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AN ASSESSMENT OF THE RELATIVE IMPORTANCE OF HUMAN AND NATURAL IMPACTS ON THE PAST AND FUTURE FISHERIES OFF CANADA'S WEST COAST

Бимиш Р.Дж. Оценка относительного значения антропогенных и природных факторов на прошлое и будущее рыбного промысла у западного побережья Канады // Изв. ТИНРО. — 2004. — Т. 137. — Р. 45–66.

Промысел рыбы у западного побережья Канады ведется с конца XIX века. Традиционно его основными объектами были лососи, палтус, сардина и сельдь, с середины XX века активно добываются донные виды рыб, а с 1980-х гг. — хек. Численность всех видов испытывает значительные колебания: так, промысел сардины возобновился в 1990-е годы после 45-летнего перерыва, численность сельди резко уменьшалась в 1960-е, а лососей — в 1990-е годы. Несомненно, значительное влияние на численность промысловых видов рыб оказывает промысел. Но не меньшее значение имеют изменения климатических факторов. Значение изменений климата более выражено в масштабах десятилетий, что связано с глобальными процессами. В обозримом будущем изменения климата продолжатся, что неминуемо окажет воздействие на состояние рыбных запасов и промысел. Ожидается, что западное побережье Канады останется важным рыбопромысловым районом, но виды, для которых этот район является южной периферией ареала, как треска и лососи р. Фрейзер, будут испытывать значительные флуктуации численности при отрицательном тренде. Вместе с тем резко возрастет влияние на промысел бурно развивающейся марикультуры. Предполагается, что в течение ближайших 30 лет мировое потребление морепродуктов возрастет вдвое, однако новые потребности в основном будут удовлетворяться за счет марикультуры. Рост производства в марикультуре стимулирует правительственные органы к уменьшению степени эксплуатации природных ресурсов и к переходу на экосистемные принципы управления ими. Не исключено, что открытие механизмов климатических изменений приведет к созданию новой теории рыболовства, что в будущем позволит эффективно управлять рыбной промышленностью.

Commercial fishing started in the late 1800s on Canada's west coast. The early fisheries were for Pacific salmon, Pacific halibut, Pacific sardine, and Pacific herring. Major fisheries for groundfish started in the mid-1900s with an increased rockfish fishery starting in the 1970s. The most recent major fishery started for Pacific hake in the 1980s. In general, the fisheries that started in the late 1800s are still important. Pacific halibut is at historic high abundances and Pacific sardines are returning to Canadian waters after an absence of 45 years. Pacific salmon catches reached historic high levels in the mid-1980s despite predictions that this would not be possible. The catches declined to historic low levels in the late 1990s, again despite predictions of high and stable catches. In recent years Pacific salmon abundances have returned to average levels and in some cases to historic high levels. Pacific herring catches collapsed in the mid-1960s but have recovered to average or above average levels. There is no question that some fluctuations in catch resulted from fishing effects.

However, it is now generally accepted that climate and climate change had a powerful influence on the population dynamics of the key commercial species. The impact of climate is most pronounced at the decadal-scale, which is associated with planetary events. The future of the fisheries on Canada's Pacific coast will be strongly influences by continued changes in climate and the escalating development of aquaculture. Within the next 30 years, the world demand for seafood will double. This level of increased production of seafood can only come from aquaculture. As aquaculture becomes a common source of affordable seafood, it will be possible for management agencies to reduce exploitation rates and begin to manage according to ecosystem-based principles. Canada's west coast fisheries should continue to be productive, except that species at the southern limits of their distribution such as Pacific cod, and sockeye, pink, and chum salmon from the Fraser River should experience greater fluctuations in abundance and an overall decreasing trend. Most importantly, it is probable that the mechanisms that cause the decadal-scale shifts in climate will be discovered, resulting in a new theory of fishing and an ability to manage fisheries and the fishing industry well into the future.

Introduction

The major changes in the abundances of Canada's west coast fisheries over the past 100 years are related to both fishing impacts and climate changes. However, it has only been in recent years that climate has been recognized as having large and non-random effects on the population dynamics of Pacific coast fisheries (Beamish et al., 1997a; Beamish et al., 2000a). There also is an accumulating literature that shows that climate states or regimes exist and that these states shift quickly. With hindsight, we can see that some changes in the past that were thought to be from fishing (Ricker, 1958), were, in fact, mainly due to a climate-induced change in the productivity of an ecosystem.

In this report, I review the history of the major fisheries on Canada's Pacific coast (Fig. 1). I include commentary on the relative impacts of fishing and climate on the observed trends in catch. In addition to the commercial fishery, aquaculture has become a major source of seafood production on Canada's west coast. The impact of aquaculture on commercial Pacific salmon fisheries has been to lower the landed value. Reduced prices to fisherman, in turn, have reduced the demand for quota resulting in reduced exploitation rates. There is little doubt that the future of the west coast fishery will be closely associated with the development of aquaculture in Canada and around the world. In addition, greenhouse gas induced climate change and an emphasis on ecosystem-based management will have a major influence on the management of our fisheries. Fisheries eventually will be managed on an ecosystem basis, which may be interpreted as understanding how productivity is regulated and how that productivity can be exploited.

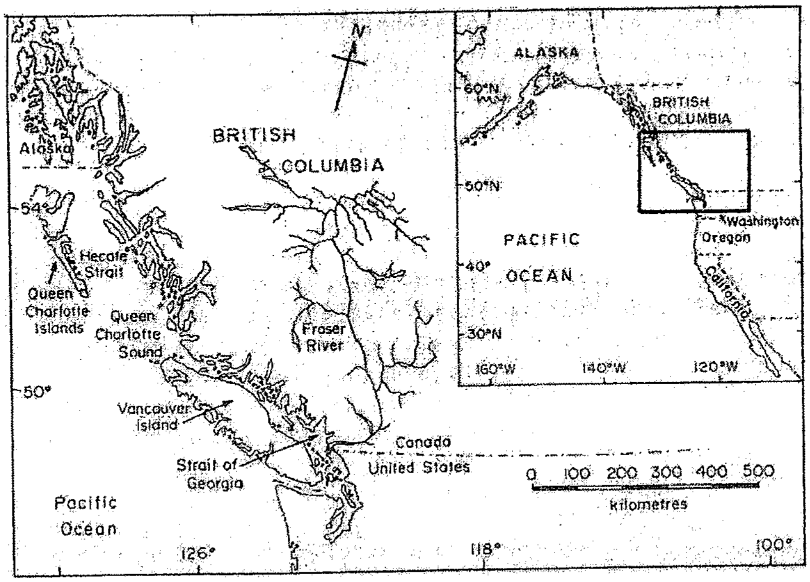

Fig. 1. The west coast of Canada showing key study areas

History of the major fisheries off the Pacific coast of Canada

Canada was officially a country in 1867 and commercial fishing became an important industry in the late 1800s. Early fisheries were for Pacific salmon (*Oncorhynchus spp.*), Pacific halibut (*Hippoglossus stenolepis*), Pacific herring (*Clupea harengus pallasii*), and Pacific sardine (*Sardinops sagax*).

Pacific salmon

The Canadian Pacific salmon catches from 1920 to 2001 have averaged 65,000 tons (Fig. 2, A) and ranged from 2 to 24 % of the total Pacific catch of pink (*O. gorbuscha*), chum (*O. keta*), sockeye (*O. nerka*), chinook (*O. tschawytscha*), and coho (*O. kisutch*).

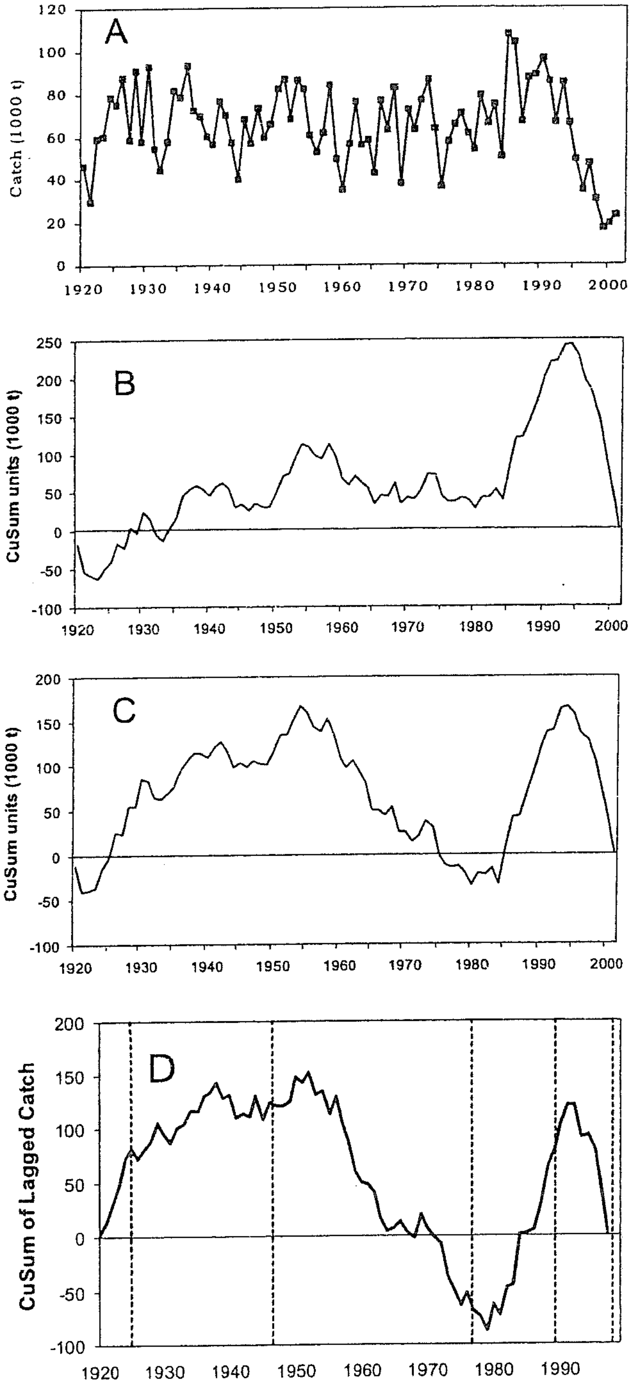

Fig. 2. (**A**) Canadian catch of Pacific salmon from 1920 to 2001; (**B**) Cumulative sum (CuSum) of total catch of pink, chum, sockeye, coho and chinook salmon indicating the timing of major changes in trends; (**C**) CuSum of total catch of pink, chum and sockeye salmon, showing an increasing trend to the mid-1950's, decreasing to the mid-1980's, followed by a sharp increase and sharp decrease in the mid-1990's; (**D**) CuSum of the pink, chum and sockeye salmon only, lagged to year of ocean entry. Dashed vertical lines indicate timing of regime shifts

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Despite these small catches relative to total Pacific catches, it has been possible to show that there were persistent trends in the catches and in the production of Pacific salmon stocks in Canada (Beamish, Bouillon, 1993; Beamish et al., 1995, 1997b, 1999, 2000b; Noakes et al., 1998, 2000). Beamish and Noakes (2002) used a cumulative sum analyses (Murdoch, 1979; Scandol, 2003) to show trends and change points in the trends of the total catch of five species of Pacific salmon in Canada (Fig. 2, B). A positive trend in the CuSum chart indicates above average catches and a negative trend represents catches that are below average. The catch data for coho and chinook salmon represent about 10 % of the catch for all species and were less reliable prior to 1950. Therefore, a second analysis was performed after removing these species (Fig. 2, C). Both analyses show clear trends in the catches, with shifts in the mid-1950s, early 1980s and late 1990s. The life histories of the various Pacific salmon species differ with respect to the time spent in the ocean (Groot, and Margolis, 1991). Beamish and Noakes (2002) adjusted the catch data by lagging catches of pink, chum, and sockeye back to the year of ocean entry. When this was done, the trends in catch were even clearer (Fig. 2, D). Catches were about average from about 1930 to the early 1950s. Catches declined through to the early 1980s, when they increased through to the early 1990s. There was a precipitous decline in catch in the 1990s. In all cases, there was a change in trend shortly after a regime shift. Catch data for Pacific salmon is an index of production because harvest rates are high (60 to 80 %), indicating that much of the population is captured by the fishery. However, the decline in catch in the 1990s was a consequence of both reduced marine survival and management decisions to reduce catches in order to minimize the impact of fishing on the number of spawning adults (Beamish, Noakes, 2002). In recent years, following the 1998 regime shift, there has been an improvement in marine survival as indicated by the almost historic high return of pink salmon to the Fraser River in 2001 (Fig. 3; Beamish, 2002). These pink salmon entered the Strait of Georgia from the Fraser River as juveniles in the spring of 2000. Studies by Beamish and co-authors (2001, 2002) showed that there was a doubling of production of some plankton species in 2000 compared to previous years, indicating that the basin-wide regime shift in mid-1998 affected primary production in the Strait of Georgia about one and a half years later. Once the existence of regimes is recognized, it is evident that the increase to historic high catches in the mid-1980s immediately followed by historic low catches in the late 1990s is mainly a result of natural changes in trends in marine survival and not fishing. The recognition of trends in marine survival also provides an explanation why it was believed in the early 1970s that it would not be possible to rebuild salmon stocks to the high levels observed in the mid-1980s (Ricker, 1973).

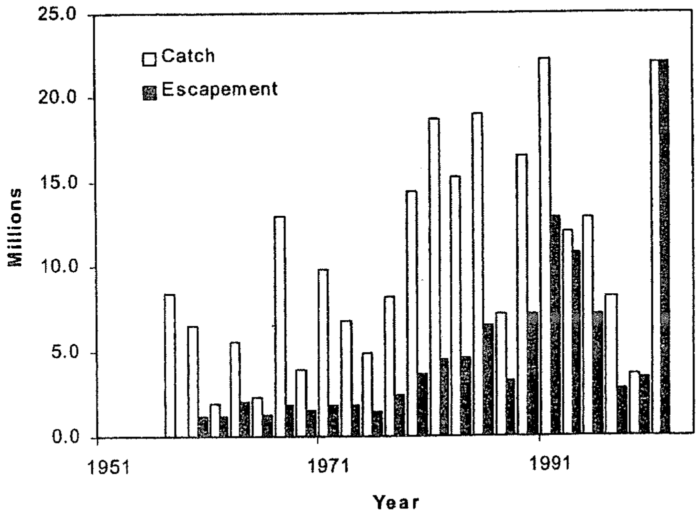

Fig. 3. Catch and escapement (returns to river) of Fraser River pink salmon from 1957 to 2001

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Catches after 2000 have remained low because of management action to protect a few stocks that are in low abundance and because prices paid to fisherman for pink salmon are so low, there is little demand for quota. The low prices appear to be related to the reduced demand that is related to aquaculture production.

Pacific halibut

The Pacific halibut fishery is one of the oldest and perhaps the most successful fishery off Canada's Pacific coast (Fig. 4, A). Canadian and United States fishermen started fishing Pacific halibut commercially in 1888. The catches rose quickly to levels exceeding 30,000 tons from 1914 to 1916. An International Commission began to oversee the fishery in 1923 because the halibut that were fished in the Canadian and United States fisheries were recognized as one population and catches were declining. However, it was not until 1930 that catch was regulated by the commission. Today, the abundance is considered to be at the highest levels in history (Fig. 4, A; Clark, and Hare, 2002). A historic high abundance of a large, top predator is apparently inconsistent with world trends (Pauly et al., 1998; Myers, and Worm, 2003). The catch recorded for Canada is a function of the available quota and effort up to 1977 as fishing was possible off the Pacific coast of the United States. After 1977 Canadian fishermen were restricted to fishing only in waters off Canada (Fig. 4, C). The International Pacific Halibut Commission has reconstructed the exploitable biomass for the total population (Fig. 4, A) and for the exploitable biomass of halibut resident off the west coast of Canada (Fig. 4, B).

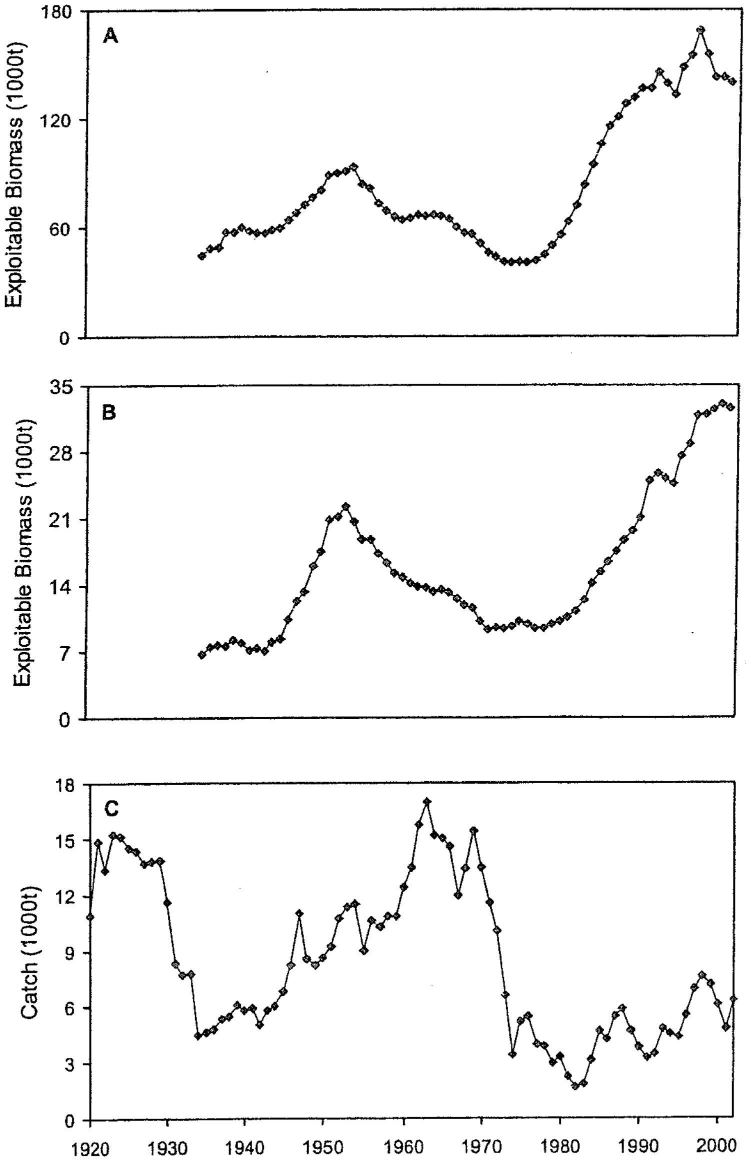

Fig. 4. (**A**) Exploitable biomass of the total west coast Pacific halibut population from 1935 to 2001; (**B**) Exploitable biomass of Pacific halibut in Canadian waters from 1935 to 2001; (**C**) Canadian landings of Pacific halibut from 1920 to 2002

McCaughran (1997) reported that the productivity of the population declined from 1959 to 1972 consistent with a change in the marine survival after the 1947 regime shift. At this time very high catch rates were set at approximately 38,000 tons. At the same time, foreign and domestic trawl fisheries caught and discarded large numbers of juvenile halibut that were incidental to their directed fisheries on other species. The combined effect was that the population was at historic low levels in 1973. McCaughran (1997) reported that the population would have declined naturally and that the high fishing rate and large by-catch of juvenile halibut in the trawl fishery simply increased the rate of decline.

Pacific halibut are now known to exhibit a non-random response to environmental conditions in the ocean (McCaughran, 1997; Clark, and Hare, 2002). The population will increase when the environment is favourable and the spawning biomass is adequate under the current approach to management. Clark and Hare (2002) showed that inter-annual and decadal-scale environmental variability is the major source of recruitment variability under the current management strategy. Recruitment beginning about age eight years is related to the particular climate and ocean regime during the spawning year. According to their analysis, the period from about 1947 to 1976 was associated with reduced marine survival, while the period after 1977 was a period of above average marine survival. Another way of wording their conclusion would be to say that fishing does not affect recruitment under the current approach to management, which has a conservative exploitation rate and maintains an adequate spawning biomass. The evidence is convincing that climate changes at the regime scale have been a major influence on the dynamics of the Pacific halibut fishery.

Pacific sardine

The fishery for Pacific sardines started in British Columbia in 1917 and quickly became the largest fishery on Canada's Pacific coast with catches averaging about 40,000 tons (Fig. 5, A, B). The Pacific sardines fished in Canadian waters were part of a population that was most abundant from southern California to southern British Columbia. The population off Canada's west coast consisted of older and larger fish that migrated north in early summer (Hart, 1943) and returned south in the fall. The sardines fished off Canada were believed by some to be part of a genetically distinct population that spawned at the northern limit of the spawning distribution in the south (Felin, 1954; Radovich, 1982). Others believed that it was one population in which the older fish migrated successively farther north as they aged (Schweigert, 1988).

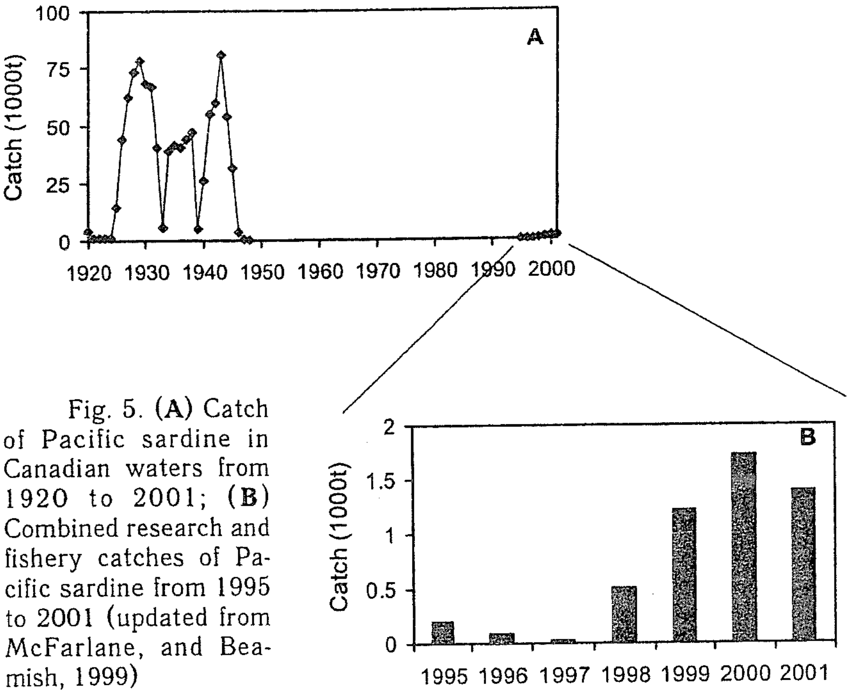

Fig. 5. (**A**) Catch of Pacific sardine in Canadian waters from 1920 to 2001; (**B**) Combined research and fishery catches of Pacific sardine from 1995 to 2001 (updated from McFarlane, and Beamish, 1999)

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The Canadian Pacific sardine fishery was concentrated off the west coast of Vancouver Island, and extended south to the coast of Washington State. Virtually all of the catch was reduced into fish meal and oil. The Canadian and United States fisheries in the 1930s and 1940s combined to become the largest fishery in both countries (Wolf, 1992). The Canadian fishery collapsed suddenly in 1947, followed rapidly by collapses in the fisheries off the United States, all of which had collapsed by 1951 (MacCall, 1979). Initially the collapse was blamed on over-fishing, but recently the collapse was regarded as another example of over-fishing at a time of unfavourable environmental conditions (MacCall, 1979; Ware, and Thomson, 1991). If over-fishing was the principal cause of the collapse, then the fishery would have captured every one of the sardines that traditionally migrated into the Canadian zone, which is unlikely. The mechanism responsible for the natural decline remains to be discovered, but a clue is the amazing synchrony in the abundance fluctuations among the sardine fisheries in the Pacific Ocean off Japan, Chile, and North America (Kawasaki, 1991). It is important to note that virtually no Pacific sardines were reported from waters off Canada after the collapse through to the early 1990s (Hargreaves et al., 1994). The population of Pacific sardines in the south started to increase in the late 1970s. Beginning about 1992, Pacific sardines appeared off the west coast of Canada (Hargreaves et al., 1994; McFarlane, and Beamish, 1999). The increase in abundance persisted through to the present and reflects a dramatic increase in the general population (McFarlane, and Beamish, 1999; McFarlane et al., 2000). In recent years, a small fishery for Pacific sardines occurred off the west coast of Vancouver Island on Canada's Pacific coast (Fig. 5, B). It is now generally accepted that the fluctuations in Pacific sardine abundance off Canada are related to climate and climate changes on a decadal-scale. Fishing effects in Canada and the United States would exacerbate the natural decline of this short-lived species (Radovich, 1982) but it was a change in climate that started the decline in the late 1940s and the increases in the late 1970s.

Pacific herring

The Pacific herring fishery appears to have started in British Columbia about 1877 (Hourston, and Haegele, 1980). Pacific herring are recruited to the fishery at age 2+ and few live past 7 or 8 years, although the maximum age is 13 years. Prior to 1970 Pacific herring were fished to produce fish meal and fish oil. Since 1970 virtually all Pacific herring are fished for roe, which is sold in Japan. Pacific herring are easily fished when they migrate inshore to spawn in the intertidal areas.

After the collapse of the Pacific sardine in the late 1940s, Pacific herring became the major fishery off Canada's Pacific coast, and catches steadily increased to over 200,000 tons in the early 1960s (Fig. 6, A). However, catches declined dramatically in the mid-1960s and the fishery was closed in 1967. Anecdotal stories relate the concerns of fishermen who reported that there were few adult Pacific herring left in the populations in the mid-1960s. There is little doubt that over-fishing was the major factor causing the collapse of the Pacific herring fishery. However, there is evidence that the early 1960s was a period of reduced marine survival for other species including Pacific salmon. Minobe (2000) identified a minor regime shift about 1960 and another in the mid-1960s. Thus, there may be a relationship between the minor regime shift and reduced productivity of Pacific herring. A reduction of marine survival during the time that catches exceeded 200,000 tons would be the classic explanation of a major collapse resulting from excessive over-fishing at a time of recruitment failure. The present fishery is small compared to the past, catching between 15 and 30 % of past levels. The smaller catches are a result of a prohibition of reduction fisheries and a limited demand only for herring roe for the Japanese market.

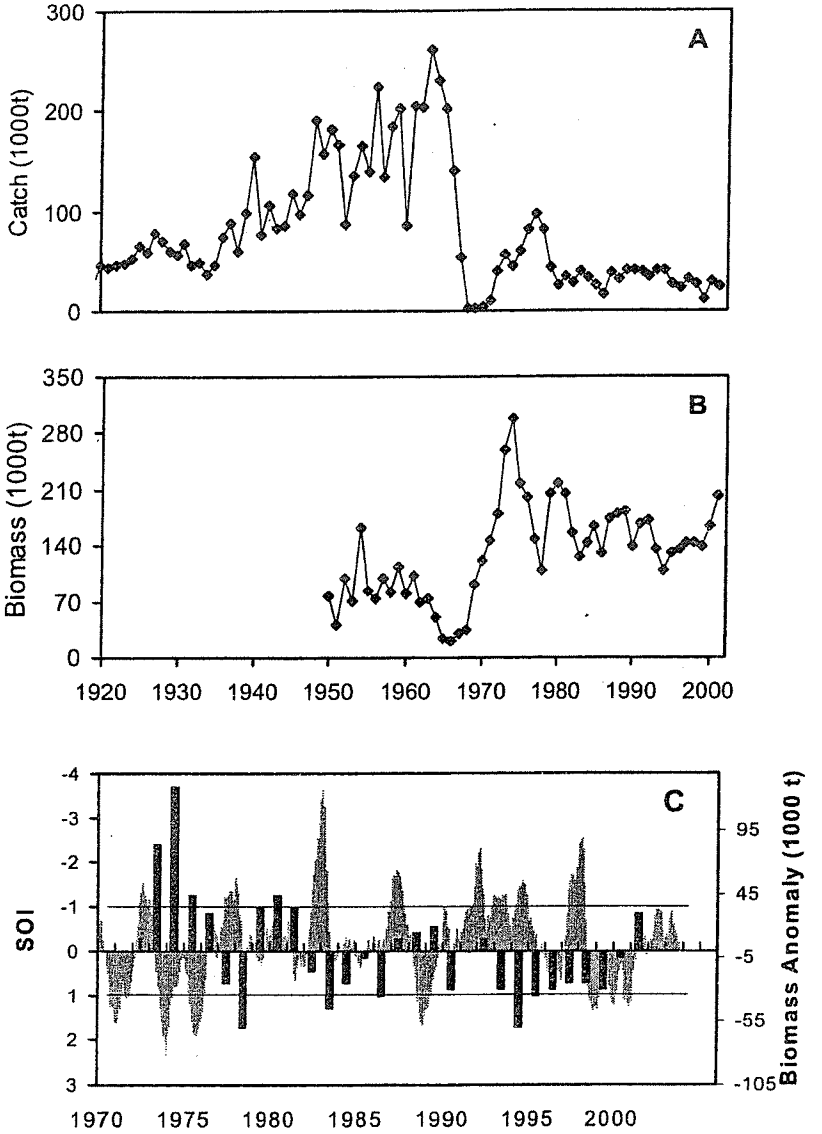

Fig. 6. (**A**) Canadian catches of Pacific herring from 1920 to 2001; (**B**) Estimated spawning biomass of Pacific herring in Canadian waters from 1950 to 2001; (**C**) Monthly Southern Oscillation Index (SOI, grey) and anomaly of herring spawning biomass (black bars) from 1972 to 2001

In British Columbia, herring are managed in five separate areas (Hourston, and Haegele, 1980). The portion of Pacific herring outside of these major assessment areas may be about 10 % of the entire population (Jake Schweigert, personal communication, Pacific Biological Station, Nanaimo, B.C., Canada). We combined the available biomass estimates from each of the five areas since 1972 when the fishery was reopened (Fig. 6, B). There is no apparent trend in the biomass, particularly in relation to climate trends. Ware (1991) showed that climate related changes in the ocean environment strongly affected the trends in abundance of Pacific herring off Canada's west coast. The mode of climate variability that most affected the recent abundance trends of Pacific herring is the El Nino Southern Oscillation (Ware, 1991). Fig. 6 (C) compares the pattern of Pacific herring recruitment anomalies with the pattern of the Southern Oscillation Index showing that there is the same relationship. However, the pattern of the Southern Oscillation Index is related to regimes (Beamish et al., 2000a), indicating an indirect relationship between the fluctuations in herring abundance and regimes.

Sablefish

In the early 1900s, a fishery started for sablefish (*Anoplopoma fimbria*). The sablefish fishery was reported to be as large as about 6,000 tons in the 1910s. This

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early fishery provided a smoked or salted meat product as well as using the livers for vitamin A and D production. The fishery was encouraged as a way to adapt to a shortage of meat during the First World War (Ketchen, and Forrester, 1954). Catches declined in to the 1920s, possibly because of a reduced demand after the War. It was not until the late 1960s that catches of sablefish increased as a consequence of foreign fishing outside of Canada's exclusive fishing zone. Following the extension of the exclusive fishing zone in 1977, the fishery accounted for annual catches ranging from 830 t in 1978 to 5,381 t in 1989 (Fig. 7, A). The average commercial landings from 1978 to 2002 have been 4,071 tons.

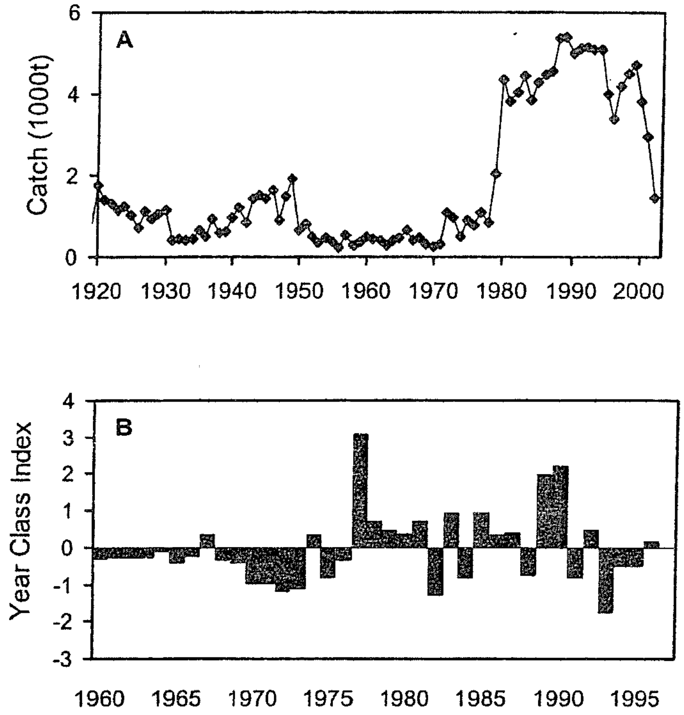

Fig. 7. (**A**) Catches of sablefish in Canadian waters (foreign catches not included) from 1920 to 2002; (**B**) Year class index of sablefish from 1960 to 1997 (King et al., 2000)

Sablefish are a slow growing, long-lived species once they mature (Beamish, and McFarlane, 2000). Common ages in the fishery can range from about 10 years through to 25 years, but can reach 60 to 110 years old. The fishery is a deep-sea fishery using baited traps set on the bottom at depths ranging from 300 to 1000 m. McFarlane and Beamish (1992) proposed that successful spawning was associated with optimal climate and ocean conditions. According to this hypothesis, the long life span of sablefish was an adaptation for surviving long periods of conditions unfavourable for reproduction. It was observed that despite a large fecundity, strong year classes resulted from both large and small spawning biomass (McFarlane, and Beamish, 1986). It was also observed that the production of strong year classes was closely associated with copepod production at a site off the west coast of Vancouver Island (McFarlane, and Beamish, 1992). Furthermore, there was a close relationship between the intensity of the Aleutian Low pressure system and copepod production. Thus, the decadal-scale pattern of the Aleutian Low that was linked to regimes and regime shifts (Beamish et al., 1999) was related to production of sablefish.

An index of year class strength of sablefish was developed using estimates of age, juvenile length data from commercial and research surveys, discard data from other fisheries, and larval surveys (King et al., 2000). The index that was produced (Fig. 7, B), increased abruptly and significantly in 1977, clearly showing a shift in productivity that was synchronous with changes in other climate and ocean indicators. The change in the index in 1989 was not statistically significant. King and co-authors (2000) suggested that the 1989 shift might be a "minor" regime shift compared to the 1977 shift. However, since the King and co-authors (2000) paper, there have been substantial reductions in the exploitable biomass and associated reductions in catch (Kronlund et al., 2002). This is evidence that reduced productivity following the regime shift in 1989 persisted into the 1990s as suggested by the index that was available up to 1997. It is possible, therefore, that there was a substantial reduction in the marine survival of sablefish following the 1989 regime shift.

In general, the strength of year classes of sablefish prior to 1977 was below average, from 1977 to about 1990 they were above average, and from 1990 to about 2000 there was reduced marine survival. There is some unpublished evidence that stronger year classes were produced after the 1998 regime shift. The periods of above average year class strength coincided with stronger Aleutian Lows, more frequent south-westerly winds, below average temperatures in the subarctic Pacific and warmer sea surface temperatures off the west coast of British Columbia (King et al., 2000). In general, the pattern of year class success matches the patterns of regimes and regime shifts. This is evidence that there are trends in sablefish production that are related to climate and ocean conditions on a decadal-scale.

Groundfish fisheries

Groundfish fisheries included a variety of species that generally, but do not always live near the bottom. Some species that are grouped into the groundfish category such as spiny dogfish (*Squalus acanthias*) and Pacific cod (*Gadus macrocephalus*) were fished in the 1940s and 1950s, but in general, groundfish fisheries can be considered to develop in the 1960s and 1970s. The Pacific hake (*Merluccius productus*) fishery started in 1980s after being developed by the Russian fishing fleet.

The relative importance of groundfish fisheries and the key species, especially the rockfish species (*Sebastes alutus, S. flavidus, S. reedi, S. entomelas* and *S. brevispinis*), is shown in Fig. 8. The percentage of landed biomass is shown for 20-year intervals beginning in 1940. Pacific herring was either the largest or second largest catch over this 60-year period. Similarly, Pacific salmon catches remained high, declining to the third highest total catch in the late 1990s. Catches of Pacific hake rose quickly, dominated the total catch of all species, and remain as the dominant species in the commercial catch, despite a declining total biomass off Canada and the United States (Fig. 9). The number of species that are significant in the catch increased in the 1980s, through to the present as the groundfish fishery developed. In particular, there was an increase in rockfish (*Sebastes spp.*) species that is evident in the catches shown for the year 2000. The history of the Pacific ocean perch fishery prior to 1956 is difficult to document due to poor catch records, and also because early rockfish catches were not commonly reported by species (Westrheim, 1987). Thus, it is probable that the early rockfish catch data also was dominated by Pacific ocean perch. In the late 1950s Pacific ocean perch were identified in the catch which began to rise due to a dramatic increase in foreign fishing. Total catches increased rapidly from 3,000 t in 1956 to a maximum of 48,600 t in 1966 (Westrheim, 1987), of which the majority was caught by the Russian fleet. At this time Pacific ocean perch represented over 50 % of the total rockfish catches (Forrester et al., 1978). By the time the 200-mile limit was implemented in 1977, the all-nation catches had declined to approximately 6,000 t annually. With the exception of a decrease in catch between 1991 and 1993 due to a change in fishing regulations (Richards, 1994), the Canadian fishery has maintained the catch close to the 6,000 t level since the 1980s.

The major change in Canada's Pacific coast fisheries has occurred in recent years as a result of a major increase in the aquaculture of salmon and a natural

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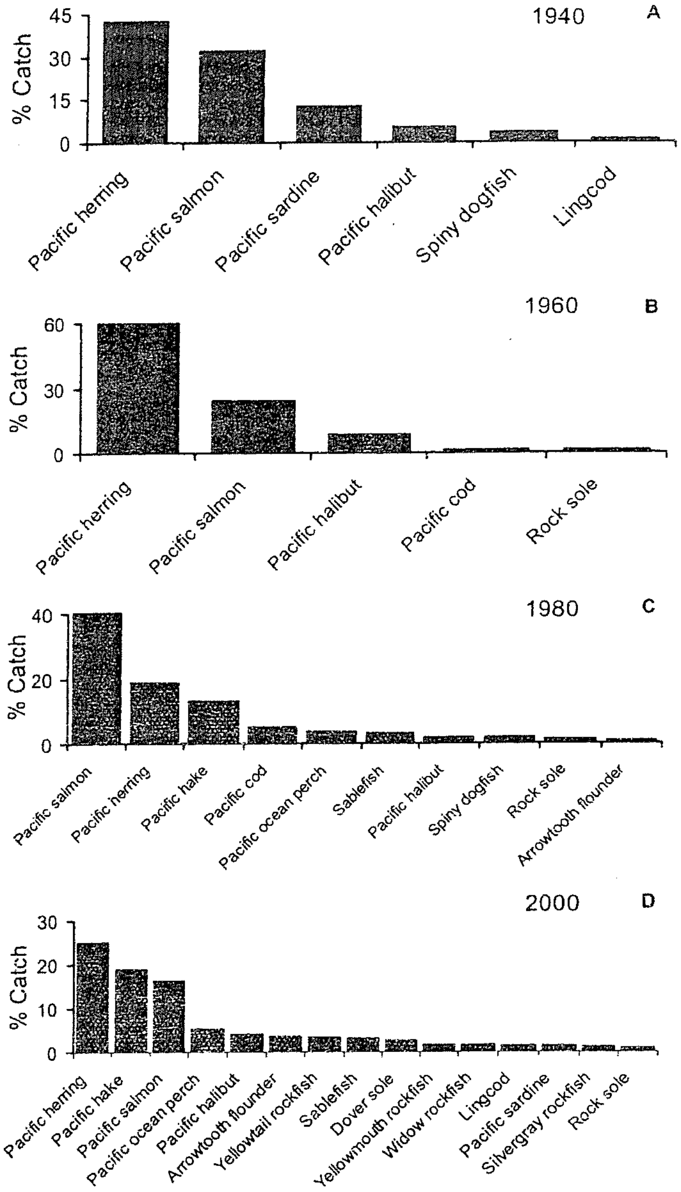

Fig. 8. Percent contribution of major species to the total British Columbia commercial landings in (**A**) 1940, (**B**) 1960, (**C**) 1980, and (**D**) 2000. Only species representing over 1 % of the catches are shown. See Table 1 for scientific names

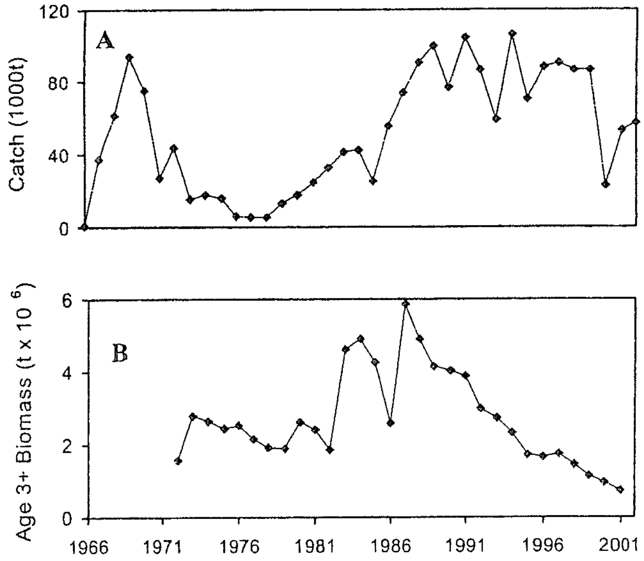

Fig. 9. (**A**) Total Canadian catch of Pacific hake from 1967 to 2002; (**B**) Total population biomass of age 3+ Pacific hake from 1972 to 2001

Table 1

List of species mentioned in the paper (Hart, 1973)

Species	Species
Sockeye salmon (*Oncorhynchus nerka*)	Pacific halibut (*Hippoglossus stenolepsis*)
Coho salmon (*O. kisutch*)	Spiny dogfish (*Squalus acanthias*)
Pink salmon (*O. gorbuscha*)	Sablefish (*Anoplopoma fimbria*)
Chum salmon (*O. keta*)	Pacific ocean perch (*Sebastes alutus*)
Chinook salmon (*O. tschawytscha*)	Silvergray rockfish (*S. brevispinis*)
Pacific herring (*Clupea harengus pallasii*)	Widow rockfish (*S. entomelas*)
Pacific hake (*Merluccius productus*)	Yellowtail rockfish (*S. flavidus*)
Pacific sardine (*Sardinops sagax*)	Yellowmouth rockfish (*S. reedi*)
Pacific cod (*Gadus macrocephalus*)	Atlantic salmon (*Salmo salar*)

decline in the marine survival of wild salmon. The change can be seen in landed value. In 2000, the landed value of all aquaculture exceeded the landed value of all other commercial fisheries (Table 2). Most of the landed value of aquaculture comes from the culture of Atlantic salmon (*Salmo salar*) which accounts for 95 % of the landed weight of all cultured fish species (Fig. 10). In fact, in 2001 the weight of aquaculture produced salmon exceeded the long term average catch of all wild Pacific salmon of about 60,000 tons. In 2000, the landed value of wild salmon was only approximately 16 % of the landed value of aquaculture produced salmon (Table 2). In general, the landed value of all commercial fisheries, including wild and aquaculture fisheries has remained approximately constant since the late 1980s.

Table 2

Landed value of all species in 2000

Species	Catch (t) x10^3	Canadian Dollars x10^6	Catch, %	Canadian dollars, %
Clupea harengus	29.67	61.36	17.80	11.70
Onchorynchus spp.	19.15	47.06	11.48	8.97
Sebastes spp.	17.19	28.17	10.31	5.37
Merluccius productus	22.37	3.50	13.42	0.67
Sebastes alutus	6.18	7.90	3.70	1.51
Hippoglossus stenolepsis	6.10	37.53	3.66	7.16
Ophiodon elongatus	3.04	6.51	1.82	1.24
Anoplopoma fimbria	2.81	24.11	1.69	4.60
Gadus macrocephalus	0.71	1.17	0.43	0.22
Groundfish	17.61	12.50	10.56	2.38
Other fish	0.81	1.11	0.49	0.21
Total	**110.33**	**229.26**		
Total Aquaculture	**56.40**	**295.10**	**33.83**	**56.28**
Total	**166.73**	**524.36**		

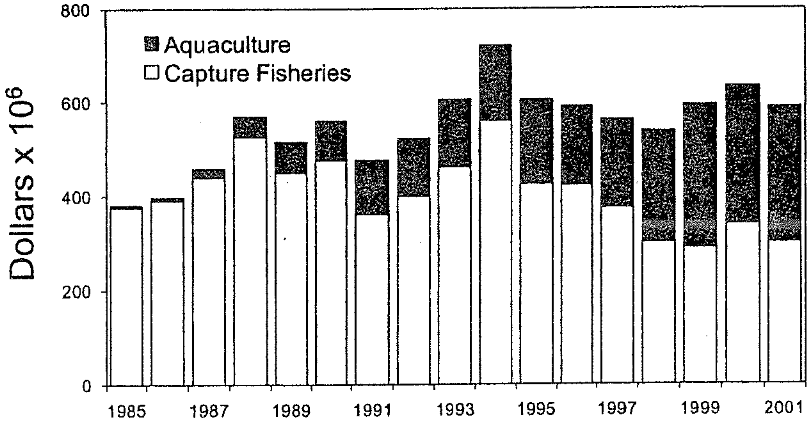

Fig. 10. Landed value in Canadian dollars of salmon from aquaculture and capture fisheries in British Columbia

Table 1

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Impact of climate and climate change

In 1954, Ricker published his famous paper on stock and recruitment (Ricker, 1954). In 1958, he examined the impact of climate on the relationship he developed (Ricker, 1958). In this study of climate impacts, he assumed that the kind of weather that affected Pacific salmon (and other species) did not follow recognizable trends. Ricker was always careful to document his assumptions and it is important to note that he used a random model for climate impacts because there was no evidence of persistent trends in climate. There now is clear evidence of trends in climate that persist for decadal periods and then shift quickly to new states (Trenberth, 1990; Beamish, and Bouillon, 1993; Latif, and Barnett, 1994; Hare, and Francis, 1995; Hurrell, 1995; Mantua et al., 1997; Zhang et al., 1997; Thompson, and Wallace, 1998; Beamish et al., 1999, 2000a; Overland et al., 1999; Minobe, 2000; Benson, and Trites, 2002; Gregg, 2002). In fact, there is evidence that decadal-scale variability and sudden shifts to new climate states have been a feature of the Pacific North American climate for at least 400 years (Gredalof, and Smith, 2001).

Regimes can be defined as persistent states in biological or climate data series or both. Currently, both biological and climatological data are used to characterize regimes. Eventually, it will be necessary to define the start and end of a regime according to the mechanism that causes regimes to occur and to shift. Until the mechanism is discovered, it is useful to define a regime as a climatological and biological state of a marine ecosystem that persists for about ten years. A regime shift is a sudden change to a new state that occurs in months and not years. Regimes are large-scale events that have regional impacts. Because regional ecosystems differ in their dynamics, the impacts of regimes and regime shifts would not be expected to be the same in all ecosystems. For example, the ecosystem north of the central coast of British Columbia may differ in the dynamics that affect production as the atmospheric circulation patterns diverge north and south about this latitude (Beamish et al., 2000a). This means that a regime shift may affect the dynamics of Pacific salmon differently north and south of the latitude where atmospheric circulation patterns change. There also are clear indications that regimes and regime shifts are related to global-scale processes (Beamish et al., 1999). Evidence of global linkages among patterns of atmospheric circulation can be traced back as far as Walker and Bliss (1932) who identified linkages among large-scale persistent weather patterns in the Atlantic and the Pacific.

Useful indices of regimes and regime shifts are the Aleutian Low Pressure Index (ALPI) (Beamish et al., 1997a); Arctic Oscillation (AO) (Thompson, and Wallace, 1998); Pacific Decadal Oscillation (PDO) (Mantua et al., 1997); and the Atmospheric Forcing Index (AFI) (McFarlane et al., 2000; Fig. 11). The ALPI (Fig. 11) is a measure of the intensity of the winter Aleutian Low pressure system over the North Pacific. Positive values of the index indicate periods of intense (large) Aleutian Low, increased precipitation in the subarctic Pacific Ocean, and decreased upwelling along the coast of North America. The converse holds for negative values. The AO (Fig. 11) is an index of sea level pressure over the North Pole. In the positive "warm" phase, there is below average sea level pressure over the Arctic, stronger surface westerly winds in the Western Atlantic, and enhanced northward advection of warm Atlantic water into the Arctic Ocean. In the negative "cool" phase there is higher than average sea level pressure and strong surface winds in the Arctic that limit the northward intrusion of warm Atlantic water. The PDO (Fig. 11) reflects sea surface temperatures in the Pacific basin. In the positive phase of the PDO there is warming along the west coast of North America and cooling in the central Pacific. A negative PDO indicates warming in the central North Pacific and cooling along the coast of Canada. The AFI (Fig. 11) is a composite index that includes elements of the PDO, ALPI, and a new measure of atmospheric circulation in the

Pacific which is the Pacific equivalent of the Atmospheric Circulation Index (ACI) (McFarlane et al., 2000). A comprehensive review of many indices is available in Beamish and co-authors (2000a). Regardless of what they measure, the timing of the changes of all climate and ocean indices is similar. This is the strongest evidence that regime shifts are a global phenomenon. Synchronous changes in climate and ocean conditions occurred in 1925, 1947, 1977, 1989, and 1998. The timing and magnitude of shifts is not exact in all indices. For example, the 1989 regime shift is not evident in the recent index of PDO (Fig. 11), however it was evident when Hare and Mantua (2000) examined the change earlier. Minobe (2000) proposed that there were both major and minor climate regime shifts in the last century. There were major shifts in the 1920s, 1940s, and in the 1970s.

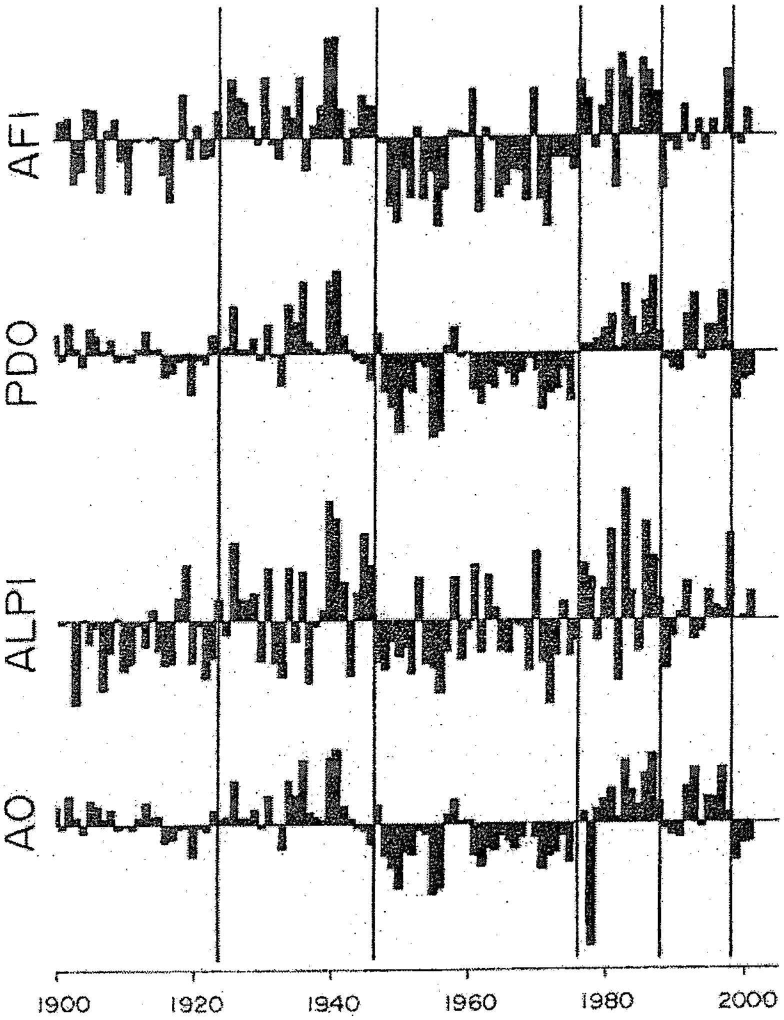

Fig. 11. Climate-ocean indices, Arctic Oscillation (*AO*), Aleutian Low Pressure Index (*ALPI*), Pacific Decadal Oscillation (*PDO*), and Atmospheric Forcing Index (*AFI*) for the years 1900 to 2002. Solid vertical lines indicate the regime-shift years

Relationship between regimes and the history of the major fisheries off Canada's Pacific coast

Beamish and Noakes (2002) assessed the relationship between regimes, regime shifts and the Canadian catches of Pacific salmon, as mentioned previously. Similar assessments were published by Beamish and Bouillon (1993, 1995); Beamish and co-authors (1997a, 2000a). The trends between the Aleutian Low Pressure Index and Pacific salmon catches in Figures 2 and 12 are remarkably similar, indicating that the decadal-scale pattern of the Aleutian Low is related to the trend in Canadian catches. It is also important to note how the pattern of the Aleutian Low changed in recent years. From 1977 to 1989, there were intense winter trends as a result of very low pressures in the sub-arctic Pacific. The 1990s were characterized by average low pressures, but a change to very low pressures occurred late in the 1990s. As indicated previously, Pacific salmon catches were low in the late 1990s, in part because of low abundance resulting from poor marine survival. This situation changes after the 1998 regime shift and abundances are about normal or in some cases at historic high levels (Beamish et al., 2001, 2002).

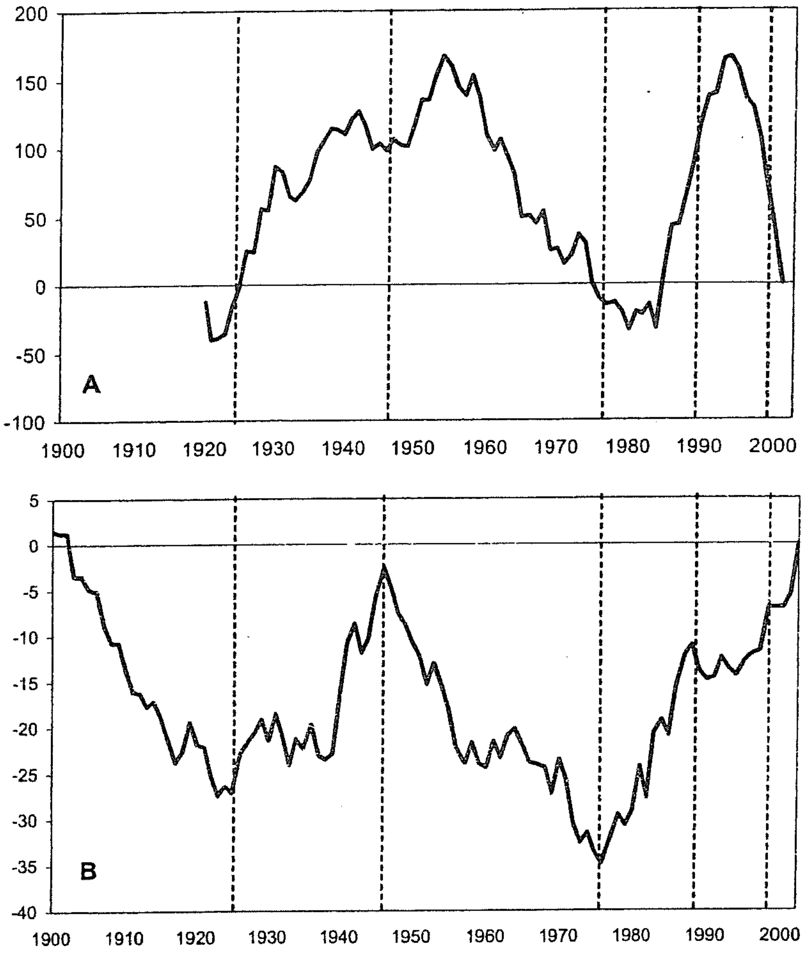

Fig. 12 CuSum of (**A**) Canadian pink, chum and sockeye salmon catch and (**B**) Aleutian Low Pressure Index (ALPI) from 1900 to 2002. Vertical dashed lines indicate timing of regime shifts

Pacific halibut catches are now accepted as being strongly related to the impacts of regimes and regime shifts (Clark, and Hare, 2002). In fact, it is correct to conclude that scientists have shown that the current management approaches eliminate fishing as a major factor in the dynamics of Pacific halibut. The collapse of the sardine fishery about 1947 and the increase in the abundance of the population off Mexico and California in the late 1970s is now accepted as a result of regime changes (McFarlane et al., 2002). The most convincing evidence of a strong relationship between sardine abundance fluctuations and regimes and regime shifts was shown by Kawasaki (1991). The remarkable synchrony in abundance trends among the large sardine populations in the Pacific off North America, Japan, and South America remains unexplained, but the timing of change is too similar to the changes in regimes to spend time looking for other explanations.

The effect of regimes on Pacific ocean perch productivity was considered for the first time in the 2001 stock assessment (Schnute et al., 2001). A key finding in the assessment was that trends in Pacific ocean perch recruitment reflected climate regime shifts. Schnute and co-authors (2001) found that production was low prior to 1976, high during 1976–1988 and low again between 1989 and 1998. Schnute and co-authors (2001) stressed the importance of maintaining sufficient adult biomass so that the population can take advantage of future periods of improved recruitment.

Moderate impacts of climate on recruitment were assessed for Pacific hake as interannual variability in the ocean environment appears to affect the year class strength more than regime responses. However, the movement of Pacific hake from the south into the Canadian zone is a regime-related response. The regime response of Pacific herring recruitment is weaker, in part because recruitment into the fishery is affected by top-down, predation-based impacts. There was a fishery-related collapse for Pacific herring, but the collapse also resulted from a too high fishing rate after a minor regime shift to a marine environment that resulted in reduced survival. With hindsight, there is solid evidence that persistent trends in climate were associated with trends in catch of most of the major fisheries off Canada's Pacific coast. This observation appears remarkable because it has been long believed that virtually all of the major changes resulted exclusively from fishing. The observation of significant climate-related effects is even more significant when scientists also accept that our greenhouse gas emissions are in the process of altering the climate that caused these changes. Clearly it is time to re-examine the earlier interpretations of the relative effects of fishing and climate on the populations dynamics of Canada's Pacific fisheries and, probably, all commercial fisheries.

Future of Canada's Pacific coast fisheries — the interaction of climate change, aquaculture, and new managements approaches

Speculating on the future is always a risky business. However, there is a reasonable degree of certainty that our climate will change and production from aquaculture will continue to increase. It is also possible that the almost global interest in ecosystem based management and the development of aquaculture will result in a general reduction in exploitation rates.

Scientists at the University of Washington used two global climate change models to study the possible changes in the intensity of the Aleutian Low as a consequence of the increasing concentration of greenhouse gases in the atmosphere (Mote et al., 1999). Beamish and Noakes (2002) used their model results (Fig. 12) to examine the potential impacts on Pacific salmon production. They used the total Canadian catch of five species of Pacific salmon by all countries to establish a pattern of residuals from the mean from 1950 to 2000 (Fig. 13). Positive standard deviations greater than 0.5SD were considered to be good and coloured black. Negative standard deviations less than 0.5SD were considered to be below average production and were hatched. Average production was between these two levels and was coloured grey. A similar colour schedule was developed for the results of each Global Climate change model. If the model results were similar to the production trends of Pacific salmon, there would be a general match of the colours from 1950 to 2000. There is some agreement with the model results and the Canadian catches, but in general the agreement at the yearly level is only approximate. Looking at the next 100 years, however, there is little doubt that there will be stronger Aleutian Low (Fig. 14), which means that there will be stormier winters. The frequency of the black colour, particularly in the latter one half in this century, is an indication that Pacific salmon production could increase relative to the period from 1950 to 2000. In general, the model results suggest that the subarctic Pacific may be more productive in the next 100 years. If Pacific salmon freshwater habitat can be maintained and exploitation rates are reduced, it is possible that average catches will increase, except, for perhaps stocks at the southern limit of their distribution such as Fraser River stocks of pink, chum, and sockeye.

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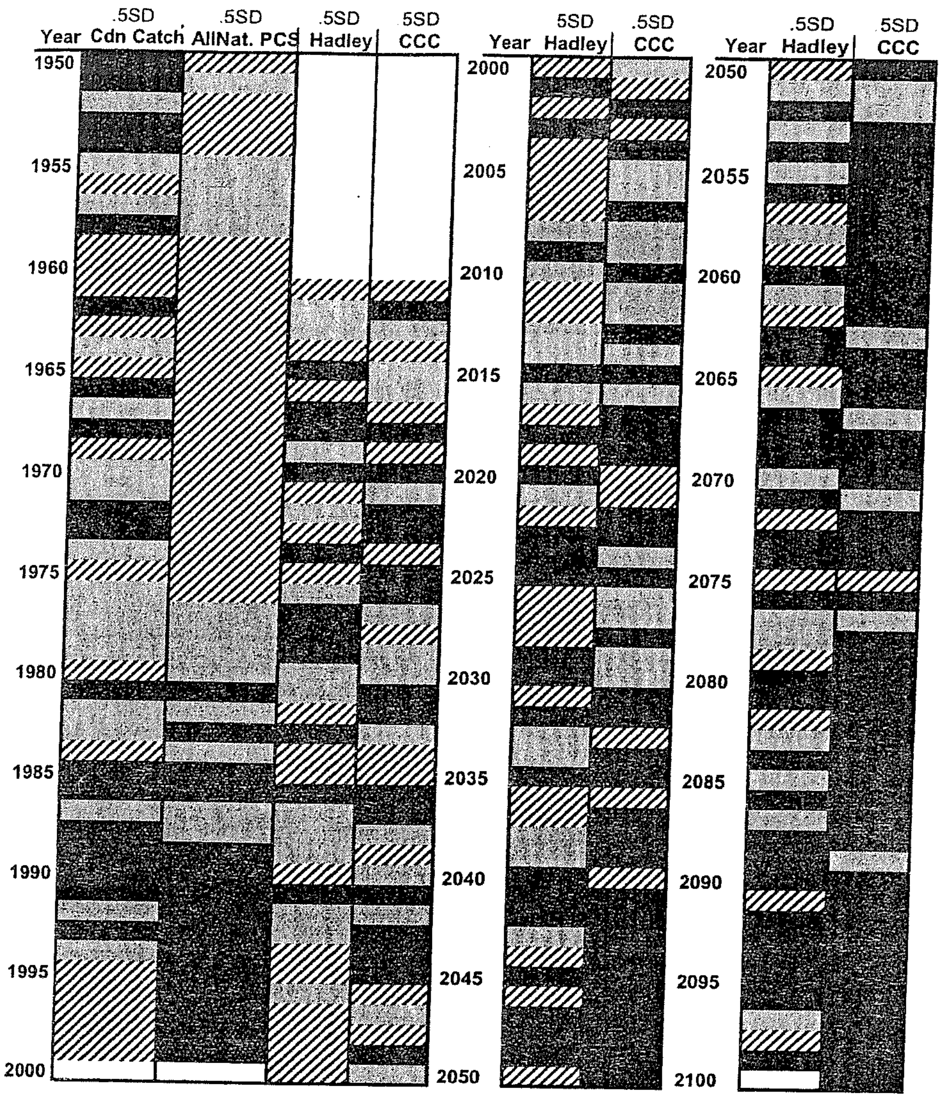
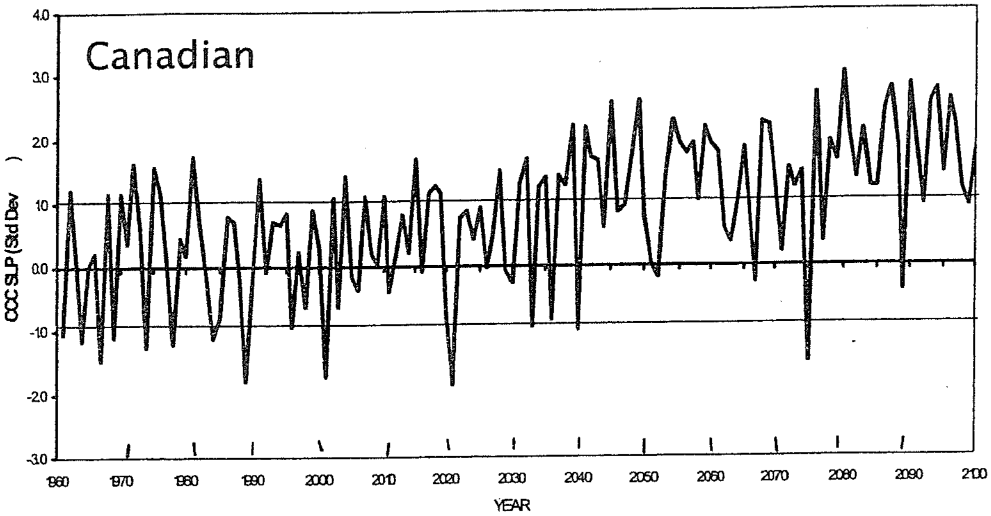


Fig. 13. Positive (black), negative (hatched), and average (gray) standard deviations of Canadian Pacific salmon catch, all nation Pacific salmon catch and Hadley and Canadian climate models of the expected changes in the Aleutian Low. Positive values correspond to years of above average catch and intense Aleutian Low

The demand for seafood for human consumption may almost double by 2030. This increase in production most probably will not come from commercial fisheries, as most scientists believe that we have reached the catch limit of the world's commercial fisheries (Fig. 15). An increasing demand for seafood will most certainly provide opportunities for commerce and employment in aquaculture. In fact, aquaculture and aquafeeds are the fastest growing food production systems on the planet. One possible limiting factor is the limited supply of fish meal and fish oil that comes from the world's small pelagic fisheries. Already, alternate sources of protein for aqua feeds have been found. Additional sources of protein substitutes for meal may be produced by genetically modifying plants. In the last seven years, the percentage of all acreage planted with genetically modified seed has increased from close to zero to almost one third of all acreage (Fig. 16). Technology is changing how we get our protein, and it is likely that technology will be used to develop inexpensive substitutes for fish meal and fish oil. In fact, some major freshwater cultured fish such as tilapia (*Tilapia spp.*) and catfish (*Ictalurus spp.*) are fed almost entirely on vegetable-based feeds.



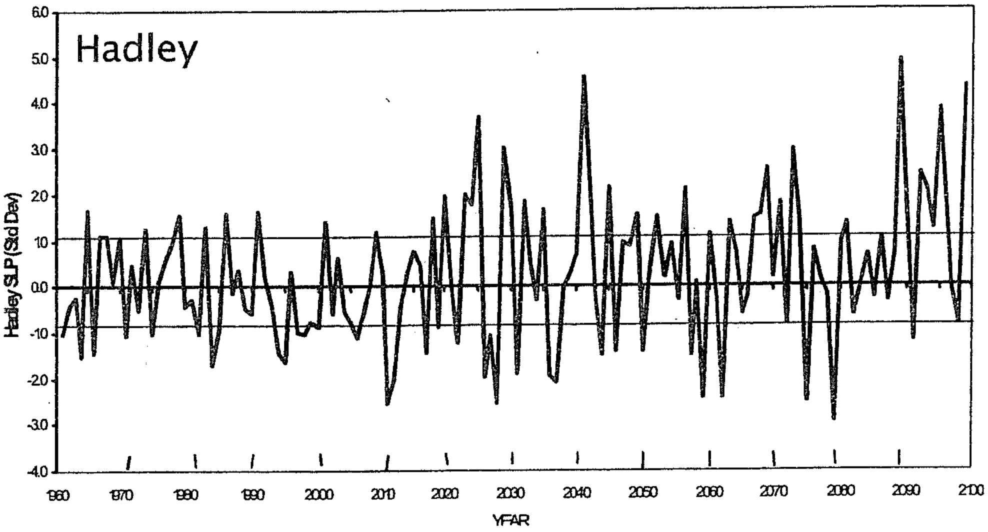


Fig. 14. Deviations from the mean of Sea level pressure (SLP) in the Aleutian Low by Canadian (CCC) and Hadley climate models for the period 1960 to present with projections to 2100

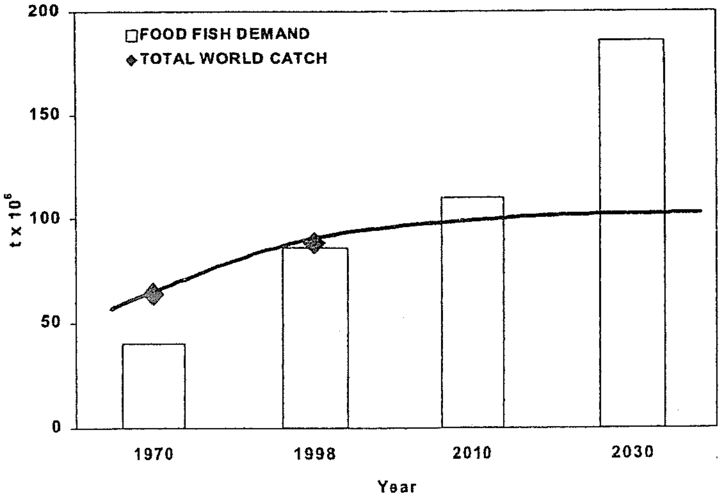
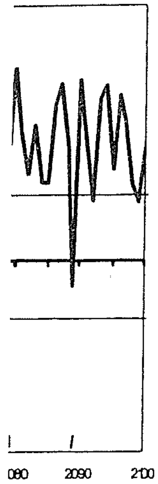


Fig. 15. Total world catch of all marine species (solid line) and food fish demand for 1970 and 1998 with FAO projections for 2010 and 2030. Total world catch is projected through to 2030 as being unchanged



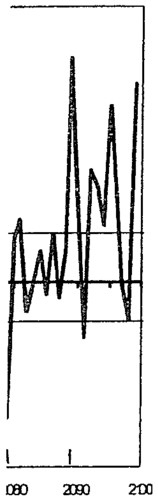


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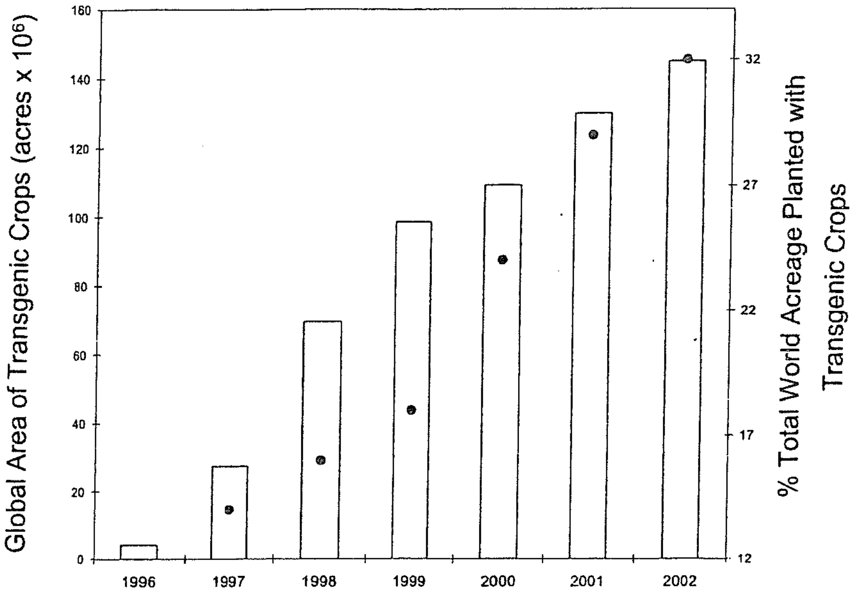
Fig. 16. Global area planted with transgenic crops (bars) and the percent of the total world acreage planted with transgenic crops (black circles) from 1996 to 2002



The rate of fishing could be lower because more fish will come from aquaculture. Fisheries could be managed by forecasting longterm trends in ocean productivity. Regimes and regime shifts will have major impacts on fisheries management science. Global warming will result in more intense Aleutian Low and a trend to increased productivity but with decadal-scale oscillations (regimes). Species at their southern limits such as pink, sockeye, chum, Pacific cod will fluctuate more and gradually decline.

It is apparent that past views about managing fisheries in order to optimize, stabilize, or even sustain catches need to be modified to recognize the influences of natural regimes and regime shifts. Stock and recruitment relationships clearly exist, but they now need to be seen as applying more specifically to the regime in which they were determined.

In conclusion, off Canada's Pacific coast we have seen new fisheries develop in the last 100 years, but the old, established fisheries remain generally healthy. In the future, fisheries will be managed according to models that are sensitive to climate changes and ecosystem impacts. However, it is the development of aquaculture that will have the greatest impact on our future fisheries, as it will allow management to be more precautionary. Greenhouse gas climate change has been modelled to increase the winter storminess in the subarctic Pacific. If this is true, it is good for fish production in general. However, the productivity of fish off Canada's Pacific coast that are at their southern limit will be reduced by global warming. This will affect pink, chum, and sockeye salmon that are produced in the Fraser River. Overall, the next 100 years should result in a fishing history similar to the last 100 years, with stocks being generally healthy and well managed.

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