proposed DPS and that such structure might be revealed by new information in the future.

Assessment of Extinction Risk

Population Status and Trends

Since the geographic extent of the DPS that includes Pacific cod in Puget Sound is uncertain, the BRT considered three potential areas, extending from Puget Sound to Southeast Alaska in their analysis of extinction risk for the DPS. Consequently, known information about the status of stocks in these areas is described in following sections and considered in determining extinction risk. The status of Pacific cod stocks beyond southeast Alaska were not considered in analyses of extinction risk.

Puget Sound

The assessment of the status of Pacific cod in Puget Sound is based primarily on trends in fishery statistics since 1970 (Palsson 1990, Palsson et al. 1997). In general, recreational and commercial fishing effort increased during the 1970s and stabilized during the 1980s. These fisheries are dependent on one or two age classes, based on length frequency data. Palsson (1990) reported that mean lengths estimated from biological samples collected since 1970 did not show long-term patterns. However, catches showed alternating periods of good catch years with periods of poor catch years. Six cycles have occurred since 1942, with a peak catch of 1,588 mt in 1980 (see Fig. 39). Catches fluctuated around a 900 mt level between the mid-1970s and mid-1980s (Fig. 39, Palsson 1990). Due to concerns for the status of Pacific cod, commercial fishing for Pacific cod was prohibited in Puget Sound south of Admiralty Inlet, in 1987. Catches then declined fairly steadily to low levels, about 13.6 mt in 1994 (Palsson et al. 1997).

The primary stock indicator for Puget Sound, north of Admiralty Inlet, was the catch rate from the commercial bottom trawl fishery (Palsson et al. 1997). Catch rates (Table 17) ranged between 42 and 73 kg/hour during the 1970s, stabilized at about 39 kg/hour until 1988, but then declined continuously to a low of 12 kg/hour by 1994. Trends in trawl effort (hours) were similar. Since 1994, unpublished data (W. Palsson[27]) indicate that catch rates in the bottom trawl fishery were somewhat higher than the low in 1994, ranging from 36 kg/hr in 1995 to 17.2 kg/hr in 1998 (Table 17). The primary stock indicator for Puget Sound south of Admiralty Inlet was the catch rate from the recreational fishery. Since the late 1970s, catch rates in the recreational fishery (Table 18) have declined fairly steadily from 0.6 Pacific cod/angler trip to less than 0.05 Pacific cod/angler trip following the 1989-1994 period (Palsson 1997). Unpublished data (W. Palsson[28]) indicate that the catch rate in the recreational fishery was less than 0.01 Pacific cod/angler trip every year during 1994-1998 (Table 18). Recreational catches estimated from the National Marine Recreational Fisheries Statistical Survey in Puget Sound were 2,430 and 920 Pacific cod in 1996 and 1997, respectively (WDFW 1998).

Bottom trawl surveys were conducted throughout Puget Sound in 1987, 1989, and 1991. Surveys covering various regions of Puget Sound were conducted in 1994, 1995, 1996, and 1997. Estimated biomass and numbers in the population vulnerable to the survey trawl, and average size of Pacific cod within each WDFW management region (see Fig. 14) are shown in Table 19

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[27] W. Palsson, WDFW, 16018 Mill Creek Blvd., Mill Creek, WA 98012-1296. Pers. commun. to C. Schmitt.

[28] W. Palsson, WDFW, 16018 Mill Creek Blvd., Mill Creek, WA 98012-1296. Pers. commun. to C. Schmitt.

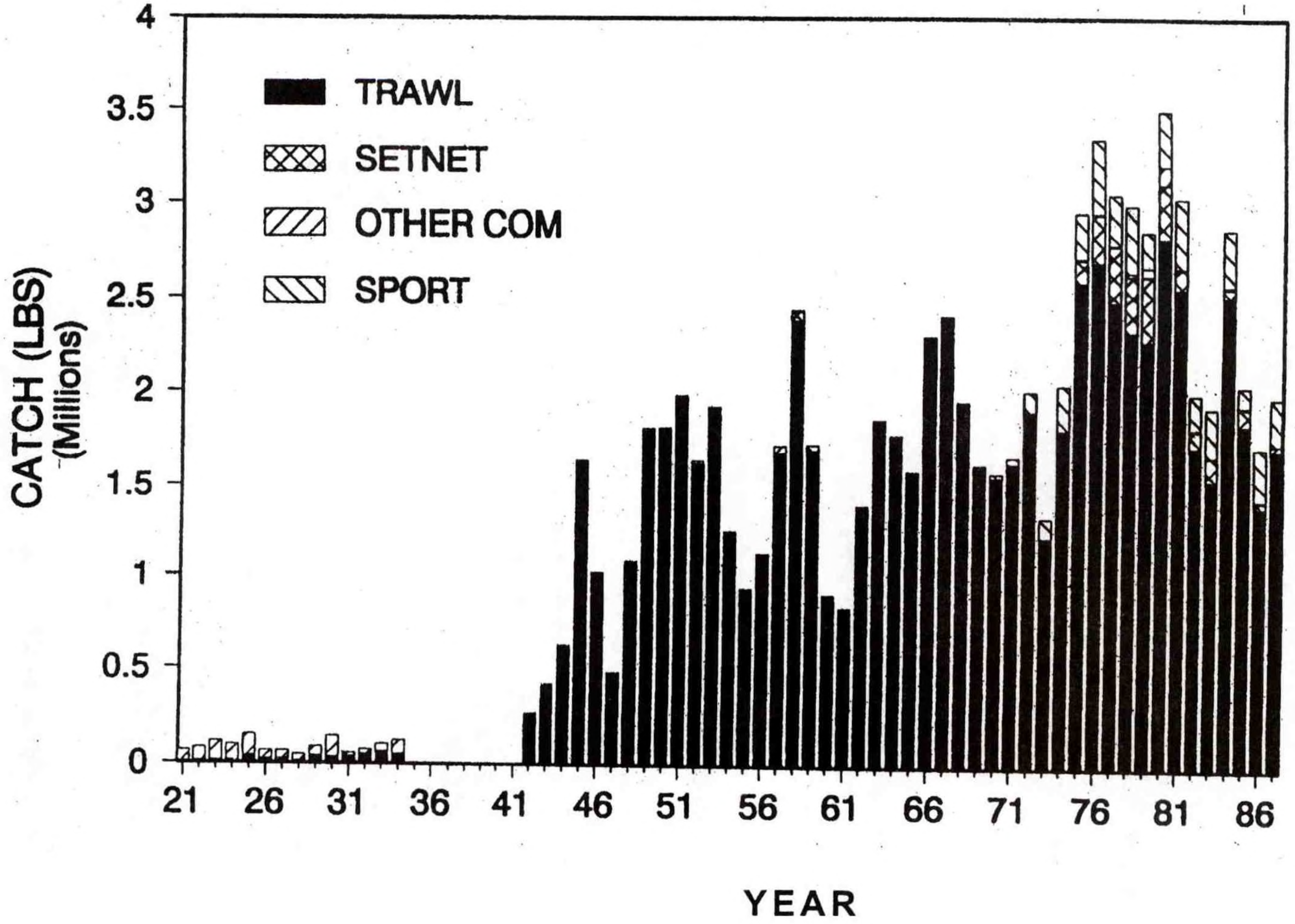

Figure 39. Historical Pacific cod catch in Puget Sound by trawl, set net, other commercial and recreational gear. Modified from Palsson (1990, figure 6).

(W. Palsson[29]). Estimates for biomass and numbers of fish in 1987 were much higher than in other years, but this may be due to other factors than a change in fish abundance. The 1987 survey was exploratory, being the first such survey ever conducted in Puget Sound. Also, the survey vessel used in 1987 was much larger than those used in subsequent years and the survey was conducted in the fall, whereas other surveys were presumably conducted in the spring. Otherwise, there is no apparent trend in the estimated abundance of Pacific cod in Puget Sound, both in number and weight, since the 1987 survey. In the three years when all management regions were surveyed, the estimated biomass of Pacific cod exceeded 2,500 mt and estimated numbers of Pacific cod exceeded 4.7 million fish each year (Table 19).

South Sound includes both Port Townsend Bay, where Pacific cod once supported bottom trawl and set net fisheries during the winter, and Agate Passage, where a popular sport fishery once harvested Pacific cod on their spawning grounds. The abundance of adult Pacific cod that aggregate on or near spawning grounds has declined, based on fishery statistics. Relatively intense fisheries for Pacific cod occurred in Port Townsend Bay and at Agate Passage during the winter spawning period in the 1970s and early 1980s (Palsson et al. 1997).

Pacific cod aggregate during the late winter to spawn demersal eggs in or near Agate Passage. This aggregation has supported a recreational fishery, which was monitored for Pacific cod catches and fishing effort during most years between 1977 and 1989 (Palsson 1990). Catch rates and estimated catches and effort fluctuated during this period (Table 20). The highest catch estimated in this fishery was 32,800 Pacific cod taken during 8,100 angler trips during 1981. Estimated catch and effort reached a low of 146 Pacific cod taken during 393 angler trips in 1989 (Palsson 1990). After 1989, catches and effort remained at low levels (W. Palsson[30]) and several restrictions were placed on recreational and commercial fisheries for Pacific cod in Puget Sound. The Agate Passage area was closed to Pacific cod fishing in 1991 due to concerns over the low numbers of Pacific cod. The daily bag limit in the recreational fishery for Pacific cod in other areas of Puget Sound south of Admiralty Inlet was reduced from fifteen fish to two fish in 1991 and to zero in 1997. In addition, the bottom trawl fishery near Port Townsend and Protection Island was closed during the winter to protect Pacific cod and other marine fish, beginning in 1991.

Pilot hydro-acoustic surveys were conducted in Agate Passage and nearby Port Madison and Port Orchard in 1987 before, during, and after the historic peak fishing period (Lemberg et al. 1988). Four surveys were conducted to determine the feasibility of assessing Pacific cod aggregations, the timing of the population increase and decrease, the distribution of fish schools,

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[29] W. Palsson, WDFW, 16018 Mill Creek Blvd., Mill Creek, WA 98012-1296. Pers. commun. to C. Schmitt.

[30] W. Palsson, WDFW, 16018 Mill Creek Blvd., Mill Creek, WA 98012-1296. Pers. commun. to C. Schmitt.

and to relate the results to concurrent recreational fishery monitoring. Fish targets and schools were observed in all three areas during most surveys; however, these fish could not be positively identified by species because fish were not collected during the surveys. The acoustic signals corresponded to typical signals for British, such as Pacific herring in the upper water column, and some relatively large individual targets and dense small schools along the bottom that may have been Pacific cod. More signals were observed in Port Orchard than in Agate Passage.

During the late 1990's, similar acoustic surveys were conducted for one night each year during the former peak fishing period in Agate Passage. No acoustic sign that could be interpreted as Pacific cod were observed in any of the surveys (W. Palsson[31]).

British Columbia

Within British Columbia, four stocks of Pacific cod are defined for management purposes: Strait of Georgia, west coast Vancouver Island, Queen Charlotte Sound, and Hecate Strait. Tagging studies indicate that there is very little movement of Pacific cod among areas (DFO 1999). Catches in each of these areas between 1955 and 1991 are given in (Table 21) (Westrheim 1996) and updated through 1999 (Table 22). The status of Pacific cod stocks in British Columbia has not been recently evaluated, except for Hecate Strait, where Pacific cod stocks are at low levels.

Pacific cod in Hecate Strait are fished mainly with trawls. Annual yields have varied between a high of 8,870 mt in 1987 to a low of 403 mt in 1996 (DFO 1999). The most recent assessment of Pacific cod in Hecate Strait indicates that stock biomass was at historically low levels in 1994-96 (Haist and Fournier 1998) and that there has been a slight increase in the past two years. Recruitment estimates are low, with the last nine year classes falling below the long-term average. The 1998 year class is the smallest ever. This is the longest run of below-average year-classes in the time series, which goes back to 1956. Projections for Pacific cod in Hecate Strait indicate that the stock will decline in the next two years (DFO 1999).

For the Strait of Georgia during 1955-91, catch, effort, and catch rates for Pacific cod in the commercial trawl fishery generally fluctuated without trend, except for a precipitous decline after 1988 (Westrheim 1996). During 1970-1991 when catch data were available for Puget Sound and the Strait of Georgia, catch patterns in the Strait of Georgia closely matched those in Puget Sound, as shown in Fig. 40A (Schmitt et al. 1994). In both areas, catches synchronously ranged between 500 and 1,000 mt during the early 1970s, then rose to about 1,500 mt per year during the late 1970s and early 1980s. After a peak in 1981, catches fell to less than 100 mt by 1991. Catches in the Strait of Georgia continued to decline, to zero by 1999 (Table 22).

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[31] W. Palsson, WDFW, 16018 Mill Creek Blvd., Mill Creek, WA 98012-1296. Pers. commun. to C. Schmitt.

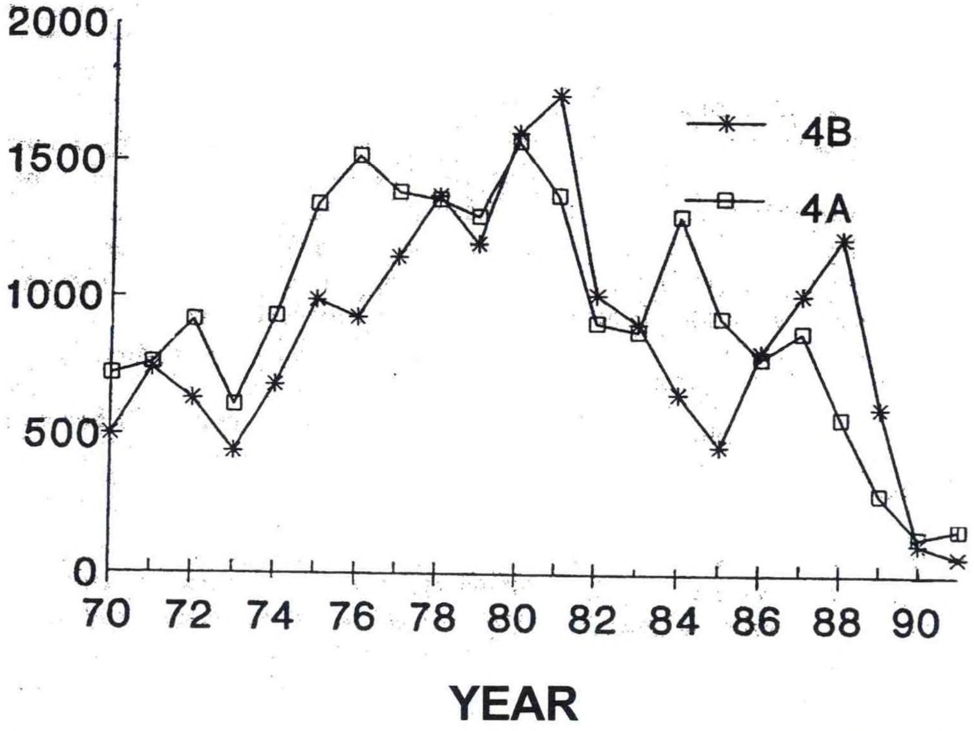

Figure 40A. Pacific cod catches (metric tons) from 1970 to 1991 in Area 4B (Strait of Georgia) and Area 4A (Puget Sound and U.S. portion of Strait of Georgia). Modified from Schmitt et al. (1994, their figure 4).

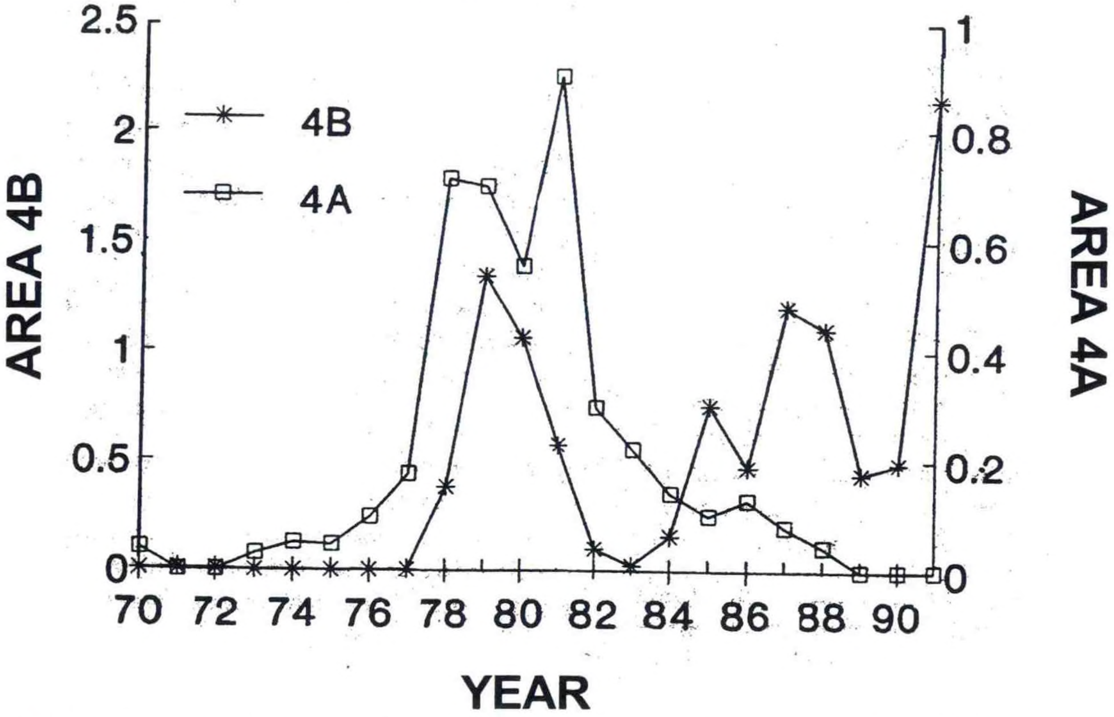

Figure 40B. Walleye pollock catches (thousands of metric tons) from 1970 to 1991 in Area 4B (Strait of Georgia) and Area 4A (Puget Sound and U.S. portion of Strait of Georgia). Modified from Schmitt et al. (1994, their figure 5).

Gulf of Alaska

Pacific cod in the Gulf of Alaska are of medium abundance and are fully exploited. The estimated spawning biomass of Pacific cod is 111,000 mt in 2000, down about 15% from the 1999 estimate (Thompson et al. 1999). The estimated biomass of age 3+ Pacific cod in the Gulf of Alaska is 567,000 mt, down about 13% from the previous year's estimate. However, estimated spawning biomass and age 3+ biomass in the late 1990s are about the same as they were during the late 1970s (Table 23). Estimates were about one-third larger during the mid-1980s (Thompson et al. 1999). The stock is projected to decline as a result of poor year-classes produced from 1990-1994. Preliminary indications of the 1995 year class suggest it may be above average (Witherell 1999).

Information on the status of Pacific cod in Southeast Alaska is limited. The assessment of Pacific cod for the Gulf of Alaska does not provide estimates of abundance, catches or catch rates for subareas within the Gulf. However, area-swept biomass estimates from triennial bottom trawl surveys during 1984-1999 indicate that the abundance of Pacific cod in Southeast Alaska fluctuated between 4,000 mt in 1984 to 11,000 mt in 1990. In 1999, the biomass of Pacific cod was near its highest level, about 10,000 mt, with a confidence interval of 4,000 to 16,000 mt. (M. Martin[32]).

The catch history for Pacific cod in inside waters of Southeast Alaska fluctuated generally without trend between 64 mt and 436 mt during 1987-1998 (Table 24). The catch in 1998 was 294 mt. (ADFG[33]).

West Coast of U.S.

Commercial landings of Pacific cod off the U.S. west coast peaked in 1988 at 3,343 mt and have steadily declined since that peak to an estimated 404 mt in 1998 (Table 25). The majority of these landings are reported from Washington State ports (PFMC 1999). The bulk of the large catches from 1987 to 1989 was composed of an exceptionally strong 1985 year class that was also present in the west Vancouver Island and Hecate Strait stocks (Dorn 1993). The stock off the U.S. west coast reportedly is more prone to recruitment failure than the northern stocks of Pacific cod, suggesting that the environmental conditions necessary for successful spawning and larval success occur infrequently in this area (Dorn 1993).

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[32] Michael Martin, NMFS, F/AKC2, 7600 Sandpoint Way NE, Seattle, WA 98115-6349. Pers. commun. to C. Schmitt.

[33] Alaska Department of Fish and Game. Pers. commun. to C. Schmitt.

Table 17. Fishery trends for Pacific cod in Northern Puget Sound (modified from Palsson et al. 1997). The commercial trawl catch includes fisheries in the Strait of Juan de Fuca. A new fishery targeted on Pacific cod of unknown origin began in the western Strait of Juan de Fuca in 1995. Data since 1994 courtesy of W. Palsson (WDFW, 16018 Mill Creek Blvd., Mill Creek, WA 98012-1296, pers. commun. to C. Schmitt). Dashes indicate data were not available.

Year	Trawl catch rate (kg/hr)	Sport catch rate (fish/trip)
1970	50.4	--
1971	63.3	--
1972	73.7	--
1973	45.4	--
1974	57.5	--
1975	66.9	--
1976	64.3	–
1977	54.9	0.29
1978	45.6	0.04
1979	42.1	0.41
1980	62.8	0.79
1981	47.7	0.50
1982	38.7	0.05
1983	40.2	0.29
1984	55.4	0.17
1985	40.5	0.18
1986	37.3	0.02
1987	41.5	0.16
1988	33.8	0.00
1989	24.0	0.02
1990	13.5	0.06
1991	14.7	0.01
1992	25.3	0.00
1993	23.0	0.00
1994	12.3	0.00
1995	36.1	0.00
1996	28.0	0.00
1997	22.0	0.00
1998	17.2	0.00

Table 18. Fishery trends for Pacific cod in Southern Puget Sound (modified from Palsson et al. 1997). The Pacific cod sport fishery in Southern Puget Sound was closed beginning in 1997. Data since 1994 courtesy of W. Palsson (WDFW, 16018 Mill Creek Blvd., Mill Creek, WA 98012-1296, pers. commun. to C. Schmitt). Dashes indicate data were not available.

Year	Trawl catch rate (kg/hr)	Sport catch rate (fish/trip)
1970	16.9	--
1971	30.4	--
1972	48.7	--
1973	38.3	--
1974	55.2	--
1975	61.8	--
1976	56.5	--
1977	43.2	0.78
1978	28.8	1.02
1979	12.6	0.42
1980	11.5	0.65
1981	27.5	0.57
1982	13.2	0.59
1983	9.8	0.34
1984	14.9	0.56
1985	9.6	0.28
1986	9.2	0.42
1987	12.3	0.30
1988	17.8	0.16
1989	8.0	0.08
1990	4.1	0.01
1991	9.7	0.02
1992	6.8	0.05
1993	3.0	0.00
1994	0.0	0.01
1995	--	0.00
1996	–	0.00
1997	--	--
1998	--	–

Table 19. Estimated biomass, number and size of Pacific cod in the Puget Sound population from WDFW trawl surveys (W. Palsson, WDFW, 16018 Mill Creek Blvd., Mill Creek, WA 98012-1296. Pers. commun. to W. Lenarz.). Dashes indicate data were not available.

Biomass (mt)

Year	Gulf-Bellingham	Strait of Juan de Fuca	North Sound	Hood Canal	Central Sound	South Sound	Southern areas combined
1987	147.73	1,599.87	1,747.60	26.33	1,049.93	201.83	1,278.09
1989	149.24	1,100.11	1,249.35	50.81	66.71	34.02	151.54
1991	20.04	245.21	3,192.18	0.00	32.37	11.11	42.48
1994	204.02	--	--	--	--	--	--
1995	--	--	--	--	252.25	--	--
1996	--	--	--	0.00	--	19.18	--
1995-1996	--	--	--	--	--	--	271.43
1997	263.11	--	--	--	--	--	--

Numbers (thousands of fish)

Year	Gulf-Bellingham	Strait of Juan de Fuca	North Sound	Hood Canal	Central Sound	South Sound	Southern areas combined
1987	95.40	1,462.49	1,557.89	45.66	1,378.48	187.02	1,611.16
1989	92.24	2,475.13	2,567.37	46.99	101.23	58.61	206.83
1991	30.79	287.78	7,349.95	0.00	30.50	16.37	46.87
1994	270.32	--	--	--	--	--	--
1995	--	--	--	--	209.42	--	--
1996	--	--	--	0.00	--	26.53	--
1995-1996	--	--	--	--	--	--	235.95
1997	332.32	--	--	--	--	--	--

Table 19. (Continued).

	Size (kg/ fish)						
Year	Gulf-Bellingham	Strait of Juan de Fuca	North Sound	Hood Canal	Central Sound	South Sound	Southern areas combined
1987	1.55	1.09	1.12	0.58	0.76	1.08	0.79
1989	1.62	0.44	0.49	1.08	0.66	0.58	0.73
1991	0.65	0.43	0.43	--	1.06	0.68	0.93
1994	0.75	--	--	--	--	--	--
1995	--	--	--	--	1.20	--	--
1996	--	--	--	--	--	0.72	--
1995-1996	--	--	--	--	--	--	1.15
1997	0.79	--	--	--	--	--	–

Table 20. Standardized results from Agate Passage fishery monitoring for Pacific cod. Modified from Palsson (1990). Dashes indicate data were not available.

Year	Catch per angler trip					Seasonal catch	Angler trips
	Peak weekday	Peak weekend	Non-peak day	Relative season	New season		
1977	5.9	2.1	5.5	5.2	--	8,900	2,300
1978	--	--	--	--	--	--	--
1979	7.5	1.1	4.1	4.6	--	--	--
1980	10.2	2.1	3.6	5.1	--	--	--
1981	8.6	3.4	3.1	4.6	--	32,800	8,100
1982	--	--	--	--	--	--	--
1983	--	--	--	--	--	--	--
1984	7.6	2.1	1.2	3.0	--	9,000	3,400
1985	5.1	0.0	1.2	2.1	--	--	--
1986	4.4	1.9	0.1	1.5	1.4	4,980	3,440
1987	8.6	4.3	0.4	3.0	2.2	11,194	5,202
1988	3.8	1.9	0.6	1.6	1.6	3,500	2,160
1989	0.3	0.3	0.0	0.1	0.4	146	393

Table 21. Canadian or Canada-U.S. annual nominal catch (t), equivalent nominal effort (h), and median CPUE (kg/h), by region, for Pacific cod in British Columbia waters, 1955-91 (modified from Table 7.3.1.2 in Westrheim (1996)). Dashes indicate data were unavailable.

	Strait of Georgia (4B)			West Vancouver Island (3Cn+3D)			Queen Charlotte Sound (5A+5B)			Hecate Strait (5C+5D)		
Year	Catch (t)	Effort (h)	CPUE (kg/h)	Catch (t)	Effort (h)	CPUE (kg/h)	Catch (t)	Effort (h)	CPUE (kg/h)	Catch (t)	Effort (h)	CPUE (kg/h)
1955	967	9,546	101	--	--	--	--	--	--	--	--	--
1956	578	5,050	114	1,468	7,012	209	1,753	6,001	292	--	--	--
1957	607	4,161	146	1,814	12,061	150	2,744	4,902	560	--	--	--
1958	650	5,277	123	850	4,827	176	1,178	4,682	252	--	--	--
1959	1,047	6,364	165	907	6,784	135	946	3,367	281	--	--	-
1960	744	5,652	132	635	7,099	89	618	2,988	207	--	--	-
1961	415	3,468	120	420	4,198	100	240	882	272	1,616	5,317	304
1962	479	4,870	98	633	5,815	109	422	1,389	304	1,690	6,440	262
1963	677	5,311	127	1,231	6,522	189	677	3,583	189	2,927	7,443	393
1964	713	7,529	95	1,221	5,813	210	1,275	3,059	417	5,228	8,022	651
1965	484	3,185	152	2,768	12,780	217	1,940	5,049	384	9,119	13,022	700
1966	297	2,798	106	3,136	12,212	257	1,811	3,545	511	9,519	12,635	753
1967	475	2,511	189	1,941	11,486	169	1,501	3,144	477	5,112	10,526	486
1968	349	3,974	88	1,425	14,261	100	960	3,043	315	5,165	11,378	454
1969	388	3,280	118	1,092	9,011	121	699	5,095	137	2,959	9,404	315
1970	502	4,089	123	1,095	8,838	124	299	1,467	204	1,339	4,518	296
1971	740	4,766	155	3,328	11,290	295	928	4,664	199	1,474	5,241	281

Table 21. (Continued).

Year	Strait of Georgia (4B) Catch (t)	Effort (h)	CPUE (kg/h)	West Vancouver Island (3Cn+3D) Catch (t)	Effort (h)	CPUE (kg/h)	Queen Charlotte Sound (5A+5B) Catch (t)	Effort (h)	CPUE (kg/h)	Hecate Strait (5C+5D) Catch (t)	Effort (h)	CPUE (kg/h)
1972	630	3,504	180	5,629	18,136	310	2,320	8,382	277	2,694	6,160	437
1973	441	2,453	180	3,712	15,883	234	1,914	6,289	304	4,003	6,608	606
1974	681	3,305	206	3,474	13,481	258	2,292	7,518	305	4,764	6,195	769
1975	991	5,165	192	4,000	16,901	237	2,444	6,682	366	4,982	6,020	552
1976	927	3,966	234	3,797	23,277	163	2,271	7,040	323	5,016	11,578	433
1977	1,148	5,183	221	2,948	16,047	184	1,268	5,198	244	3,523	9,293	379
1978	1,373	5,656	243	1,998	10,198	196	1,959	5,430	361	2,102	6,388	329
1979	1,192	3,939	304	1,861	6,690	278	1,904	5,167	368	4,695	10,671	440
1980	1,606	7,143	225	1,152	7,732	149	1,335	4,440	301	4,540	12,998	349
1981	1,742	7,110	245	918	4,999	184	858	2,721	315	3,182	10,157	313
1982	1,011	3,882	260	1,123	7,000	160	603	2,525	239	2,077	5,735	362
1983	907	4,106	221	694	4,745	146	183	783	234	2,717	6,598	412
1984	652	4,103	159	675	3,759	180	382	2,045	187	1,748	5,096	343
1985	463	1,661	279	493	2,432	203	299	1,619	185	1,064	4,162	256
1986	803	4,116	195	498	2,524	197	241	1,110	217	2,099	4,039	520
1987	1,015	4,768	213	809	6,187	131	3,242	7,173	452	8,870	9,801	905
1988	1,223	4,585	267	1,807	11,162	162	1,849	4,749	389	6,198	9,751	636
1989	604	3,055	198	2,994	20,588	145	765	2,488	307	4,789	9,103	526
1990	114	906	126	1,955	12,592	155	773	3,420	226	3,611	8,264	437
1991	68	481	141	2,188	21,239	103	2,008	7,016	286	7,920	20,662	383
Mean	749	4,349	174	1,852	10,154	178	1,303	4,129	302	4,088	8,588	461

Table 22. Annual landings (metric tons) of Pacific cod in British Columbia waters by major area, 1992-99 (J. Fargo, DFO, Pacific Biological Station, Nanaimo, British Columbia, Canada. Pers. commun. to C. Schmitt.).

Year	Strait of Georgia (4B)	West Vancouver Island (3Cn+3D)	Queen Charlotte Sound (5A+5B)	Hecate Strait (5C+5D)
1992	412	2,773	2,773	5,103
1993	158	2,527	2,527	3,965
1994	90	1,211	1,211	1,562
1995	24	653	653	1,325
1996	3	78	142	360
1997	6	81	129	1,147
1998	5	112	117	1,004
1999	0	55	84	564

Table 23. Time series of estimates for Pacific cod age 3+ biomass, spawning biomass, and survey biomass (in 1000's of mt) in the Gulf of Alaska (Modified from Thompson et al. (1999)). Dashes indicate data were not available.

Year	Age 3+ biomass	Spawning biomass	Survey biomass
1978	610	123	--
1979	653	140	--
1980	799	151	--
1981	840	158	--
1982	888	170	--
1983	929	184	--
1984	940	200	543
1985	938	210	--
1986	929	218	--
1987	958	220	504
1988	955	218	--
1989	931	216	--
1990	938	207	489
1991	894	192	--
1992	883	179	--
1993	854	172	474
1994	830	172	--
1995	795	171	--
1996	734	164	381
1997	675	151	--
1998	645	134	--
1999	611	128	381

Table 24. Pacific cod harvest (mt), and effort (permits), in inside waters of Southeast Alaska, (NSEI and SSEI subdistricts), 1987 - September 1998 (Source: Alaska Department of Fish and Game [ADFG], pers. commun. to C. Schmitt. Refer to footnote 33, page 144).

Year	Harvest	Permits
1985	64.6	61
1986	153.4	123
1987	354.6	259
1988	237.3	278
1989	172.4	318
1990	140.6	338
1991	267.4	322
1992	402.1	377
1993	436.7	319
1994	182.6	220
1995	153.9	237
1996	290.1	281
1997	353.2	298
1998	294.0	301
1999 (1/1-9/30)	284.7	307

Table 25. Estimated commercial landings (mt) of Pacific cod off the U.S. west coast, 1983-1998. Modified from PFMC (1999).

Year	Landings
1983	597
1984	585
1985	409
1986	331
1987	2,280
1988	3,343
1989	2,188
1990	1,064
1991	1,795
1992	1,778
1993	1,369
1994	866
1995	504
1996	445
1997	595
1998	404

Table 26. Total annual production (releases) of yearling chinook in Puget Sound (WDFW hatchery data, 1970-1996, from Jim West, WDFW, pers. commun. to C. Schmitt) (Pacific States Marine Fisheries Commission (PSMFC). Electronic data submission from the Regional Mark Processing Center, Pacific States Marine Fisheries Commission, 1995. (contact Ken Johnson, PSMFC, (503) 650-5400, data available online at http://www.streamnet.org/online_data.html).

Release year	Brood year	Number Released by WDFW hatcheries	Number released as recorded by PSMFC
1970	1968	309,410	309,410
1971	1969	154,144	154,144
1972	1970	308,586	299,545
1973	1971	1,433,176	1,101,794
1974	1972	2,431,663	3,881,112
1975	1973	2,828,795	4,322,118
1976	1974	3,425,036	3,907,155
1977	1975	3,814,445	3,840,381
1978	1976	3,771,348	4,197,545
1979	1977	4,780,178	4,837,258
1980	1978	4,896,991	5,329,803
1981	1979	4,706,793	5,166,103
1982	1980	4,557,862	3,192,183
1983	1981	2,861,975	2,467,792
1984	1982	3,254,478	2,907,968
1985	1983	2,891,611	3,025,263
1986	1984	3,888,587	3,313,942
1987	1985	2,134,195	1,723,479
1988	1986	2,907,101	2,422,347
1989	1987	3,411,504	2,936,828
1990	1988	3,931,137	3,429,537
1991	1989	3,449,795	3,351,810
1992	1990	3,652,264	3,564,959
1993	1991	3,591,670	3,348,496
1994	1992	3,510,903	3,032,219
1995	1993	2,473,324	2,573,909
1996	1994	3,874,724	3,248,906
1997	1995	--	4,605,054
1998	1996	--	3,462,491

Summary and Conclusions of Pacific Cod Risk Assessment

Quantitative information on the abundance of Pacific cod stocks and on potential factors affecting their abundances is limited, and members of the BRT expressed considerable uncertainty in assessing extinction risks. Members of the BRT identified several concerns, especially about the status of Puget Sound stocks. The apparent loss of the major known spawning locations (Port Townsend Bay and Agate Passage) in Puget Sound is a serious concern. However, fisheries reductions and closures in Puget Sound to protect Pacific cod may have limited opportunities to detect spawning if it occurs in other locations. Also, given the general synchronicity of the changes in apparent Pacific cod abundance from Puget Sound to Southeast Alaska, some BRT members are concerned that factors affecting the decline of the Puget Sound stocks will similarly affect the stocks in British Columbia and Southeast Alaska in the near future. In contrast, some members of the BRT considered the declines in apparent abundance of Pacific cod in Puget Sound and along the west coast as a natural phenomenon, possibly not uncommon over the geologic history for this species. Pacific cod in these areas are at the southern extreme of their range and the current decline in abundance may represent a relatively temporary shrinkage of their range in response to unfavorable environmental conditions.

Data were insufficient to conduct quantitative analyses of the extinction risks for Pacific cod. However, Palsson (1990) discussed potential factors contributing to the decline of Pacific cod in Puget Sound through the 1980s. He concluded that the decrease in stock abundance corresponded to a change to a warmer oceanographic regime, an increase in the abundance of pinnipeds, and an increase in fishing effort. Pacific cod populations in Puget Sound have remained low, although fishing effort for Pacific cod dropped substantially during the 1980s and has been at extremely low levels during the 1990s. Dorn (1993) and Westrheim (1996) also suggested that a warmer oceanographic regime may have unfavorable effects on Pacific cod south of Alaska. In addition to those factors, West (1997) also considered the loss or degradation of nearshore nursery habitats as a factor which may decrease survival of juveniles. As noted earlier, small juveniles usually settle into intertidal/subtidal habitats, commonly associated with sand and eel grass, and the areal extent and quality of such habitats have declined in Puget Sound.

In the limited studies of the diets of pinnipeds in Puget Sound, Pacific cod have not been major components of the diet (Schmitt et al. 1995) and the extinction risks of pinniped predation for Pacific cod have not been evaluated quantitatively. Furthermore, predation by fish has not been examined in Puget Sound. For example, increased releases of yearling chinook salmon from state hatcheries coincided with changes in Pacific cod abundance. Releases of yearling chinook salmon increased more than ten-fold during the 1970s and stabilized at two to four million released each year during the 1980s. In limited diet studies of chinook salmon in Puget Sound, unidentified marine fish larvae were reported (Buckley 1999). Therefore, it is not known if yearling chinook salmon releases have an adverse effect on the abundance of Pacific cod. Changes in the abundance of other fish species and their potential effects on Pacific cod populations in Puget Sound, or a larger hypothetical DPS, are poorly known. West (1997) suggested that declines in the abundance of two primary prey species, Pacific herring and walleye pollock, may have contributed to the decline of Pacific cod in Puget Sound. The effects of contaminants or toxins from phytoplankton blooms ("red tides") on Pacific cod abundance have also not been evaluated. Overall, it is uncertain which factors, either singly or in combination, may be significantly contributing to the current low stock sizes of Pacific cod.

Given the uncertainty about the northern boundary for the Pacific cod DPS that includes Puget Sound, the BRT considered and assessed extinction risks for three different DPS scenarios: 1) Georgia Basin; 2) Puget Sound through Dixon Entrance; and 3) Puget Sound through Southeast Alaska. As with the DPS considerations for Pacific cod, the BRT struggled with the assessment of extinction risks. In general, the BRT considered the risks of extinction to diminish as the size of the population segment under discussion grew to encompass more spawning locations and greater numbers of Pacific cod.

The majority of the BRT concluded that Pacific cod encompassed by DPS scenarios 2 (Puget Sound to Dixon Entrance) and 3 (Puget Sound through Southeast Alaska) are not in danger of extinction, nor are they likely to become so in the foreseeable future. A minority of the BRT felt that Pacific cod within either DPS scenario 2 or 3, although not presently in danger of extinction, are likely to become so in the foreseeable future. In fact, most BRT members could not rule out the possibility that Pacific cod in DPS scenario 2 (Puget Sound to Dixon Entrance) are likely to become endangered in the foreseeable future.

The BRT was divided on the extinction risk status of Pacific cod encompassed by scenario 1 (Georgia Basin). Although the BRT agreed that Pacific cod in the Georgia Basin DPS scenario are not presently in danger of extinction, the BRT was nearly equally divided on the question of whether Pacific cod in this population segment are likely to become endangered in the foreseeable future if present trends continue. As a whole, the BRT gave slightly higher support to placing Pacific cod in this population segment in the category of not in danger of extinction, nor likely to become so in the foreseeable future.

WALLEYE POLLOCK

General Biology

Geographical distribution

Walleye pollock are found in the waters of the Northeastern Pacific Ocean from the Sea of Japan, north to the Sea of Okhotsk, east in the Bering Sea and Gulf of Alaska, and south in the Northwestern Pacific Ocean along the Canadian and U.S. west coast to Carmel, California (Fig. 41) (Phillips 1942, 1943; Hart 1973; Bailey et al. 1999). Currents, eddies, and meso-scale physical structures along a coast influence the distribution of early life-history stages. The distributions of later life-history stages of walleye pollock appear to be influenced by temperature, light, and prey abundance, variables that may change in an area from year to year (Bailey 1989; Swartzman et al. 1994; Olla et al. 1996; Sogard and Olla, 1996a, b; Brodeur et al. 1997).

Adult walleye pollock are generally a semi-demersal species that inhabit the continental shelf and slope (Saunders et al. 1989). Moreover, various life history stages are capable of inhabiting nearshore areas, large estuaries (such as Puget Sound), coastal embayments, and open ocean basins, such as the Aleutian Basin of the Bering Sea (Bailey et al. 1999). The primary densities of numerous populations are in the North Pacific Ocean, including the northern Gulf of Alaska, Bering Sea, and the Sea of Okhotsk, suggesting that walleye pollock populations in Puget Sound are relatively isolated and distant (Fig. 42, Table 27) (Bailey et al. 1999, Bakkala et al. 1986). Adults occur as deep as 366 m (Hart 1973), but the vast majority occur between 100 and 300 m. Spawning takes place at depths of from 50 to 300 m (Garrison and Miller 1982, Bailey et al. 1999). Eggs are pelagic and are found throughout the water column (Bailey et al. 1999, Kanamaru et al. 1979). Larvae and small juveniles are pelagic, and are generally found in the upper water column to depths of 60 m (Garrison and Miller 1982, Bailey et al. 1999). Postlarvae and small juveniles occupy a wider depth range, generally with diel movements which involve rising to the surface at night to feed and sinking down in schools during the day (Garrison and Miller 1982, Merati and Brodeur 1996). Juvenile pollock have been found in a variety of habitat types, including eelgrass (over sand and mud), gravel and cobble (Miller et al. 1976); however, because of their pelagic mode, they are not thought to consistently associate with many types of substrates (Matthews 1987).

Information about the bathymetric distribution of Puget Sound walleye pollock was reported by Quinnell and Schmitt (1991). In a resource survey conducted in Puget Sound in 1987, they collected walleye pollock from four depth strata: 10-40 m, 41-80 m, 81-120 m, and > 120 m. The largest numbers of walleye pollock were collected at 41-80 m (43%) and > 120 m (41%). A gradual increase in mean length was observed between these two depth ranges, with walleye pollock from 41-80 m having a mean of 11 cm, those from 81-120 m have a mean of 13 cm, and those from > 120 m having a mean of 17 cm. This progression suggests that the tendency for juvenile walleye pollock to move into deeper waters with age, as has been reported in coastal walleye pollock populations, also occurs in Puget Sound.

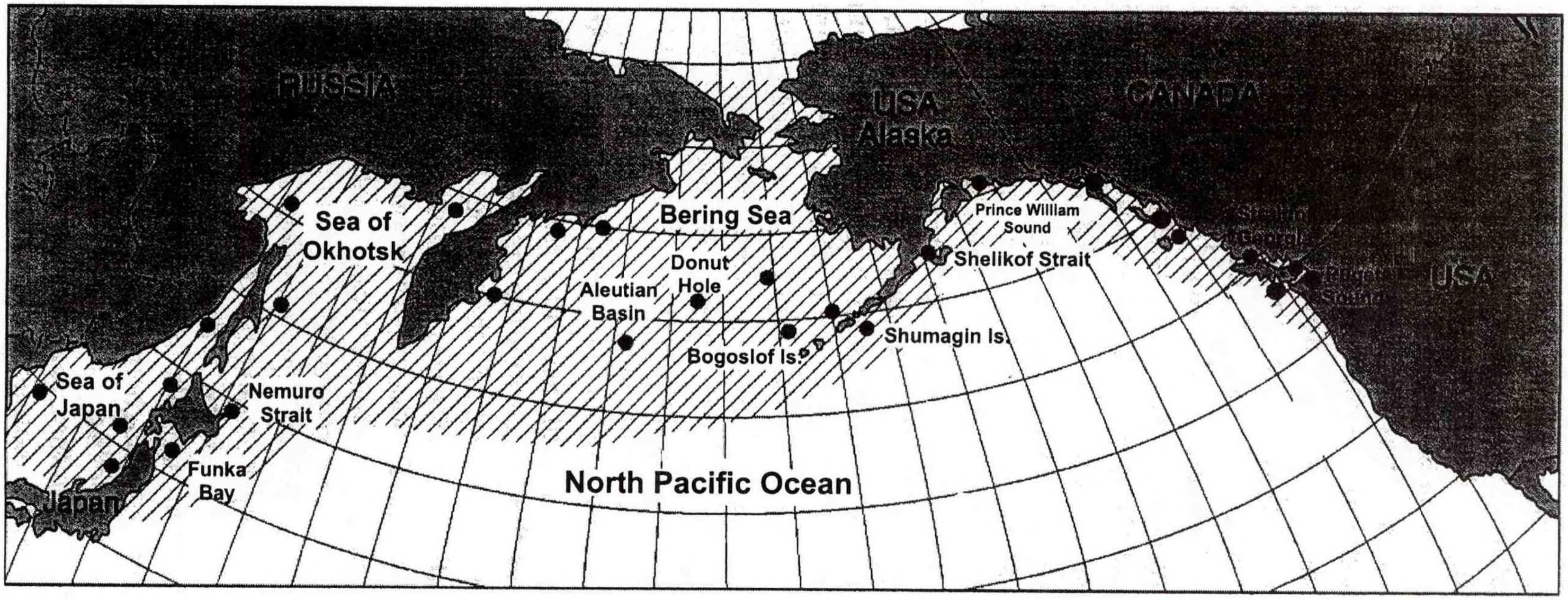

Figure 41. Geographic distribution (cross hatching) and major known spawning locations (●) of walleye pollock. Modified from Bailey et al. (1999, their fig. 1).

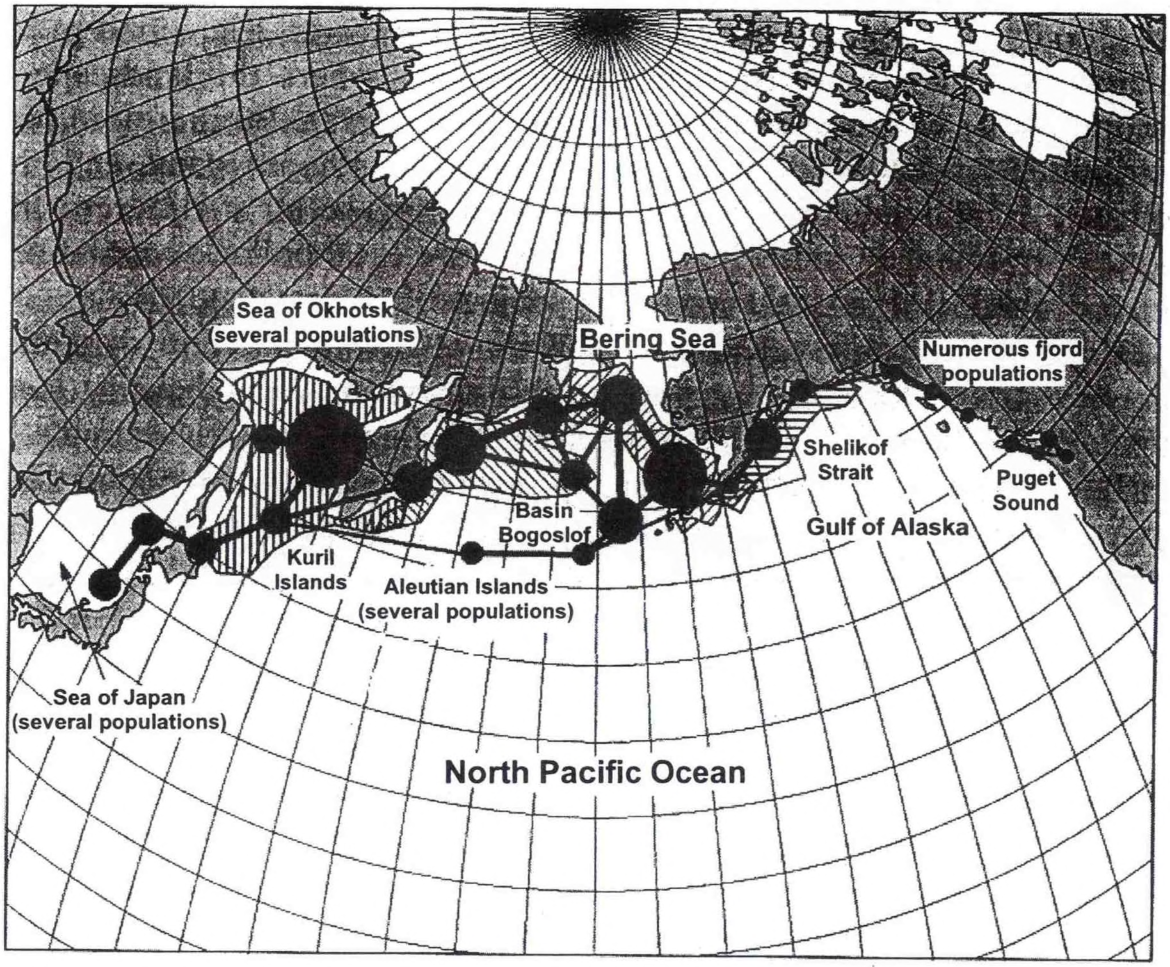

Figure 42. Hypothetical model of the population structure of walleye pollock. Filled circles represent spawning populations scaled to approximate abundance. Hatched regions represent the proposed distributions of several major populations (Okhotsk, east Bering, west Bering, Shelikof) during the feeding season, indicating overlap. Lines show some of the potential connections among populations scaled to relative gene flow through migration or larval transport. Modified from Bailey et al. (1999, their fig. 16).

Table 27. Commercial catches of walleye pollock in metric tons by region of the northeast Pacific Ocean for selected years (Modified from Bakkala et al. 1986).

Region/ Year	Aleutian Islands region	Eastern Bering Sea	Gulf of Alaska	British Columbia	Washington State
1970	179	1,256,565	9,343	65	34
1972	1,442	1,874,534	34,001	269	2
1974	22,661	1,588,390	61,880	84	40
1976	4,290	1,177,822	86,527	1,357	19
1978	6,282	979,454	96,842	2,641	603
1980	58,156	958,359	114,670	4,109	402
1982	57,754	956,030	168,787	1,006	91

Migration

Walleye pollock are not considered to be a migratory species, but prespawning adults do make relatively short migrations to regional spawning grounds (Muigwa 1989). These grounds are generally in sea valleys, canyons, indentations in the outer margin of the continental shelf, or in fjords, such as Puget Sound (Bailey et al. 1999). A variety of biological and environmental factors, including hydrographic fronts, temperature, light intensity, prey availability, and depth determine the distribution of juvenile and adult walleye pollock. This species is considered by some to be an opportunistic colonizer, able to take advantage of ecological niches by rapid growth, early maturity, and high fecundity (Bailey et al. 1999).

Larvae tend to aggregate in patches under the influence of currents, geographical formations, and availability of prey. Juveniles form schools, and move in to deeper water with growth. Adults and juveniles continue to practice the above-mentioned diel vertical migrations (Bailey et al. 1999).

Reproduction and development

Walleye pollock are oviparous and have external fertilization (NOAA 1990). During spawning, walleye pollock apparently pair and spawn after a complex courtship (Sakurai 1982, Baird and Olla 1991). Females spawn several batches of eggs over a short period of time (multiple-batch spawning) (Sakurai 1982, Hinckley 1987). Eggs are usually spawned in deep water and remain at 100-400 m at most spawning localities (Kendall et al. 1994), but can also be spawned in shallower waters in coastal bays. Walleye pollock eggs are pelagic, colorless, spherical and transparent. Incubation times for artificially fertilized eggs held at temperatures ranging from 6-10°C ranged from 10 to14 days, and the hatching success ranged from 0.3-80%. However, at 2°C, the incubation time was 24 to 27 days and hatching success was 83-94% (Table 28) (Garrison and Miller 1982). Fertilized eggs from walleye pollock captured near British Columbia were 1.35-1.45 mm in diameter (Hart 1973); however, walleye pollock from the Bering Sea possessed larger eggs (1.48-1.66 mm) (Serobaba 1968). Larvae are about 3.5-4.5 mm in length at hatching, with a yolk sac that is absorbed in about 11-21 days at 6-7°C, depending upon the availability of prey. Larvae metamorphose at about 25 mm (Dunn and Matarese 1987).

Early-stage larvae grow about 0.10-0.20 mm per day (Nishimura and Yamada 1984, Kendall et al. 1987, Bailey et al. 1996), and metamorphose into juveniles at a length of about 18 mm (Bailey 1989, Grover 1990, Merati and Brodeur 1996). In the first year, juveniles grow about 1 mm per day, reaching 80-100 mm in length in six months and 120-140 mm by the end of the first year. In western Gulf of Alaska waters, males have been reported to be sexually mature at age-3 and at a length of 29-32 cm; similarly, 3-year-old females (30-35 cm) were sexually mature (Garrison and Miller 1982). The growth rates of juvenile and adult walleye pollock in the Georgia Basin appears to be retarded compared to walleye pollock from coastal waters. In a study reported by Saunders et al. (1989), they found that male walleye pollock from coastal waters off of British Columbia reached a maximum length of approximately 50 cm by age-7, whereas male walleye pollock from the Strait of Georgia reached a maximum length of 40 cm by age-5. Female walleye pollock from these areas showed a similar trend, but their maximum length was a few cm longer.

Table 28. Incubation times and hatching success of walleye pollock eggs incubated at various temperatures. Data from Hamai et al. (1971).

Temperature (°C)	Incubation time (days)	Survival (%)
10	10	0.3-32
6	13.8-14.4	72-83
2	24.5-27.4	83-94

Trophic interactions

Early-stage walleye pollock larvae feed chiefly on copepod nauplii (Nakatani 1988, Canino et al. 1991) and juveniles mostly prey on euphausiids, copepods, decapod larvae, and larvaceans (Grover 1990, Merati and Brodeur 1996, Brodeur 1998, Bailey et al. 1999). Adults are carnivorous, and feed primarily on euphausiids, small fishes, copepods, and amphipods (Bailey et al. 1999). Walleye pollock tend to be opportunistic feeders preying on whatever food organisms are available. For example, Bering Sea juvenile and adult walleye pollock generally feed on fish in the winter; euphausiids in the spring; and a wide variety of prey in the summer and fall, including copepods, euphausiids, and fish (Dwyer et al. 1986). In some areas, cannibalism can be an important source of food for the adult population (Dwyer et al. 1987; Livingston 1989, 1993). Up to 80% of the average stomach contents of adult walleye pollock in autumn and winter can consist of age-0 juvenile walleye pollock.

Predators of walleye pollock eggs and larvae include a variety of invertebrates, such as euphausiids and amphipods, and small fishes (Bailey et al. 1999). Juvenile walleye pollock are preyed upon by a number of seabirds (e.g., kittiwakes [*Rissa* spp.] and common murre [*Uria aalge*]) and marine mammals, including harbor seals (*Phoca vitulina*) (Bailey et al. 1999, Hunt et al. 1996, Lowry et al. 1996). Studies conducted in the Gulf of Alaska showed that walleye pollock, including adults, was the most important prey for harbor seals (Lowry et al. 1996).

Size and age distributions

Quinnell and Schmitt (1991) presented information about the length distributions of walleye pollock from Puget Sound. The mean length of walleye pollock collected in North Puget Sound was approximately 14 cm, suggesting they were largely young-of-the-year (Table 29). The mean length of walleye pollock from the Main Basin was 20 cm. Although the catch-per-unit effort for walleye pollock was quite low (0.32) in Hood Canal, fish from this region were among the largest, with a mean length of 28 cm. Of particular interest were walleye pollock collected in South Puget Sound, where the CPUE was also low (1.22), and mean length was 16 cm. This small size suggests the presence of a spawning population in or near South Puget Sound. The authors also presented length/frequency data (Fig. 43) which supported the above observations; the length distribution was bimodal, with most of walleye pollock being 9 to 14 cm, and a small number being 25 to 28 cm.

Similar regional differences in the distribution of age classes of walleye pollock have been reported in the Bering Sea (Dawson 1989). Three regions were investigated: the Eastern Bering along the shelf, an area just north of the Aleutian Islands, and the Aleutian Basin (also known as the "donut hole" located near the center of the Bering Sea). Walleye pollock from the Eastern Bering Sea were youngest (mean age 4.5 years), intermediate ages were found near the Aleutians (mean age 6.7 years), and older ages were observed in the Basin (mean age 8.9 years). In fact, very few 0- to 4-year-old walleye pollock were collected in the Basin. The author hypothesized that the Basin is a major spawning ground, and that eggs and larvae are transported by currents to the East Bering Sea shelf, which serves as a nursery area, a distance of 300 to 400 miles.

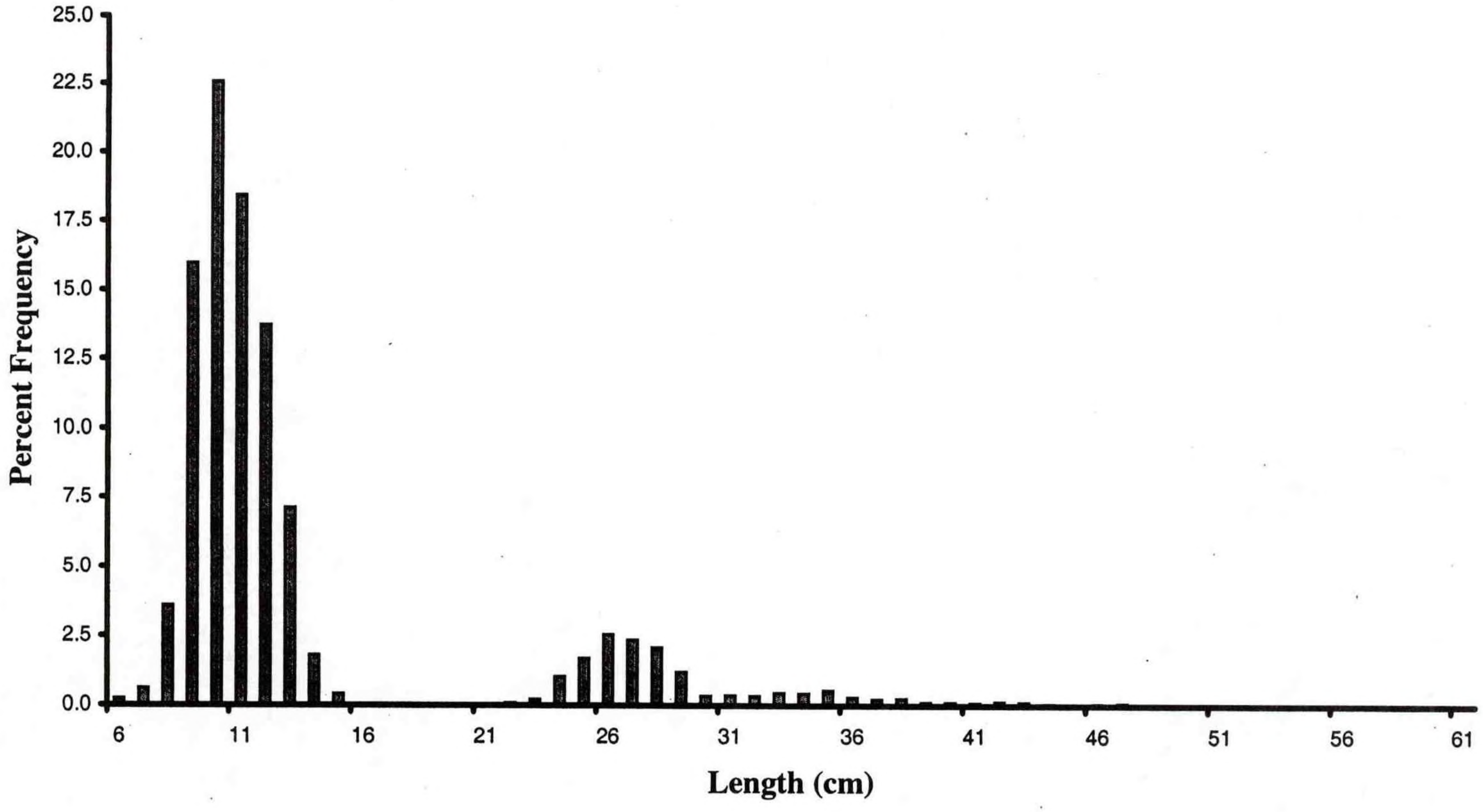

Figure 43. Proportion at length of Puget Sound walleye pollock in 1987 research trawl survey. Modified after Quinnell and Schmitt (1991, fig. 1).

Table 29. Estimated body size of walleye pollock sampled during research trawling in major regions of Puget Sound in 1987 (from Quinnell and Schmitt 1991).

	No. of tows	No. of tows with catch	Mean length (cm)	No. of fish measured
Gulf of Bellingham	11	10	13	2,334
Strait of Juan de Fuca	30	25	14	4,976
Hood Canal	7	4	28	8
Central Puget Sound	28	20	20	569
South Puget Sound	17	8	16	92

Phenetic and Genetic Information Relating to the Species Question

Phenetic and genetic information examined for evidence of DPS delineations of walleye pollock included presence of geographically-discrete and temporally-persistent spawning aggregations, stock structure, tagging studies, and variation in seasonal migrations, parasite incidence, growth rate and body size, length and age at maturity, length frequency, fecundity, meristics and morphometrics, and genetic population structure.

Life History Information

Pre-historical and historical persistence in Puget Sound

Tunnicliffe et al. (in press) examined fish remains in a complete Holocene sediment core sequence from Saanich Inlet, Vancouver Island, British Columbia. Walleye pollock first appear in the sediment record of Saanich Inlet around 6,000 BP (Tunnicliffe et al. in press). Fish abundance and species diversity peaked in Saanich Inlet between 7,500 and 6,000 BP, and the last 1,000 years have seen some of the lowest abundances of fishes in Saanich Inlet's marine history (Tunnicliffe et al. in press). The close proximity of Saanich Inlet to Puget Sound would suggest that walleye pollock were also likely established in Puget Sound by approximately 6,000 BP.

Walleye pollock were identified in prehistoric fish skeletal remains from the Duwamish No. 1 archeological site (45-KI-23), located 3.8 km upstream from Elliott Bay on the Duwamish River, utilized by aboriginal humans between A.D. 15 and A.D. 1654 (Butler 1987). Gadiforms were present throughout the occupational history of this site, and were third and fourth in rank order of taxonomic abundance in two separate studies of fish bones performed at this site (following Salmonidae, Pleuronectiformes, and in one case Squalidae) (Butler 1987). Conversely, archaeological investigations of the West Point site on the north side of Discovery Park in Seattle (utilized by hunter-fisher-gatherers between 4,250 and 200 BP) found few remains of gadiforms, although some Pacific cod bones were identified at this site (Wigen 1995). Wigen (1995) postulated that differences in the frequency of gadiform remains found between the Duwamish and West Point sites may be related to the possible use of fish traps at West Point versus hook and line methods at the Duwamish site, or perhaps to differences in the season of human occupation between the two sites. Walleye pollock remains were also reported from the early component of the Bear Cove archaeological site on northeastern Vancouver Island that was occupied 6,500 to 5,000 years ago (Carlson 1979, Hebda and Frederick 1990). In historic times, Jordan and Starks (1895) reported that walleye pollock were "occasionally taken" in Puget Sound.

Spawning location and spawn timing

Bailey et al. (1997, 1999) illustrated major spawning locations throughout the range of walleye pollock. Figure 41 is a modified version of these spawning location maps. Table A-6 summarizes available data on spawn timing in various locations for walleye pollock. Bailey et al. (1999) stated that:

> Most pollock populations spawn at predictable times, in the late winter and early spring, in the same locations year after year, usually in sea valleys, canyons, or indentations in the outer margin of the continental shelf. They are also known to spawn in fjords or deep-water bays (such as Puget Sound) and in some deep-water locations over the Aleutian Basin.

Puget Sound–Puget Sound is near the southern limit of the range of walleye pollock spawning populations (Pedersen and DiDonato 1982). Miller and Borton (1980) summarized distribution records of walleye pollock in Puget Sound as found in published records, museum collections, and various boat logs. Centers of collection of walleye pollock in Puget Sound were heavily influenced by fishing effort and ease of access, and centered around East Sound on Orcas Island, off Discovery Bay, Port Susan, Possession Sound, Saratoga Passage, Penn Cove, Holmes Harbor, the central Sound from Shilshole Bay to Port Madison, Port Orchard, Elliott Bay, Alki Point, Carr Inlet, and the mouth of Case Inlet (Miller and Borton 1980). From 1976-1980, walleye pollock was the first or second most important groundfish species taken by recreational anglers in Puget Sound (walleye pollock surpassed Pacific cod in this category in 3 of these 5 years) (Pedersen and DiDonato 1982). Although walleye pollock were once widespread and abundant in Puget Sound (Miller and Borton 1980, Matthews 1987), very little is known concerning reproductive characteristics of the species in Puget Sound (Garrison and Miller 1982). Historically, commercial and recreational fisheries for walleye pollock in Puget Sound were centered near the Canadian border in southern Strait of Georgia and at West Point, Elliott Bay, Colvos Passage, Point Defiance, and Point Fosdick (see Figs. 33, 44) (Pedersen and DiDonato 1982).

Walleye pollock reportedly form spawning aggregations on localized grounds in Puget Sound during March and April at depths of 110-145 m (Figs. 45, 46, Table A-6) (Pedersen and DiDonato 1982). Spawning walleye pollock occurred in the Washington portion of the southern Strait of Georgia in the late 1970s and early 1980s and a short-lived walleye pollock roe fishery harvested this portion of the transboundary Strait of Georgia stock (WDFW North Sound walleye pollock stock) for several years (Palsson et al. 1997). The occurrence of walleye pollock eggs near Point Roberts in the late 1970s and early 1980s and the possibility of major spawning activity in the vicinity led the Washington Department of Ecology to designate the open waters off this region as an Area of Major Biological Significance (Matthews 1987). Davis (1986) noted that the large spawning aggregation of walleye pollock in this region had decreased markedly in size by the mid 1980s (Davis 1986). This spawning aggregation on the U.S. side of the border appears to be the south-east extension of the spawning grounds of walleye pollock identified by Canadian researchers as lying between Active Pass/Mayne Island and Point Roberts (Thompson 1981, Shaw and McFarlane 1986). Pedersen and DiDonato (1982) identified a walleye pollock trawl

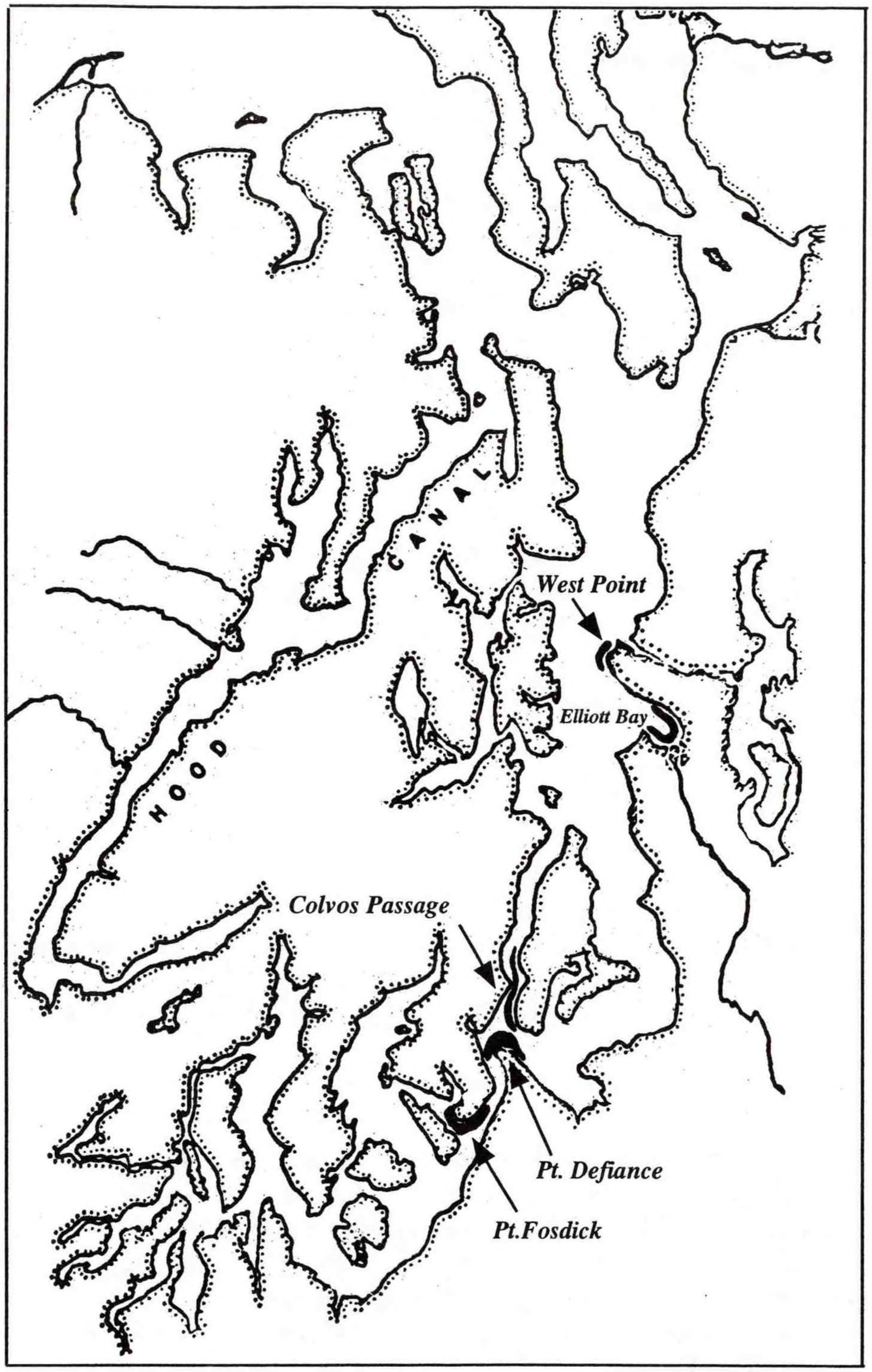

Figure 44. Historical location of major walleye pollock sport fisheries in Puget Sound as described in Pedersen and DiDonato (1982). Modified from Pedersen and DiDonato (1982, their Appendix I, fig. 2).

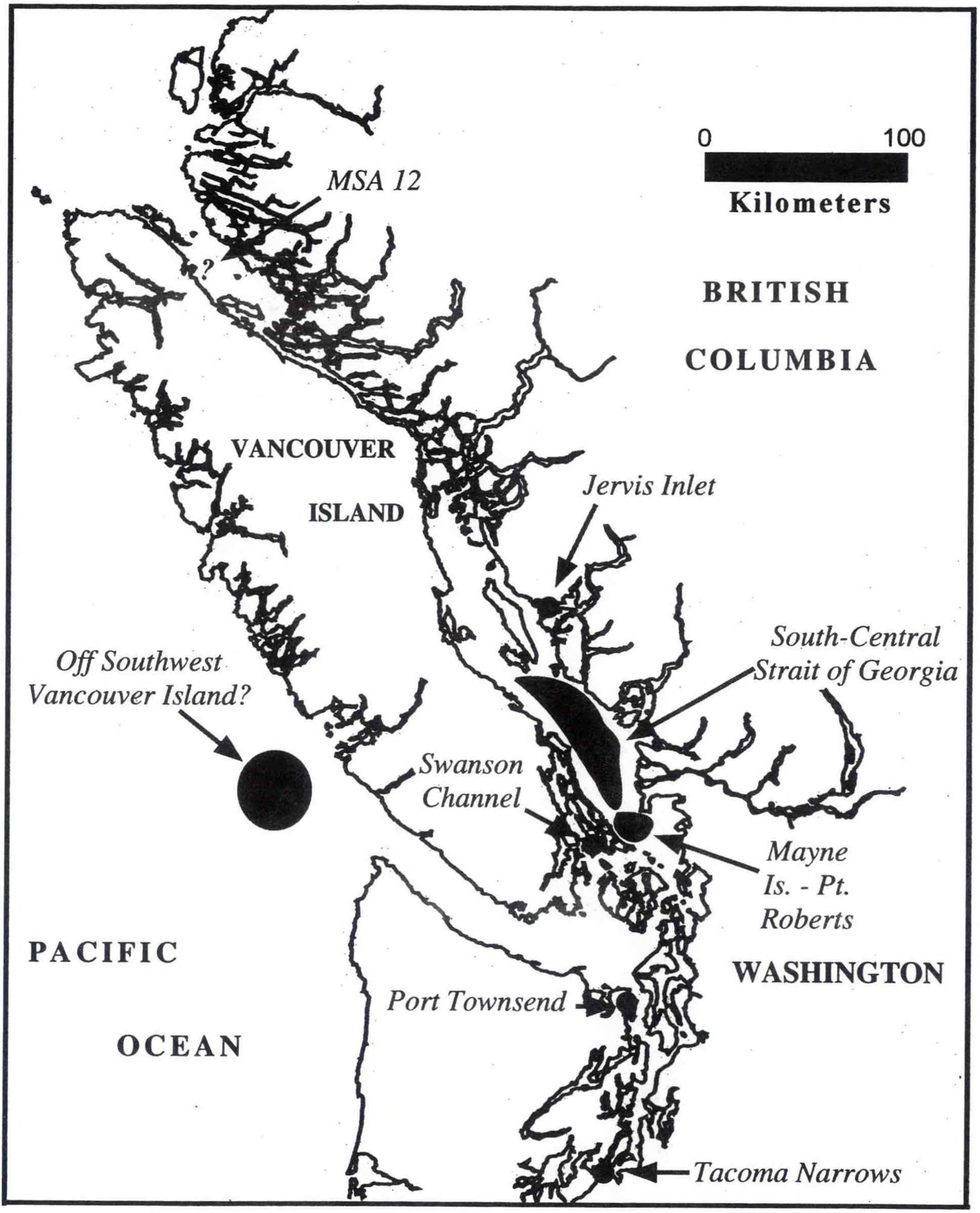

Figure 45. Current and historical spawning locations (*in italics*) of walleye pollock in Puget Sound and southern British Columbia.

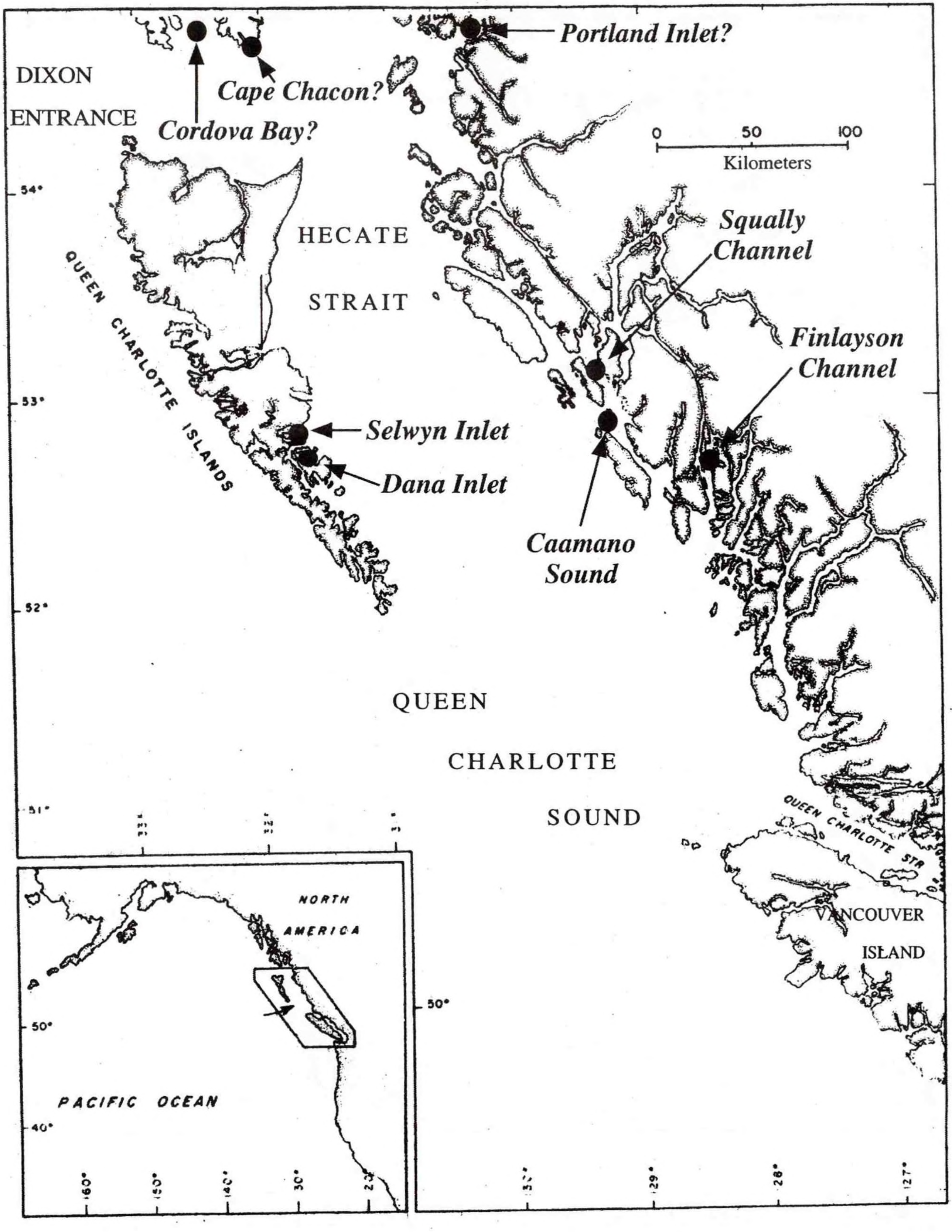

Figure 46. Known spawning locations (*in italics*) of walleye pollock along the coast of northern British Columbia.

fishery that operated from December to April (with a peak in March-April at an average depth of 128 m) along the international border, southwest of Point Roberts in an area termed "West Side" (Fig. 33). Timing and depth of this fishery suggest that it was likely targeting spawning walleye pollock.

Based on occurrence of larval walleye pollock in ichthyoplankton samples taken in 1978 and 1979 in Port Townsend Bay and Kilisut Harbor, Walters (1984) suggested that walleye pollock were spawning in the vicinity of Port Townsend from February through April (Table A-6) (Matthews 1987). In the Strait of Georgia where walleye pollock spawn in the open Strait, juveniles move quickly into nearshore nursery areas (Beamish et al. 1978a) and a similar situation may pertain to walleye pollock that spawn near Port Townsend (Walters 1984). Sogard and Olla (1993) also found juvenile walleye pollock in Port Townsend Bay in May and June, associated with seagrass habitat.

Walleye pollock were known to spawn in the vicinity of Tacoma in March and April (WDFHMD 1992), although it is uncertain if they still do so. A large recreational walleye pollock fishery occurred during the mid-1970s to 1988, (Palsson et al. 1997), in an area extending from Fox Island-Port Gibson, through the Tacoma Narrows, to Point Defiance in the vicinity of Tacoma (Fig. 44) (Pedersen and DiDonato 1982). This fishery collapsed in 1988 (Palsson et al. 1997) and was likely targeting the walleye pollock pre-spawning or spawning population.

British Columbia–Saunders et al. (1989) identified four general areas where concentrated spawning of walleye pollock occurs off the Pacific Coast of Canada during March and April: 1) the Strait of Georgia, 2) off the west coast of Vancouver Island, 3) Queen Charlotte Sound, and 4) Dixon Entrance/northern Hecate Strait (Figs. 45, 46, Table A-6). Saunders et al. (1989) noted that the simultaneously occurrence of spawning in these four distinctly separate areas suggests that, as larvae, walleye pollock form discrete stocks. Spawning distributions were derived from a series of coastwide surveys for adults in spawning condition (Cass et al. 1978, Taylor and Kieser 1980, Thompson and Beamish 1979, Thompson et al. 1981, Thompson 1981, Thompson and McFarlane 1982) or from egg and larval distribution (Mason et al. 1981a, b, c, d; Shaw and McFarlane 1986).

In the Strait of Georgia, a major spawning aggregation of walleye pollock occurs south of Texada Island and south and west of Halibut Bank (Figs. 15, 45) (Thompson 1981, Shaw and McFarlane 1986). Other spawning concentrations have been reported off the Fraser River, and between Active Pass/Mayne Island and Point Roberts (Thompson 1981, Shaw and McFarlane 1986). Some walleye pollock may also spawn at the entrance to Jervis Inlet on the mainland coast and in Swanson Channel in the Gulf Islands (Figs. 15, 45) (Thompson 1981, Saunders et al. 1989). Based on the distribution and abundance of eggs detected in ichthyoplankton surveys, conducted in 1981, Mason et al. (1984) reported four similar areas of high walleye pollock spawning activity in the Strait of Georgia; a large region in Porlier Pass from mid-Galiano Island westward to Gabriola Island and three smaller areas, the mid-Strait south of Halibut Bank, south of Bowen Island to the northwest of Vancouver, B.C., and east of Mayne Island off Active Pass in the southern Strait. Based on egg distribution detected in ichthyoplankton surveys, Mason et al. (1984) reported that walleye pollock spawn in the Strait of Georgia from the first week in February to mid-May with a peak in late March. Walleye pollock are associated with Pacific hake during spawning in the south central Strait of Georgia in two midwater layers, a shallow layer from 50-110 m and a deeper layer between 110 and 320 m (Thompson and McFarlane 1982, Shaw and McFarlane 1986, Shaw et al. 1989c). The Pacific hake:walleye pollock ratio in the 1980s in these layers ranged from 6:1 to 8:1 (Shaw et al. 1989c).

Although walleye pollock eggs and larvae have been found of the southwest coast of Vancouver Island (Saunders et al. 1989), information regarding walleye pollock spawning locations in this region was not found (Fig. 45). Thompson (1981) reported that walleye pollock were beginning to spawn off the west coast of Vancouver Island in March, but the full extent of the spawning season was unknown.

A recent trawl fishery that began to develop in 1992 in Queen Charlotte Strait (northern extension of Strait of Georgia) in MSA 12 (Figs. 45, 47) (Saunders and Andrews 1998) may have targeted spawning fish, as the walleye pollock in the area were only available during the first quarter of the year. It is assumed that the MSA 12 stock is not part of the Strait of Georgia walleye pollock stock but is related to walleye pollock in Queen Charlotte Sound.

Within Hecate Strait and Queen Charlotte Sound, spawning walleye pollock have been reported from Dana and Selwyn Inlets on the east coast of Moresby Island (Queen Charlotte Islands), and in Finlayson Channel, Squally Channel, and Caamano Sound on the mainland coast (Fig. 46, Table A-6) (Thompson et al. 1981, Thompson 1981, Shaw and McFarlane 1986). Eggs of walleye pollock have been found throughout Dixon Entrance and northern Hecate Strait, but were reportedly absent from central Hecate Strait, the northwest coast of Vancouver Island, and the west coast of the Queen Charlotte Islands and western Dixon Entrance (Saunders et al. 1989). Spawning walleye pollock are reportedly found where bottom depths exceed 90 m and are distributed between 50-130 m during the spawning period (Taylor and Kieser 1981, Shaw and McFarlane 1986). No walleye pollock in spawning condition have been reported from northern Hecate Strait, where depths do not exceed 90 m (Shaw and McFarlane 1986).

On the north side of Dixon Entrance spawning walleye pollock have been found off Cape Chacon (southern tip of Prince of Wales Island) at depths of 212-226 m, in Portland Inlet (on the mainland coast north of Prince Rupert), north of Dundas Island (on the east side of Dixon Entrance), in Cordova Bay (west of Prince of Wales Island) (Fig. 46), and throughout inside channels of Southeast Alaska south of Ketchikan (Thompson 1981).

Alaska–Although walleye pollock are continually distributed throughout Southeast Alaska to the northern Gulf of Alaska, with the exception of Shelikof Strait, little information was found on spawning locations for walleye pollock in this region. At Auke Bay in Southeast Alaska, back-calculation from the weekly distribution of 7-day-old walleye pollock larvae obtained in ichthyoplankton samples indicated that extensive walleye pollock spawning occurs from late-March to mid-May (Haldorson et al. 1989). Müter and Norcross (1994) reported similar observations of large concentrations of walleye pollock larvae during ichthyoplankton surveys in

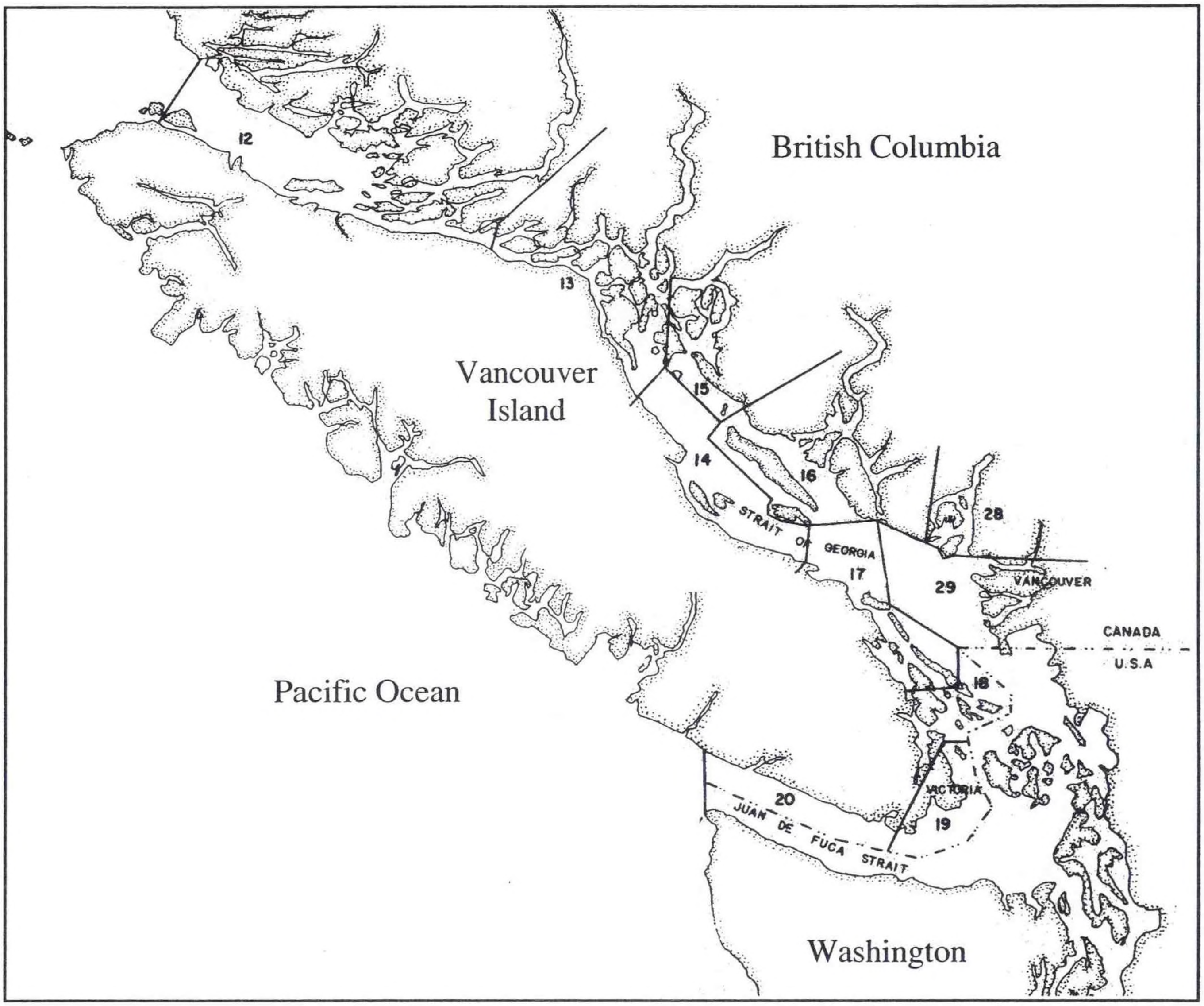

Figure 47. Minor Statistical Areas (MSA) in the Strait of Georgia and vicinity, including Area 12.

ichthyoplankton samples in Prince William Sound, indicating spawning was occurring in the vicinity during late-March to early June. Müter and Norcross (1994) thought it likely "that many embayments along the Gulf of Alaska are utilized by this species." Hirschberger and Smith (1983) summarized fisheries surveys in the Gulf of Alaska spanning the years 1975-81 that recorded walleye pollock spawning "at numerous locations in the Shelikof Strait and Kodiak Island region, and along the edge of the outer continental shelf from Chirikof Island to the northeastern Gulf of Alaska."

The most important spawning location for walleye pollock in the Gulf of Alaska is Shelikof Strait, a deep (> 250 m) and narrow channel located between Kodiak Island and the Alaska Peninsula (Dunn and Matarese 1987, Kim 1989, Bailey et al. 1997). Spawning in Shelikof Strait is concentrated near Cape Kekurnoi at depths of 150-250 m in early April, and the area of spawning varies little over the season, which lasts until late May (Kim 1989, Kendall and Picquelle 1990, Kendall and Nakatani 1992, Kendall et al. 1996). No concentrations of spawning walleye pollock similar to the magnitude of that seen in Shelikof Strait have been observed elsewhere in the Gulf of Alaska, although Lloyd and Davis (1989) identified several additional walleye pollock spawning locations in the Gulf of Alaska, including near Middleton Island, east of Kodiak Island, near the Shumagin Islands, and along the Alaska Peninsula. Kendall and Picquelle (1990) saw evidence of some walleye pollock spawning south of Chirikof Island. Brown and Bailey (1992) analyzed hatch date distributions of walleye pollock juveniles in the western Gulf of Alaska, as determined by daily increments deposited on otoliths, and found evidence of several minor spawning populations of walleye pollock located near Unimak Pass and around Kodiak Island.

Bering Sea–Aggregations of spawning walleye pollock have been consistently observed in several areas in the eastern Bering Sea, and spawning has been found to occur in all months of the year (Fig. 41, Table A-6) (Bailey et al. 1997, Dunn and Matarese 1987). Based on the distribution of spawning fish and larvae, Maeda and Hirakawa (1977) concluded that the spawning grounds of walleye pollock in the eastern Bering Sea were separated by the shallow seas around the Pribilof Islands and by a sea valley near the southeastern part of the islands. These authors stated that one area of spawning activity stretched from northwest of Unimak Island to southwest of the Pribilof Islands and a second occurred near the continental slope to the northwest of the Pribilof Islands (Maeda and Hirakawa 1977). Hinckley (1987) concluded that three separate spawning stocks exist in the Bering Sea: 1) the Aleutian Basin, 2) the northwest continental slope, and 3) a combination of the southeast and northwest continental shelves and the southeast continental slope. This conclusion was based on spatial and temporal observations of fish in spawning condition, length-at-age differences, differences in the length-fecundity relationship, and histological examination of ovaries (Hinckley 1987). Mulligan et al. (1989) referred to unpublished data from 1982 and 1983 (Bailey, unpubl. data) that agreed with Hinckley's (1987) spatial and temporal distribution of spawning walleye pollock in the eastern Bering Sea. Walleye pollock were observed spawning from January to March in the Aleutian Basin, from April to June on the southeast slope and southeast and northwest shelves, and from July to November on the northwest slope (Mulligan et al. 1989). Dunn and Matarese (1987) also reported that spawning walleye pollock occurred in the Aleutian Basin from January to March in depths of 100-250 m, and on the continental slope and shelf to the southeast of the Pribilof Islands from March to June. In addition, walleye pollock eggs have been observed along the outer continental shelf and slope from the Aleutian Islands to 60°N from February to July (Dunn and Matarese 1987). Dawson (1989, 1994) used age composition, length-at-age, and morphometrics to suggest that there is one stock of walleye pollock on the eastern Bering Sea shelf that spawns mainly on the southeastern continental shelf, a second stock in the Aleutian Basin that spawns in the Bogoslof Island area, and a third stock termed "Aleutian Islands," whose spawning location was not identified.

Fadeyev (1989) came to a different conclusion concerning spawning populations of walleye pollock in the northern Bering Sea, based on ichthyoplankton and acoustic-trawl survey. Fadeyev (1989) concluded that a single unified population occurs in this region, with spawning taking place primarily in the Unimak Island to Pribilof Islands area and that there is no separate walleye pollock stock or local spawning area to the north of the Pribilof Islands. Bulatov (1989) stated that Bering Sea walleye pollock spawn over a 10 month period from January to October and suggested there were two main peaks of spawning; winter spawning over deep water from February to early March and spring spawning over the continental shelf from the end of April to early May. Bulatov (1989) identified the main centers of reproduction in the Bering Sea as Olyutorsky Bay off east Kamchatka and Unimak Island. Bulatov and Sobolevskii (1991) concluded that Bering Sea walleye pollock spawn during February to March in the southeastern part of the Aleutian Basin in the vicinity of Bogoslof Island.

Asia–Bakkala et al. (1986) listed numerous spawning locations of walleye pollock along the Asian coast, including: 1) Olyutorsky Bay to Cape Navarin in the western Bering Sea, 2) the east coast of the Kamchatka Peninsula to the northern Kurile Islands, 3) the east coast of Iturup Island in the southern Kurile Islands 4) the west coast of the Kamchatka Peninsula, 5) Terpeniya Bay on the east coast of Sakhalin Island, 6) the west coast of Sakhalin Island, 7) Nemuro Strait (between Hokkaido and the southernmost Kurile Islands), 8) the northern coast of Hokkaido, 9) the west coast of Hokkaido, 10) Funka Bay (Uchiura Bay) off southeast Hokkaido, 11) Cape Erimo on the east coast of Hokkaido, 12) Sado Island to Toyama Bay on the west coast of Honshu Island, and 13) Peter the Great Bay to the Bay of Korea off the Asian mainland (Fig. 41, Table A-6).

Kitano (1972) stated that walleye pollock spawn from mid-March to the end of May on the western coast of Kamchatka and from early April to the end of May on the east coast of Kamchatka. Several researchers (Avdeev and Avdeev 1989 and citations therein) distinguish two to seven walleye pollock populations in the Sea of Okhotsk. On the other hand, the broad area of spawning in the eastern, northern, and northwestern parts of the Sea of Okhotsk, during April and May, and the broad distribution of eggs and larvae led Zver'kova (1987) to question the level of isolation among local spawning populations. A more recent study (Kotenev et al. 1998) of spawning stock structure in the eastern Sea of Okhotsk off western Kamchatka, identified five groups of walleye pollock that were separated by sizes of mature fish and place and time of spawning. Three of these groups spawned in the winter and two in the spring (Kotenev et al. 1998).

Maeda (1972) stated that walleye pollock spawned earlier in southern regions of Japan than in the north; from January to February in the Niigata Region (northwest coast of Honshu, Japan) and from February to April in the vicinity of Hokkaido. Maeda et al. (1988) reported that walleye pollock spawn on the continental shelf off the southwest coast of Hokkaido between Otobe and Ainuma in depths of 120-200 m. Distribution of eggs indicates that spawning occurs in January and February in this region (Maeda et al. 1988). Hamatsu and Yabuki (1995) found that peak spawning of walleye pollock along the Pacific coast of eastern Hokkaido north of Cape Erimo occurred during March.

Walleye pollock in Korean waters of the Sea of Japan are at the southern limit of their distribution in Asia and, unlike Pacific cod, do not extend into the Yellow Sea (Fig. 41) (Gong and Zhang 1986). As in Puget Sound, walleye pollock in Korean waters generally move to shallower waters in the winter to spawn (Gong and Zhang 1986). Walleye pollock spawn in Korean waters at depths of 50-100 m in three general areas: 1) off Gyeonbuk and Gangweon (southeast to central east coast of Korea) from November to December, 2) off Hamnan (northeast coast of Korea) in December, and 3) off Hambuk (extreme northeast coast of Korea) in January and February (Gong and Zhang 1986).

Walleye pollock management stocks

The WDFW recognizes two stocks of walleye pollock in Puget Sound, North Sound and South Sound stocks, which are differentiated by spawning location, growth rates, and other biological characteristics (Palsson et al. 1997). Several stocks of walleye pollock are recognized in British Columbia based on parasitological data, utilization of discrete spawning grounds, and differences in age and growth parameters (Shaw and McFarlane 1986). Walleye pollock in Dixon Entrance, northern Hecate Strait, and southern Southeast Alaska are considered a single stock, as are walleye pollock in the Strait of Georgia. Length frequency analysis indicated that there is "little intermingling" of walleye pollock stocks north and south of Queen Charlotte Sound, and that walleye pollock in Dixon Entrance are part of the same stock as found off Southeast Alaska (Thompson 1981, Shaw and McFarlane 1986, Saunders et al. 1989). Strait of Georgia walleye pollock are regarded as one stock, based on their smaller size at any given age, and the fact that they are smaller and younger at maturity than walleye pollock in Dixon Entrance (Shaw and McFarlane 1986, Saunders et al. 1989). Further evidence for stock separation of walleye pollock in the Strait of Georgia, off the west coast of Vancouver Island, and north of Queen Charlotte Strait was shown by a comparison of the prevalence of 13 species of parasites that indicated walleye pollock in these three regions were discrete from one another (Shaw and McFarlane 1986, Saunders et al. 1989).

Two walleye pollock stocks are recognized in the Gulf of Alaska: an Eastern Gulf stock and a Western/Central Gulf stock (Bailey et al. 1999). Walleye pollock in the U.S. portion of the Bering Sea/Aleutian Islands are divided into three stocks for management purposes: 1) eastern Bering Sea, 2) Aleutian Islands, and 3) Bogoslof Island-Aleutian Basin (Bailey et al. 1999). The eastern Bering Sea continental shelf has a stock that is thought to be separate from the eastern

Bering Sea stock. Walleye pollock from the eastern and western Bering Sea are thought to mix during feeding in the northern Bering Sea. For current management purposes, the mixing of these two "stocks" is also thought to occur in the "donut hole" or Aleutian Basin (Bailey et al. 1999).

Tsuji (1989) summarized knowledge concerning walleye pollock stock structure around Japan and recognized five separate stocks: North Japan Sea, Kitami, Nemuro, Pacific, and South Primorskan. The North Japan Sea stock occurs on the west coasts of Hokkaido and Sakhalin and along the Russian coast in the southern Tatar Strait. The Kitami stock occurs along the east coast of Sakhalin and the northern coast of Hokkaido. The Nemuro stock spawns in the Nemuro Strait between Hokkaido and the southern Kurile Islands and shares feeding grounds with the Kitami stock. The Pacific stock ranges along the Pacific coast of Hokkaido and northern Honshu. The South Primorskan stock occurs principally along the east coast of the Korean Peninsula, but also extends onto the southwest coast of Honshu in the Sea of Japan (Tsuji 1989).

Tagging and distribution

There is very little tagging information for walleye pollock that can be used to estimate the degree of interchange, if any, between spawning populations or for that matter the degree of homing to a spawning location. Records of fish released during feeding seasons are not appropriate for discrimination of stock structure (Tsuji 1989).

Saunders et al. (1989) reported on a tagging study off Gabriola Island in the Strait of Georgia in which 942 walleye pollock were tagged and only two were subsequently recovered. However, the recovery of these two fish, one near Jervis Inlet and the other off Port Renfrew, indicated "that dispersion north and south of the central Strait of Georgia is taking place" (Saunders et al. 1989).

Tagging studies in the Bering Sea have shown individual adult walleye pollock to undertake extensive seasonal feeding and spawning migrations (Dawson 1994, Bailey et al. 1999). Low (1989) cited discussions with Soviet scientists describing walleye pollock tagging studies that showed "populations off Kamchatka, the northern Okhotsk Sea, and Sakhalin Island are intermixing even during spawning." Several tagging experiments summarized by Tsuji (1989) indicate extensive migration of walleye pollock during the feeding seasons in Japanese coastal waters and in the Sea of Okhotsk. However, only two of these studies appear to have included fish tagged on the spawning grounds. Walleye pollock tagged just after the spawning season in April of 1968 in Ishikari Bay off western Hokkaido "were recaptured in the next spawning period at locations in a wide range up to the southern Sakhalin coast" (Tsuji 1989, p. 168), although the majority of recaptures appear to have occurred in Ishikari Bay during the 1969 and 1970 spawning seasons (Tsuji 1989, his Fig. 19). A second tagging experiment summarized by Tsuji (1989) involved walleye pollock tagged during the spawning season in the Nemuro Strait (a known spawning ground), between Hokkaido and the southernmost Kurile Islands. Nine tagged walleye pollock were recaptured during successive spawning seasons in Nemuro Strait, while all recaptures in other areas (Sea of Okhotsk) occurred during the feeding migration and not during spawning (Tsuji 1989).

Gong and Zhang (1986) reported that of over 47,000 walleye pollock tagged off the coast of Korea from 1931-1936, 226 were recaptured off Korea and 13 were recaptured off the west coast of Hokkaido (Tsuji 1989). Further details of this tagging program were provided in Tsuji (1989), and it is apparent that recaptures of Korean tagged walleye pollock off Hokkaido occurred in only one year (1935 fishing season) of the study, during the active feeding period, which was not during the spawning season. Tsuji (1989) suggested that this one-time migration of Korean walleye pollock to Hokkaido may have resulted from straying of an exceptionally large year class.

Seasonal migrations

Juvenile walleye pollock ranging in length from 21-87 mm were found to be associated with shallow seagrass beds in Port Townsend Bay in Puget Sound in May through June 1992 (Sogard and Olla 1993). It was postulated that juvenile walleye pollock were utilizing seagrass beds as cover from predation, although other factors such as prey items may also attract juveniles to seagrass beds. As walleye pollock juveniles increased in size in Port Townsend Bay they evidently migrated to deeper water beyond the range of seagrass. It is unknown whether juvenile walleye pollock utilize seagrass beds as nursery habitat in other regions of the species' range (Sogard and Olla 1993). Miller et al. (1976) also found juvenile walleye pollock in shallow nearshore eelgrass, cobble, and gravel habitats in northern Puget Sound.

Age-frequency data reviewed by Saunders et al. (1989) indicates that young walleye pollock are segregated from adults in the each of the major walleye pollock areas in British Columbia: Dixon Entrance/Hecate Strait, Queen Charlotte Sound, west coast of Vancouver Island, and Strait of Georgia. Younger walleye pollock are frequently encountered in nearshore areas and progressively migrate to more offshore areas with age (Saunders et al. 1989). It appears likely that walleye pollock in Dana and Selwyn Inlets leave these areas at age-3, moving out into Hecate Strait and Queen Charlotte Sound at that time (Saunders et al. 1989).

Bakkala et al. (1986) stated that walleye pollock in Asian waters migrate toward the coast from demersal and pelagic waters to spawn in depths of 70-150 m at temperatures of 2°-5°C. Although, in Funka Bay and Nemuro Strait they spawn in depths of 300 m or more.

Parasite incidence

Arthur (1983, 1984) and Avdeev and Avdeev (1989) utilized regional differences in the frequency of parasite infestation to detect walleye pollock stock structure off the west coast of Canada and in the Sea of Okhotsk, respectively. The principle requirement for indicator parasites is that their infestation "be of sufficient duration to make them potentially useful as biological tags" (Arthur 1983, 1984; Avdeev and Avdeev 1989). Arthur (1983) surveyed 13 species of parasites in walleye pollock from Swanson Channel in the Strait of Georgia, the west coast of

Vancouver Island, Queen Charlotte Sound, and Dixon Entrance, and found four species that contributed significantly to stock separation (two trematodes, one cestode flatworm, and a nematode roundworm). Based on these parasitological data, Arthur (1983) stated that "stocks of walleye pollock from the Strait of Georgia and the west coast of Vancouver Island are relatively discrete from each other and from fish from the two northern areas." One species of trematode flatworm (*Prosorhynchus* sp. metacercaria), was found in 100% of walleye pollock from Dixon Entrance, 60% in Queen Charlotte Sound, 10% off the west coast of Vancouver Island, but was absent from Strait of Georgia walleye pollock. Arthur (1983) stated that this parasites' absence from Strait of Georgia walleye pollock indicates that "little or no immigration of adult fish from other areas to this stock occurs." Unfortunately, with the exception of the Strait of Georgia sample, all of the walleye pollock collected for Arthur's (1983) parasitological study were collected outside of the spawning season and have the potential to represent a mixture of spawning populations.

Avdeev and Avdeev (1989) investigated the regional differences in the occurrence of 9 indicator parasites amongst 6-yr-old walleye pollock from various spawning areas within the Sea of Okhotsk. These parasitological data allowed Avdeev and Avdeev (1989) to distinguish between seven spawning groups in the Sea of Okhotsk (Swan's shoal, southwestern Kamchatka, western Kamchatka, Shelikhov Gulf, Pritauyskiy, and Swan's Height) and a minimum of three separate groups off the east coast of Kamchatka (Komandorsky Islands, east coast of Kamchatka, and Shirshov Ridge).

Growth rate and body size

Determination of exact age in walleye pollock has been problematical and until ageing methods are validated and methods are standardized for ageing of older fish the problem of ageing errors will remain in walleye pollock growth and mortality studies (Chilton and Beamish 1982, Lai and Yeh 1986). Lai and Yeh (1986) compared otolith, scale, dorsal fin ray, and pectoral fin ray as structures to determine age of walleye pollock and found good agreement among these methods for ages less than 5 years, but the use of both otolith surface readings and "break and burn" techniques gave the best precision and percentage agreement among readers for older fish.

Palsson et al. (1997, 1998) referred to unpublished data on growth rate differences as an indication that the South Sound walleye pollock are of a different biological stock than those in North Sound. Matthews (1987) stated that walleye pollock in Puget Sound rarely live for more than 10 years, have an average body length of 48 cm and a maximum size of 91.4 cm. By comparison, data in Saunders et al. (1989) indicates that maximum age of walleye pollock is 12 years in Dixon Entrance/Hecate Strait, 11 years in Queen Charlotte Sound, 10 years in the Strait of Georgia, and 8 years off the west coast of Vancouver Island. Maximum length in cm of walleye pollock in Dixon Entrance/Hecate Strait, Queen Charlotte Sound, Strait of Georgia, and off the west coast of Vancouver Island were reported to be 71, 74, 66, and 61, respectively (Saunders et al. 1989). Shaw and McFarlane (1986) stated that walleye pollock in the Strait of Georgia reached a maximum age of 8 years.

Thompson (1981), Shaw and McFarlane (1986), and Saunders et al. (1989) provided evidence that walleye pollock in the Strait of Georgia are smaller for a given age than walleye pollock found off the west coast of Vancouver Island or further north in Queen Charlotte Sound and Dixon Entrance. Shaw and McFarlane (1986) and Saunders et al. (1989) stated that walleye pollock growth rates are similar coastwide in British Columbia until age-2, after which growth rate is reduced in the Strait of Georgia. Saunders et al. (1989, their Fig. 9) illustrated some growth rate differences (as mean length-at-age) between areas in the Strait of Georgia; however, the growth rates for east of Mayne Island, U.S. portion of the Strait of Georgia, and central Strait of Georgia were very similar for both sexes. Saunders et al. (1989) also illustrated mean length-at-age data (their Fig. 11) for the now defunct walleye pollock fishery in the U.S. portion of the Strait of Georgia from 1978 to 1985 that indicated this relationship was stable over time.

Nishimura and Yamada (1988) postulated that rapid initial growth and small body size attained in the first year (consistent across year classes) of Sea of Okhotsk walleye pollock compared to walleye pollock in the Sea of Japan and Pacific Ocean side of Japan may indicate a genetic sub-population in the Sea of Okhotsk.

Length and age at maturity

Table A-7 summarizes length at first maturity, at 50% maturity, and at 100% maturity for selected walleye pollock populations. Virtually all male and female walleye pollock in Puget Sound mature at age-1 (between 25 and 38 cm in length) in South Puget Sound (WDFW 2000). Walleye pollock were found to mature later in the U.S. portion of the Strait of Georgia than in South Puget Sound; 37% of males and 43% of females were mature at age-2, and 92.5% of males and 93% of females were mature at age-3 (WDFW 2000). Thompson (1981) and Shaw and McFarlane (1986) provided evidence that walleye pollock in the Strait of Georgia spawn at a smaller size than do walleye pollock found off the west coast of Vancouver Island or further north in Queen Charlotte Sound and Dixon Entrance. Saunders et al. (1989) also reported that walleye pollock in the Strait of Georgia matured at smaller sizes (length at 50% maturity of 26-32 cm for males and 30-35 cm for females) than did walleye pollock from more northern areas in Dixon Entrance and Queen Charlotte Sound (length at 50% maturity of 37-41 cm for males and 39-44 cm for females). Walleye pollock from the west coast of Vancouver Island (length at 50% maturity of 37-40 cm for males and 40 cm for females) were more similar to northern samples than to the Strait of Georgia walleye pollock (Saunders et al. 1989).

Length frequency analysis

Analysis of length frequency data for walleye pollock stocks in British Columbia suggested that little intermingling of walleye pollock occurred north and south of Queen Charlotte Sound and that walleye pollock in Dixon Entrance are part of a larger Southeast Alaska stock (Thompson 1981, Shaw and McFarlane 1986, Saunders et al. 1989).

Otolith elemental composition

Mulligan et al. (1989), Mulligan (1997), and Severin et al. (1995) reported on efforts to discriminate walleye pollock stock structure through the analysis of elemental composition of the early larval increments retained on juvenile and adult otoliths. Juvenile walleye pollock collected from four areas in the Bering Sea could be correctly assigned to their collection site with 65% accuracy based on otolith chemistry (Mulligan et al. 1989). Mulligan et al. (1989) suggested mis-identifications "may be explained by a chemical similarity of adjacent water masses." Severin et al. (1995) were able to correctly assign specimens of walleye pollock, collected from five locations in the Gulf of Alaska and Bering Sea, to their capture locality 60-80% of the time using discriminant analysis of a combination of otolith chemistry and age and length data. Development of the full potential of otolith elemental composition in stock discrimination will require a more complete correlation of otolith chemistry and chemical oceanographic parameters (Severin et al. 1995).

Fecundity and egg size

Caution should be taken when comparing fecundity of walleye pollock between different regions due to the possibility of interannual variability within regions (Hinckley 1987) and the lack of standardization of methodology. However, some comparisons do reflect geographical differences in fecundity (see Table A-8 and Fig. 48). In most studies the length-fecundity relationship for walleye pollock has been found to be curvilinear and can be expressed as:

$$F = aL^b$$

Where F is fecundity in number of eggs, L is fork length in cm, and a and b are coefficients that characterize the y-intercept and the slope of the curve, respectively. Table A-8 presents fecundity-length relationships for selected walleye pollock populations. Fecundity estimates are not available for walleye pollock in Puget Sound (Matthews 1987). Miller et al. (1986) compared published studies of walleye pollock fecundity and found that, for similar size females, reported fecundity from the Bering Sea was almost half that reported for Shelikof Strait, which in turn was about half the reported fecundity of walleye pollock in the Strait of Georgia (see Fig. 48). Hinckley (1987) also noted a general trend of declining fecundity for walleye pollock with increasing latitude.

Female walleye pollock are batch spawners in that groups of eggs ripen and are spawned at intervals of 1-7 d in separate spawning events, over a period of several weeks to a month, as observed in captive fish (Dunn and Matarese 1987, Balykin 1988, Sakurai 1989, Hinckley 1990). In laboratory studies of walleye pollock obtained from Puget Sound, the number of egg batches spawned per female ranged from 2 to 21, over a period of 3 to 26 days (Hinckley 1990). Balykin (1988) determined that female walleye pollock in the western Bering Sea spawn eggs in a total of 4 batches, based on the distribution of ovarian egg sizes. Sakurai (1989) reported that captive walleye pollock females spawned repeatedly over a month period with intervals of 1-7 days between spawning events. Several thousand to about 50 thousand eggs were released at a time

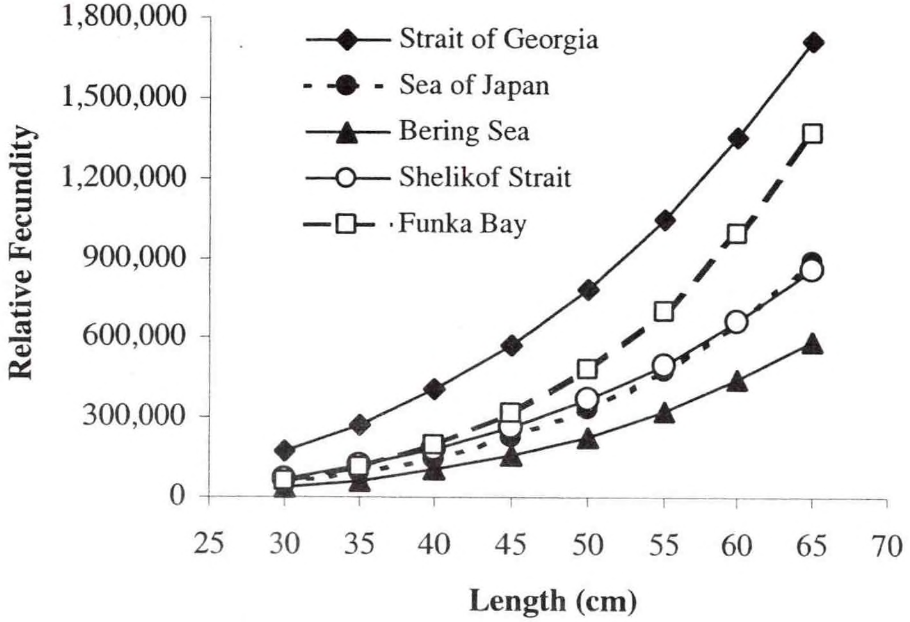

Figure 48. Length-fecundity relationships for selected populations of walleye pollock throughout the species range (data from fecundity-length equations in Table A-8).

(Sakurai 1989). The number of eggs spawned by an individual female has been shown to decrease with successive spawning events (Sakurai 1989, Hinckley 1990).

The average egg size in successive spawning events also decreases in later spawnings of captive female walleye pollock (Sakurai 1989, Hinckley 1990). In Shelikof Strait, egg size of walleye pollock has been shown to vary interannually and to decrease during the spawning season (Hinckley 1990). Sakurai (1989) also stated that egg diameter of spawning walleye pollock populations become smaller over time, presumably due to the decreasing trend in egg size of individual repeat spawners in the population. Hinckley (1990) reviewed geographic variation in egg size of walleye pollock and stated that "there appears to be a positive correlation between egg size and latitude in walleye pollock" and that this correlation is likely related to latitudinal temperature gradients.

Morphological Differences

Meristic and morphometric variability

Numerous researchers have analyzed morphometric and/or meristic variability in walleye pollock in an attempt to identify population or stock structure (see recent summary in Bailey et al. 1999). The original separation of walleye pollock has been divided into two subspecies, *Theragra c. chalcogramma* (Pallas) and *T. c. fucensis* (Jordan and Gilbert) (the later having been described from Puget Sound (Jordan and Gilbert 1883), was based mainly on differences in median fin-ray counts of four specimens from Puget Sound and three from Alaska (Wilimovsky et al. 1967). Schultz and Welander (1935) re-examined walleye pollock fin-ray and vertebral counts for 27 specimens from Puget Sound and 30 from Alaska, and found little difference in fin-ray counts from the two areas suggesting this may not be a valid character for subspecific determination in walleye pollock, although they chose not to synonymize the two subspecies (Wilimovsky et al. 1967). Wilimovsky et al. (1967) examined variability in seven morphometric and eight meristic characters in walleye pollock from northern Washington, southern B.C, Southeast Alaska/northern B.C., Aleutian Islands, Bering Sea, Western Bering Sea, and the Sea of Okhotsk. Neither morphometric nor meristic characters showed significant differences between geographic areas, although some meristic counts showed clinal trends in north-south reduction (Wilimovsky et al. 1967). Based on these studies, Wilimovsky et al. (1967) synonymized *T. c. chalcogramma* and *T. c. fucencis* and invalidated these subspecific names.

Serobaba (1977) examined population structure of Bering Sea walleye pollock through the analysis of 27 morphometric characters and identified four "groupings"; eastern Bering Sea, northern Bering Sea, western Bering Sea, and southern Bering Sea. Specimens examined by Serobaba (1977) were collected on the "feeding grounds" in the Bering Sea and do not represent spawning populations, which limits the studies' utility for distinguishing population structure. Dawson (1989) had little success in discriminating young-of-the-year walleye pollock from 5 different regions in the Bering Sea using morphometric characters. However, Dawson (1994) was able to show that shape of walleye pollock varied significantly between areas in the Bering

Sea. Walleye pollock from the central Aleutian Basin and Aleutian Islands were well separated from each other and from all other areas in this analysis (Dawson 1994). Samples from the northwest Bering Sea and western Bering Sea were well separated from one another and moderately well separated from all other areas (Dawson 1994). Dawson (1994) stated that walleye pollock samples from the eastern Bering Sea were most similar in shape and could not be successfully discriminated, indicating some interchange occurs between regions on the eastern Bering Sea shelf.

A more recent study (Temnykh 1994), examined morphometric characters of walleye pollock collected during the spawning season and did not find differences between populations across the entire western Bering Sea. However, walleye pollock from the western Bering Sea, Sea of Okhotsk, and southeastern Kamchatka were found to be morphologically distinct. Temnykh (1994) observed a high level of polymorphism in morphometric characters with "a high degree of overlap of morphological subsets in each sample," and although each area had a morphotype characteristic of its area, in each area examined "pollock are present with the morphotypes of other, frequently rather remote, regions." Temnykh (1994) postulated that this polymorphism may result from "mixing of pollock resulting from the absence in this species of strongly pronounced homing."

A number of studies of geographic variation in morphometric and meristic characters of walleye pollock in Japanese coastal waters, and beyond, have indicated population structure (Ishida 1954, Ogata 1959, Hashimoto and Koyachi 1969, Iwata and Hamai 1972, Iwata 1975a, Koyachi and Hashimoto 1977). Ishida (1954) observed that similar-sized walleye pollock had larger otoliths in the Sea of Japan than in the Sea of Okhotsk. However, otoliths of fish from off the Pacific Ocean coast of Japan and in the Sea of Japan were of equal size (Ishida 1954). Ogata (1959) found significant differences in counts of vertebrae between walleye pollock on the Pacific Ocean side and the Sea of Japan side of Japan. Within the Sea of Japan, Ogata (1959) differentiated three stocks: 1) the west coast of Hokkaido, 2) western and northern coasts of Honshu, and 3) the south-east coast of Siberia. Based on differences in vertebral counts, Iwata and Hamai (1972) determined that there were eight "local forms" of walleye pollock in the Sea of Okhotsk and the waters around Japan; 1) northeastern Sea of Okhotsk form, 2) western Sea of Okhotsk form, 3) western Sakhalin form, 4) western Hokkaido form, 5) northern Kurile Island form, 6) Rausu form (southern Kurile Islands), 7) east of Cape Erimo form (Pacific coast of Hokkaido), and 8) west of Cape Erimo form (Pacific coast of Hokkaido). As is common in a number of fish species, Iwata and Hamai (1972) noted that the mean number of vertebrae increased with latitude in walleye pollock. The vertebral study of Iwata and Hamai (1972) was expanded on and also presented in Iwata (1975a). Morphometric analyses of walleye pollock by Iwata (1975a) led to the identification of six "local forms"; northern Sea of Japan, Uchiura (=Funka) Bay, eastern Kamchatka westward to Kushiro, Rausu, western Sea of Okhotsk, and eastern Sea of Okhotsk.

Koyachi and Hashimoto (1977) examined meristic character variation across almost the entire geographic range of walleye pollock and identified 12 "sub-populations": 1) western

Honshu, 2) northern Honshu, 3) Hokkaido, and 4) Pormorskaya, all in the Sea of Japan; 5) southern Hokkaido and northern Honshu, and 6) southern Kurile Islands, both on the Pacific Coast of Japan; 7) southwestern Sea of Okhotsk, 8) northern Sea of Okhotsk; 9) Kamchatka Peninsula, 10) eastern Bering Sea, 11) Gulf of Alaska, and 12) Pacific coast of Canada. Koyachi and Hashimoto (1977) found vertebral counts to be the most informative, and also noted higher counts in northern waters than in southern waters. Hashimoto and Koyachi (1977) distinguished 7 "sub-populations" of walleye pollock in waters near Japan by means of allometric and morphometric comparisons: 1) northwestern Honshu, 2) western Hokkaido, and 3) Pormorskaya in the Sea of Japan; 4) southern Hokkaido and northern Honshu, and 5) southern Kurile Islands, both on the Pacific Ocean side of Japan; 6) southwestern Sea of Okhotsk, and 7) northern Sea of Okhotsk. Other "sub-populations" tentatively identified by Hashimoto and Koyachi (1977) were Kamchatka Peninsula, eastern Bering Sea, Gulf of Alaska, and the Pacific coast of Canada.

Genetic Information

Several molecular genetic techniques have been used to infer population structure in walleye pollock, especially in the Bering Sea and the Gulf of Alaska. The results of these give a general indication of the level of genetic differentiation that might be expected for populations in Puget Sound and adjoining areas. A detailed study of genetic population structure in Puget Sound is lacking, although samples from Puget Sound have been included in studies of geographically large-scale variability. The results of previous studies of walleye pollock and the results of empirical and theoretical studies of high gene flow species of fish indicate that only low levels of genetic differentiation would be expected among populations of walleye pollock where physical barriers to migration are lacking (Waples 1987, Ward et al. 1994).

Bailey et al. (1999) recently reviewed genetic population structure studies for walleye pollock and illustrated a hypothetical model of population structure for walleye pollock in the North Pacific Ocean (Fig. 42). On very broad spatial scales across the North Pacific, protein electrophoretic studies of several species detected population differences that apparently resulted from isolation in the distant past. A similar North Pacific Ocean discontinuity in gene frequency has been observed for the enzyme superoxide dismutase (*SOD*) in walleye pollock (Iwata 1973, 1975a, b, c; Grant and Utter 1980). In this case, the demarcation between the two oceanic groups appears to be located on the Asian side of the Bering Sea or in the Sea of Okhotsk. These ocean-wide differences indicate that fish generally do not disperse over large distances across the North Pacific. If they did, gene frequency differences across the North Pacific would disappear. The lack of mixing also implies that partially isolated stocks may exist on a smaller geographical scale. The presence of ocean-wide gene frequency differences may provide the basis for identifying stocks and dispersal pathways between stocks in areas of mixing between the two major groups.

Grant and Utter (1980) found some significant genetic differences between walleye pollock samples from the Gulf of Alaska and those from the southeastern Bering Sea; however, only the *SOD* locus showed significance in tests between these two regions. Bailey et al. (1999) stated that

"F_{ST} among samples within each region was 0.021, and is typical of values for several other species of marine fishes with apparently high equilibrium levels of gene flow between populations." Seeb et al. (in press) reported that although an examination of variation at 29 allozyme loci between walleye pollock from the Bering Sea and Gulf of Alaska revealed no striking differences, *SOD* allele frequencies did distinguish Gulf of Alaska and eastern Bering Sea samples of spawning fish. Seeb et al. (in press) also reported that as alleles of *SOD* genes in other species have been shown to be under directional selection. This may also be the case for *SOD* in walleye pollock. Yanagimoto (in press) summarized Japanese studies of walleye pollock genetic analyses and reported that *SOD* alleles also show a clinal trend in frequencies in the western Bering Sea through Hokkaido. This has served to discriminate populations from these two major regions.

Mitochondrial DNA (mtDNA) has been used to study walleye pollock, but with little success in detecting population groupings. Mulligan et al. (1992) sampled four localities: 1) Gulf of Alaska, 2) the "donut hole" in the mid-Bering Sea, 3) Bogoslof Island in the southeastern Bering Sea, and 4) Adak Island in the Aleutian Archipelago. Tests of haplotypic frequencies showed significant differences between the Adak Island sample and the three other samples. Nevertheless, the overall level of differentiation between these samples was small ($F_{ST} = 0.019$) and was similar to the level detected with allozymes (Grant and Utter 1980). The apparent lack of stock structure in the Bering Sea may lie with the failure to sample populations during spawning, when stock separation is expected to be the largest.

A second study of mtDNA variability in the Bering Sea populations showed another pattern of differentiation among samples. Shields and Gust (1995) sampled walleye pollock from six areas: 1) western Bering Sea, 2) northwestern Bering Sea, 3) the "donut hole", 4) Aleutian Islands, 5) southeastern Bering Sea, and 6) Gulf of Alaska. None of these samples differed from each other in pairwise tests. However, the comparison between samples 1-2 combined and samples 5-6 was significant. These results indicate at least some east-west differentiation across the Bering Sea. The samples for this study also appear to have been collected out of the spawning season when stocks may have been mixed.

Yanagimoto (in press) reported on Japanese studies of RFLP analysis of mtDNA (see "Glossary") that found significant differences among walleye pollock samples from three areas in the Bering Sea (west, northeast, and southeast) but no differences between these areas and the "donut hole." The apparent discrepancy between mtDNA RFLP studies of Mulligan et al. (1992) and studies reported in Yanagimoto (in press) may be due to differences in the restriction enzymes used in the two studies (Yanagimoto in press). Seeb et al. (in press) also examined RFLP polymorphism at the mtDNA genes for cytochrome *b*, cytochrome oxidase, and the ND 5/6 regions, and detected no haplotype differences between spawning populations of walleye pollock from Prince William Sound and Shelikof Strait.

In Atlantic cod, the analysis of microsatellite loci resolved fine scale genetic differences between stocks that were not isolated by any apparent barriers to gene flow (Bentzen et al. 1996). Early studies of microsatellite variability in walleye pollock showed variable results, possibly because of technical difficulties in the DNA analysis itself or because of the sampling of mixed populations outside spawning areas. More recent studies of walleye pollock populations with microsatellites are based on improved technologies and on spawning-area samples (Seeb et al. in press, O'Reilly et al. in press).

Seeb et al. (in press) did not find differences at two microsatellite loci between spawning populations of walleye pollock in 1997 from Prince William Sound, Shelikof Strait, and Bogoslof Island. O'Reilly et al. (2000) reported the development of 14 new microsatellite loci that should prove useful in analysis of population structure in walleye pollock. Based on some of these new microsatellite loci, O'Reilly et al. (in press) presented preliminary results of genetic variation at 10 microsatellite loci among six samples: Port Townsend, Washington (juveniles), Prince William Sound (adult spawners), southeast Bering Sea at Unimak Island (March, adult spawners), southeast Bering Sea at Unimak Island (April, adult spawners), northwest Bering Sea (non-spawning adults), and Funka Bay, Japan (adult spawners). O'Reilly et al. (in press) found significant single locus differences in all pair-wise population comparisons, differences at 6-10 loci between both Port Townsend and Prince William Sound and other east Pacific populations, and differences at 8-10 loci for comparisons between Japan and east Pacific samples. O'Reilly et al. (in press) stated that "population pairs surveyed here appear to follow an isolation by distance model" where geographical distance is measured along the continental shelves. The finding most significant to this status review is that "global significance of single locus tests of differentiation were observed between walleye pollock from Port Townsend and Prince William Sound, suggesting genetic structuring within the northeast Pacific" (O'Reilly et al. in press).

Information Relevant to the Walleye Pollock DPS Question

As stated in the previous "Approaches to the Species Question and to Determining Risk" section, four broad types of information were analyzed by the BRT in its determinations of whether walleye pollock in Puget Sound represent a "discrete" and "significant" population and therefore qualifies as a DPS under the ESA: habitat characteristics, phenotypic and life-history traits, mark-recapture studies, and analysis of neutral genetic markers. As such data can only be properly evaluated in relation to similar information for the biological species as a whole, Puget Sound walleye pollock data were compared with data from walleye pollock from throughout the species' range.

As detailed in the previous sections on "Environmental Features..." and "Phenetic and Genetic Information Relating to the Species Question," specific information for Puget Sound walleye pollock was available in the following categories: 1) physical habitat, 2) spawning time and location, 3) migration patterns, 4) year-class strength, 5) growth rate and body size,6) size and age at maturity, 7) length frequency, 8) meristics and morphometrics, and 9) very limited data on genetic population structure relative to a recent microsatellite DNA study. Information on tagging, parasite incidence, fecundity, and local genetic population structure for walleye pollock in Puget Sound was largely unavailable. A similar assemblage of data was available for walleye pollock from the Strait of Georgia, including fecundity and parasite-incidence data; although, year-class strength and length frequency data were lacking. Very little biological data was found for walleye pollock in Southeast Alaska, data on physical habitat, spawning time and location, migration patterns, parasite incidence, growth rate and body size, size and age at maturity, length frequency, and meristics and morphometrics were available from central and northern British Columbia. Limited genetic population structure information was available for walleye pollock off Southeast Alaska. The previous section on "Approaches to the Species Question and to Determining Risk" should be consulted for a general discussion of the relative usefulness of the various categories of data for DPS delineation. Issues of biological data quality for walleye pollock are addressed for each category in the preceding section entitled "Phenetic and Genetic Information Relating to the Species Question."

Discussion and Conclusions on Walleye Pollock DPS Determinations

The BRT considered several possible DPS configurations for populations of walleye pollock in the northeastern Pacific Ocean in its attempt to identify a "discrete" and "significant" segment of the biological species that incorporates Puget Sound fish. After careful consideration of the available information, its usefulness for delineating walleye pollock DPSs, and the accompanying uncertainty, the BRT concluded that aggregations of spawning walleye pollock in the eastern North Pacific Ocean, south of the provisional northern boundary of 140°W, are part of a single DPS and can be thought of as a "species" under the ESA. Since the area occupied by this unit roughly corresponds to the region identified by Briggs (1974, p. 278) as containing a "well-defined lower boreal fauna," the walleye pollock in this area will hereafter be identified as the Lower boreal Eastern Pacific DPS (Fig. 3).

The BRT's conclusion that the walleye pollock DPS is significantly larger than Puget Sound was supported by the following considerations: 1) the walleye pollock reproductive traits of pelagic spawning and pelagic eggs and larvae, 2) the ecological similarity of fjord-type marine habitat in Puget Sound to habitats along the coasts of British Columbia and Southeast Alaska, and 3) comparisons made with walleye pollock from areas outside of Puget Sound where much more data is available concerning the biology and population structure of walleye pollock populations. The BRT did not preclude the possibility that further information on the behavior, ecology, and genetic population structure might provide a basis for delineating smaller DPSs of walleye pollock within the Lower boreal Eastern Pacific DPS.

Although the BRT acknowledged that more studies on genetic population structure were available for analysis in the case of walleye pollock than for the other gadiforms under review, most of these genetic studies were flawed by samples having been collected outside of the spawning season, which may result in collections that represent mixtures of different populations or stocks. Most studies of genetic population structure in walleye pollock have revealed low levels of differentiation where physical barriers to migration are lacking. These genetic studies did not include spawning aggregations of walleye pollock from Puget Sound. However, microsatellite DNA data on walleye pollock showed statistically significant differences between samples from Port Townsend and populations in the southeastern Bering Sea and Gulf of Alaska. Overall, the BRT found the available evidence for genetic differentiation of walleye pollock populations at scales smaller than Asia versus North America to be ambiguous. Numerous spawning populations occur in embayments along southeastern Alaska, British Columbia, and Puget Sound and may be more or less demographically independent of one another. No genetic information on these populations is available.

The BRT examined several scenarios as to where the northern boundary of the Lower boreal Eastern Pacific DPS may occur, including: 1) the Georgia Basin, 2) the northern end of Vancouver Island, 3) Southeast Alaska to 140°W, and 4) the Aleutian Islands. Although none of the BRT members ruled out the possibility that the Georgia Basin could be the northern boundary of the DPS (scenario 1), there was little support for scenarios 2 or 4. The majority opinion of the BRT supported scenario 3. Evidence supporting a walleye pollock DPS that extends from Puget Sound northward to encompass all of Southeast Alaska includes: 1) the more or less continuous distribution of spawning sites for walleye pollock throughout the region, 2) that regulatory agencies in the area consider walleye pollock in northern British Columbia and Southeast Alaska to consist of a single stock, 3) recognition of a significant zoogeographic faunal break in Southeast Alaska, 4) the consideration that walleye pollock north through Southeast Alaska are spawning in fjords, whereas further north walleye pollock are spawning in more open water, and 5) the unlikely potential for walleye pollock from Southeast Alaska to mix with walleye pollock from the central and western Gulf of Alaska. The boundary between Gulf of Alaska and Southeast Alaska walleye pollock management units has been set at 140°W (Dorn et al. 1999b). Densities of walleye pollock vary to either side of 140°W and there is a substantial reduction in abundance east of 140°W (Dorn et al. 1999b). With the above considerations in mind, the BRT provisionally placed the northern boundary of the Lower boreal Eastern Pacific DPS at 140°W (Fig. 3).

Within the Lower boreal Eastern Pacific DPS, walleye pollock spawn in numerous geographically-discrete aggregations, including (but not limited to) Port Townsend, Tacoma Narrows (although it is uncertain whether remnants of this spawning aggregation still exist), the south-central Strait of Georgia, off the west coast of Vancouver Island, and in numerous inlets in Queen Charlotte Sound, Hecate Strait, Dixon Entrance, and the inside waters of Southeast Alaska (Figs. 3, 45, 46). Therefore, the BRT considered whether there is evidence for multiple populations or stocks of walleye pollock within the Lower boreal Eastern Pacific DPS and, perhaps, multiple DPSs within the region.

Evidence that supports a geographically smaller DPS included: 1) geographically-discrete and temporally-persistent spawning aggregations of walleye pollock, 2) regional differences in the frequency of occurrence of the trematode flatworm parasite (*Prosorhynchus* sp.), 3) synchronous trends in commercial catch between Puget Sound and the Strait of Georgia, which differs from the trends in other areas, and 4) regional demographic differences. However, the latter two lines of evidence may be related to climate or environmental factors working on a large scale (see previous section on “Approaches to the Species Question and to Determining Risk” for a general discussion of the relative usefulness of the various categories of data for DPS delineation). In addition, although spawning aggregations of walleye pollock appear to be persistent, evidence for a direct parent/offspring linkage is missing. The BRT considered the above evidence and agreed that there are probably multiple stocks of walleye pollock within the DPS. Some BRT members expressed the opinion that there is enough stock structure and local adaptation among walleye pollock to support a geographically smaller DPS that would include Puget Sound populations. Although the BRT as a whole did not find compelling evidence for multiple DPS of walleye pollock in the Georgia Basin, the precautionary approach would indicate that walleye pollock in Puget Sound should be managed as a stock separate from the Strait of Georgia. The BRT also recognized that the Lower boreal Eastern Pacific DPS may represent fish that are uniquely adapted to survive at the southern end of the species’ range.

Although the BRT could not with any certainty identify multiple populations or DPSs of walleye pollock within the Lower boreal Eastern Pacific area, they acknowledged the possibility that more than one DPS for walleye pollock may exist in the range from Puget Sound to Southeast Alaska. However, the BRT was unable to find compelling evidence that this finer DPS structure exists. As an example of the uncertainty inherent in the walleye pollock DPS decision it should be noted that none of the BRT members ruled out the possibility that there could be a DPS for walleye pollock at the level of the Georgia Basin.

Assessment of Extinction Risk

Population Status and Trends

The BRT considered the status and trends of walleye pollock in the Lower boreal Eastern Pacific DPS in their analysis of extinction risk. Although multiple DPSs within this geographic area were not ruled out, the BRT did not evaluate extinction risks for smaller areas, such as Georgia Basin. Known information about the status of stocks in the Lower boreal Eastern Pacific bioregion is described in following sections and considered in determining extinction risk. The status of walleye pollock stocks off the west coast of Washington, Oregon, California, and Alaska beyond the Lower boreal Eastern Pacific bioregion were also not considered in the analyses of extinction risk.

Puget Sound

Trends in fishery statistics for walleye pollock in Puget Sound are the basis for assessing the status of stocks (Palsson et al. 1997). The primary stock indicator for Puget Sound, north of Admiralty Inlet, was the catch rate in the bottom trawl fishery. Trawl catch rates between 1970 and 1994 were low, usually less than 3 kg/hour, except during 1978-1981, when they were about ten times higher, ranging from 21 to 46 kg/hour (Table 30). Similarly, catches were usually less than 50 mt, except during the peak 1978-1981 period when catches usually exceeded 500 mt. During 1992-1994, negligible amounts of walleye pollock were landed by the commercial trawl fishery in northern Puget Sound (Table 30). Palsson et al. (1997) reported that it is unclear whether the stock is depressed, not targeted by the fishery, or was simply unavailable to the fishery during these years.

Walleye pollock in southern Puget Sound are on the extreme southern end of their distribution, yet a sport fishery near Tacoma once made walleye pollock the most common bottomfish harvested in Puget Sound recreational fisheries. Catches in southern Puget Sound exceeded 181 mt per year from 1977 to 1986. After 1986, catches dropped and the fishery collapsed (Palsson et al. 1997). The primary stock indicator for Puget Sound, south of Admiralty Inlet, was the recreational catch rate from the WDFW boat-based recreational survey (Palsson et al. 1997). Catch rates exceeded 1.3 walleye pollock per angler trip in 1978 and 1979, then declined rather steadily to 0.5 fish per trip in 1986 and to negligible levels by 1991, where they remained through 1998 (Table 31). Due to concerns about the status of the population, the daily bag limit for walleye pollock in the recreational fishery in Puget Sound was reduced from 15 fish to five fish in 1992. The walleye pollock daily bag limit was changed from five fish per day to zero in 1997.

Recreational catches in Puget Sound remained very low during the late 1990s. Results from the WDFW boat-based recreational survey showed that 9 walleye pollock were reportedly landed during 90,000 bottomfish angler trips from Puget Sound in 1996, and results of the Marine Recreational Fisheries Statistical Survey indicate no walleye pollock were reportedly caught in recreational fisheries in Puget Sound during 1996 and 1997 (WDFW 1998). More recent data are not yet available.

Bottom trawl surveys were conducted throughout Puget Sound in 1987, 1989, and 1991. Subsequent surveys covered only portions of Puget Sound in 1994, 1995, 1996, and 1997. Estimated biomass and numbers in the population vulnerable to the survey trawl, and average size of walleye pollock within each WDFW management region (see Fig. 14) are shown in Table 32 (W. Palsson[34]). Estimates for biomass and numbers of fish in 1987 were much higher than in other years and the average sizes of walleye pollock taken were usually smaller. This may not represent a change in fish abundance, but may be due to other factors. The 1987 survey was exploratory, being the first such survey ever conducted in Puget Sound. Also, the survey vessel used in 1987 was much larger than those used in subsequent years and the survey was conducted in the fall, whereas other surveys were presumably conducted in the spring. Otherwise, there was no apparent trend, except that the abundance of walleye pollock in central Puget Sound in 1995 was much larger than in other years. For the three years when all management regions were

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[34] W. Palsson, WDFW, 16018 Mill Creek Blvd., Mill Creek, WA 98012-1296. Pers. commun. to C. Schmitt.

surveyed, estimated biomass exceeded 975 mt of walleye pollock in Puget Sound and numbers exceeded 7 million fish each year (Table 32).

British Columbia

Discrete walleye pollock stocks are present in Dixon Entrance/Hecate Strait, Queen Charlotte Sound, west coast Vancouver Island, and the Strait of Georgia. Walleye pollock in Dixon Entrance/Hecate Strait are thought to be part of a stock that includes the southern waters of southeast Alaska but the relationship with large Gulf of Alaska stocks is unclear. It is possible that high abundance in the Gulf of Alaska results in movement into northern Canadian waters (Saunders and Andrews 1998).

A stock assessment for walleye pollock in 1997 (Saunders and Andrews 1998) provides the most recent information on the status of stocks in Canadian waters. Catch histories during 1954-1996 are given for each management area in Table 33. During 1970-1991 when catch data were available for Puget Sound and the Strait of Georgia, catch patterns in the Strait of Georgia closely matched those in Puget Sound until the late 1980s when catch patterns began diverging, as shown in Fig. 40B (Schmitt et al. 1994). In the Strait of Georgia (Area 4B), excluding minor Area 12 (see Fig. 47), sustainable yield estimates range from 470 to 1,760 mt. Within Area 12, a detailed assessment has not been done and yields between 1,000 and 2,580 mt are recommended. It is believed that walleye pollock within Area 12 are not part of the Strait of Georgia stock, but rather contribute to the body of walleye pollock residing in Queen Charlotte Sound. In Queen Charlotte Sound, catches dropped from 695 mt in 1995 to 57 mt in 1996. A detailed assessment has not been completed for walleye pollock in Queen Charlotte Sound.

Off the west coast of Vancouver Island (Area 3C and 3D, see Fig. 12), walleye pollock are taken incidentally in the joint venture fishery for Pacific hake and domestic fisheries off the southwest coast of Vancouver Island. Walleye pollock catches in both fisheries increased dramatically in 1996 compared to 1995. The total catch in these fisheries was estimated to be 2,737 mt in 1996, compared to 14 mt in 1995. This increase appeared to be due to the 1994 year-class entering the fishery as two-year-olds. A detailed assessment has not been done for this area.

The walleye pollock fishery in northern Hecate Strait and Dixon Entrance (Areas 5C and 5D, see Fig. 12) occurs mainly in the winter, and landings during the 1990s have been at record highs. However, walleye pollock landings in 1996 were 882 mt, well below the quota of 3,190 mt. The status of this stock is not well known, although Saunders and Andrews (1998) recommend a quota ranging from 330 mt to 1,320 mt until an assessment can be done.

Gulf of Alaska

Walleye pollock in the Gulf of Alaska are managed as a single stock, and the exploitable biomass (age 3+) for 1999 was projected at 738,000 mt (Witherell 1999). The stock is considered to be at medium relative abundance. The 1994 year-class is forecast to be above average, primarily in Shelikof Strait. Preliminary information suggests weak year-classes in 1995 and 1996, and a moderate 1997 year-class. Under these recruitment scenarios, the biomass of spawners is expected to decline through 2003 (Witherell 1999).

A formal stock assessment for the Southeast Alaska portion of the Gulf of Alaska has not been conducted. Historically, there has been very little directed fishing for walleye pollock in Southeast Alaska, and catches in the Southeast and East Yakutat statistical areas averaged 27 mt during 1991-1998 (Table 34). However, commercial trawling is currently banned east of 140°W, and bottom trawl surveys indicated a substantial reduction in walleye pollock abundance in this region (Dorn et al. 1999b).

Stock structure of walleye pollock in the Southeast Alaska portion of the Gulf of Alaska is poorly understood and may be characterized by numerous fjord populations. In the 1996 and 1999 bottom trawl surveys, higher catch rates in Southeast Alaska occurred mainly from Cape Ommaney to Dixon Entrance, where the shelf is more extensive. Smaller fish (<40 cm) dominated the size composition for the 1993, 1996, and 1999 surveys. It is thought that these juvenile fish are unlikely to influence the population dynamics of walleye pollock in the central and western Gulf of Alaska. Ocean currents are generally northward in this area, suggesting that juvenile settlement is a result of spawning further south (Dorn et al. 1999b).

Dorn et al. (1999b) estimated the biomass of walleye pollock in Southeast Alaska from area-swept estimates of bottom trawl survey data, split to match the area east of 140°W. Walleye pollock biomass estimates from bottom trawl surveys are highly variable, partially as a result of differences in survey coverage among years. The 1996 and 1999 surveys had the most complete coverage of shallow strata in Southeast Alaska and indicated that the stock size of walleye pollock was about 30,000-50,000 mt (Dorn et al. 1999b).

Table 30. Fishery trends for walleye pollock in Northern Puget Sound (modified from Palsson et al. 1997). Data since 1994 courtesy of W. Palsson (WDFW, 16018 Mill Creek Blvd., Mill Creek, WA 98012-1296, pers. commun. to C. Schmitt). Dashes indicate data were not available.

Year	Trawl catch rate (kg/hr)	Sport catch rate (fish/trip)
1970	2.0	--
1971	0.1	--
1972	0.1	--
1973	0.8	--
1974	3.0	--
1975	0.7	--
1976	1.1	--
1977	3.9	0.0
1978	46.0	0.0
1979	37.9	0.0
1980	21.4	0.0
1981	42.9	0.0
1982	6.9	0.0
1983	1.1	0.0
1984	0.7	0.0
1985	0.3	0.0
1986	1.4	0.0
1987	1.8	0.0
1988	0.9	0.0
1989	0.6	0.0
1990	0.3	0.0
1991	0.2	0.0
1992	0.0	0.0
1993	0.0	0.0
1994	0.0	0.0
1995	0.0	0.0
1996	0.0	0.0
1997	0.0	0.0
1998	0.0	0.0

Table 31. Fishery trends for walleye pollock in Southern Puget Sound (modified from Palsson et al. 1997). The walleye pollock sport fishery in Southern Puget Sound was closed beginning in 1997. Data since 1994 courtesy of W. Palsson (WDFW, 16018 Mill Creek Blvd., Mill Creek, WA 98012-1296, pers. commun. to C. Schmitt). Dashes indicate data were not available.

Year	Trawl catch rate (kg/hr)	Sport catch rate (fish/trip)
1970	0.4	--
1971	0.5	--
1972	0.4	--
1973	2.7	--
1974	1.5	--
1975	2.1	--
1976	2.0	--
1977	1.6	0.71
1978	1.1	1.31
1979	4.1	1.37
1980	3.6	0.97
1981	1.2	0.88
1982	1.0	0.85
1983	0.5	0.59
1984	0.2	0.99
1985	0.0	0.52
1986	1.0	0.49
1987	0.5	0.26
1988	0.4	0.25
1989	0.1	0.02
1990	0.0	0.01
1991	0.0	0.00
1992	0.0	0.00
1993	0.0	0.00
1994	0.0	0.00
1995	--	0.00
1996	--	0.00
1997	--	--
1998	--	–

Table 32. Estimated biomass, number and size of walleye pollock in the Puget Sound population from WDFW trawl surveys (source: W. Palsson, WDFW, 16018 Mill Creek Blvd., Mill Creek, WA 98012-1296. Pers. commun. to W. Lenarz.). Dashes indicate data were not available.

Biomass (mt)

Year	Gulf-Bellingham	Strait of Juan de Fuca	North Sound	Hood Canal	Central Sound	South Sound	Southern areas combined
1987	842.08	909.79	1,751.87	6.96	365.29	78.30	450.55
1989	241.37	226.68	468.05	6.75	32.18	9.57	48.50
1991	101.29	564.60	737.98	0.00	15.86	1.84	17.70
1994	113.82	--	--	--	--	--	--
1995	--	--	--	--	564.67	--	--
1996	--	--	--	15.59	--	3.24	--
1995-1996	--	--	--	--	--	--	583.50
1997	177.63	--	--	--	--	--	--

Numbers (thousands of fish)

Year	Gulf-Bellingham	Strait of Juan de Fuca	North Sound	Hood Canal	Central Sound	South Sound	Southern areas combined
1987	34,410.24	38,861.56	73,271.80	55.24	2,527.40	954.54	3,537.18
1989	1,218.12	2,175.73	3,393.85	30.84	92.92	45.34	169.10
1991	1,658.25	14,317.56	7,060.63	0.00	88.46	13.03	101.49
1994	1,539.87	--	--	--	--	--	--
1995	--	--	--	--	5,993.34	--	--
1996	--	--	--	166.23	--	14.47	--
1995-1996	--	--	--	--	--	--	6,174.04
1997	1,461.73	--	--	--	--	--	--

Table 32. (Continued).

	Size (kg/ fish)						
Year	Gulf-Bellingham	Strait of Juan de Fuca	North Sound	Hood Canal	Central Sound	South Sound	Southern areas combined
1987	0.02	0.02	0.02	0.13	0.14	0.08	0.13
1989	0.20	0.10	0.14	0.22	0.35	0.21	0.29
1991	0.06	0.12	0.10	--	0.18	0.14	0.17
1994	0.07	--	--	--	--	--	--
1995	--	--	--	--	0.09	--	--
1996	--	--	--	0.09	--	0.22	--
1995-1996	--	--	--	--	--	--	0.09
1997	0.12	--	--	--	--	--	–

Table 33. Total landings (t) of walleye pollock by major statistical area, 1954-1996. Walleye pollock landed from Minor Area 12 (see Fig. 47) are indicated by (parentheses). See Figure 12 for geographical boundaries of major areas (Saunders and Andrews 1998).

	Major groundfish statistical area					
Year	4B	3C+3D	5A+5B	5C+5D	5E	Total
1954	147	3	14	0	0	164
1955	418	5	1	3	0	427
1956	380	52	5	14	0	451
1957	248	4	3	7	0	262
1958	121	0	0.3	14	0	135
1959	260	8	0.4	2	0	270
1960	95	5	4	10	0	114
1961	115	0.1	7.3	1	0	123
1962	49	6	0	12	0	67
1963	13	7	6	4	0	30
1964	33	2	5	2	0	42
1965	26	10	0	9	0	45
1966	37	0.4	1.1	82	0	121
1967	33	0	1	55	0	89
1968	16	2	7	17	0	42
1969	30	14	33	47	0	124
1970	45	0	0	8	0	53
1971	80	5	0	0	0	85
1972	71	0.3	172	1	0	244
1973	9	0.1	71	13	0	94
1974	11	0	12	49	0	72
1975	1	0	31	71	0	103
1976	26	7	469	820	0.2	1,322
1977	50	10	236	583	12	891
1978	380	6.4	293	1,711	21	2,411
1979	1,341	31.3	143	1,804	67	3,386
1980	1,056	1,693	35	1,186	18	3,988

Table 33. (Continued).

	Major groundfish statistical area					
Year	4B	3C+3D	5A+5B	5C+5D	5E	Total
1981	570	964	12	642	22	2,210
1982	100	887	7	811	1	1,806
1983	25	23	21	992	28	1,089
1984	157	113	18	627	0.1	915
1985	748	84	1	1,176	2	2,011
1986	469	100	0	95	0	664
1987	1,237	1,351	34	4	0	2,626
1988	1,095	255	4	10	0	1,364
1989	436	940	6	29	0	1,411
1990	485	622	134	330	0	1,571
1991	2,140	436	44	468	0	3,088
1992	1,620 (1,354)	1,753	395	1,356	3	5,121
1993	3,353 (3,353)	656	325	4,427	2	8,763
1994	3,082 (3,074)	192	181	1,283	61	4,799
1995	1,875 (1,875)	16	695	1,675	4	4,265
1996	705	2,837	57	882	31	4,512

Table 34. Walleye pollock catches (mt, including discards) during 1991-1998 in the Gulf of Alaska. Modified from Dorn et al. (1999b).

Year	Southeast Alaska (state)	Southeast Alaska (east of Yakutat)	Prince William Sound (state)	West of Yakutat to Shumagin Is.	Total Gulf of Alaska
1991	0	30	0	107,512	107,542
1992	1	20	1	90,835	90,857
1993	3	4	8	108,893	108,908
1994	0	2	2	107,331	107,335
1995	0	47	2,813	69,758	72,618
1996	0	2	794	50,467	51,263
1997	4	92	1,826	88,208	90,130
1998	7	1	1,657	123,742	125,407
Mean	2	25	888	93,343	94,258

Summary and Conclusions of Walleye Pollock Risk Assessment

The BRT considered extinction risk for walleye pollock in the Lower boreal Eastern Pacific DPS. In most respects, the BRT's deliberations for the walleye pollock DPS considered similar risk factors to those described earlier for Pacific cod. Walleye pollock and Pacific cod have similar life histories, except at the egg stage, and both populations in Puget Sound and off the West Coast are at the southern extreme of the range for these species. Data were insufficient to quantitatively assess the extinction risks for walleye pollock, and the same list of potential factors affecting Pacific cod abundance were considered as potential risk factors for walleye pollock. The contributions of these potential risk factors, either singly or in combination, to the current low abundance of walleye pollock in Puget Sound, are not well known.

A major difference in deliberations for these two species is that a single DPS was identified for walleye pollock whereas three scenarios were considered for Pacific cod. Also unlike Pacific cod, the populations of walleye pollock in waters of British Columbia did not appear to be declining or at low levels, although information on the status of these stocks is very limited. Consequently, walleye pollock stocks with apparent low abundance were mainly those in Puget Sound and not as widespread as for Pacific cod. In addition, walleye pollock spawn pelagic eggs whereas Pacific cod spawn demersal eggs. It is unknown whether this difference in spawning requirements contributes significantly to the different trends observed in stock conditions between the two species.

The BRT concluded that walleye pollock in the Lower boreal Eastern Pacific DPS are not in danger of extinction, nor are they likely to become endangered in the foreseeable future if present trends continue. However, most BRT members could not entirely rule out the possibility that walleye pollock in this DPS, although not presently in danger of extinction, are likely to become so in the foreseeable future.

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APPENDIX A:

LIFE HISTORY TABLES

Table A-1. Spawning duration (shaded) and peak spawning (heavy shading) of Pacific hake in selected locations.

Location Population	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Depth (m)	Temp (C°)	Source
British Columbia												
South-central Strait of Georgia				▨	▨■	■	▨			150-320	--	McFarlane and Beamish (1985)
					▨	▨	▨			50-120, 150-320	--	Shaw et al. (1990)
Stuart Channel (Gulf Islands)	▨	▨	▨	▨	▨	▨	▨			--	--	Beamish et al. (1978a)
Washington												
Port Susan			▨	▨	▨	▨	▨	▨		110-145	--	Kimura and Millikan (1977)
					■	■	■			--	--	Kimura et al. (1981)
			▨	▨	▨■	■▨	▨			--	--	Goñi (1988)
Dabob Bay			▨	■	■	▨				--	--	Fox (1997)
California												
Off southern California		▨	■	■	■▨	▨	▨			130-500	--	Bailey et al. (1982)

Table A-2. Length (cm) at first maturity, at 50% maturity (L/50), and at 100% (L/100) maturity of selected Pacific hake populations. Values in **bold** are standard lengths, others are fork length. M=males; F=females; B=both sexes. Dashes indicate data were unavailable.

Region Location	Length at first maturity	L/50	L/100	Month and Year(s) covered	Source
Southern Baja California	--	--	**12.9** (M); **14.0** (F)	Jan. 1970	MacGregor (1971)
Central Baja California	--	--	**15.9** (M); **20.2-22.2** (F)	Jan. 1970	MacGregor (1971)
Northern Baja California and Southern California	--	--	**28.5** (M); **34.0** (F)	March 1963	MacGregor (1971)
California	--	--	40.0 (B)	Before 1962	Best (1963)
Offshore Vancouver Island	--	--	45.0 (B)	1963-67	Nelson and Larkins (1970)
West Coast Vancouver Island Inlets	--	38.5 (M); 40.1 (F)	--	Aug-Sept 1983	Shaw et al. (1985b)
Puget Sound					
Port Susan	30.0 (B)	29.0 (M); 30.3 (F)	--	1965-74	Kimura and Millikan (1977)
	--	28.8 (F)	--	1982-85	Goñi (1988)
		28.9 (F)	--	1984-86	Goñi (1988)
		≅ 29.8 (F)	32.0 (F)	1980-1984	data from W. Palsson (WDFW)
		≅ 21.5 (F)	≅ 25.0 (F)	1990-1998	data from W. Palsson (WDFW)
Strait of Georgia					
South-central Strait of Georgia	--	37.0 (M); 37.0 (F)	--	Jan. 1976	Cass et al. (1980)
	--	33.1 (M); 37.1 (F)	--	Jan.-Feb. 1981	McFarlane et al. (1983)
	--	33.0 (M); 37.0 (F)	--	1974-81	McFarlane and Beamish (1985)
	--	32.0 (M); 34.5 (F)	40.0 (M); 45.0 (F)	Feb. 1983	Shaw et al. (1985a)
	--	30.2 (M); 34.2 (F)	40.0 (M); 45.0 (F)	April 1983	Shaw et al. (1985a)
	--	30.0 (M); 33.8 (F)	35.0 (M); 39.0 (F)	March 1984	Shaw et al. (1986)
	--	29.9 (M); 33.2 (F)	--	March 1985	Shaw et al. (1987)
Stuart Channel (Gulf Islands)	--	30.7 (M); 34.4 (F)	--	Feb. 1983	Shaw et al. (1985a)

Table A-3. Spawning duration (shaded) and peak spawning (heavy shading) of Pacific cod in selected locations.

Location Population	Dec	Jan	Feb	Mar	Apr	May	June	July	Depth (m)	Temp (°C)	Source
Northeast Pacific											
Alaska											
South of Kodiak Island			▨	▨	▨	▨	▨	▨	200	5.4	Dunn and Matarese (1987)
Gulf of Alaska & Aleutian Is.			▨	■	■	■	▨	▨	60-320	--	Parrack (1986)
South of Pribilof Islands		▨	▨	▨					--	--	Fredin (1985)
Eastern Aleutian Islands	▨	▨	▨	▨	▨				--	--	Fredin (1985)
British Columbia											
Hecate Strait				■					--	6.5-6.9	Westrheim (1977)
Northern Hecate Strait (5D)			■	■	▨				--	--	Foucher and Westrheim (1990)
White Rocks	▨	▨	■	▨	▨				100-120	6-7	Ketchen (1961)
Southern Hecate Strait (5C)			■	■					--	--	Foucher and Westrheim (1990)
Strait of Georgia											
Nanoose Bay		▨	▨	▨					--	--	Forrester and Ketchen (1963)
			▨	▨					70-90	7.5-8.5	Ketchen (1961)
S. W. Vancouver Island			■	■					--	7.6-7.7	Westrheim (1977)
		▨	■	■					--	--	Foucher and Westrheim (1990)
Washington											
Puget Sound											
Agate Passage		▨	■	■	▨				--	--	Bargmann (1980); Wildermuth (1986)
Port Townsend Bay		▨	▨	▨					22-37	7-9	Miller et al. (1978)

Table A-3 (continued). Spawning duration (shaded) and peak spawning (heavy shading) of Pacific cod in selected locations.

Location Population	Dec	Jan	Feb	Mar	Apr	May	June	July	Depth (m)	Temp (°C)	Source
Northwest Pacific											
Northwest Bering Sea		▨	▨	▨	▨	▨			--	--	Musienko (1970)
Gulf of Anadyr				■	■	▨			--	--	Vinnikov (1996)
Navarin region				■	■	▨			--	--	Vinnikov (1996)
Olyutorskii Bay			▨	■	▨	▨			--	--	Vinnikov (1996)
Kronotskii Gulf		▨	■	▨					--	--	Moiseev (1953)
Komandorski Islands		▨	■	■	▨	▨			--	--	Moiseev (1953)
Karagin Bay			▨	■	▨	▨			--	--	Moiseev (1953)
Ozernoi Bay			▨	■	▨	▨			--	--	Vinnikov (1996)
S. E. Kamchatka				▨	▨	▨			--	--	Moiseev (1953)
W. Kamchatka				▨	▨	▨			--	--	Moiseev (1953)
			▨	■	▨	▨			170-180	--	Rovnina et al. (1997)
Peter the Great Bay			▨	▨	▨				50-100	2-3	Moiseev (1953)
W. Sakhalin Island		▨	▨	▨					50-100	2-3	Moiseev (1953)
Japan											
South coast of Hokkaido	■	■							--	--	Hattori et al. (1992b)
Hokkaido coast	▨	▨	▨	▨					--	--	Referenced in Mishima (1984)
Mutsu Bay	▨	▨							--	--	Referenced in Mishima (1984)
	▨	▨							--	--	Referenced in Mishima (1984)
Tohoku Region	▨	▨	▨	▨					--	--	Referenced in Mishima (1984)
Yamagata Prefecture		▨	▨						--	--	Referenced in Mishima (1984)
Ishikawa Prefecture	▨	▨	▨						--	--	Referenced in Mishima (1984)
Korea											
Eastern stock											
Chinhae Bay	▨	■▨							--	5-9	Zhang (1984)
Yeongil Bay		▨	■▨						--	--	Zhang (1984)

Table A-4. Results of Pacific cod tagging during the spawning season in selected areas. Recoveries presented as percent recoveries escaping fishery during tagging operations. (Modified after Table 4 in Palsson (1990)).

	Season and year of tagging	Total tagged	Returns escaping fishery	Puget Sound (%)	Port Townsend (%)	Juan de Fuca (%)	MSA 19 (%)	US Strait of Georgia (%)	Gulf Islands (%)	MSA 29 (%)	Nanoose Bay (%)	MSA 14 (%)	WA coast (%)	SW Vancouver Island (%)	Other (%)
Agate Passage	Winter 1977	643	60	76.6	6.7	6.7	6.7	1.7	0.0	0.0	0.0	0.0	0.0	1.7	0.0
Port Townsend	Winter 1977	2456	78	12.8	12.8	64.1	3.8	1.3	1.3	0.0	0.0	0.0	1.3	0.0	2.6
Bellingham Bay	April 1968	1318	86	0.0	3.5	0.0	0.0	90.7	1.2	0.0	3.5	0.0	0.0	1.2	0.0
US Strait of Georgia	Mar-Apr 1967	2474	180	0.0	3.3	0.0	0.0	91.7	1.7	0.0	2.8	0.0	0.6	0.0	0.0
Nanoose Bay	1955-59	1975	107	0.0	0.0	0.9	6.5	41.1	22.4	6.5	2.8	13.1	2.8	3.7	0.0

Table A-5. Length (cm) at first maturity, at 50% maturity (L/50), and at 100% (L/100) maturity of Pacific cod in selected locations. M=males; F=females; B=both sexes. Dashes indicate data were unavailable.

Region Location	Length at first maturity	L/50	L/100	Month and year(s) covered	Source
Alaska					
Kodiak Island	36.0 (M); 26.0 (F)	45.0-47.0 (B)	--	Jan.-Apr. 1977-80	Brown et al. (1984)
Eastern Bering Sea	50.0 (B)	60.0 (M); 62.0 (F)	--	--	Fredin (1985)
Hecate Strait	--	50.0 (M); 55.0 (F)	--	--	Ketchen (1961)
	--	50.0 (M); 55.0 (F)	--	1960-61	Thomson (1962)
	--	48.4 (B)	--	Jan.-Feb. 1989	Foucher et al. (1989)
	--	53.0 (M); 56.0 (F)	--		Westrheim (1977)
Reef Island	--	40.3 (B)	--	Jan.-Feb. 1989	Foucher et al. (1989)
Horseshoe	--	50.1 (B)	--	Jan.-Feb. 1989	Foucher et al. (1989)
	--	48.0 (B)	--	Nov. 1987	Tyler et al. (1988)
White Rocks	--	51.9 (B)	--	Jan.-Feb. 1989	Foucher et al. (1989)
White Rocks/Bonilla	--	47.2 (B)	--	Nov. 1987	Tyler et al. (1988)
Butterworth	--	49.4 (B)	--	Jan.-Feb. 1989	Foucher et al. (1989)
Two Peaks	--	53.1 (B)	--	Jan.-Feb. 1989	Foucher et al. (1989)
Two Peaks/ Butterworth	--	54.8 (B)	--	Nov. 1987	Tyler et al. (1988)
Strait of Georgia	--	49.0 (M); 55 (F)	--	before 1961	Ketchen (1961)
Puget Sound	--	44.0 (B)	--	--	Matthews (1987)
S. W. Vancouver Island	--	50.0 (M); 53.0 (F)	--	--	Westrheim (1977)
Northwest Pacific					
W. Kamchatka	--	69.0 (M); 73.0 (F)	--	1938-39	Ketchen (1961); Thomson (1962)
Korea					
Eastern stock	58.0 (M); 62.0 (F)	--	--	--	Zhang (1984)
Western stock	32.0 (M); 38.0 (F)	--	--	--	Zhang (1984)

Table A-6. Spawning duration (shaded) and peak spawning (heavy shading) of walleye pollock in selected locations.

Location Population	**Jan**		**Feb**		**Mar**		**Apr**		**May**		**June**		**July**		**Aug**		**Sept**		**Oct**		**Nov**		**Dec**		**Spawning depth (m)**	**Temp (°C)**
Bering Sea [a]	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨					40-3300	-1.8-8.5
Aleutian Basin [b]	▨	▨	▨	▨	▨	▨																			--	--
Southeastern slope and shelf [b]					▨	▨	▨	▨	▨	▨	▨	▨													--	--
Northwest slope and shelf [b]											▨	▨	▨	▨	▨	▨									--	--
Bogoslaf Island [c]			▨	▨	▨	▨																			--	--
Gulf of Alaska																										
Gulf of Alaska [d]			▨	▨	■	■	■	■	▨	▨	▨	▨	▨	▨	▨	▨									150-350	1.1-7.2
Shelikof Strait [e, f]				▨	▨	■	■	▨	▨	▨															200-300	5.5
Resurrection Bay [g]					▨	▨	▨	▨																	--	--
Southeast Alaska [h]					▨	▨	▨	▨																	165-395	--
Auke Bay [i]						▨	▨	▨	▨																--	--
British Columbia																										
Dixon Entrance/Hecate Strait [h]			▨	▨	■	■	■	■	▨	▨															--	6-7
East coast of Moresby Is.																										
Dana Inlet [h]				?	■	■	?																		37-180	--
Selwyn Inlet [h]				?	■	■	?																		37-180	--
Mainland Inlets																										
Caamano Sound [j]					?	■	■	?																	181-366	--
Squally Channel [j]					?	■	■	?																	181-366	--
Finlayson Channel [j]					?	■	■	?																	181-366	-
Strait of Georgia																										
South-Central Strait [k]			▨	▨	▨	■	▨	▨	▨																130-200	--
South-Central Strait [h]					▨	■	■	▨																	--	7-9
Active Pass to Point Roberts [j]						?	■	▨																		--
Jervis Inlet [j]				?	▨	▨																				--
West of Texada Island [j]				?	▨	▨																				--
Halibut Bank to Entrance Is. [j]				?	▨	▨																				--

Table A-6 (continued). Spawning duration (shaded) and peak spawning (heavy shading) of walleye pollock in selected locations.

Location Population	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Spawning depth (m)	Temp (°C)
Washington														
Puget Sound														
Port Townsend [l]		▨	▨	▨									---	-
Tacoma [m]			■	■									--	--
Northwest Pacific														
Kamchatka														
Southeastern Kamchatka [n]			▨	▨	▨								--	--
Kamchatka, east coast [o]				■	■								--	--
Eastern Kamchatka [n]				? ■	?								--	--
Olyutorsky Bay [n]				■	■								--	--
Sea of Okhotsk														
Kamchatka, west coast [o]			■	■	■								--	--
Japan														
Hokkaido														
Hokkaido vicinity [p]		▨	▨	▨									--	--
Funka Bay [f]	■	■	■									▨	100-120	2-6
Cape Erimo [q]			■										--	--
Honshu														
Niigata Region [p]	▨	▨											--	--
Korea														
Gyeongbuk and Gangweon [r]											▨	■	50-100	--
Hamnan [r]												■	50-100	2-8
Hambuk [r]	▨	▨											50-100	--

[a] Bulatov (1989)
[b] Hinckley (1987)
[c] Bulatov and Sobolevskii (1991)
[d] Hirschberger and Smith (1983)
[e] Miller et al. (1986)
[f] Kendall and Nakatani (1992)
[g] Müter and Norcross (1994)
[h] Thompson (1981)
[i] Haldorson et al. (1989)
[j] Thompson and Beamish (1979)
[k] Mason et al. (1984)
[l] Walters (1984)
[m] WDFHMD (1992)
[n] Balykin (1997)
[o] Kitano (1972)
[p] Maeda (1972)
[q] Kendall and Nakatani (1992)
[r] Hamatsu and Yabuki (1995)
[s] Gong and Zhang (1986)

Table A-7. Fork length (cm) at first maturity, at 50% maturity (L/50), and at 100% (L/100) maturity of selected walleye pollock populations. M=males; F=females; B=both sexes. Dashes indicate data were unavailable.

Region Location	Length at first maturity	L/50	L/100	Month and Year(s) covered	Source
British Columbia Coast					
Dixon Entrance	--	38.7 (M); 40.5 (F)	--	1979	Shaw and McFarlane (1986)
	--	41.4 (M); 43.5 (F)	--	1980	Shaw and McFarlane (1986)
Queen Charlotte Sound	--	37.4 (M); 38.8 (F)	--	Aug 1983	Saunders et al. (1989)
West Coast Vancouver Island					
West Coast V. I.	--	37.1 (M); 40.1 (F)	--	Aug 1983	Saunders et al. (1989)
West Coast V. I. Inlets	--	38.5 (M); 40.1 (F)	--	Aug-Sept 1983	Shaw et al. (1985b)
Strait of Georgia					
Central Strait of Georgia	--	30.5 (M); 33.0 (F)	--	1979	Shaw and McFarlane (1986)
	--	30.0 (M); 32.5 (F)	--	1980	Shaw and McFarlane (1986)
	--	27.8 (M); 33.0 (F)	--	1981	Shaw and McFarlane (1986)
	--	27.1 (M); 31.9 (F)	--	Feb 1983	Saunders et al. (1989)
	--	28.9 (M)	--	Apr 1983	Saunders et al. (1989)
	--	26.0 (M); 30.2 (F)	--	Mar 1984	Saunders et al. (1989)
	--	29.0 (M); 31.0 (F)	31.0 (M); 32.0 (F)	Mar 1984	Shaw et al. (1986)
	--	32.5 (F)	--	Mar 1988	Saunders et al. (1989)
Jervis Inlet	--	32.1 (M)	--	Feb 1983	Saunders et al. (1989)
	--	35.1 (F)	--	Mar 1988	Saunders et al. (1989)
E. Mayne Island	--	29.5 (M); 34.6 (F)	--	Feb 1983	Saunders et al. (1989)
Northwest Pacific					
West Bering Sea	--	42.0 (F)	--	--	Balykin (1986)
Kronotskii Gulf	--	41.0 (F)	--	--	Balykin (1986)
Southeastern Kamchatka	--	37.0 (F)	--	--	Balykin (1986)
Eastern Kamchatka	--	--	43-45 (M)	--	Referenced in Balykin (1997)
Korea	30.0(B)	--	--	--	Gong and Zhang (1986)

Table A-8. Length-fecundity relationship for female walleye pollock from selected regions. L, fork length.

Region Location	n	F, fecundity	R^2	L=40 cm	L=50 cm	L=60 cm	Source
Northeast Pacific							
Bering Sea							
Combined Bering Sea areas [a]	91	$0.1719L^{3.6046}$	0.907	102,344	228,762	441,367	Hinckley (1987)
Southeast shelf [a]	25	$0.1926L^{3.5439}$	0.865	91,664	202,133	385,697	Hinckley (1987)
Aleutian Basin [a]	20	$469.2282L^{1.5575}$	0.769	146,755	207,745	275,965	Hinckley (1987)
Aleutian Basin (Donut Hole) [a]	118	$3.51223L^{2.89948}$	0.73	155,140	296,287	502,686	Teshima et al. (1989)
Southeast slope [a]	28	$4.6528L^{2.8066}$	0.944	145,900	272,925	455,275	Hinckley (1987)
Northwest slope [a]	38	$0.0872L^{3.7869}$	0.995	101,709	236,780	472,278	Hinckley (1987)
Gulf of Alaska							
Shelikof Strait [b]	60	$1.2604L^{3.2169}$	--	179,546	368,065	661,673	Miller et al. (1986)
Strait of Georgia							
Strait of Georgia [c]	113	23,522L-599,713	--	341,167	576,387	811,607	Mason (1985)
Central Strait of Georgia	--	$6.771L^{2.981}$	--				Thompson (1981) Shaw and McFarlane (1986)
Northwest Pacific							
Western Bering Sea [d]	42	$0.005L^{4.5613}$	0.875	101,495	280,855	645,136	Balykin (1986)
Kronotskiy Gulf	41	$0.00043L^{5.1946}$	--	90,267	287,699	741,742	Referenced in Balykin (1986)
Southeast Kamchatka	37	$0.19L^{3.7223}$	--	174,623	400,710	789,889	Referenced in Balykin (1986)
Japan							
Northeast Sea of Japan [a]	--	$0.16L^{3.72}$	--	145,809	334,417	658,935	Zver'kova (1977)
Funka Bay [e]	94	$0.00000873L^{3.98}$	--	198,250	481,853	995,534	Kendall and Nakatani (1992)
Southeastern Hokkaido [f]	50	$0.00000178L^{4.25}$	0.92	203,786	526,069	1,141,728	Hamatsu et al. (1993)

[a] yolked oocytes

[b] oocytes ≥ 0.198 mm

[c] linear equation, yolked oocytes ≥ 0.180 mm

[d] all oocytes

[e] yolked oocytes, Length in mm.

[f] Length in mm.

APPENDIX B:

PROJECTIONS FOR PORT SUSAN PACIFIC HAKE POPULATION

Projections for Port Susan Pacific hake population

Conditions that prevailed during the 1982 to 1999 period were assumed to continue for the projections. Population productivity was assumed to not change. Warm conditions have prevailed since 1976 (Fig. 6). These conditions may have lowered productivity. Conditions may become cooler in the future (1999 and early 2000 were cool). If so, productivity may be higher than assumed for the projections and the results may be too pessimistic. Human consumption was assumed to be zero. Consumption of Pacific hake by California sea lions during the 1986-1999 period was assumed to continue at the same rate. As previously described, it appears that numbers of California sea lions in Puget Sound increased until 1986 and then fluctuated without trend. Consumption of Pacific hake by harbor seals was assumed to be at 1999 levels. Harbor seal counts had increased in the Puget Sound and Eastern Bays, but Steve Jeffries (S. Jeffries[35]) expressed the opinion that they may have reached their carrying capacity in the Sound. If the harbor seal populations continue to increase after 1999, Pacific hake consumption is likely to increase and projection results would tend to be too optimistic. Pacific hake biomass was projected for 100 years starting in 2000 for each of the hypothetical 10 levels of predation by pinnipeds. 1000 runs were made for each level of projections.

The first projections were made using equation (1) to describe stock productivity. Biomass in year (i+1) was projected to be:

$$\mathrm{Bio}(i+1) = (1+ \mathrm{Prod}(i))\mathrm{Bio}(i) - (C_{sl}(i) + C_{hs}) \qquad (4)$$

Prod(i) was drawn randomly with equal probability from the 1982-1998 set of productivities shown in Table 11. When i was greater than 1999, $C_{sl}(i)$ was drawn randomly with equal probability from the 1986-1999 set of consumption by sea lions at the specified hypothetical level shown in Table 9. When i was 1999 $C_{sl}(i)$ was set to the value shown in Table 9 for 1999. C_{hs} was set at consumption by harbor seals at the specified hypothetical level shown in Table 10. Results indicate that the probability of extinction of the Port Susan population within a short period of time is high, if the assumed model is valid (Fig. B-1).

Projections were next made using equation (2) to describe stock productivity. Biomass in year (i+1) was projected to be:

$$\mathrm{Bio}(i+1) = \mathrm{Bio}(i)e^{-(Z(i))}. \qquad (5)$$

Where,

$Z(i) = M + F(i) - G(i)$,

M = Constant instantaneous rate of natural mortality,

F(i) = Instantaneous rate of exploitation mortality from all causes in year i,

---

[35] S. Jeffries, WDFW, 600 Capitol Way N., Olympia, WA 98501-1091. Pers. commun. to W. Lenarz.

$F(i) = F_{sl}(i) + F_{hs}(1999)$,

$F_{sl}(i)$ = Instantaneous rate of mortality caused by exploitation by sea lions in year i, (Drawn randomly from 1986-1999 set in Table B-1, except set to value for 1999 when i =1999.)

$F_{hs}(1999)$ = Instantaneous rate of mortality caused by exploitation by harbor seals in 1999 (from Table B-2), and

$G(i)$ = Instantaneous rate of productivity in year i. It includes migration to and from other populations, and was drawn randomly from 1982-1998 set in Table 12.

The population never actually reached 0 when equation 5 was used. Summarizations were made of probabilities of the biomass falling below 10 kg, 1 mt, or 50 mt or approximately 100, 10,000, or 500,000 fish. (In recent years the average weight of Port Susan Pacific hake was about 0.1 kg, Table 7.) Pacific hake usually occur in loose aggregations (if not dense schools). Individual trawl catches can be as large as 50 mt. A biomass of 10 kg probably would be undetectable and when breeding populations fall to around 100 individuals, genetic bottlenecks are likely. The IUCN proposed that populations of marine fish be considered vulnerable when numbers drop below 10,000 animals (Musik 1999). Results of the projections indicate that the probability of biomass falling to less than 1 mt is below 0.5 for 100 years (Figs. B-2, B-3). However the probability of biomass falling to less than 50 mt exceeds 0.5 in about 55 years under the highest hypothetical level of predation by pinnipeds (Fig. B-4).

Generation time for Port Susan Pacific hake was estimated to be about 4 years. Musick (1999) suggested examining trends in numbers over three generations as an indicator of risk. Projected 12 year trends of average biomasses under model 2 range from increasing under the lowest level of pinniped predation to very little change under the highest level of pinniped predation (Fig. B-5). However the averages can be misleading because average values are strongly influenced by relatively very robust results of some of the replications. Projected 12 year trends of median biomasses under model 2 indicate that 50% or more of the replicates had negative 12 year trends (Fig. B-6).

In summary, results of the hypothetical projections indicate that uncertainty about rates of predation of Pacific hake by pinnipeds and the form of the relationships between Pacific hake predation by pinnipeds and commercial fishing precludes definitive conclusions concerning the risk of extinction of the Port Susan Pacific hake population. It seems unlikely that reality will be as pessimistic as projected using model 1. Even if sea lions continue to target Pacific hake in a model 1 fashion on the Port Susan spawning grounds if Pacific hake biomass falls to very low levels, it seems that model 2 would be more appropriate for other spatial-temporal situations. However, model 2 may be too optimistic because Pacific hake and pinniped behavior may result in pinnipeds being able to increase exploitation rates on Pacific hake with positive net energy results even when overall Pacific hake abundance falls to very low levels.

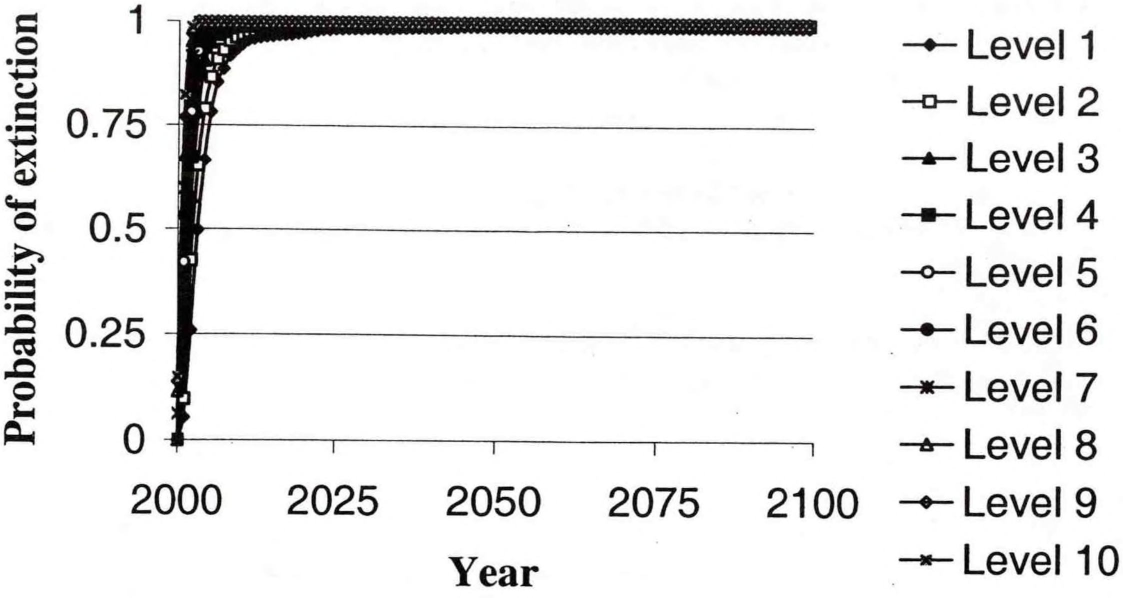

Figure B-1. Estimates of probability of extinction of the Port Susan population of Pacific hake using Model 1 and 10 hypothetical levels of pinniped predation.

Table B-1. Ten hypothetical levels of Fsl(i) in Puget Sound. Ten levels are based on assumptions detailed in text.

Year	Ten hypothetical levels of Fsl(i)									
1986	0.04	0.05	0.07	0.08	0.09	0.11	0.12	0.13	0.15	0.16
1987	0.02	0.03	0.04	0.05	0.05	0.06	0.07	0.08	0.08	0.09
1988	0.02	0.02	0.03	0.04	0.04	0.05	0.05	0.06	0.07	0.07
1989	0.01	0.02	0.03	0.03	0.03	0.04	0.04	0.05	0.05	0.06
1990	0.02	0.02	0.03	0.04	0.04	0.05	0.05	0.06	0.07	0.07
1991	0.03	0.04	0.05	0.06	0.06	0.08	0.08	0.09	0.10	0.11
1992	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.10	0.11	0.12
1993	0.04	0.05	0.06	0.08	0.09	0.10	0.11	0.13	0.14	0.15
1994	0.06	0.08	0.10	0.12	0.14	0.16	0.18	0.19	0.21	0.24
1995	0.07	0.09	0.12	0.14	0.16	0.19	0.22	0.24	0.26	0.29
1996	0.05	0.07	0.09	0.11	0.12	0.14	0.16	0.17	0.19	0.21
1997	0.03	0.04	0.06	0.07	0.08	0.09	0.10	0.11	0.12	0.13
1998	0.02	0.03	0.04	0.05	0.06	0.07	0.07	0.08	0.09	0.10
1999	0.02	0.03	0.04	0.05	0.05	0.06	0.07	0.08	0.08	0.09

Table B-2. Ten hypothetical levels of Fhs(1999) in Puget Sound and Eastern Bays combined. Ten levels are based on assumptions detailed in text.

Ten levels of Fhs(1999)									
0.06	0.08	0.10	0.11	0.13	0.15	0.16	0.18	0.19	0.21

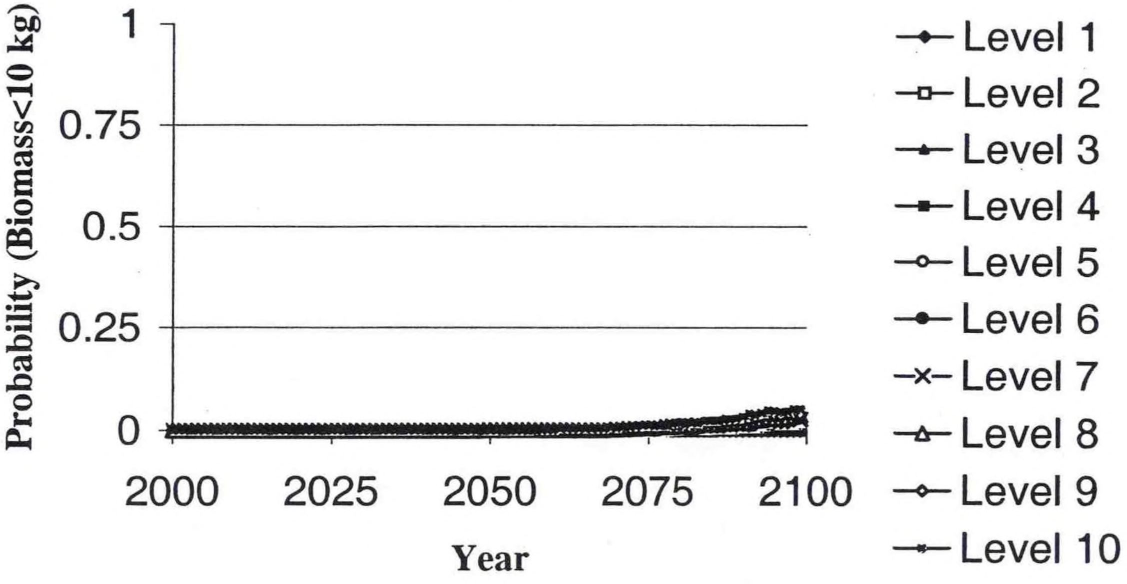

Figure B-2. Estimates of probability that biomass of the Port Susan population of Pacific hake is less than 10 kg using Model 2 and 10 hypothetical levels of pinniped predation.

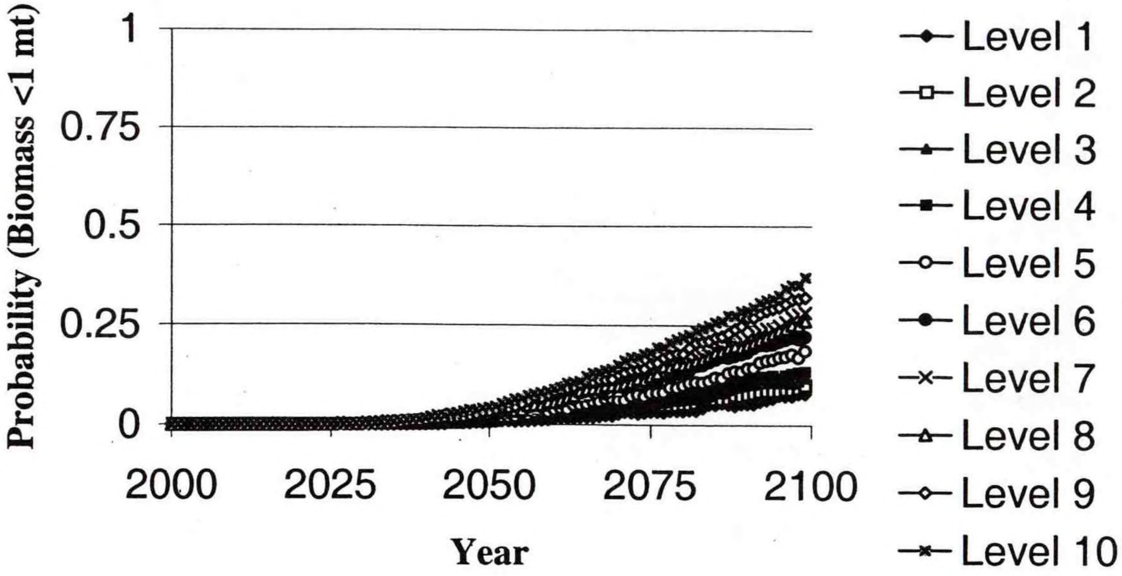

Figure B-3. Estimates of probability that biomass of the Port Susan population of Pacific hake is less than 1 mt using Model 2 and 10 hypothetical levels of pinniped predation.

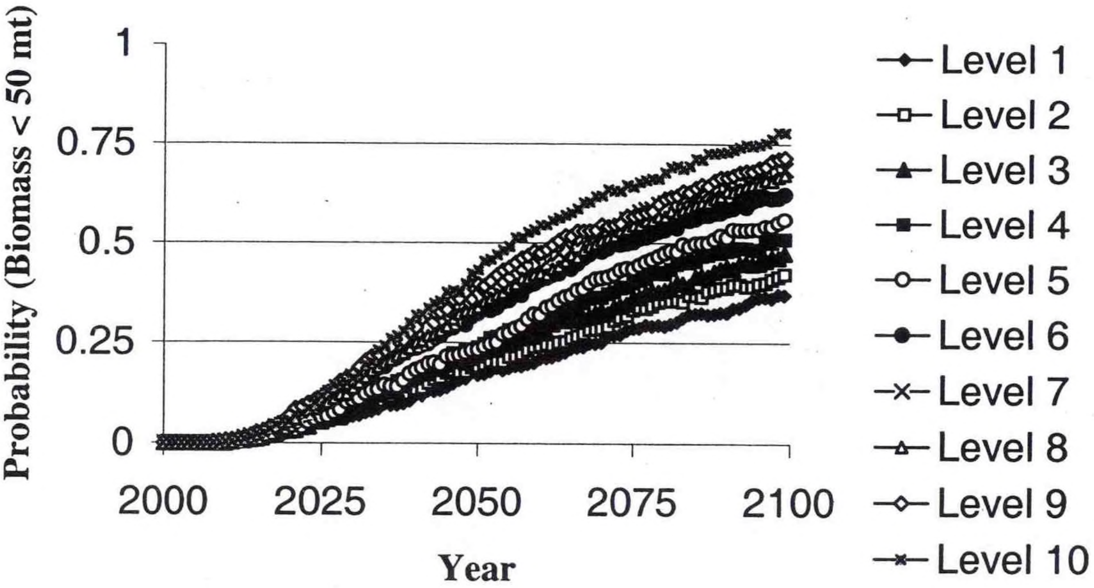

Figure B-4. Estimates of probability that biomass of the Port Susan population of Pacific hake is less than 50 mt using Model 2 and 10 hypothetical levels of pinniped predation.

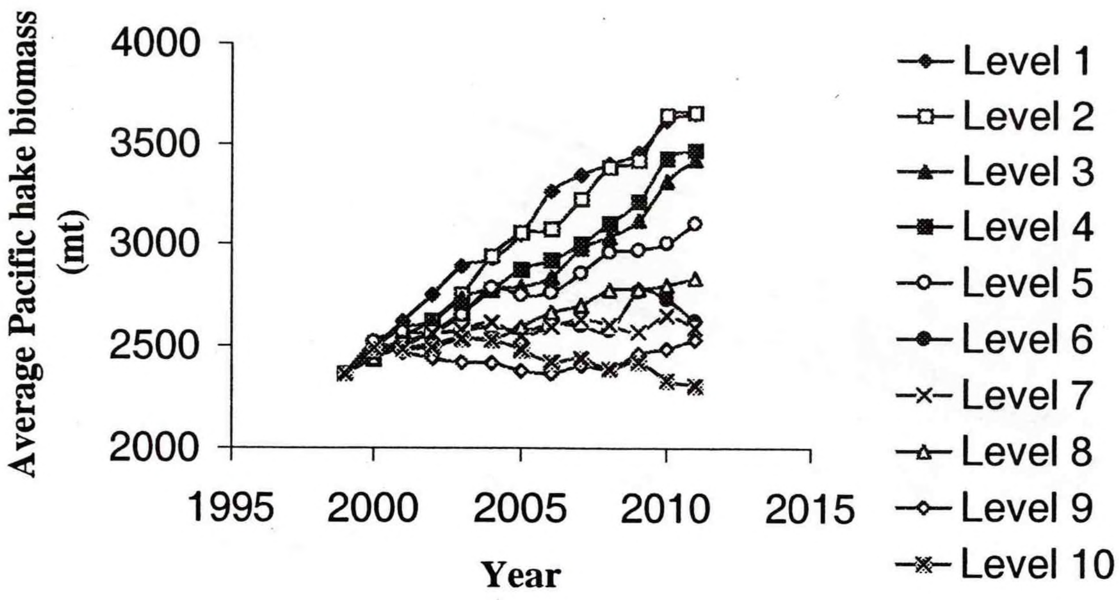

Figure B-5. Projected 12 year trends in average Port Susan Pacific hake biomass using Model 2 under 10 hypothetical levels of pinniped predation.

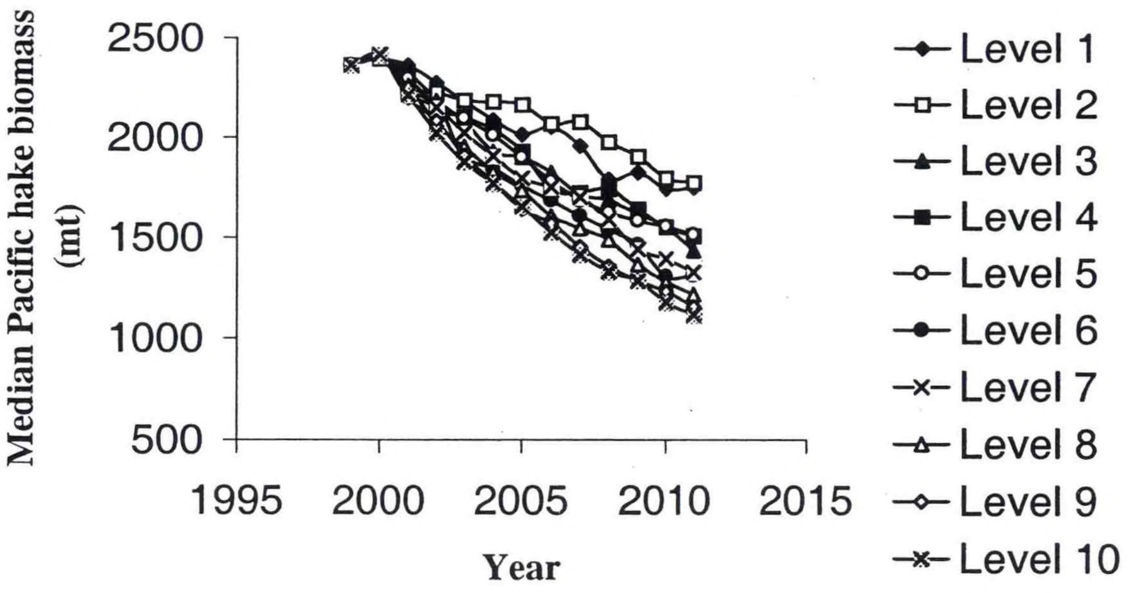

Figure B-6. Projected 12 year trends in median Port Susan Pacific hake biomass using Model 2 under 10 hypothetical levels of pinniped predation.

GLOSSARY

allele

An alternative form of a gene that can occur at the same location (locus) on homologous (paired) chromosomes. A population can have many alleles for a particular locus, but an individual can carry no more than two alleles at a diploid locus.

allozymes

Alternative forms of an enzyme that have the same function, are produced by different alleles, and are often detected by protein electrophoresis.

anthropogenic

Caused or produced by human action.

Biological Review Team (BRT)

The team of scientists who evaluated a scientific information considered in the National Marine Fisheries Service status review.

co-managers

Federal, state, and tribal agencies that cooperatively manage groundfish in the Pacific Northwest.

CPUE

Catch-per-unit effort

DNA (deoxyribonucleic acid)

DNA is a complex molecule that carries an organism's heritable information. DNA consists of a polysugar-phosphate backbone from which the bases (nucleotides) project. DNA forms a double helix that is held together by hydrogen bonds between specific base pairs (thymine to adenine, guanine to cytosine). Each strand in the double helix is complementary to its partner strand in terms of its base sequence. The two types of DNA commonly used to examine genetic variation are mitochondrial DNA (mtDNA), a circular molecule that is maternally inherited, and nuclear DNA, which is organized into a set of chromosomes (see also allele and electrophoresis).

distinct population segment (DPS)

A population, or group of populations of a vertebrate organism that is “discrete” from other populations and “significant” to the biological species as a whole.

electrophoresis

Electrophoresis is the movement of charged particles in an electric field. This process has been developed as an analytical tool to detect genetic variation revealed by charge differences on proteins or molecular weight in DNA. Data obtained by electrophoresis can provide insight into levels of genetic variability within populations and the extent of genetic differentiation between them.

endangered species

A species in danger of extinction throughout all or a significant portion of its range.

EPA

U.S. Environmental Protection Agency

ESA

U.S. Endangered Species Act

evolutionarily significant unit (ESU)

An ESU represents a distinct population segment of Pacific salmon under the Endangered Species Act that 1) is substantially reproductively isolated from nonspecific populations and 2) represents component an important component of the evolutionary legacy of the species.

euryhaline

Organisms that tolerate a wide range of salinities.

F statistics

A series of coefficients used to quantify the distribution of genetic variation within and among populations and groups of populations. Most often used is FST, which describes overall differentiation among a group of populations, or more specifically, the correlation of genes among individuals in each population.

genetic distance

A quantitative measure of genetic difference between a pair of samples.

genetic drift

The occurrence of random changes in the gene frequencies of populations.

Georgia Basin

The semi-enclosed marine basin comprised of the Strait of Georgia, Puget Sound, and the Juan de Fuca Strait together with the lands that drain into these marine waters.

haplotype

The collective genotype of a number of closely linked loci; the constellation of alleles present at a particular region of genomic or mitochondrial DNA.

heterozygous

The condition of having two different alleles at a given locus of a chromosome pair.

heterozygosity

A measure of allelic diversity at a locus (or averaged over several loci) whereby alternate alleles at a locus are different.

locus (pl. loci)

The site on a chromosome where a gene is found; often used more or less synonymously with gene (cf. polymorphic locus, allozymes, isozymes).

meristic trait

A discretely varying and countable trait (e.g., number of fin rays or basibranchial teeth); cf. traits with continuous variation (e.g., weight, length) or discrete variation (e.g., male, female, mature, immature).

microsatellite

A class of repetitive DNA. Microsatellites are simple sequence repeats one to eight nucleotides in length. For example, the repeat unit can be simply "CA", and might exist in a tandem array (CACACACACA...) 50 or more repeat units in length. The number of repeats in an array can be highly polymorphic

Minor Statistical Area (MSA)

Geographical subdivisions of the marine waters of the Strait of Juan de Fuca and Strait of Georgia used by the Canadian Department of Fisheries and Oceans for marine fish management purposes.

mitochondrial DNA (mtDNA)

The DNA genome contained within mitochondria and encoding a small subset of mitochondrial functions; mtDNA is typically circular and 15-20 kilobases in size, containing little noncoding information between genes.

morphometric trait

A discretely varying trait related to the size and shape of landmarks from whole organs or organisms analyzed by appropriately invariant biometric methods in order to answer biological questions.

NMML

National Marine Mammal Laboratory

NWFSC

Northwest Fisheries Science Center

nuclear DNA (nDNA)

The DNA contained in the chromosomes within the nucleus of eukaryotic cells. The nuclear genome in Pacific salmon is approximately 4.6 billion base pairs in size.

otolith

Crystalline calcium-carbonate structures within the inner ear of fish. These structures have distinctive shapes, sizes, and internal and surface features that can be used for age determination and species identification.

phenotype

The appearance (or other measurable characteristic) of an organism that results from interaction of the genotype and environment.

polymorphic

Having more than one form (e.g., polymorphic gene loci have more than one allele).

polymorphic locus

A locus characterized by more than one allele in a sample. If different alleles can be detected at a gene locus, the locus is considered polymorphic. If all alleles are of the same type, the locus is considered monomorphic. Many population genetic analyses are based on the frequency of different alleles at polymorphic loci.

population

A group of individuals of a species living in a certain area that maintain some degree of reproductive isolation.

principal component analysis (PCA)

An ordination technique for analyzing data from several variables, such as allelic frequencies or morphological data. The method finds linear trends (principal components) through the clouds of sample points in multidimensional space. These principal components account for the greatest amount of variation present in the data. The residual variance is removed from the data with the calculation of each successive principal component.

protein electrophoresis

An analytical laboratory technique that measures differences in the amino acid composition of proteins from different individuals. Because the amino acid sequence of proteins is coded for by DNA, data provided by protein electrophoresis provide insight into levels of genetic variability within populations and the extent of genetic differentiation between them. See electrophoresis.

Puget Sound

A coastal fjord-like estuarine inlet of the Pacific Ocean located in northwest Washington State between the Cascade and Olympic mountains and covering an area of over 9,000 km^2 including 3,700 km of coastline.

RFLP

(restriction fragment length polymorphism) variations occurring within a species in the length of DNA fragments generated by a specific restriction endonuclease. Such variation is generated either by base substitutions that cause gain or loss of sites, or by insertion/deletion mutations that change the length of fragments independent of restriction site changes.

species

Biological - A small group of organisms formally recognized by the scientific community as distinct from other groups. legal - refers to joint policy of the USFWS and NMFS that considers a species as defined by the ESA to include biological species, subspecies, and DPSs.

Strait of Georgia

The body of water separating the southern portion of Vancouver Island and the British Columbia mainland. The strait extends from Cortes Island and Desolation Sound in the north to the San Juan Islands in the south.

Strait of Juan de Fuca

The body of water separating the southern portion of Vancouver Island and the Olympic Peninsula in Washington. The strait extends from the Pacific Ocean east to the San Juan and Whidbey Islands.

threatened species

A species not presently in danger of extinction but likely to become so in the foreseeable future.

trophic

Pertaining to nutrition. A trophic migration would be a movement of fish to a feeding area.

WDFW

Washington Department of Fish and Wildlife, which co-manages groundfish fisheries in Washington State with WWTIT and other fisheries groups. The agency was formed in the early 1990s by combining the Washington Department of Fisheries and Washington Department of Wildlife.

WWTIT

Western Washington Treaty Indian Tribes, an organization of Native American tribes with treaty fishing rights recognized by the United States. WWTIT co-manages groundfish fisheries in western Washington in cooperation with WDFW and other fisheries groups.

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