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Adult Return of Farmed Atlantic Salmon Escaped as Juveniles into Freshwater

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Abstract.—The origin of Atlantic salmon *Salmo salar* adult returns from the ocean to the Magaguadavic River, New Brunswick, was determined for the 1996 smolt cohort by using scale examination of the freshwater–seawater transition zone and a discriminant function analysis based on scale measurements depicting the first year of growth in freshwater. Adult returns consisted of 57% farmed fish that escaped from sea cages, 34% wild fish that were the progeny of naturally spawned fish, and 9% farmed fish that were demonstrated to have escaped from hatcheries into the river as juveniles—the first report of farmed hatchery escapees into freshwater returning as adults. The analysis determined that 20% of returns previously thought to be wild were in fact farmed salmon that had escaped into freshwater from hatcheries. By comparison, using the same analysis, we determined that 51% of smolts from the same cohort migrating out to sea 1 and 2 years earlier were farmed escapees from hatcheries. The difference in proportion in the smolt run and adult return indicated that the return of farmed juvenile escapees from the ocean feeding grounds was considerably less than that of wild fish. For a single cohort, comparison of the counted number of returning adults with the estimated number of smolts partitioned by freshwater origin yielded a return rate of 0.45% for wild salmon and only 0.09% for the hatchery escapees. However, even with the benefit of a low return rate, the 20% incidence of farmed hatchery escapees in the returns allowed into the river to spawn presented a significant potential for interbreeding with wild salmon in the river.

The widespread escapes of Atlantic salmon *Salmo salar* from sea cages on fish farms, their dispersal at sea, and their straying to rivers to spawn have been well documented (Norway: Gausen and Moen 1991; Lund et al. 1991; Hansen et al. 1999; Iceland: Gudjonsson 1991; Scotland: Youngson et al. 1997; Canada: Carr et al. 1997a). In contrast, the escape of juvenile salmon from commercial land-based hatcheries into freshwater and their occurrence in large numbers in wild smolt runs have only recently been revealed (Stokesbury and Lacroix 1997; Clifford et al. 1998). Farm-stock salmon were found to escape in the outflow of hatcheries into rivers at any time between the fry and smolt stages and to emigrate as smolts after various periods of time in the river (Stokesbury et al. 2001). With the rapid expansion and concentration of salmon farming on the east coast of North America in a small area on the border of Canada and the United States, the number of hatcheries located on nearby rivers with wild salmon stocks has greatly increased (Baum 1998; Chang 1998). These hatcheries raise selected domesticated strains (e.g., Saint John River strain in New Brunswick, Canada, and Saint John River, Penobscot River, and Norwegian Landcatch strains as well as hybrids of the three in Maine, USA) under accelerated regimes designed to produce 1-year-old smolts intended for grow out in sea cages. The escape of farmed salmon from these hatcheries has the potential to exacerbate the impacts documented from the interbreeding of escapees from sea cages with wild salmon (McGinnity et al. 1997; Fleming et al. 2000). However, except for hatchery escapees that remain in rivers as precocious male parr, the scale of interaction depends on the survival of hatchery escapees at sea and their successful return to rivers to spawn. Our objective was to identify the proportions of wild adults returning from oceanic feeding grounds to a river that were truly wild (i.e., the progeny of naturally spawned salmon) and those that were nonwild (i.e., farm-stock salmon escaped from hatcheries, excluding sea cage escapees), and to estimate the return rates of both populations to assess the potential for interbreeding.

The Magaguadavic River is located among the salmon farming industry in the Bay of Fundy on the east coast of Canada. Since 1992, the numbers of farmed Atlantic salmon escaped from sea cages and straying to the river have been monitored in

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relation to the wild salmon population (Carr et al. 1997a). The wild salmon run to the mouth of the river has steadily decreased since 1992, from 293 to 14 adults in 2000, and escapees have dominated the run since 1994 (accounting for 67–90% of the total) but have also decreased from a peak of 1,200 escapees in 1994 (Jonathan Carr, Atlantic Salmon Federation, personal communication). Stokesbury and Lacroix (1997) determined that between 51% and 67% of migrating smolts sampled at the mouth of the river in 1996 were fish that had escaped as juveniles from the three large farm-stock hatcheries along the river. Continued smolt sampling at the same location confirmed the magnitude of this estimate and the interannual persistence of hatchery escapees (33–84% hatchery escapees in 1998–2000; J. Carr, personal communication). In the present study, we identified the origin of adult salmon returns from the 1996 smolt cohort to the Magaguadavic River from 1997 to 1999 for a comparison with the origin previously determined for smolts in that cohort.

Methods

Scale samples were taken and examined from all adult Atlantic salmon returns to the Magaguadavic River in Passamaquoddy Bay, New Brunswick, that could have originated from the 1996 smolt cohort previously sampled by Stokesbury and Lacroix (1997) in that river. This included 1-sea-winter (1-SW) salmon in 1997 ($n = 94$) and 2-SW salmon in 1998 ($n = 5$), but no 3-SW salmon returned in 1999. A trap at the top of a fish ladder at the mouth of the river just above the head of tide ensured that all salmon entering the river were captured and sampled (Carr et al. 1997a). Fork length was measured for all salmon. A preliminary in situ examination of scales from all fish was used to identify farm salmon escaped from sea cages. Specifically, we examined the transition zone on scales representing the change in growth rate between freshwater and seawater; escapees from sea cages could be identified by a diffuse rather than distinct transition zone (Lund and Hansen 1991). Sea cage escapees ($n = 53$) were not released back into the river according to the management policy for that river. All other salmon, which at that time were thought to be wild, were released back into the river to spawn.

Scales were later mounted, photographed, and stored as JPEG images, and the images were magnified and examined by using Image Tool software (Stokesbury et al. 2001). Scales images from sea cage escapees were reexamined for confirmation of initial identification made in situ. For all remaining samples (i.e., those considered not to be escapees from sea cages), several properties of the scale images were measured to identify the freshwater origin of the adults as described by Stokesbury and Lacroix (1997) for scale samples from the 1996 smolt run in the Magaguadavic River ($n = 192$). Briefly, the number of circuli in the first freshwater year (i.e., to the first annulus) were counted, the distance of the first annulus was measured (nearest 0.01 mm) from the center of the focus to a position between the last circuli of winter growth and the first circuli of spring growth, and total scale length was measured. Linear measurements were made along a line perpendicular to a reference line as described by Schwartzberg and Fryer (1993). Fish length at the formation of the first annulus (i.e., age 1) was back-calculated by the Frasier–Lee method as described by Stokesbury and Lacroix (1997). A few of the scale samples ($n = 6$) had only scales that were regrown and thus were missing the central freshwater portion needed for the above measurements, these samples were excluded from the classification analysis.

We used a discriminant function analysis to classify the freshwater origin of returning adult salmon that were not escapees from sea cages as being either wild (i.e., progeny of naturally spawned fish) or hatchery escapee (i.e., progeny of farm-stock fish escaped into freshwater as juveniles from hatcheries). The independent input parameters were (1) the number of circuli laid in the first year in freshwater and (2) the back-calculated length (mm) of the fish at freshwater age 1. The discriminant function was computed by using the same parameters determined from scales of Magaguadavic River salmon of known origin ($n = 54$ for wild and $n = 70$ for hatchery) and applied to the results from scales of adult returns of unknown origin, as described by Stokesbury and Lacroix (1997). The discriminant function separated the two groups of known origin ($n = 124$) with 100% accuracy (Wilks' lambda = 0.0564, $P < 0.00001$) and explained 94.4% of the variance between these two groups (Table 1).

The method was found to be highly accurate for predicting the origin of smolts of unknown origin (Stokesbury and Lacroix 1997). The two input parameters accurately captured the very large difference in growth between wild and hatchery fish during the first year in freshwater (Table 1). The accelerated temperature and feeding regime in the hatcheries produce salmon that first feed in Feb-

TABLE 1.—Predicted freshwater origin (i.e., hatchery escapee or wild) of Atlantic salmon adult returns to the Magaguadavic River in 1997 and 1998 that were not escapees from sea cages. The discriminant function analysis was based on the number of circuli in the first year and back-calculated length at age 1 for samples of fish of known wild and known hatchery origin. Parenthetical values are percentages.

Group	*n*	Mean number of circuli	Mean fork length (mm)	Canonical loading	Predicted number	
					Hatchery escapee	Wild
Known wild	54	9.5	72	−4.618	0	54 (100)
Known hatchery	70	38.3	195	3.257	70 (100)	0
Adult returns	40				8 (20)	32 (80)

ruary and are already larger than 50 mm by the time fry emerge from the redds in the wild (Lacroix and Fleming 1998), and the scales of hatchery fish already have many circuli by the time of scale focus formation in wild 25-mm-long fry (Stokesbury and Lacroix 1997; Stokesbury et al. 2001). Therefore, because this difference is established so early in the freshwater phase, it would be captured by the two parameters used to characterize the first year of growth, regardless of the time at which hatchery fish escaped. The likelihood is low that the method applied to a fish of age 1 and older (e.g., smolts and adult returns) would incorrectly classify a hatchery fish as wild. Another discriminant function, developed by Stokesbury et al. (2001), incorporated eight scale characteristics measured for the very early part of the first year of growth (i.e., only until circuli 6 is laid down) to accurately predict the origin of age-0 juvenile Atlantic salmon captured in rivers during the first summer and for which the earlier function that required scales from a fish that was age 1 or older could not be used. This function was 90% accurate in predicting the origin of juvenile salmon (fork length ≥50 mm) in the Magaguadavic River. However, the function is not considered to be more accurate than that used by Stokesbury and Lacroix (1997) for smolts and applied here to adults when both functions are used after the first annulus is laid down. The use of the same method and function for classification of both smolts and adults of the same cohort provided a sound basis for comparison and for the use of relative proportions to determine return rates.

Return rates (i.e., from smolt to returning adult at the mouth of the river) were estimated from the number of returning adults predicted to be of wild and hatchery escapee origin and the estimated number of smolts of each origin from the same cohort in the Magaguadavic River. The number of wild smolts in 1996 was calculated with a stock–recruitment function derived by using a habitat-based process model that simulates Atlantic salmon population dynamics at a river system scale (Korman et al. 1994). Key model parameters used to define the stock or habitat were fixed and reflected characteristics of the Magaguadavic River and its salmon population salmon over the 1992–1996 period (Lacroix et al. 1998). Total egg deposition in 1992 and 1993 was calculated from the number of wild salmon counted entering the river in each year, the number of spawners (based on evidence of sexual maturation), the observed sex ratios, and mean fork length and fecundity for females of each age-class (1-SW, 2-SW maiden and repeat spawners) as described by Lacroix et al. (1998). Egg depositions in 1992 and 1993 were used to predict the number of age-3 and age-2 smolts, respectively, in the spring of 1996, which yielded an estimate of 7,100 wild smolts for 1996. No estimation error was generated using this approach. The estimated egg-to-smolt survival was 0.7%, which is of similar magnitude to that predicted by other models for salmon in rivers of eastern Canada (Symons 1979; Chaput et al. 1998). The total number of smolts (i.e., wild plus hatchery) was calculated by dividing the estimated number of wild smolts (7,100) by the proportion (0.396) of these wild smolts in all the smolts sampled throughout the run in 1996; the proportion value is from Stokesbury and Lacroix (1997), and the calculation assumes equal catchability of wild and hatchery smolts. This gave a total estimate of 17,929 smolts; multiplying this by the proportion (0.510) of smolts determined to be hatchery escapees (value from Stokesbury and Lacroix [1997], corrected for the presence of 9.4% stocked hatchery fish) yielded an estimate of 9,144 smolts of farm-stock origin that escaped as juveniles from hatcheries.

Results

Adult salmon returns to the Magaguadavic River that were thought to be wild (i.e., excluding salm-

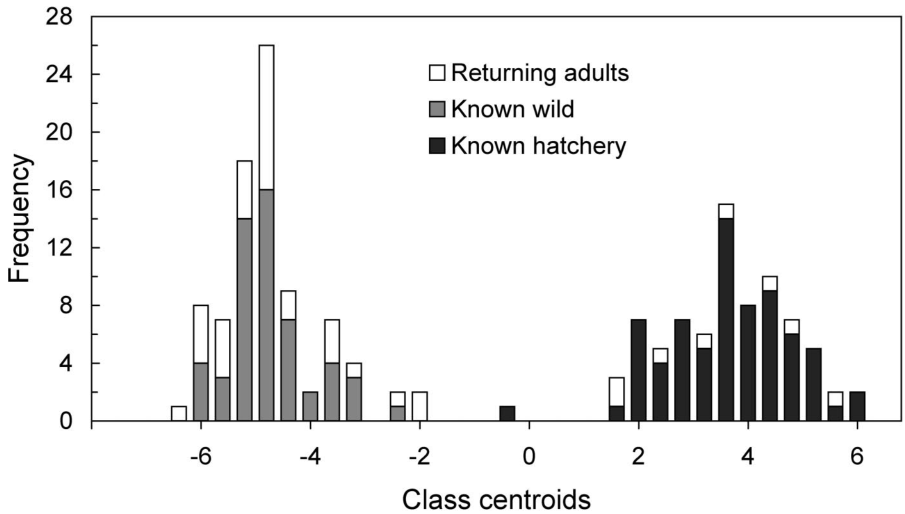

FIGURE 1.—Frequency of distribution by class for Atlantic salmon of known wild and known hatchery origin and of adult salmon returns to the Magaguadavic River in 1997 and 1998 that were not escapees from sea cages. Class centroids are based on a canonical discriminant function with number of circuli in the first year and back-calculated fork length at age 1 as independent variables.

on escapees from sea cages that strayed to the river) were clearly separated into two distinct modes representing different freshwater origins by using the discriminant function (Figure 1). That there was no uncertainty in classification is shown by the lack of overlap between the two modal groups of class centroids for wild and hatchery fish. The analysis predicted that 80% of adult salmon returns were indeed wild (i.e., progeny of naturally spawned fish) and that 20% were actually farm-stock salmon that had escaped as juveniles from hatcheries along the river and emigrated from the river as smolts (Table 1).

Farmed salmon escapees from sea cages straying to the river made up 57% of the adult salmon of all sources that entered the river as 1-SW fish in 1997 and as 2-SW fish in 1998 (Table 2). The remainder of adult returns included 34% wild fish and 9% farmed fish escaped from hatcheries into the river as juveniles, according to the results of the discriminant analysis in Table 1. Most salmon returns were 1-SW fish but 5–6% of sea cage escapees and wild salmon were 2-SW fish. In contrast, no hatchery escapees returned as 2-SW salmon. There was little difference in the fork length of 1-SW and 2-SW salmon of different origins entering the river, and the size range of wild fish was bracketed by the size range of sea cage escapees (Table 2). Length would therefore be a poor characteristic for identifying the origin of adult salmon entering the river—in contrast to the use of length at freshwater age 1 as a key variable in the discriminant function.

The calculated smolt-to-adult return rate of wild fish to the river was 0.45%, 5 times greater than the return rate of farm-stock juveniles escaped from hatcheries (Table 3). However, returns were low and, regardless of the large difference in return rate, the number of hatchery escapees still represented 20% of the total spawning stock allowed into the river. Therefore, even though escapees from sea cages (57% of total returns) captured at the mouth of the river were not released in the river, the hatchery escapees presented a significant potential for farm-stock fish to interact and interbreed with wild fish.

TABLE 2.—Number and fork length of Atlantic salmon returns from a smolt cohort (1996) to the Magaguadavic River as 1-sea-winter (SW; 1997) and 2-SW (1998) fish classified by their predicted origin.

Origin	Sea age (SW)	*n* (%)	Fork length (mm) Mean	Fork length (mm) Range
Wild	1	30 (32)	565	455–600
	2	2 (2)	763	760–765
Hatchery escapee	1	8 (9)	538	445–659
Sea cage escapee	1	50 (54)	589	415–742
	2	3 (3)	761	690–845

Discussion

This is the first report of farmed hatchery escapees into freshwater returning as adults. The

TABLE 3.—Estimated return rate of Atlantic salmon from a smolt cohort (1996) to the Magaguadavic River as 1-sea-winter (SW; 1997) and 2-SW (1998) fish according to their predicted freshwater origin.

Origin	Proportion of 1996 smolts[a]	Estimated number of 1996 smolts[b]	Number of adult returns	Return rate (%)
Wild	0.396	7,100	32	0.451
Hatchery escapee	0.510	9,144	8	0.087

[a] Proportion of smolts of each origin in 1996 as determined by Stokesbury and Lacroix (1997).
[b] Number of wild smolts estimated using a stock–recruitment function derived from a model calibrated for the river (Lacroix et al. 1998) and number of hatchery escapees calculated using their proportion in column 1 and the total estimate of 17,929 smolts (e.g., 7,100 ÷ 0.396).

proportion of hatchery escapees (20%) in the population of Atlantic salmon thought to be wild that returned to the Magaguadavic River to spawn was much lower than in the population of smolts of the same cohort as previously sampled migrating out of that river (51% hatchery escapees, from Stokesbury and Lacroix 1997). This proportional difference resulted in a lower calculated return rate from the ocean for salmon of farm-stock origin escaping into the river as juveniles compared with the return rate of wild fish (0.09% for hatchery escapees and 0.45% for wild salmon). These rates translated into very low numbers of adult returns and the absence of 2-SW hatchery escapees.

The lower frequency of return of hatchery escapees back to the river from the ocean represents an underperformance that could be a function of a lower rate of marine survival but could also be a result of poor homing ability and extensive straying to other rivers. Lower survival of the hatchery strain at sea could be a result of the hatchery-rearing environment or the fitness of the strain (McGinnity et al. 1997; Fleming et al. 2000). Straying from the home river could be a function of poor imprinting for hatchery salmon that escaped late as smolts rather than as young parr. The opportunity for imprinting for hatchery escapees that spent time in the river should be similar to that of wild salmon (Jonsson 1997).

The return rate of wild salmon was also low compared with historical returns of about 2–10% for the nearby Saint John River and other stocks in the Maritime Provinces (Ritter 1989; Marshall et al. 1997, 1999; Cunjak and Therrien 1998; Department of Fisheries and Oceans 1999). However, returns from tagged hatchery smolts released in the Saint John River for enhancement purposes in the same year as this study were similarly low: 0.6–0.8% 1-SW salmon and 0.1% 2-SW salmon for smolts stocked in 1996 and 1997 (Department of Fisheries and Oceans 1999). These low return rates appear to be a general phenomenon for wild salmon stocks in the Bay of Fundy and on the Atlantic coast of Nova Scotia since approximately 1990 (Amiro and Jefferson 1998; Department of Fisheries and Oceans 1999; Marshall et al. 1999). The reason for this decline in return rates still eludes explanation.

The presence of 9% farm-stock hatchery escapees in total returns of adult salmon in addition to the 57% sea cage escapees increased the proportion of farmed salmon returning to the river to 66%. This would overwhelm the wild population if not for the management decision since 1997 to not release sea cage escapees into the Magaguadavic River and thus prevent interaction and interbreeding with wild salmon. However, hatchery escapees were still considered to be fish of wild origin and were released into the river on the basis of the general criteria used for distinguishing between wild salmon and escapees from sea cages (Carr et al. 1997a). The large number of hatchery escapees identified in the smolt run of the river by Stokesbury and Lacroix (1997) suggested that a more thorough examination of returns was warranted to exclude hatchery escapees from returns, and the present study confirms the need to modify procedures if the goal is to remove the potential for interbreeding of farm-stock and wild salmon in that river. The possibility of genetic interaction will be eliminated only if these hatchery escapees are not released back into the river.

Hatcheries that raise farm-stock smolts for grow out in sea cages are becoming increasingly common on salmon rivers in New Brunswick and Maine (Baum 1998; Chang 1998). Juvenile salmon escaped from these hatcheries have been found to coexist with wild juvenile salmon and are prevalent in rivers of Passamaquoddy Bay on the border of Canada and the USA (Stokesbury et al. 2001). In most of these rivers, no mechanism exists for examining adult salmon returns and removing hatchery or sea cage escapees. The return of hatchery escapees would boost the number of farm-stock salmon already entering these open rivers and increase the potential for interbreeding with wild salmon. In addition, hatchery escapees may pose a greater threat than sea cage escapees because of a potentially higher reproductive success associated with their time in the wild. Jonsson (1997) demonstrated a relationship between the reproductive success of farmed fish and how long the fish had lived in nature before reaching sexual maturity. Lacroix et al. (1997) found the rate of sexual maturation of sea cage escapees straying to the Magaguadavic River to be very low, averaging 15% from 1994 to 1996, and Carr et al. (1997b) found that sea cage escapees in that river in 1994 failed to reach known spawning areas because their migration distance was less than that of wild salmon. These observations for sea cage escapees clearly enhance the relative impact that hatchery escapees could have on the wild stock.

Repeated escape events of juveniles from hatcheries such as those documented in the Magaguadavic River (Stokesbury and Lacroix 1997; Stokesbury et al. 2001; J. Carr, personal communication) have the potential to overwhelm the weak native stocks in rivers of Maine and New Brunswick located in the Bay of Fundy. The presence in rivers of farm-stock salmon escaped as juveniles raises the potential for direct ecological and behavioral interactions with wild salmon that could affect the growth and survival of the latter while in freshwater (see review by Lacroix and Fleming 1998; Fleming et al. 2000). Hatchery escapees have a substantial size advantage over wild juvenile salmon (Lacroix and Fleming 1998), and their abundance can be high in some rivers, especially in areas downstream of hatcheries (Stokesbury et al. 2001).

The number of hatchery escapees estimated in the smolt run was larger than the number of wild smolts emigrating from the river. The estimate of more than 9,000 escapees is not unrealistic given that three hatcheries on the river produce as many as 2 million farm-stock smolts annually. A low escape rate of 0.5% annually from these hatcheries would introduce 10,000 farm-stock juvenile salmon per cohort into the river, a quantity that would eventually lead to a complete swamping of habitat occupied by the few remaining wild juvenile salmon (Carr et al. 1997a; Stokesbury et al. 2001). In addition, the presence of progeny of farmed salmon in the river could adversely impact the wild juvenile population. McGinnity et al. (1997) found that although the survival of the progeny of farmed salmon to the smolt stage was significantly less than that of wild salmon, the progeny of farmed fish grew faster and displaced wild fish downstream.

From a management perspective, the study demonstrated that the benefits of a low return rate for hatchery escapees were negated by the low numbers of wild salmon. The 20% incidence of farmed hatchery escapees in the returns allowed into the river to spawn presented a significant potential for interbreeding with wild salmon in the river, and the behavior and reproductive success of these fish should be evaluated. The presence of farm-stock hatchery escapees as juveniles in some rivers and then as adults in returns has probably introduced errors in stock assessments in rivers of the Bay of Fundy. The unidentified presence of hatchery escapees in the returns would lead to overestimates of the return rates for wild salmon. The influx of unidentified hatchery escapees into rivers with hatcheries rearing farm stocks would also mask any decrease in production of wild juvenile salmon and decrease the reliability of estimates of the juvenile population in those rivers. The present study and those of Stokesbury and Lacroix (1997) and Stokesbury et al. (2001) confirm the need for a precautionary approach in the management of salmon stocks in rivers located in areas of salmon farming.

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