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Chapter 9

Biology, fisheries, assessment and management of Pacific hake (*Merluccius productus*)

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9.1 Introduction

Pacific hake (*Merluccius productus*) is the most productive and economically important commercial fish species off the west coast of North America, south of Alaska. The largely mid-water and domestic fisheries catch upwards of 200,000 t each year and are managed jointly by the United States and Canada. Pacific hake migrate along the coast each year, typically spawning near the southern end of their range in the winter. Their movement, growth and reproductive success are all heavily dependent on environmental conditions along the coast. Pacific hake are an important part of the California Current Large Marine Ecosystem (CCLME) along with being a key target for North American west coast fisheries.

9.2 Stocks

Three or more biologically and genetically distinct stocks of Pacific hake occur along the west coast of North America. These stocks include the large coastal stock and smaller, spatially restricted inshore stocks, one within Puget Sound and another in the Strait of Georgia (Iwamoto *et al.*, 2004; Figure 9.1). A 'dwarf' Pacific hake stock had previously been recognised off Baja California but is now considered a separate species (Vrooman and Paloma, 1977; Ermakov, 1982; Mathews, 1985; Grant and Leslie, 2001). Here, we focus on the large coastal stock of Pacific hake, which is the most abundant groundfish population in the CCLME. The majority of this population migrates annually from offshore of southern California and Mexico (~lat. 30–35°N) during the winter spawning season to coastal areas as far north as Haida Gwaii (formerly the Queen Charlotte Islands; lat. 53°N) or, in some years, southeast Alaska (~58°N), during the spring, summer and fall. Although there is thought to be little overlap in time and space among hake stocks, recent research supports the hypothesis that hake from the separately managed inshore stocks overlap with the large coastal stock, particularly in the summer. Gao *et al.* (2010) found evidence of two stocks of hake off the Washington coast based on isotopic signatures in the core of otoliths. This finding is consistent with Puget Sound or Strait of Georgia stocks being found throughout the Strait of Juan de Fuca and near the northern-western tip of Washington. In addition, King *et al.* (2012) reported genetic evidence, supported by differences in biological parameters and parasite infection levels, of three separate stocks of resident Pacific hake in Canadian waters. They also found that there was likely mixing of inshore resident stocks and the coastal stock during the summer, especially

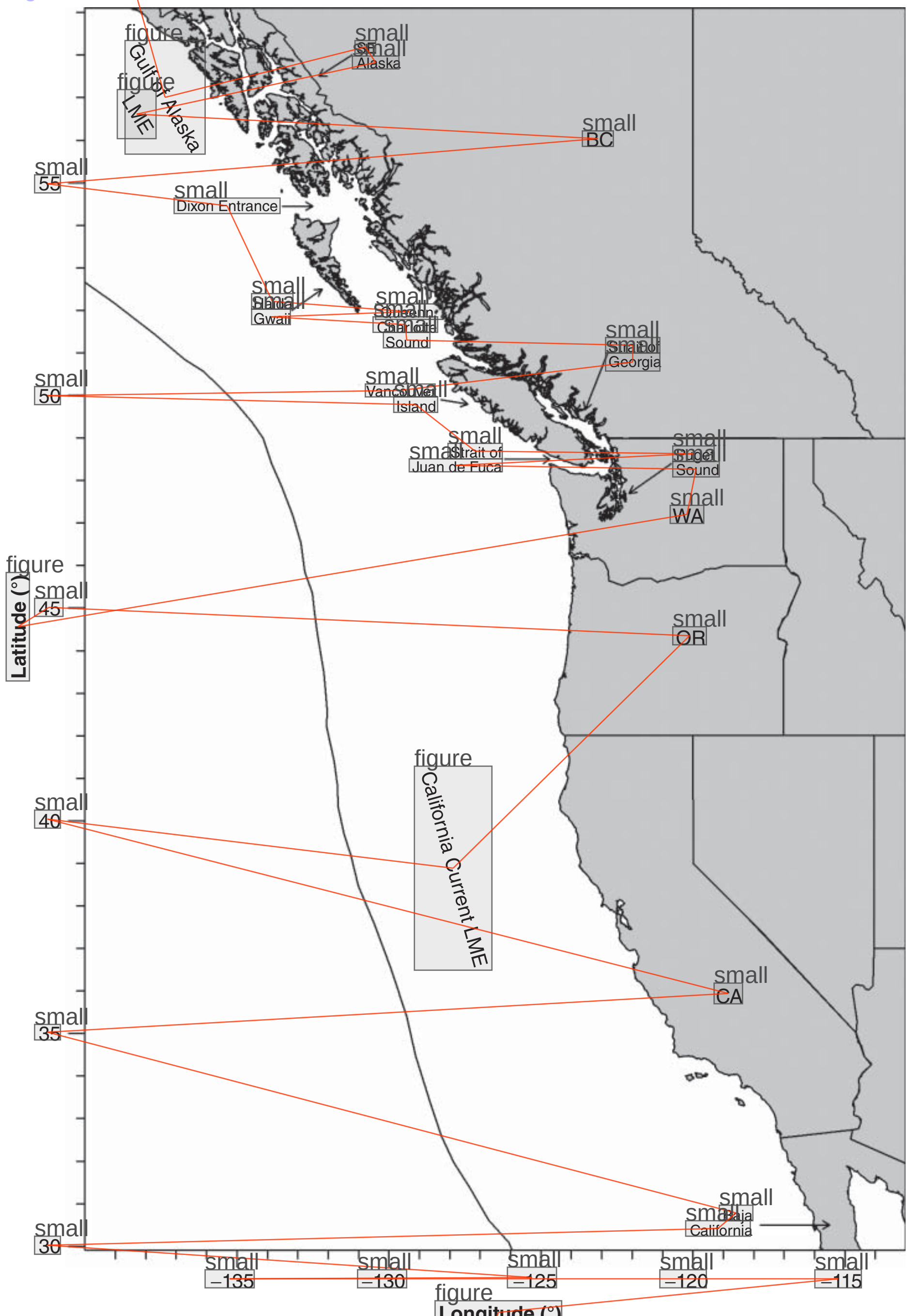

Figure 9.1 Map of West Coast of North America from Baja California to Southeast Alaska, with labels indicating center of California Current LME and important geographic locations, including those where smaller stocks of Pacific hake reside. In the summer, the Strait of Georgia stock extends into Queen Charlotte Sound, while the Puget Sound stock may extend through the Strait of Juan de Fuca. The large coastal stock occurs along the entire coast depicted here, depending on the year (and time of year).

in Queen Charlotte Sound where the Canadian fishery operates to varying degrees each summer. On the basis of these two studies, mixing of inshore resident and migratory coastal stocks occurs in some, if not all years, resulting in some harvest of resident Pacific hake by the fishery targeting the coastal stock. The exploitation level of inshore stocks is likely dependent on the relative population sizes of coastal and inshore stocks and their spatial distributions in any year.

9.3 Biology, life history and ecology

9.3.1 Environment

Pacific hake reside primarily within the CCLME. Climate and ocean conditions affect the distribution and abundance of coastal Pacific hake throughout its life history (cf. Ressler *et al.*, 2007 for a more extensive review of this topic). The California Current exhibits spatially complex and temporally varied flow dynamics. During the spring and summer, northerly wind stress drives coastal upwelling and southward surface flow, while in fall and winter, southerly wind stress leads to downwelling and northward surface flow (e.g. Hickey, 1979; Strub and James, 2000; Figure 9.2, top). Along Vancouver Island, the large volumes of freshwater discharged from coastal rivers onto the continental shelf result in northward surface flow in the summer as well (Thomson *et al.*, 1989). The California Undercurrent, a subsurface northward flow, exists year-round on the continental shelf and upper slope, at a varying proximity to the shelf break (reviewed by Hickey, 1989; Huyer *et al.*, 1989; Thomson *et al.*, 1989; Pierce *et al.*, 2000; Agostini *et al.*, 2006; Figure 9.2, bottom). The Undercurrent is nearly contiguous from lat. 33° to 51°N, with a relatively narrow core (10–20 km) at depths of 200–300 m where mean sustained velocities of 10–20 cm/ s have been recorded (Pierce *et al.*, 2000). Upwelling brings cool, dense and nutrient-rich waters to or near to the surface along the coast, increases the productivity of the CCLME (Mann and Lazier, 1996; Batchelder *et al.*, 2002) and contributes to favourable feeding areas for Pacific hake during the summer months.

Climate forcing at inter-decadal (e.g. regime shifts) and inter-annual time scales (e.g. El Niño/La Niña events) affects the distribution and productivity of marine species within the CCLME (McFarlane *et al.*, 2000; Benson and Trites, 2002; King, 2005). Regime shifts, detected from coincidental changes in the distribution, survival, and abundance of many marine plankton and fish species, occurred in 1925, 1947, 1977, 1989 and 1998 (King, 2005). These shifts represent relatively abrupt, widespread and persistent changes in productivity, with effects cascading through all trophic levels. Within these regimes, ocean conditions are affected by El Niño events, resulting in warming of coastal waters offshore of the shelf-break and stronger poleward flow in the CCLME, and La Niña events, that couple cooling of surface temperatures with reduced poleward flow. A warming trend detected in all global oceans accounts for

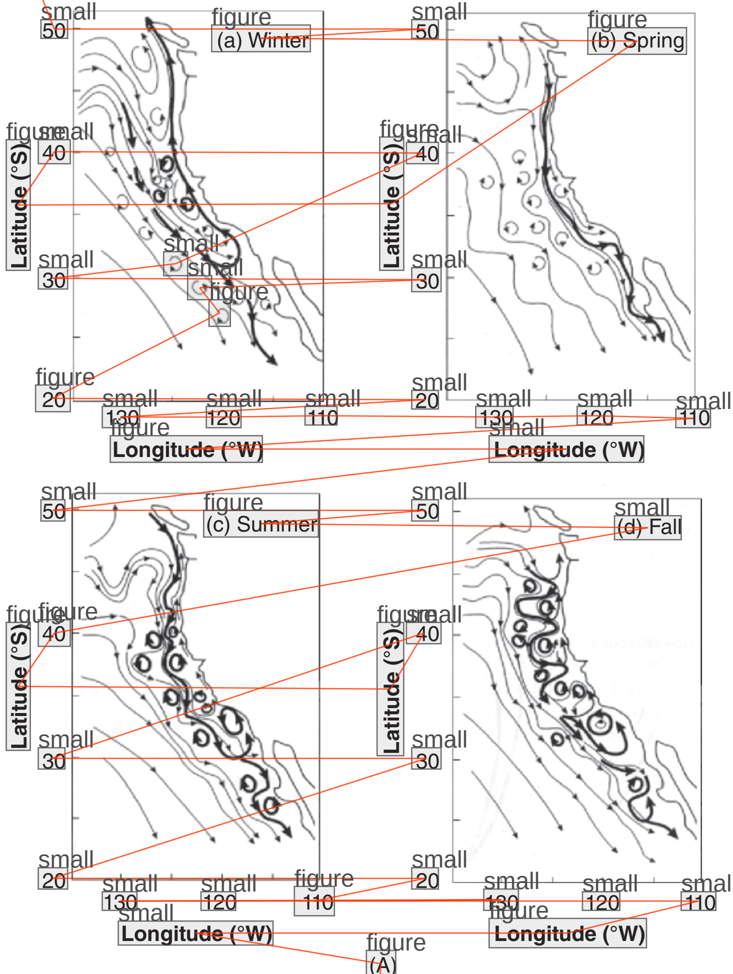

Figure 9.2A Circulation in the CCLME. Conceptual drawing of seasonal evolution (top) by Strub and James (2000) based on the literature and analysis of satellite altimetry data. Note prevailing poleward flow on shelf and slope in winter (a), and prevailing equatorward flow between spring and fall transition (b–d.) Seaward of the shelf and slope, equatorward flow exists all year. Meanders and eddies are superimposed upon broad patterns, particularly during summer and fall. At bottom (**Figure 9.2B**), coast-wide average velocity section showing equatorward flow (negative) near the surface and the poleward (positive, shaded) undercurrent beneath during summer 1995. This velocity section is based on acoustic Doppler current profiler (ADCP) data collected during the 1995 acoustics-trawl survey for Pacific hake (7 July–28 August, 1995) and analyzed by Pierce *et al.* (2000). The depth range for this average section is from 22 to 125–325 m, depending on bottom depth. This figure reprinted from review by Ressler *et al.* (2007), originally based on Strub and James (2000; top panel) and Pierce *et al.* (2000; bottom panel) with permission of Elsevier.

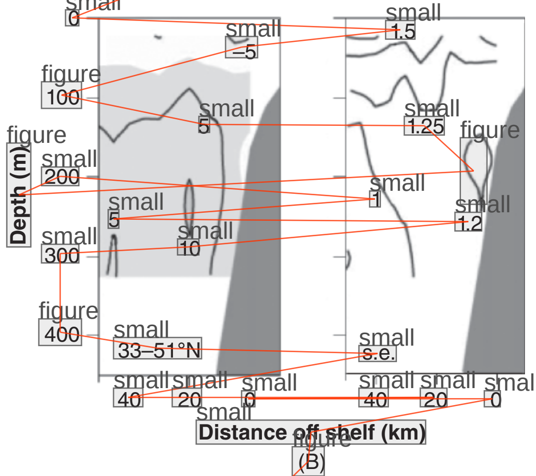

Figure 9.2B

a 1°C increase in average annual water temperature in the CCLME over the past 50 years (Di Lorenzo *et al.*, 2005). This warming is likely to have widespread consequences for the CCLME, including the patterns in spawning, recruitment, abundance and distribution of the coastal Pacific hake stock that we describe in this chapter. King *et al.* (2011) concluded that warmer years would likely reduce recruitment success for Pacific hake and/or result in a northward shift in spawning and rearing areas. However, increased upwelling could increase euphausiid density at the continental shelf break resulting in increased growth of Pacific hake, while warmer conditions would likely result in farther average northward migration and development of resident stocks farther north as well.

9.3.2 Embryos and larvae

Spawning is hypothesised to occur in dense aggregations several 100 km offshore of southern and Baja California in January through March, at depths of 100–500 m (Alverson and Larkins, 1969), but spawning aggregations have seldom been directly observed (Alverson and Larkins, 1969; Bailey *et al.*, 1982; Stauffer, 1985; Saunders and McFarlane, 1997). Occasional reports of successful spawning north of this region have been made over the years (Bailey, 1980; Hollowed, 1992; Dorn, 1996; Saunders and McFarlane, 1997; Benson *et al.*, 2002) consistent with the expected shift associated with warming of the CCLME. Fertilised embryos and larvae remain beneath the mixed layer (Bailey, 1982), and as larvae grow, they move inshore to the continental shelf and slope (Bailey, 1981).

The survival of larval Pacific hake is strongly influenced by environmental conditions (such as upwelling, advection and water temperature) experienced during the first few months after spawning (Bailey, 1981; Bailey and Francis, 1985; Bailey *et al.*, 1986; Hollowed, 1992; Agostini, 2005). Cold ocean years typically produce weak year classes, while more variation in year class strength occurs among warm ocean years. Cold ocean years along the west coast also have stronger upwelling, equatorward transport after the spring transition and offshore advection (the opposite conditions prevail in warm years). Depressed Pacific hake recruitment in cooler years may be due to advection of embryos and larvae to un-favourable habitat or the presence of different dominant zooplankton prey and/or predator species (Bailey, 1981; Hollowed, 1992; Agostini, 2005). Warm years with weak upwelling and offshore advection early in the year might allow larvae to quickly reach favourable coastal habitat and take advantage of upwelling-driven biological production later in the year (Hollowed and Bailey, 1989).

9.3.3 Juveniles and adults

9.3.3.1 North–south distribution

The north–south distribution of the migrating coastal stock ranges on average from about 25° to 55°N, with adults from southern and offshore spawning areas feeding off Oregon, Washington and British Columbia from April/May through September/October (Alverson and Larkins, 1969; Bailey *et al.*, 1982; Francis, 1983; Dorn, 1995; Figure 9.3, left panel). Age structure, size

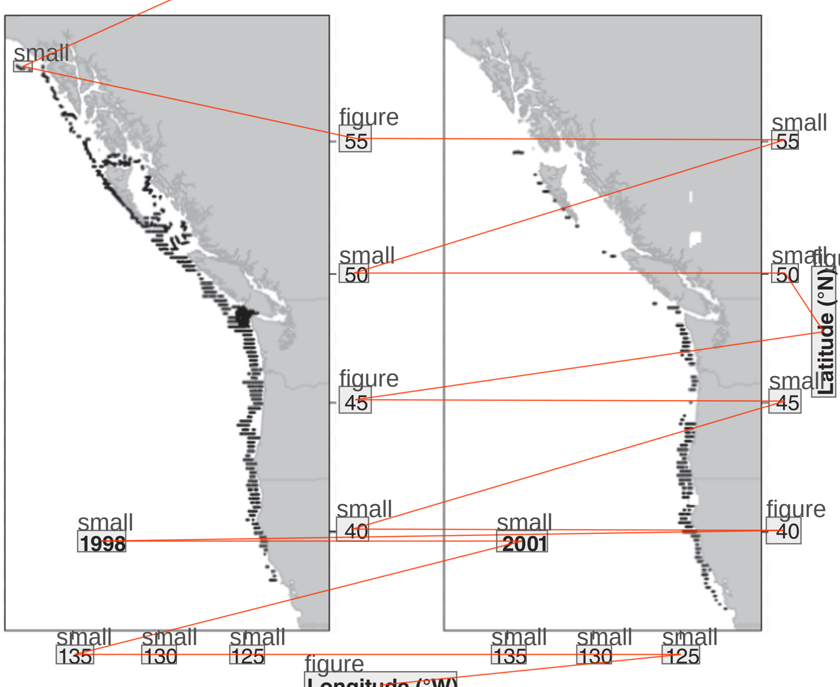

Figure 9.3 Observations of the presence of Pacific hake in the acoustic survey in two contrasting years demonstrating the variability in distribution between warm (1998) and cold (2001) years.

distribution and environmental conditions are all important factors in determining the spatial distribution and annual coast-wide migration of the Pacific hake stock and its availability to both monitoring surveys and commercial fishing operations. Usually, the oldest, largest fish travel the greatest distances north into Canadian waters (Stauffer, 1985; Dorn, 1992) likely because they can sustain higher swimming speeds (Ware, 1978; Francis, 1983). A greater fraction of these fish also tends to be females, which, beyond the age of 3 years are on average larger than males (Dark, 1975; Beamish and McFarlane, 1985). During warm years, Pacific hake migrate farther northward than in cool years (Dorn, 1995; Ware and McFarlane, 1995; Saunders and McFarlane, 1997; Wilson *et al.*, 2000; Figure 9.3) due to an intensified northward California undercurrent, weaker upwelling and equatorward surface flow and changes in prey distribution.

The northward feeding migration begins during the winter and early spring, when poleward transport dominates. These conditions favour the northward movement of Pacific hake. When equatorward transport in surface waters and upwelling conditions in the springtime are strong, the northward movement of Pacific hake is impeded because the fish must swim against strong southward currents, they may avoid cold upwelled waters, or they may find favourable feeding areas farther south after upwelling has improved productivity. The role of ocean conditions in the timing of the southward migration in the fall is less known. Thomson *et al.* (1989) noted that Pacific hake typically disappear from the La Pérouse Bank area around the time of the fall transition and linked this disappearance to marked declines in prey production. Saunders and McFarlane (1997) suggested that factors influencing southward migration might be similar to those influencing northern migration (i.e. age-dependent swimming speed and favourable current patterns).

Changes in adult Pacific hake migration may affect where spawning occurs (Figure 9.4, right panel) and how well the embryos, larvae and juveniles of succeeding year classes grow and survive. Ressler *et al.* (2007) reviewed evidence of a more northerly distribution of both spawning and summertime feeding aggregations, including a more northerly distribution of adult hake in summer surveys, year-round presence of adult hake in southeast Alaska and the presence of hake larvae and juveniles off Oregon, Washington and British Columbia in summer during some recent years.

9.3.3.2 Cross-shelf distribution

Pacific hake form dense daytime aggregations on the continental shelf break and near the edges of mid-shelf banks and basins, sometimes extending 40 km or more offshore over water depths as great as 2000 m (Bailey *et al.*, 1982; Dorn, 1995; Ware and McFarlane, 1995; Swartzman, 2001). Pacific hake are found primarily between depths of 50 and 500 m during the day, most commonly in aggregations at depths of between 150 and 250 m.

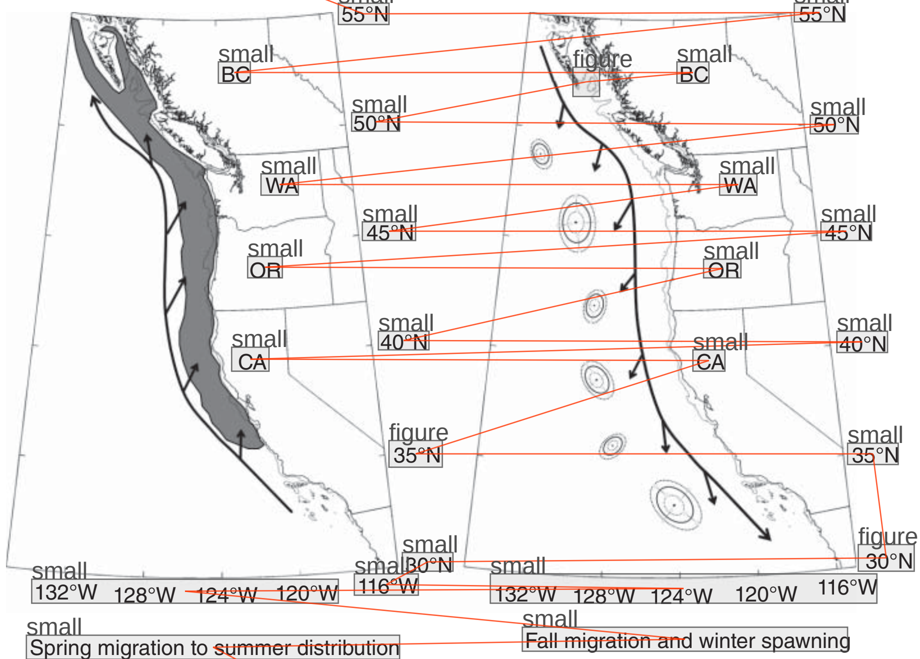

Figure 9.4 Left, shaded area represents summer distribution of adults on shelf and slope in recent years. Right, oblong areas represent variable, patchy offshore spawning locations, inferred from recent collections of larvae and young juveniles and reports of a northward shift of spawning location in the literature. Arrows indicate the general direction of movement and migration in both panels. The 200-m isobath is shown in grey. This figure reprinted from review by Ressler *et al.* (2007).

From south to north in the CCLME, Pacific hake aggregations increase in depth and move further offshore along the continental shelf to the shelf break (Swartzman, 1997). This pattern probably reflects ontogenetic effects on depth preferences, that is, smaller, younger juvenile fish do not migrate as far north as older Pacific hake (Hollowed, 1992; Dorn, 1995; Ware and McFarlane, 1995), and juvenile Pacific hake exhibit a greater preference for shallower shelf locations than mature fish (Methot and Dorn, 1995; Saunders and McFarlane, 1997). At least in some years, hake have been shown to be preferentially aggregated off the shelf break at the depth of the sub-surface poleward-flow of the California Undercurrent (Agostini *et al.*, 2006).

Temperature gradients may be an important mechanism driving Pacific hake depth distribution, but preferred temperature ranges for Pacific hake have not been established. The distribution of Pacific hake across years demonstrates that they are able to live within a range of temperatures. Temperature and depth are correlated with other factors, including currents and prey availability. Swartzman (2001) suggests that euphausiids sense and orient to oceanographic factors (e.g. bottom depth, temperature and flow) and Pacific hake sense and orient to euphausiids.

9.3.3.3 Diel migrations

Adult Pacific hake form pelagic schools during the day, mostly between the depths of 50 and 500 m, then disperse and migrate towards the surface at dusk; during spawning, they neither feed nor migrate vertically (Best, 1963; Nelson and Larkins, 1970; Bailey *et al.*, 1982; Stauffer, 1985). The vertical migration is usually thought to facilitate predation upon fish and zooplankton in the water column (Alton and Nelson, 1970) and may be influenced by several factors (e.g. prey, light, avoidance of predation and metabolism), as observed in other marine fishes (Neilson and Perry, 1990).

9.3.4 Prey and predation

Pacific hake is both an important food source for many predators and likely the most important consumer of zooplankton and forage fish in the CCLME (Field, 2004). Larvae and smaller juvenile hake feed on copepod eggs, copepods and juvenile euphausiids (Sumida and Moser, 1980; Grover *et al.*, 2002; Cass-Calay, 2003). The diet of large juveniles and adults is composed primarily of euphausiids, fish and pandalid shrimp, with evidence of adult cannibalism on juveniles (Alton and Nelson, 1970; Bailey *et al.*, 1982; Livingston, 1983; Brodeur *et al.*, 1987; Buckley and Livingston, 1997, Field *et al.*, 2006; Emmett and Krutzikowsky, 2008). The amount of spatial overlap (and cannibalism) between adult and juvenile fish varies annually in response to environmental and demographic factors as discussed previously (Buckley and Livingston, 1997). Larger zooplankton and fish become more important dietary components as Pacific hake grow. Pacific hake are usually considered to be opportunistic feeders (Best, 1963), particularly upon schooling or aggregating prey (Livingston and Bailey, 1985). The daily ration for juvenile and adult Pacific hake has been estimated variously between 0.4% and 3.5% of body weight (Francis, 1983; Livingston, 1983; Rexstad and Pikitch, 1986; Tanasichuk *et al.*, 1991). Euphausiids nearly always appear as a very important component of the Pacific hake diet, but some studies have demonstrated seasonal and inter-annual changes in the mix of prey types utilised throughout the CCLME (e.g. Bailey *et al.*, 1982; Livingston, 1983; Buckley and Livingston, 1997; Emmett and Krutzikowsky, 2008). These shifts include from primarily euphausiid prey (primarily *Thysanoessa spinifera*) to increased consumption of Pacific herring in late summer off Vancouver Island (Tanasichuk *et al.*, 1991; Ware and McFarlane, 1995) and during the 1997–1998 El Niño (Nelson, 2004), and from mostly fish prey to euphausiids in the summertime off Oregon and Washington (Brodeur *et al.*, 1987).

Pacific hake are also important prey for other species. Pacific hake embryos and larvae are preyed upon by copepods, amphipods and gelatinous zooplankton (Bailey and Yen, 1983; Livingston and Bailey, 1985). Pacific hake juveniles and adults are also prey for other nekton, including dogfish (*Squalus acanthias*), sablefish (*Anoplopoma fimbria*), lingcod (*Ophidon elongates*), arrowtooth flounder (*Atheresthes stomias*), rockfishes (*Sebastes* spp.) and tunas (*Thunnus* spp.), as well as apex predators such as California sea lions (*Zalophus californianus californianus*), Steller sea lions (*Eumetopias jubatus*), harbor seals (*Phoca vitulina richardii*), sperm whales (*Physeter macrocephalus*) and other tooted whales, sooty shearwaters (*Puffinus griseus*), western gulls (*Larus occidentalis*) and common murres (*Uria aalge*) (Fiscus, 1979; Ainley *et al*., 1982; Livingston and Bailey, 1985; Baraff and Loughlin, 2000; Field, 2004). The predation of Humboldt squid (*Dosidicus gigas*) upon adult Pacific hake has recently received attention (Field *et al*., 2007; Zeidberg and Robison, 2007), as these squid have become periodically more common in the northern CCLME. In particular, the northward expansion of Humboldt squid in 2009 resulted in considerable overlap in depth and geographic range with Pacific hake. This hake forms an important link between upper and lower trophic levels in the CCLME.

9.3.5 Population dynamics

Pacific hake live more than 20 years, attaining lengths of over 50 cm of total length, with 50% reaching maturity by the age of 4 years, at about 37 cm. Dorn *et al*. (1993) estimated a natural mortality rate (M) of 0.23 per year. Hamel and Stewart (2009) used a meta-analytical approach incorporating multiple life-history correlates to develop a log-normal prior for M with mean 0.193 per year.

Recruitment dynamics in the coastal stock of Pacific hake are characterised by episodic strong year classes, which can vary in number by as much as two orders of magnitude or more relative to weak year classes (Bailey and Francis, 1985; Methot and Dorn, 1995; JTC, 2013; Figure 9.5). The occurrence of these dominant year classes appears to be largely independent of spawning stock size, so a reliable stock–recruitment relationship has been difficult to establish (Bailey and Francis, 1985; JTC, 2013). Varying levels of mortality during the pre-recruit period is a common explanation for similar recruitment dynamics in other species.

Hollowed *et al*. (2001) found that Pacific hake appeared to respond more strongly to inter-annual variability than to decadal climatic variability. Strong year classes often occurred in years with unusually warm surface temperature anomalies in coastal waters north of the tropics, ‘Niño North’ conditions that do not always correspond to El Niño events. The frequency of these conditions will affect the size and variability of the coastal Pacific hake stock.

Individual growth of Pacific hake can also be quite variable (Dorn, 1992). Helser *et al*. (2008) examined length-at-age data from the acoustic and bottom trawl surveys and found that both of the von Bertalanffy growth parameters K (Brody growth coefficient) and L_∞ (asymptotic size) declined for individual cohorts from the early 1970s and the mid-1980s and subsequently increased again. Temporary decreases in parameter estimates could be due to warmer waters and reduced productivity following the 1977 regime shift,

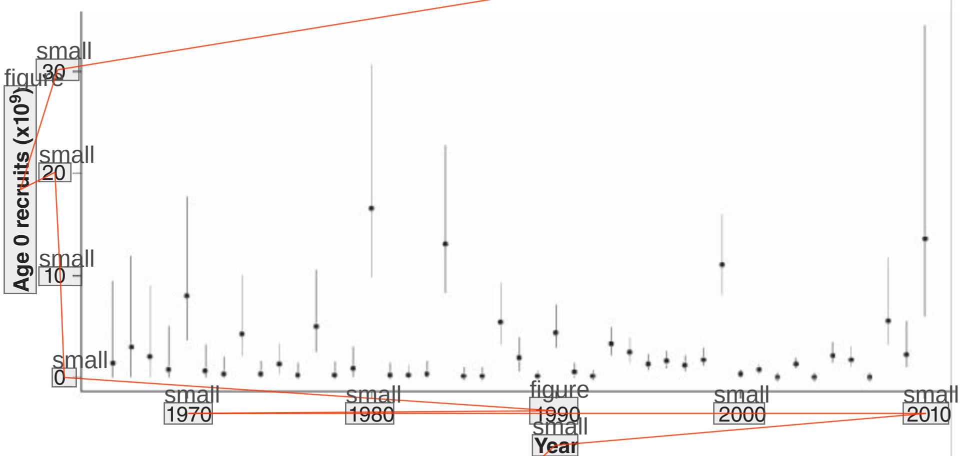

Figure 9.5 Median estimated recruitment of Pacific hake (billions of age 0 hake) from the 2013 assessment. The grey lines indicate 95% posterior credibility estimates.

increased competition due to strong year classes, or both. Individual growth was depressed during the 1983-1984 El Niño (Hollowed and Francis, 1987), perhaps due to reduced euphausiid abundance (Miller *et al.*, 1985; Rexstad and Pikitch, 1986).

9.4 Fisheries

The fishery for the coastal population of Pacific hake occurs along the coasts of California, Oregon and Washington in the United States and British Columbia in Canada, typically from May through December. The primary fishery is conducted with mid-water trawls over bottom depths of 100–500 m; Pacific hake are also caught incidentally in other coastal fisheries. Catch averaged 222,000 t per year during 1966–2012, with nearly three-quarters of that catch coming from the U.S. waters. Recent coast-wide catches have been greater than the long-term average, averaging 243,000 t per year during 2008–2012 (Figure 9.6).

Pacific hake were caught incidentally in commercial fisheries targeting more valuable species dating from the late 19th century but were discarded or processed into animal food and fishmeal until the 1960s. Annual landings never exceeded a few 100 t during this period. In 1964, the U.S. National Marine Fisheries Service (NMFS) demonstrated the potential for large catches of Pacific hake (up to 30 t in a single half-hour trawl) off Washington and Oregon using state-of-the-art depth telemetry systems on mid-water trawlers. The domestic fishery in the United States grew from less than 500 t in 1964 to about 9000 t in 1967, although these levels were not sustained afterwards due to lack of profitability.

Foreign fleets noticed the increased harvest opportunity, and in 1966, factory trawlers from the former Union of Soviet Socialist Republics began harvesting

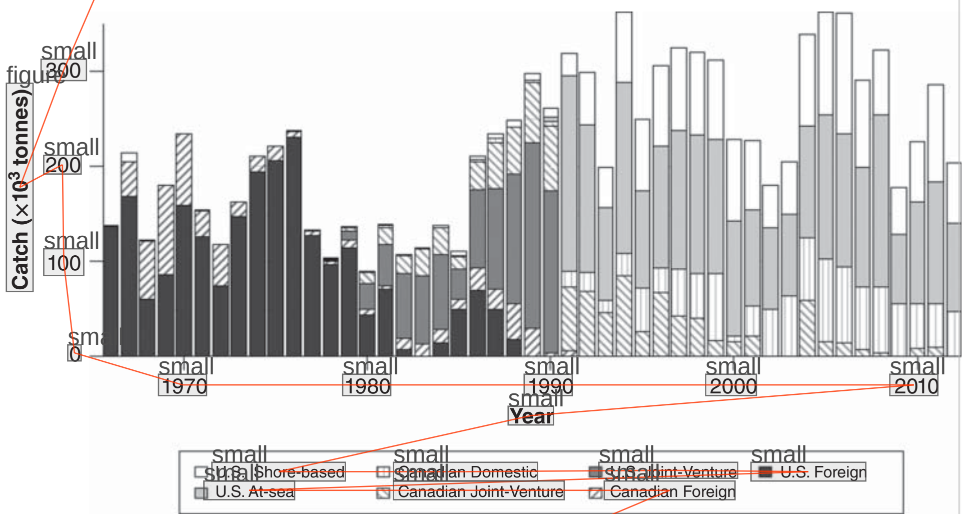

Figure 9.6 Total Pacific hake catch (tonnes) used in the 2013 assessment by sector. The U.S. Tribal catches from 1966 to 2012 are included in the appropriate U.S. sectors.

Pacific hake. Japanese vessels, whose primary target was Pacific ocean perch (*Sebastes alutus*), also harvested Pacific hake in the late 1960s. Vessels from Poland, the Federal Republic of Germany, the German Democratic Republic and Bulgaria joined the fishery for Pacific hake in the 1970s. Foreign annual catch of Pacific hake from 1966 through 1979 averaged 167,000 t.

Joint venture fisheries commenced in 1978 and completely supplanted the foreign fishery by 1989 in the United States and 1992 in Canada. The entry of domestic motherships and catcher-processors into the U.S. Pacific hake fishery in 1990 accelerated the change to a wholly domestic U.S. fishery that took the entire catch by 1991. The domestic Pacific hake fishery in Canada developed at a slower pace in the absence of these larger domestic processing vessels and remains largely a domestic shoreside fishery, with a small joint venture fishery in most years.

9.4.1 Management strategy and challenges

Since implementation of the Magnuson-Stevens Fishery Conservation and Management Act in the United States and the declaration of a 200-mile fishery conservation zone in Canada in the late 1970s, annual harvest quotas have been the primary management tool used to limit the catch of Pacific hake. Scientists from both countries collaborated through the Technical Subcommittee of the Canada–U.S. Groundfish Committee, and there were informal agreements on the adoption of annual fishing policies. During the 1990s, however, disagreements between the United States and Canada on the allotment of the catch between the U.S. and Canadian fisheries led to quota overruns. This, coupled with the decline of abundant year classes from the mid-1980s, led to Pacific hake being declared overfished (i.e. below 25% of – average – unfished spawning biomass) in the United States in 2002. The strong 1999 year class was subsequently observed in the acoustic survey and fisheries, and a new assessment and abundance estimate led to the stock being declared rebuilt in 2004.

The allocation issue was resolved with the development and eventual implementation of the Agreement between the Government of the United States of America and the Government of Canada on Pacific Hake/Whiting (the Treaty), which was signed in November 2003. The Treaty specifies a process for developing annual stock assessments and total allowable catch (TAC), including a default harvest rate of $F_{40\%}$ and fixed allocations of 73.88% and 26.12% for the United States and Canada, respectively. The Hake Treaty established a Joint Management Commission (JMC) that decides the annual TAC. JMC decisions are guided by the terms of the Treaty and the JMC's three advisory bodies consisting of the Joint Technical Committee (JTC), the Scientific Review Group (SRG) and an Advisory Panel. The JTC conducts the annual stock assessment and develops potential yield amounts for JMC consideration. The SRG assures the technical integrity of the stock assessment and the assessment's potential yield estimates. The Advisory Panel is composed of hake industry participants from the United States and Canada, who provide their perspectives about the fishery.

Management of the coastal Pacific hake fishery is shared among the JMC, who recommends the annual TAC, the U.S. NMFS (NOAA Fisheries) and the Canadian Department of Fisheries and Oceans (DFO), which are responsible for domestic management of their countries fisheries. In the United States, NOAA Fisheries receive advice from the Pacific Fishery Management Council (PFMC), which recommends specific management and enforcement measures. Canada gives priority to domestic fisheries in allocating yield between domestic and joint venture fisheries.

An Individual Vessel Quota (IVQ) system was implemented for the British Columbia trawl fleet in 1997, with allocation based on a combination of vessel size and landings history. Although vessels may deliver joint venture hake quota to domestic shore-side processors, they are not permitted to deliver domestic allocation to joint venture/processor operations at sea. There is no direct allocation of quota to individual shoreside processors. IVQ holders declare the proportion of their hake quota that will be landed in the domestic market, and shoreside processors must secure catch from vessel license holders (Devitt, 2009).

In the United States, yield is allocated among coastal tribes and the three domestic sectors. Washington coastal tribes have a treaty right to request amounts of fish to conduct fisheries within their respective usual and accustomed fishing areas. The Makah tribe has been full participants in the hake fishery since 1996. Beginning in 2009, the Quileute tribe has been requested and allocated an amount but has yet to harvest any hake. The Quinault tribe has also expressed interest in the hake fishery.

A formal allocation structure for the U.S. non-tribal fishery sectors was developed by the PFMC and implemented by NOAA Fisheries in 1997. Each year, the non-tribal allocation is divided among the shore-based trawl sector (42%), the mothership sector (24%) and the catcher-processor sector (34%). This action stabilised the fishery and resolved a highly contentious allocation battle and alleviated the race to fish. The allocation provides each group with a relative amount of stability in business planning by reducing the excessive competitive pressures associated with an open-access, derby style fishery: it slowed the pace of the fishery and opened opportunities for the fishery to act more rationally, improve product quality and expand product forms.

Shortly after the 1997 allocation agreement, the companies licensed to operate in the at-sea catcher-processor sector of the U.S. Pacific hake fishery formed the Pacific Whiting Conservation Cooperative (PWCC) to promote rational harvest, optimal utilisation and minimal waste in the fishery. The PWCC fishing cooperative ended the race-for-fish in the catcher-processor sector 14 years before the comprehensive rationalisation of the U.S. Pacific hake fishery. Their efforts resulted in decreased bycatch and waste, improved product quality and reduced fishing effort. The PWCC also sponsors scientific research, including stock assessment-related projects and bycatch avoidance programs. The cooperative model developed by the PWCC was later adopted in other fisheries, such as the walleye pollock (*Theragra chalcogramma)* fishery off Alaska.

Management of the U.S. fishery transitioned in 2011 to a fully rationalised fishery, with an individual quota share program for the shoreside fishery and formal cooperatives for the mothership sector in addition to those for the catcher-processor sector. Bycatch of other groundfish species is strictly managed under the quota share system in the shoreside hake fishery, while sector-specific overfished rockfish species catch limits are used to ensure their minimal bycatch in the mothership and catcher-processor fisheries. Endangered Species Act listed salmonid impacts are managed under the aegis of a NOAA Fisheries Biological Opinion, for which specific measures include closed areas, seasonal fishery structure and overall limits on Chinook salmon (*Oncorhynchus tshawytscha*) bycatch.

Mid-water trawl nets are required in the U.S. hake fishery. These are four-seam nets designed to catch schooling fish such as walleye pollock and Pacific hake, whose schools tend to behave in unison. Bycatch of non-hake species in the Pacific hake fishery is generally quite low, as Pacific hake tend to aggregate in large acoustically recognisable schools in the pelagic zone and mid-water trawl gear is fished off the bottom minimising interactions with non-hake species. Nonetheless, bycatch of limiting rockfish species has occasionally been an issue. The U.S. non-tribal hake fishery sectors are held to hard bycatch limits that, if exceeded, can result in closure of non-tribal fisheries, to limit impacts on certain depleted rockfish species. Prior to 2009, the rockfish bycatch limits were not sector specific; that is, high bycatch in one sector could close the fishery for all the non-tribal sectors. In both 2007 and 2008, there were mid-season closures due to bycatch of limiting species, but the fishery was reopened later in the year once bycatch quota was reallocated from other fisheries. Despite these closures, about 90% of the U.S. hake TAC was achieved in both those years, similar to other recent years without closures. The bycatch limits were applied at the specific sector level beginning in 2009, minimising the potential for one sector to affect the other sectors. Under the trawl rationalisation program, bycatch in the shoreside hake fishery is now managed using a quota share system.

The three U.S. non-tribal sectors track tow-by-tow catch and bycatch amounts using real-time catch information collected by fishery observers. When the rare high bycatch tow occurs, that information is shared with the rest of the fleet so that other vessels can avoid fishing in the area of high bycatch. The U.S. hake industry also works in partnership with NOAA Fisheries in testing newly developed bycatch reduction devices (BRDs) specifically designed for the hake fishery. Lomeli and Wakefield (2012) tested two open escape window BRD designs, with the goal of providing a tool to reduce the bycatch of Chinook salmon and rockfish in the hake fishery. The most successful design reduced bycatch by about 80% for Chinook salmon and 20% for widow rockfish (*Sebastes entomelas*).

The coastal Pacific hake stock is characterised by low recruitment punctuated by very strong year classes (Figure 9.5), leading to highly variable estimates of catch at F_{MSY}. The fishery is managed to sustain the stock through these fluctuations in recruitment. The 40–10% rule, which decreases allowable catch from the F_{MSY} rule when the spawning stock is below 40% of modeled average unfished biomass (catch goes to zero at 10% of unfished biomass), providing a precautionary mechanism to curtail harvest when the stock is low, had been used in the PFMC process for many years before being written into the Treaty. The JMC determines TAC by considering current stock status, uncertainties in the data and model projections and the potential effect on future stock status, while limited by the $F_{40\%}$ default harvest rate and the 40–10% rule. The coast-wide fishery, on average, has attained 85% of the TAC in the most recent years (2008–2012), mostly due to unused tribal allocation and bycatch restrictions.

A final challenge to the management of Pacific hake is the potential overlap of the coastal stock and its fishery with other smaller stocks. An overlap is unlikely to be a major risk biologically for the large coastal stock (although it could contaminate the compositional data used for assessment) but could be biologically risky to the other, smaller stocks, depending on the fishing mortality experienced by those stocks.

9.5 Monitoring

9.5.1 Fishery observing

As with most other commercial trawl fisheries on the U.S. west coast, the U.S. Pacific hake fishery is currently fully monitored by observers both for total catch and to account for bycatch of other fish stocks. Observers also collect biological samples for stock assessment-related scientific work. The U.S. fishery observers began monitoring Pacific hake catch on foreign vessels in 1977, more than two decades before most other U.S. west coast fisheries carried observers. Domestic catcher-processors and at-sea processing vessels (motherships) voluntarily began carrying observers in 1991, in what was essentially an outgrowth of the observing conducted on many of these same vessels in the Alaska walleye pollock fishery. From 2004 to 2010, vessels delivering Pacific hake to shoreside plants operated under an electronic monitoring program that required no at-sea discarding of catch, at-sea monitoring using cameras and catch monitors at the shoreside processing facilities to record catch and bycatch. Since 2011, comprehensive observer coverage in the U.S. Pacific hake fishery has been mandatory, with human observers onboard catcher-processors, motherships, catcher vessels delivering to motherships and catcher vessels delivering to shoreside plants; there are also port samplers that monitor the catch delivered to shoreside plants.

Canada first deployed fishery observers on foreign vessels targeting Pacific hake in 1987. Since 1996, on-board observers have monitored and sampled the catch of all domestic groundfish vessels, and all landed catch from trawlers is subject to a dockside monitoring program. Currently, surveillance and monitoring measures include a combination of at-sea observers (10–100% coverage) on vessels fishing for Pacific hake in Canadian waters (for headed-gutted freezer vessels, 100% at-sea observer coverage is required); electronic monitoring (e.g. deck cameras) and full retention of all fish brought on board; and 100% dockside (offload) monitoring. This monitoring program is supplemented by coast-wide surveillance via over-flights by fishery enforcement officers and patrol vessels (Devitt, 2009).

9.5.2 Fishery-independent surveys

The adult stock of coastal Pacific hake has been surveyed acoustically starting in (for more details cf. review by Ressler *et al.*, 2007), although earlier surveys covered only part of the coastal stock's range. The stock was surveyed on a triennial basis from 1977 through 2001 with a switch to a biennial schedule from 2003 to 2011. A supplemental survey was conducted in 2012, followed by the regular biennial survey in 2013. Surveys between 1977 and 1992 were conducted entirely by the NOAA's Alaska Fisheries Science Center. In 1995, the operation became a joint United States–Canada survey with the addition of the DFO Canada, Pacific Biological Station, and in 2003, NOAA's Northwest Fisheries Science Center took over the U.S. portion of the survey.

The acoustic survey is conducted in the summer months, from mid-June through early September, typically moving south to north from Monterey, California, to Dixon Entrance, Alaska, using a design that covers waters from about 50 to 1500 m deep along parallel transects at 10-nm spacing. The parallel transect design was developed when computing power and analytical techniques designed to minimise or remove spatial and/or temporal autocorrelation in data were limited. Recent surveys have used geostatistical analysis techniques (i.e. kriging) to compute biomass and variance, and as a result, zigzag transects or other less-regular transect designs could be used in the future. In some years, the survey has had to extend farther south or north in response to observed hake aggregations to cover the entire extent of the stock. The survey was expanded in the 1990s to include northern and offshore areas of the hake distribution that had not been included in the original survey design (Dorn *et al.*, 1993; Dorn, 1996), and a set of expansion factors were calculated in an attempt to calibrate the early survey data years so that they would be to be roughly comparable to the updated survey design. However, this proved an unresolvable task given the natural variation in northern migration between years.

The survey relies on 38 kHz as the primary acoustic frequency to estimate Pacific hake biomass, although additional frequencies as available on the U.S. and Canadian survey vessels are also used to help distinguish hake from other acoustic targets. Acoustic backscatter attributed to Pacific hake is scaled to biomass or abundance using a length-based model of target strength (TS), the log-transformed acoustic backscatter expected from a single fish or unit biomass. In 1995, this model was changed from a weight-based TS of −35 dB/kg to a TS-length relation of $TS = 20 \log L - 68$ (Traynor, 1996), where L is fork length in centimetres. Variability in Pacific hake TS has continued to be an active area of research (e.g. Henderson and Horne, 2007); data from the most recent field measurements (Fleischer *et al.*, unpublished data) were generally consistent with mean and variation indicated in Traynor (1996).

Sources of uncertainty in the acoustic surveys of Pacific hake abundance involve climate-ocean effects on distribution and availability of fish to the survey, the ability to acoustically differentiate Pacific hake from other acoustic targets and the uncertainty in Pacific hake TS. For example, the current stock assessment models use the acoustic-based survey biomass indices from 1995 to present only, excluding the earlier surveys that had reduced spatial coverage and used a different TS model. A second example of the uncertainty in acoustic surveys occurred during the 2009 acoustic survey with the northward expansion of Humboldt squid into the CCLME. Several factors make it difficult to acoustically distinguish Humboldt squid and Pacific hake: the TS and frequency response of Humboldt squid are similar to those of Pacific hake. There was overlap in the depth and geographic ranges of both species in 2009, and squid predation may cause an avoidance response leading to altered aggregation behaviour in hake (Holmes *et al.*, 2008). Because the proportions of backscatter attributable to hake and Humboldt squid were based on limited information, the estimated uncertainty (CV) of the acoustic survey biomass estimate was higher in 2009 than in other survey years (Stewart and Hamel, 2010). Further irruptions of Humboldt squid have not been observed during hake acoustic surveys since 2009.

9.6 Assessment and management strategy evaluation

Age-structured models have been used to model the population dynamics of the coastal stock of Pacific hake since the early 1980s. Cohort analyses were replaced by statistical catch-at-age models by the early 1990s. These latter models provide a time series of estimates of total biomass, biomass-at-age, spawning biomass and age-0 recruits. The current assessment model relies on catch, survey indices, weight-at-age and age composition data. The 2013 assessment estimated a mean unfished female spawning biomass of a little more than 2 million tonnes, with a female spawning biomass at the beginning of 2013 of 1.5 million tonnes, or 72% of unfished equilibrium female spawning biomass. Assessments have consistently found that the population dynamics of Pacific hake are characterised by infrequent large year classes, including from the years 1980, 1984 and 1999, and potentially 2008 and 2010. These large year classes have sustained the population, through long periods with moderate to low recruitments.

Prior to 1997, separate Canadian and U.S. assessments for Pacific hake were submitted to each nation's assessment review process, which resulted in differing yield options being forwarded to each country's managers for this shared trans-boundary fish stock. Multiple interpretations of Pacific hake status made it difficult to coordinate an overall management policy. From 1997 through 2010, the Stock Assessment and Review process for the PFMC in the United States evaluated assessment models and the PFMC council process, including NOAA Fisheries, has generated management advice that has been largely utilised by both nations. In 2003, the United States and Canada signed the Treaty, which specifies science and management processes. The terms of the treaty were not fully implemented until 2012, but stock assessments and management activities have conformed to the treaty for many years (Helser *et al.*, 2006; Hamel and Stewart, 2009; JTC 2012, 2013). Under the Treaty, Pacific hake stock assessments are prepared by the JTC composed of both U.S. and Canadian scientists and reviewed by the SRG, with members of both groups appointed by both Parties to the agreement. In 2012, after formal appointments were made to Treaty-specific committees, the stock was assessed and managed under the full auspices of the treaty for the first time. Between 2003 and 2011, the Parties honoured the intent of the Treaty during its implementation, which included joint stock assessment reviews and allocations to the each country based on the Treaty allocation structure.

The 2013 assessment (JTC, 2013) was a fully Bayesian assessment conducted using the Stock Synthesis modelling platform (Methot and Wetzel, 2013), with the base-case model incorporating prior information on two key parameters (natural mortality, M, and steepness of the stock-recruit relationship, h) and integrating over estimation and parameter uncertainty to provide results that could be probabilistically interpreted. The base case model showed large variations in Pacific hake biomass over the past four decades (Figure 9.7), largely related to variation in recruitment (Figure 9.5), with an apparent strong year

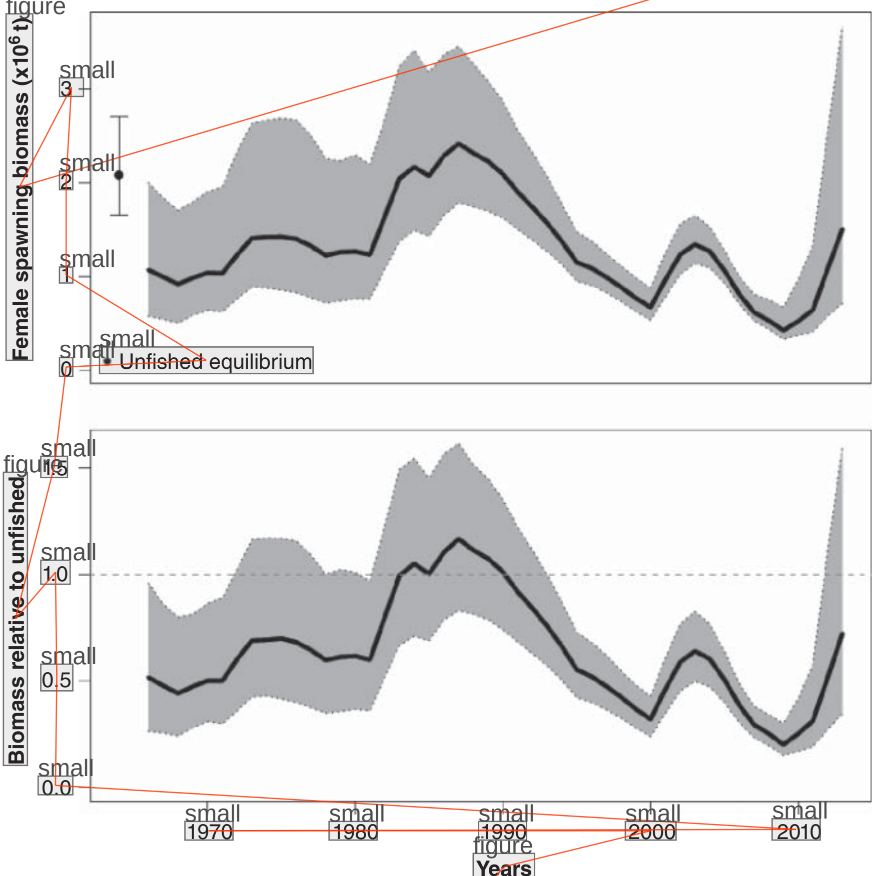

Figure 9.7 Median estimated female spawning biomass through 2013 with 95% posterior credibility intervals (a). Median relative spawning biomass (spawning biomass/estimated 'equilibrium' unfished biomass) through 2013 with 95% posterior credibility intervals (b).

class in 2010 driving an increase in biomass at the end of the time series. From a range of alternate models investigated by the JTC, a subset of sensitivity analyses was also reported in order to provide a broad qualitative comparison of structural uncertainty with the base case.

The 2013 assessment (JTC, 2013) estimated that the stock was, in fact, not overfished in the early 2000s (reaching a low of 32.3% of unfished biomass in 2000), but in contrast did meet the overfished definition in 2009 (at 20.4% of unfished biomass). As the official declaration of overfished status in the United States applies only to a current estimate, and as Pacific hake are now managed under an international treaty that does not include an 'overfished' definition, the retrospective 2009 estimate in the 2012 assessment does not impact current management.

A retrospective comparison of Pacific hake assessment models from 1991 through 2013 shows considerable variability in the estimates of Pacific hake

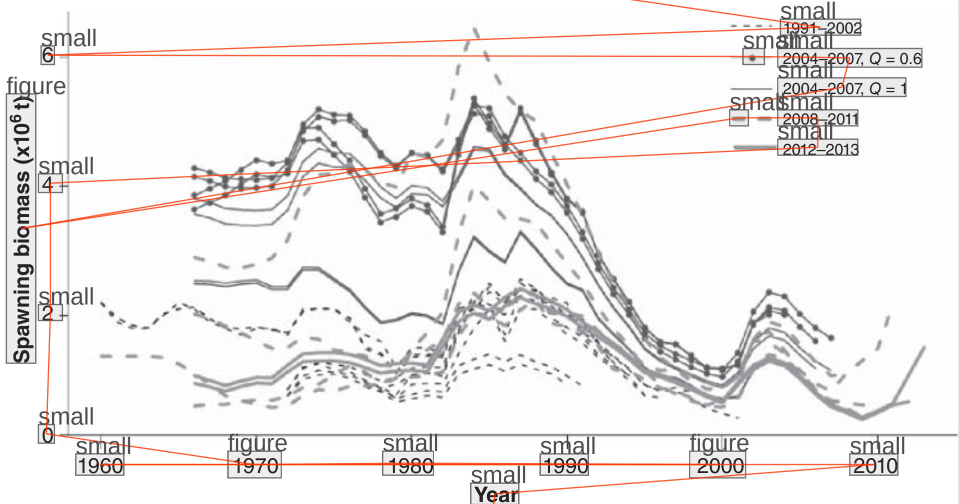

Figure 9.8 Retrospective across assessments from 1991 to 2013 of yearly spawning biomass estimates. The early assessments (1991–2002) are shown as thin dashed lines. The years from 2004 to 2007 fixed the acoustic survey catchability (q) at 0.6 or 1.0 and are shown as solid thin line with dots indicating $q = 0.6$. The recent assessments are shown as thick gray lines with 2008–2011 being a period of separate U.S. and Canadian models with quotas determined by the Pacific Fishery Management Council, and 2012–2013 representing recent management of hake using a single cooperative model managed under an agreement between the United States and Canada.

stock biomass and status (Figure 9.8). Among-model variability (particularly in the early portion of the time series) is greater than the uncertainty estimated in any individual assessment (Figure 9.7), and a substantial trend of diminishing variability is not apparent. The treatment of one parameter in particular, the catchability (q; e.g. Hilborn and Walters, 1992) of the acoustic survey, has changed over time. Prior to 2004, this value was assumed to be 1, meaning that the fully selected portions of the stock (based on age or length) were fully available to the survey and that the survey covered the entire latitudinal and longitudinal distribution of Pacific hake (and, as mentioned previously, the TS relationship was correct). During 2004–2007, two values for the catchability coefficient (q) were used to parameterise what were considered equally plausible alternative models. Since this time, q for the acoustic survey has been freely estimated within the assessment models, which has the effect of increasing the apparent uncertainty in the assessment results, as the uncertainty in q is now accounted for (rather than ignored) in the model. In reality, the assessment is more certain than before given the addition of much more and higher quality data.

A Management Strategy Evaluation (MSE) (Butterworth and Punt, 1999; Cox and Kronlund, 2008) was developed in 2012. The initial goal was to explore the performance of the current default harvest control rule and the performance of stock assessment and management with annual versus biennial acoustic surveys. Using results from the 2012 assessment (JTC, 2012), the MSE model simulated a known population forward in time under four scenarios: no fishing, catches determined from perfect knowledge of the spawning biomass, and catches predicted using simulated data with either annual or biennial surveys supplied to an assessment model with a similar setup to the 2012 assessment. Preliminary results show good progress in developing an MSE with the need for additional input from industry and managers. Although the assumptions were simplistic and the results are not recommended to be used for management advice, they do suggest that the default harvest rate ($F_{40\%}$) would result in an average female spawning biomass slightly below $B_{40\%}$, but with high variability (with median biomass near $B_{30\%}$). Decreasing the default harvest rate towards $F_{50\%}$ would result in larger average and median biomass (median biomass near $B_{40\%}$) with little change to average long-term catch, and while reducing the inter-annual variability in catch and biomass.

9.7 Products and markets

In product form, Pacific hake is a white-fleshed, mild-tasting fish. The early stages of the Pacific hake fishery produced mainly fillets, headed and gutted products, and fish meal, mostly for foreign markets. Initially, there was very little market in either the United States or Canada for the catch, due to problems with rapid softening of the flesh related to the presence of the parasites in the genus *Kudoa* (Kabata and Whitaker, 1985). By the early 1990s, quality problems were overcome by rapid cooling techniques and enzyme inhibitors, and the development of processed Pacific hake products, such as surimi, has made the fishery more profitable (Methot and Dorn, 1995).

Development of large-scale domestic fisheries was thought infeasible throughout the 1980s due to product quality concerns, cost of production and impediments to markets (Anderson 1985). Nonetheless, domestic capacity increased rapidly in the fishery. A unique problem with Pacific hake from the coastal stock is an endogenous protease produced in reaction to a muscle parasite (*Kudoa thrysites*). This parasite can cause proteolytic muscle disintegration, which can reduce the gel-forming ability of myofibrillar proteins in Pacific hake surimi. However, protease inhibitors can be added to the minced Pacific hake muscle to maintain gel-forming ability. The most effective protease inhibitors include bovine blood plasma proteins, egg white, potato-based inhibitors, or whey. In 2003, concerns about the use of bovine blood plasma, because of its potential relationship with 'mad cow' disease, affected certain markets for Pacific hake surimi (Hui, 2006).

Developments in food science and improved handling of Pacific hake onboard vessels and in processing plants have eliminated various impediments to production and marketability of Pacific hake. For example, use of cold temperature-based processes now allows for surimi production without the use of protease inhibitors.

Throughout the contemporary history of the fishery, most of the catch were processed into surimi, which is used to make shellfish analogues. In about 2003, the hake industries in both the United States and Canada began developing highly mechanised processing facilities to handle fish as efficiently as possible and to expand the diversity of product forms. Currently, higher economic return comes from the production of non-surimi forms, such as headed and gutted products, fillets and blocks. These forms now dominate production. While Pacific hake has never been a high-value fish, the total revenue to the industry is in the tens of millions of U.S. dollars per year – over 50 million dollars per year in recent years – and the market for Pacific hake remains strong.

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