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A review of Pacific salmon hatchery programmes on Hokkaido Island, Japan

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Hatchery programmes involving the mass release of cultured fish have been implemented worldwide to supplement wild populations and to increase harvests. Hokkaido Island is one of the most active regions for Pacific salmon hatchery programmes, with ca. 1.2 billion (10^9) juveniles released annually along a coastline of ca. 3000 km. During the last quarter of the 20th century, coastal catches of chum and pink salmon increased dramatically, whereas those of masu salmon did not. In addition to the development of hatchery technologies, several possible hypotheses may explain these catch trends, including climate change, closing of high-seas fisheries, rehabilitation of water quality, habitat loss caused by damming and channelling, and increased pressure from recreational fisheries. Even when these other factors have been accounted for, it is difficult to evaluate whether all hatchery programmes have actually increased net populations. To use these programmes more effectively, it is necessary to evaluate both their river- and species-specific benefits and compare hatchery programmes with other management tools, such as fishery controls and habitat rehabilitation. Future hatchery programmes should incorporate active, adaptive learning approaches to minimize the risks associated with artificial propagation and to promote sustainable salmon stocks.

Keywords: *Oncorhynchus* spp., population dynamics, sea ranching, stock enhancement.

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Introduction

Hatchery programmes involving the mass release of cultured fish have been implemented worldwide to supplement wild populations and to increase fishery harvests. Hokkaido Island is one of the most active regions for Pacific salmon hatchery programmes, with ca. 1.2 billion (10^9) juveniles released annually along a coastline of ca. 3000 km. With a few exceptions (Yoshizaki, 1982; Ushijima, 2002), the sole objective of Japanese hatchery programmes is to increase catches of Pacific salmon, and it has been claimed that these programmes are essential to sustaining the fisheries (Kobayashi, 1980; Hiroi, 1998). In contrast, recent studies have attempted increasingly to incorporate climatic variation into a general understanding of the population dynamics of Pacific salmon (Saito, 2002; Yatsu and Kaeriyama, 2005; Morita *et al.*, 2006).

The use of hatchery programmes has been long debated (Hilborn, 1992; Waples, 1999; Brannon *et al.*, 2004), and the negative effect on wild fish productivity is one of the most frequent criticisms (Levin *et al.*, 2001; Chilcote, 2003; Nickelson, 2003). Some Russian scientists have claimed that Russian wild chum salmon, *Oncorhynchus keta*, may be replaced by Japanese hatchery chum salmon (Klovatch, 2000; Zaporozhets and Zaporozhets, 2004), but there is little empirical evidence to support this claim. For sustainable use of salmon resources, it is necessary to understand the benefit of the hatchery programmes after accounting for any negative impact on wild fish populations and environmental change. We review the history of hatchery programmes and the population dynamics of Pacific salmon on Hokkaido Island. Most reviews of this topic have been conducted in only a few regions, principally North America, so we hope that the information presented here will contribute to the development of a more general understanding of the utility of hatchery programmes.

Hokkaido Island

Hokkaido, the northernmost island of the Japanese archipelago (Figure 1), contains some of the most extensive wilderness areas in Japan. Native anadromous *Oncorhynchus* spp. include chum, pink (*O. gorbuscha*), and masu salmon (*O. masou*), and ca. 200 rivers on Hokkaido have salmon populations (Kobayashi, 1980). Most (99%) of the coastal catch of pink salmon is from the Okhotsk Sea coast, although most (ca. 85%) of the masu salmon catch is from the Japan Sea and western Pacific coasts. Although chum salmon are caught along the entire coast of Hokkaido, the catch from the Japan Sea coast is small (ca. 10%).

Hatchery programmes

The hatchery programmes on Hokkaido began in 1878, and by 1888, they were well-developed for the three native *Oncorhynchus* spp. (Kobayashi, 1980, 1988). Most of the released fish were chum salmon, followed by pink and masu salmon (Figure 2). From 1888 to 1934, these programmes were privately operated (Kobayashi, 1980, 1988), and because these private hatcheries sought profit from the sale of adults, they did not always contribute to stock enhancement (Kobayashi, 1980, 1988). To improve the hatchery programmes, most private hatcheries were taken over by the Hokkaido prefectural government in 1934. From 1952 to 1996, the hatchery programmes were controlled by the Fisheries Agency of Japan as a result of the enactment of the Fisheries Resource Protection Law in 1951, and since 1999, following revision of the law, they have been controlled by the Hokkaido prefectural government. Currently, there are 16 national, three prefectural, and 117 private hatcheries in Hokkaido.

All chum and pink salmon released originate in natural broodstocks (i.e. a stock of returning adults regardless of whether they originated in a hatchery or from natural spawning), but the masu salmon released are from both natural and captive (i.e. a stock reared in captivity their entire life) broodstocks. Hatchery releases of chum and pink salmon increased dramatically during the last quarter of the 20th century (Figure 2), and since 1980, the annual number of fry released has stabilized at 1000 million and 150 million for chum and pink salmon, respectively, because of hatchery capacity limitations. After 1960, the quality of released fry improved greatly as a result of the substantial efforts of hatchery managers and scientists. The body weight of released fry increased, and the timing of their downstream migration was close to that of wild fry (see Figures in Mayama, 1985; Kaeriyama, 1999; Nagata and Kaeriyama, 2003). In contrast, the number of masu salmon juveniles released increased after 1970, owing to the development of a captive broodstock, which was established exclusively for masu salmon because of the difficulty of collecting natural broodstock. Unfortunately, captive masu salmon reared for several generations have lower genetic diversity (Edpalina *et al.*, 2004), greater growth and survival rates (Reinhardt *et al.*, 2001), and abnormal foraging behaviours (Reinhardt, 2001; Yamamoto and Reinhardt, 2003) compared with wild masu salmon. All masu salmon released before 1980 were fry, but smolts (1-year-olds) were also released after 1980 (Mayama, 1990). During 1993–2000, fry and smolts have accounted for 60–70% and 10–20%, respectively, of the total number of masu salmon juveniles released (Miyakoshi *et al.*, 2004b).

To obtain eggs from the natural broodstock for hatchery production, the returning adults were captured in weirs. Most weirs were located at the bottom of rivers or their tributaries. The number of rivers used for capturing natural broodstock increased between 1960 and 1980, but then decreased for all three species (Figure 2). Around 1980, more rivers were used for capturing pink and masu salmon hatchery broodstock than for the release of hatchery fish.

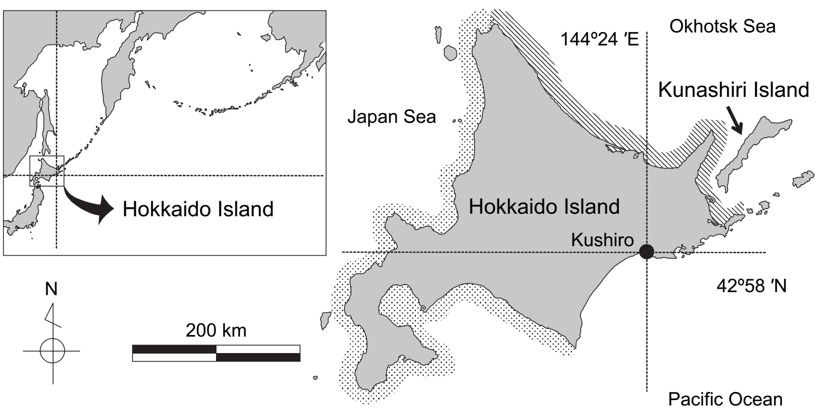

Figure 1. Map of Hokkaido Island, Japan, showing the major fishing grounds for chum salmon (entire coast), pink salmon (hatched area), and masu salmon (stippled area).

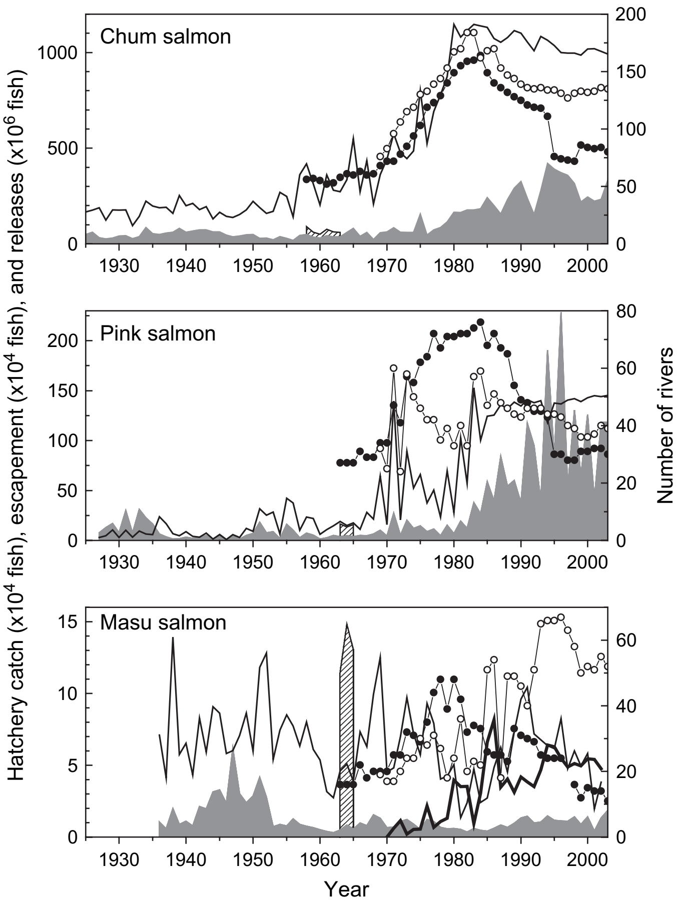

Figure 2. Long-term changes for three species of Pacific salmon on Hokkaido Island, Japan in river catches for hatcheries (shaded areas), escapement (hatched areas), the number of hatchery-released fish originating from natural (thin lines) and captive (bold line) broodstocks, and the number of rivers used to supply hatcheries (filled circles) and into which hatchery-reared fish were released (open circles). Before 1935, pink and masu salmon were counted together (shown in the panel for pink salmon). The number of released fish was described for each brood year (i.e. not release year). Data are from Hokkaido Salmon Hatchery (1954−1998), NSRC (1999−2005), Hokkaido Fish Hatchery (1954−2005), Hokkaido Salmon Hatchery (1956, 1973, 1988), and Sano (1969).

However, the number of rivers in which hatchery fish were released exceeded the number of rivers used for capturing hatchery broodstock after 1990. Many hatchery fish were released into rivers other than their natal rivers. For chum and pink salmon fry released between 2002 and 2004, 52.4% and 45.8%, respectively, were released in their river of origin (NSRC, 2003, 2004, 2005). However, long-distance transplantation was not common.

Several non-native *Oncorhynchus* spp. were also released as part of enhancement programmes (Hokkaido Salmon Hatchery, 1954−1998; Hokkaido Fish Hatchery, 1954−2005; NSRC, 1999−2005). A total of 6 million chinook salmon (*O. tshawytscha*) fry was released between 1959−1976, but the number of returning adults was not sufficient to continue the hatchery programme. In all, 0.9 million coho salmon (*O. kisutch*) fry were released from 1975−1981, but again, the few returning adults did not justify continuation of the hatchery programme scheme. A total of 14 million sockeye salmon (*O. nerka*) fry was released between 1966−2003, and 21 000 adults were recaptured. Artificial propagation of sockeye salmon continues. Although the anadromous sockeye salmon is not native to Hokkaido, the kokanee, or lacustrine sockeye salmon, is native to two lakes (Akan and Chimikeppu). A hybrid of pink and chum salmon was also released; a total of 0.5 million chum × pink salmon fry were released in the 1960s, but only a few hundred adults were recaptured. This is not the only example of hybrid salmonids being released in Japan. Historically, kokanee × chum and masu (*O. m. masou*) × amago salmon (*O. m. rhodurus*) were artificially propagated (Terao *et al.*, 1964; Taguchi, 1966).

Escapement

Information on escapement, i.e. naturally spawning adults, is scarce. Around 1960, quantitative estimates of escapement were made for three species (Figure 2), and the proportion of escapement to the total river run was highest for masu salmon (95.2%), followed by pink salmon (72.8%) and chum salmon (42.7%). Kobayashi and Harada (1966) found that escapement of pink salmon was substantial when adult body size is small because small adults could pass through the hatchery weir. Ito *et al.* (2005) found that the escapement of chum salmon increased with increasing water discharge, indicating that adult fish swam over the hatchery weir during high flows. In addition, several studies reported natural spawning of chum (Sano, 1960; Kobayashi, 1968; Suzuki, 1999; Saito, 2000), pink (Sasaki *et al.*, 1993), and masu (Sugiwaka *et al.*, 1999; Miyakoshi *et al.*, 2003) salmon. However, the contribution of naturally spawned fish to the fisheries has not been evaluated for the three species. It is widely assumed that almost all chum salmon originate in hatcheries (Hiroi, 1998; Kaeriyama, 1999). Morita *et al.* (2006) estimated that the contribution of hatchery fish to pink salmon catches was ca. 40% on average in the period 1971−2003. The contribution of hatchery fish to masu salmon catches was estimated to be 12−23% (Y. Miyakoshi, unpublished data), based on the tagging data presented in Miyakoshi *et al.* (2001a, b, 2004b).

Commercial fisheries

During recent decades, most chum and pink salmon caught in Hokkaido coastal waters have been taken in two different types of stationary traps. Most chum salmon are caught using the "chum salmon stationary trap", whereas most pink salmon are caught using the "small stationary trap". In contrast, coastal catches of masu salmon are taken using several types of gillnets, longlines, and stationary traps or by angling. Until 1990, many Pacific salmon returning to Hokkaido were also caught in offshore areas (i.e. Japan Sea, North Pacific Ocean, and Bering Sea) using gillnets and longlines.

Coastal catches of chum salmon increased dramatically during the last quarter of the 20th century (Figure 3). The total number of chum salmon stationary traps also increased after 1968, and this rise in fishing effort may also have contributed to the larger coastal catches. Coastal catches of pink salmon fluctuated greatly and increased after 1980 (Figure 3). Despite the constant number of fry released, the catch of pink salmon has fluctuated greatly: even year classes dominated after 1994. The total number of small stationary traps along the coast of the Okhotsk Sea was relatively constant, with no clear trends among years after 1968. Coastal catches of masu salmon decreased gradually after 1969 (Figure 3; $r = -0.720$, $p < 0.001$). It is difficult to evaluate the fishing effort for masu salmon because this species was caught using several types of fishing gear. In addition to commercial catches, major recreational angling for masu salmon occurs both in rivers and the sea. Ando *et al.* (2002) estimated that 65% of juveniles in an urban stream were caught by recreational anglers, and Miyakoshi *et al.* (2004a) estimated that saltwater recreational anglers were responsible for at least 12−13% of the coastal catches of masu salmon. Chum and pink salmon are also caught by saltwater recreational anglers, but no quantitative data are available.

The Japanese offshore fishery caught many Pacific salmon (Figure 3), but the number originating from Hokkaido is unknown because this fishery harvested mixed stocks of Pacific salmon. It is believed that the Japanese offshore fishery caught fish mainly from Russian stocks (Sano, 1998), so this fishery may have had little influence on Hokkaido stocks. Although Mizuguchi (1986) and Sano (1998) noted that official catch statistics from commercial vessels in the offshore area are sometimes unreliable, they probably reflect the temporal trends in catches. The Japanese offshore fishery was established in 1927 in waters off western Kamchatka (Taguchi, 1966) and resumed in 1952 after the Second World War (Sano, 1998). From 1952 to 1977, offshore catches were relatively large, but since 1978, offshore catches have decreased because of the establishment of 200-mile zones (Figure 3). The high-sea salmon fishery was closed in 1992.

Pacific salmon support important commercial fisheries on Hokkaido. The economic yield of chum salmon is second only to that of scallop (*Mizuhopecten yessoensis*). Despite recent increases in catches, the total economic yields of salmon have decreased since 1975 (Figure 4, $r = -0.819$, $p < 0.001$), with negative correlations between catches and unit price after 1975 ($r = -0.912$, $p < 0.001$), indicating that the price declined because of oversupply. Shimizu (2005) indicated that salmon prices declined because of increased catches and increased imports of farmed salmon from Norway and Chile (Figure 4). There was also limited production of farmed coho salmon in Japan.

Offshore salmon monitoring

In offshore areas, Japanese research vessels have monitored the abundance of Pacific salmon stocks since about 1970, using commercial-mesh gillnets in the Japan Sea and research gillnets consisting of ten different mesh sizes in the North Pacific Ocean and Bering Sea (Figure 3; Nagasawa *et al.*, 2004). Catch per unit effort (cpue; number of fish caught per ten tans; one tan of gillnet is 50 m long) of maturing chum salmon increased in the Bering Sea, which is the major feeding habitat for Hokkaido chum salmon ($r = 0.718$, $p < 0.001$). The cpue of pink salmon in the northwestern Pacific Ocean, which is the major feeding habitat for Hokkaido pink salmon, has fluctuated greatly, with no trends between years ($r = -0.274$, $p = 0.130$). The cpue of masu salmon in the Japan Sea, which is a feeding habitat for Hokkaido masu salmon, has also fluctuated greatly, with no trends between years ($r = 0.264$, $p = 0.261$).

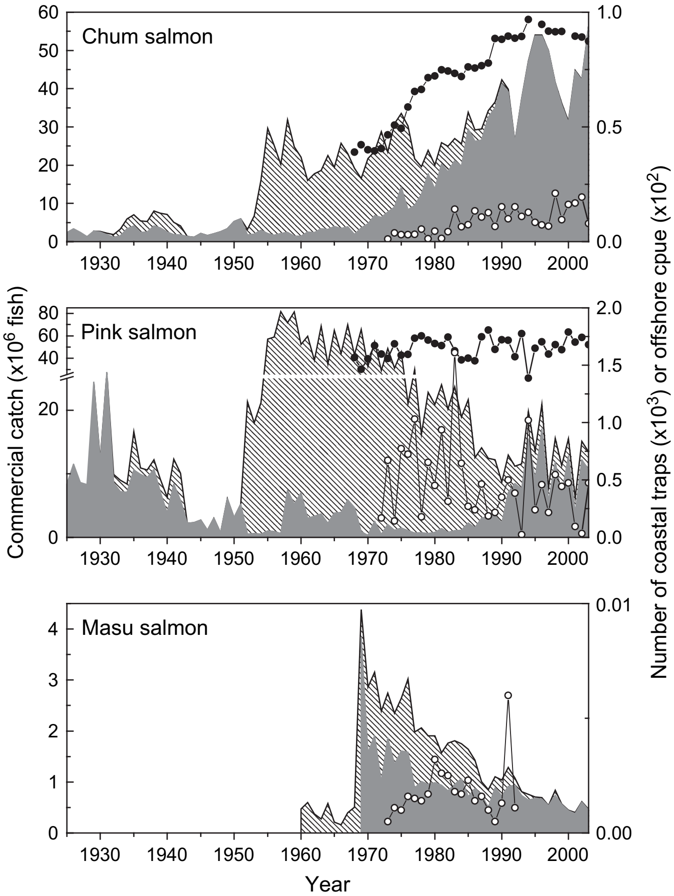

Figure 3. Long-term changes in coastal (shaded areas) and offshore (hatched areas) catches, the number of coastal stationary traps (filled circles), and offshore catch per unit effort (cpue) of Japanese Research vessels (open circles). For chum salmon, offshore cpue of maturing fish is shown. The type of coastal stationary traps differs among species (chum = chum salmon stationary traps along the entire coast around Hokkaido; pink = small stationary traps on the coast of the Okhotsk Sea). Offshore cpue of chum, pink, and masu salmon are from the Bering Sea (55−59°N, 175°W −E175°E) between late June and mid-July, northwestern Pacific Ocean (44−48°N 155−170°E) between late June and mid-July, and Japan Sea between March and May, respectively. Data are from the Hokkaido Salmon Hatchery (1954−1998), NSRC (1999−2005), the Hokkaido Fish Hatchery (1954−2005; unpublished data), Eggers *et al.* (2003), Ministry of Agriculture, Forestry, and Fisheries of Japan (1971−2005), and Fisheries Research Agency of Japan (unpublished data).

Riverine salmon habitat

During the second half of the 20th century, there were considerable changes in the riverine habitat in Hokkaido. Rivers have been increasingly fragmented by damming (Morita and Yamamoto, 2002; Fukushima, 2005), degraded by channelling (Nagata *et al.*, 2002; Kaeriyama and Edpalina, 2004), and invaded by exotic predatory fish (Takami and Aoyama, 1999; Morita *et al.*, 2004). Currently, ca. 20% of the watershed area is inaccessible to anadromous fish (Kameyama *et al.*, 2004). Fukushima and Kameyama (2006) showed that the estimated loss of masu salmon habitat resulting from damming is substantial. In contrast, river water quality has improved considerably in recent decades (Figure 5; Kuroda, 1982), and efforts have been made to rehabilitate river habitat for fish, including spawning-bed enhancement, improvement of fish passage, and re-meandering of channelized rivers (Toyoshima *et al.*, 1996; Nagata *et al.*, 2002; Sagawa *et al.*, 2004; Kawaguchi and Nakamura, 2005). Recreational fishing in rivers is prohibited for all anadromous Pacific salmon species, except fishing for juvenile masu salmon outside the smolting season.

The marine environment has also changed, and many studies have discussed the effect of these changes on Pacific salmon (e.g. Francis and Sibley, 1991; Beamish and Bouillon, 1993; Mantua *et al.*, 1997; Morita *et al.*, 2001; Saito, 2002; Goryainov and Shatilina, 2003; Yatsu and Kaeriyama, 2005). Regime shifts occurred in 1976/77, 1988/89, and 1998/99, which would have had major effects

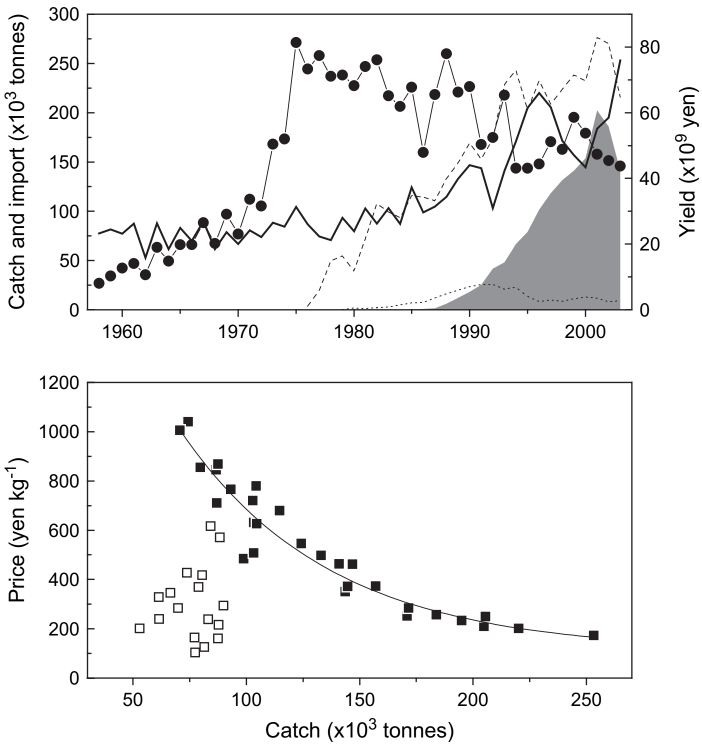

Figure 4. Top: Long-term changes in total salmon catches (solid line) and yields (filled circles) on Hokkaido Island, the quantity of imported salmon (dashed line = total; shaded area = Norway and Chile), and the production of farmed coho salmon (dotted line) in Japan. Bottom: The relationship between total salmon catches and price in Hokkaido (open squares = 1958−1974, filled squares = 1975−2003). Data are from the Hokkaido Government (2005), Fisheries Agency of Japan (1978−2005), and the Ministry of Agriculture, Forestry and Fisheries of Japan (http://www.maff.go.jp/).

on the ocean ecosystems around Hokkaido (Minobe, 2000; Sakurai *et al.*, 2000; Scheffer *et al.*, 2001).

Why has the coastal catch of salmon increased?

The number of chum and pink salmon returning to Hokkaido increased dramatically during the last quarter of the 20th century, although economic yields decreased. It has been suggested that advances in hatchery technology have been a major contributor to the recent increase in coastal catches (Kobayashi, 1980; Hiroi, 1998; Kaeriyama, 1998, 1999; Nagata and Kaeriyama, 2003). In particular, the apparent return rate of chum and pink salmon increased, and this has been attributed to increases in the body weight of the fry released and appropriate timing of their release from hatcheries (Kobayashi, 1980; Mayama, 1985; Kaeriyama, 1998, 1999; Nagata and Kaeriyama, 2003). However, Sano (1998) suggested that the increase observed in the apparent return rate could have resulted, to some extent, from artefacts, e.g. both the methodology for counting the total number of fry released and the total number caught in commercial gear changed during this period. In addition, the estimated return rate assumed a constant harvest rate (nearly 100%) and no natural spawning.

Despite the substantial efforts of hatchery programmes, the number of returning masu salmon has not increased yet. They have a longer freshwater phase than chum and pink salmon (age at smolting ranges from 1 to 3 years; Hayano *et al.*, 2003) and are probably affected to a greater extent by freshwater habitat losses caused by damming and channelling than chum and pink salmon. The positive effects of hatchery programmes and the negative effects of habitat losses may counterbalance each other.

In nature, environmental variations, including bottom-up and top-down processes, are the most important factors regulating the population dynamics of fish. Therefore, several factors may have contributed to the recent increase in coastal catches of chum and pink salmon. First, decreasing offshore catches may increase the number of returning adults (Mizuguchi, 1986; Harako, 1991; Sano, 1998). This hypothesis may be supported by evidence that the decrease in offshore catch is matched by an increase in coastal catch (see Figure 3). Although previous studies (Kaeriyama, 1998, 1999; Nagata and Kaeriyama, 2003; Morita *et al.*, 2006) did not consider the effects of offshore fisheries, they may be important in better understanding the dynamics

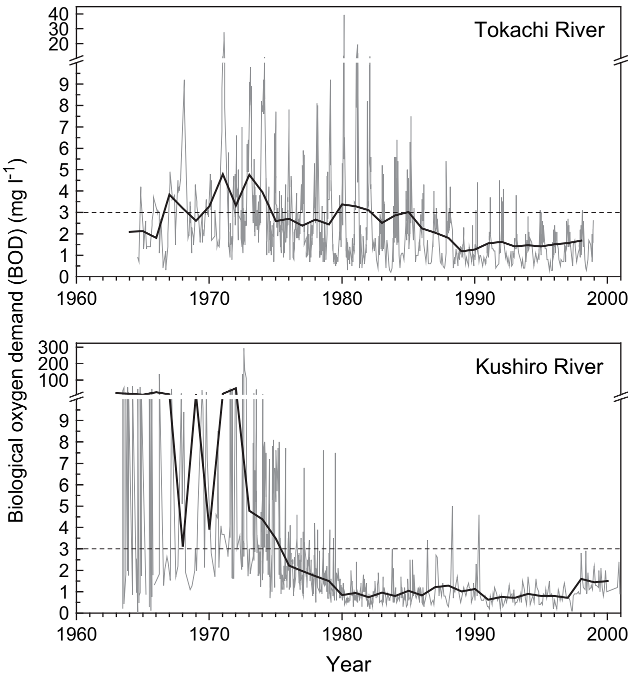

Figure 5. Long-term changes in biological oxygen demand (bold lines = annual mean, thin grey lines = raw data) in the Kushiro River (Shinkawa bridge) and Tokachi River (Tokachi-oh bridge). The dashed lines indicate the critical value capable of supporting salmon culture. Data are from the River Bureau, Ministry of Land, Infrastructure and Transport, Japan (http://www.mlit.go.jp/river/).

of returning adults. Second, the improved water quality of rivers and reduction in the number of native predatory fish may have enhanced freshwater survival. For example, white-spotted charr (*Salvelinus leucomaenis*), important predators of Pacific salmon, (Kubo, 1946; Dobrynina *et al.*, 1989; Takami and Nagasawa, 1996; Takami and Aoyama, 1997), have declined in abundance in recent years. Around 1960, many rivers had polluted areas, and concerns about the impact of water pollution on Pacific salmon emerged (Sano, 1960; Society for the Conservation of Japanese Salmon Stock, 1969), but the water quality of rivers has improved greatly since then (Figure 5; Kuroda, 1982). Third, favourable ocean conditions may have led to increases in abundance. This hypothesis is supported by evidence that Pacific salmon catches in some regions increased during the last quarter of the 20th century, irrespective of the level of artificial propagation (Beamish *et al.*, 1997; Hilborn and Eggers, 2000; Kaev and Chupakhin, 2003; but see Wertheimer *et al.*, 2001, 2004). The number of returning chum salmon increased in Russia (Figure 6), even though the number of fry released was reduced (Morita *et al.*, 2006). Similarly, coastal catches of pink salmon increased on neighbouring Kunashiri Island, which has no hatcheries (Figure 6). Salmon abundance appears synchronized among regions (chum salmon: $r = 0.842$, $p < 0.001$; pink salmon: $r = 0.843$, $p < 0.001$).

Although the development of hatchery programmes is likely to be partly responsible for increasing coastal catches of chum and pink salmon, other factors may help explain the observed trends. It is still difficult to evaluate whether hatchery programmes have actually resulted in net population increases when these are taken into account.

Concluding remarks

In Japan, considerable effort has been made to increase the number and survival of hatchery-reared fish (Nogawa and Yagisawa, 1994; Seki and Shimizu, 1996), most results being published in the grey literature. Japanese hatchery technology is well-developed, and both the quality and quantity of juveniles released are high because of the substantial efforts of hatchery managers. Japanese chum salmon are considered to be representative of the phenomenal success of hatchery programmes, which are seen as necessary to sustaining catches of Pacific salmon in Hokkaido. Unfortunately, there have been few efforts to assess whether these programmes have actually increased the population of the target species after accounting for the negative impact on wild fish and environmental changes. In particular, there have been few river-specific evaluations of their effectiveness. There are risks associated with hatchery programmes, such as competition between cultured and wild salmon, genetic impacts on wild salmon, domestication selection, and disease outbreaks (National Research Council, 1996; Altukhov *et al.*, 2000). Overall they may be replacing wild salmon rather than augmenting total salmon

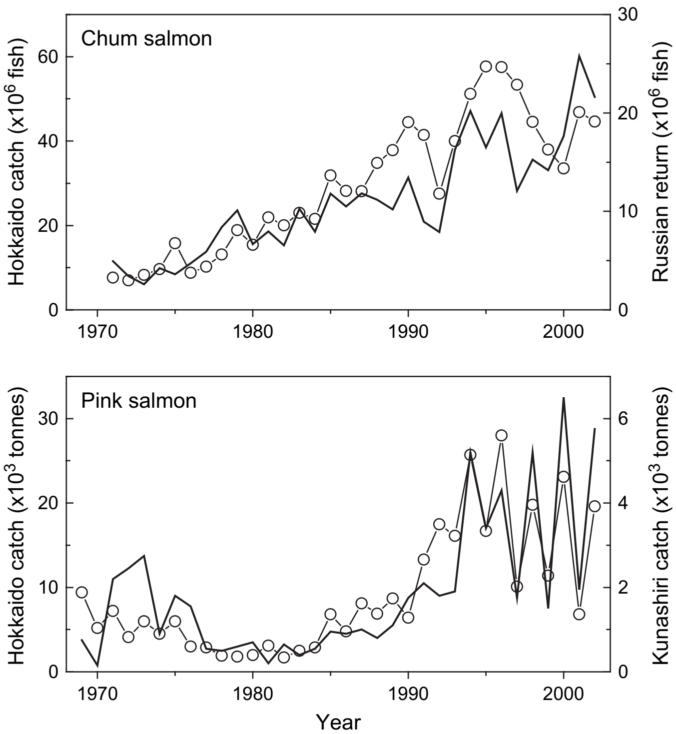

Figure 6. Top: Long-term changes in the total chum salmon catch (open circles) and total chum salmon catch plus escapement (solid line) in Russia. Bottom: Coastal pink salmon catch on Hokkaido Island (open circles) and coastal pink salmon catch on Kunashiri Island (solid line). Russian chum salmon data are from Eggers *et al.* (2003), NPAFC (2003), PRFC (2001, 2002, 2003), and NPAFC Working Group on Stock Assessment (unpublished). Kunashiri pink salmon data are from Kaev and Romasenko (2003).

production (Nickelson *et al.*, 1986; Hilborn and Eggers, 2000; Sweeting *et al.*, 2003). In addition, if genetically modified captive stock is released into rivers where wild fish occur, both wild and hatchery fish may decline (Muir and Howard, 1999; Devlin *et al.*, 2004). For the sustainable use of salmon resources, it is necessary, therefore, to consider not only the potential benefits but also the risks, associated with hatchery programmes. We suggest adopting the concept of managing hatchery and wild fish together (Fisheries Agency of Japan, 2004).

To use hatchery programmes more effectively, we need to evaluate their river- and species-specific benefits first (cf. Nickelson *et al.*, 1986; Hyatt *et al.*, 2005), and then compare hatchery programmes with other management tools. The latter should include spawning-bed enhancement (Merz *et al.*, 2004), rehabilitation of channelized streams (Nagata *et al.*, 2002), and improvements to access for migratory fish (Sagawa *et al.*, 2004), but fisheries management should be implemented more actively. Such conservation management tools will guarantee the long-term sustainability of salmon stocks. Future hatchery programmes should clarify goals and incorporate active, adaptive learning approaches to minimize the risks associated with them and promote the sustainable use of salmon stocks. Scientists in Japan have initiated a dialogue about the most appropriate future direction for Pacific salmon hatchery programmes, with special reference to wild salmon.

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