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Assessment of the Risk of Invasion of National Forest Streams in the Pacific Northwest by Farmed Atlantic Salmon

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Abstract

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This report describes the evidence for invasion of Pacific Northwest streams by Atlantic salmon (*Salmo salar*) that have escaped from marine salmon farms, and assesses the potential impact of farmed salmon invasion on native fishes inhabiting streams on National Forest System lands. The current risk to streams on National Forest lands in the Pacific Northwest from Atlantic salmon invasions appears to be low and is limited to a few areas in northwest Washington and southeast Alaska. However, long-term risks may be substantial if fish continue to escape from marine rearing pens or freshwater hatcheries. The two greatest threats appear to be that (1) Atlantic salmon could transmit a serious disease or parasite to native fishes, and (2) escaped salmon could eventually adapt to local conditions, leading to self-sustaining populations. If Atlantic salmon populations are eventually established, this species' preference for swiftly flowing stream habitats could facilitate competition with currently at-risk species such as steelhead (*Oncorhynchus mykiss*). This could result in a pattern of expansion similar to that observed in other nonnative aquatic plants and animals, in which a prolonged early colonization period is followed by a rapid phase of exponential growth as breeding populations adapt to local conditions.

Keywords: Atlantic salmon, invasive aquatic species, salmon farms, Pacific Northwest streams.

Contents

Introduction

Overview of Environmental Issues Associated With Salmon Farming

Global salmon production (all species, both farmed and captured in the wild) has more than doubled in the last 15 years from less than 1 million metric tons to about 2 million metric tons, and nearly all of the increase has resulted from Atlantic salmon culture.

Commercial farming of Atlantic salmon (*Salmo salar*) in marine net pens was developed in Norway in the 1960s. Juvenile Atlantic salmon are spawned in fresh water and reared in freshwater hatcheries until they can adapt to seawater, after which they are transferred to open cages of metal or heavy fabric mesh in sheltered marine areas where they grow to marketable size. The obvious advantages of farmed Atlantic salmon include (1) efficient production and harvest systems and (2) a product of generally uniform size and quality, easily processed and delivered to customers. Additionally, salmon farming is touted as reducing the pressure on naturally spawning stocks of salmon during a time when their numbers are sharply dwindling. In 2005, the total worldwide production of farmed Atlantic salmon was estimated to be about 400 million fish (Atlantic Salmon Federation 2005).

Based on industrial fish culture techniques pioneered by the Norwegians, Atlantic salmon farms have prospered on several continents. Most farmed salmon are produced in countries with protected bays and cold marine waters, particularly Norway, United Kingdom, Chile, and Canada. According to the Food and Agriculture Organization of the United Nations, global salmon production (all species, both farmed and captured in the wild) has more than doubled in the last 15 years from less than 1 million metric tons to about 2 million metric tons, and nearly all of the increase has resulted from Atlantic salmon culture (Jones 2004). Coincident with this rise in production, salmon prices in global markets have plummeted even as consumption rates have increased. Naylor et al. (2003) reported that ex-vessel prices per pound for wild-caught salmon declined from 36 to 82 percent, depending on the species, from 1984 to 1992, and between 1988 and 2002 (when farmed salmon production was rapidly proliferating) prices dropped an astounding 54 to 92 percent. The global salmon glut has seriously impacted local economies based on capture fisheries. In Alaska salmon fisheries, ex-vessel prices fell from $600 million in 1992 to $150 million in 2002 (Naylor et al. 2003), and commercial fishing licenses that sold for hundreds of thousands of dollars in the early 1990s are now selling for $20,000 to $30,000. The salmon farming industry itself appears to have been a victim of its own success. Some corporations have reported operating losses owing to depressed prices, and intense competition within the industry has resulted in efforts to cut production costs.

In addition to economic issues, a number of environmental concerns have arisen in connection with salmon farming. In early 2004, organochlorine pesticide residues and other chemicals known to be carcinogenic were detected in farmed salmon at concentrations greater than found in wild salmon, particularly in salmon from European farms (Hites et al. 2004). Most of the contaminants, termed "persistent organic pollutants" because of their longevity, resulted from commercial feed that contained high concentrations of fish oils from abundant pelagic species, e.g., jack mackerel (*Trachurus symmetricus*), anchoveta (*Engraulis* spp.), and herring (*Clupea* spp.), exposed to agricultural, urban, and industrial runoff in near-shore marine waters. Accumulation of uneaten food, waste products, and drugs beneath net pens has also been linked to localized pollution and potential contamination of wild fish and shellfish in the vicinity of pens (Goldburg et al. 2001).

Two of the most significant environmental concerns attached to Atlantic salmon farming in the Pacific Northwest have been (1) the possibility that escaped salmon would interact with and potentially harm native fauna, and (2) that Atlantic salmon farms would serve as epicenters for parasite and disease transmission to wild salmonids. Over the past 15 years there have been repeated escapes of salmon from pen facilities. Most escapes occur during large storms, but the precise number of escapees is rarely known. Worldwide, hundreds of thousands of Atlantic salmon have escaped from culture facilities, and where they are farmed outside of their native range, that is, in the Pacific Northwest and Chile, they have the potential to become an invasive species (Naylor et al. 2005). Salmon farms in a number of locations have created conditions favorable to parasites that infest wild fish. Particularly troublesome have been outbreaks of parasitic copepods (sea lice [*Lepeophtheirus salmonis*]). These parasites can be treated in farmed salmon with drugs but have been linked to declines of wild fish that are attacked as juvenile salmon swim by net pens on their way to sea (Krkosek et al. 2005).

The objective of this analysis is to examine the evidence for population establishment by escaped Atlantic salmon in the Pacific Northwest, and to assess the potential implications of invasions for native fishes inhabiting National Forest System streams. In addition, the analysis will assess the vulnerability of anadromous salmonid populations using National Forest System lands to salmon farming impacts when fish have left their natal watersheds.

Location of Salmon Farms on the Pacific Northwest Coast

At present, approximately 140 salmon farms occur along the Pacific coast of North America. Most fish raised in the farms are Atlantic salmon, but some farms raise Chinook salmon (*Oncorhynchus tshawytscha*) or coho salmon (*O. kisutch*), both of which are native to the region. The majority of farms (127 in January 2005) are in

British Columbia, although there are a few salmon farms in Puget Sound and the Strait of Juan de Fuca–all owned by a single corporation.

Hundreds of federal, state/provincial, and tribal salmon hatcheries also produce fish for harvest along the Pacific coast from Alaska to central California, but commercial salmon farms are limited to Washington and British Columbia. In 1990, net pen salmon farming was outlawed in Alaska, where capture fisheries dominate the economy of many coastal towns. The coasts of Oregon and California do not possess the sheltered, cold-water fjords needed for net pen rearing, and salmon farming operations have not been economically viable there. Overall, the contribution of Washington State salmon farms to total Pacific Northwest farmed salmon production is quite small. Washington farmed salmon rank 18th out of 40 agricultural commodities in the state (Washington Fish Growers Association 2005), although fish farming is growing more rapidly than other agricultural commodities. In contrast, salmon farming has become a major force in British Columbia's economy. Farmed salmon represent British Columbia's most valuable agricultural export, and the province has become the world's fourth largest farmed salmon producer (British Columbia Salmon Farmers Association 2005). Atlantic salmon make up 85 percent of the farmed fish produced in British Columbia, and approximately 90 percent of those fish are exported to the United States. Chile, however, remains the leading farmed salmon exporter to the United States at present.

The majority of salmon that escape from farming operations do so during large storms that damage the pens.

History of Farmed Salmon Escapes

The majority of salmon that escape from farming operations do so during large storms that damage the pens and enabling some or all of the fish contained within them to swim free. In most cases, the job of reporting is left to the farm operator, who may be reluctant to report the true number of escaped fish. Therefore, the accuracy of reports is uncertain, and quite likely the number of fish claimed by salmon farmers to have escaped is underestimated. Severe storms have resulted in rare but massive escapes. In 1996, 1997, and 1999, escapes of approximately 107,000, 369,000, and 115,000 fish, respectively, were reported from Washington's salmon farms (Washington Department of Fish and Wildlife 2001). British Columbia records indicate that between 1991 and 2002, in total 452,049 Atlantic salmon escaped from farms, including freshwater hatcheries and marine net pens (Canada Department of Fisheries and Oceans 2003). Again, these figures include only reported escapes. As shown in table 1, in some years no escapes were reported despite maturing Atlantic salmon being captured in commercial and sport fisheries.

Elsewhere, major storms and pen construction failures have liberated even larger numbers of farmed salmon. Soto et al. (2001) reported that salmon farms

Table 1—Atlantic salmon escapes and recoveries in Washington State from 1990 to 2002

Year	Farm production	Escape numbers	Commercial catch	Sport catch	Hatchery recoveries
1990	996,083	None reported	449	4	None reported
1991	1,362,671	None reported	1,012	17	None reported
1992	2,391,884	None reported	166	0	None reported
1993	1,728,195	None reported	225	25	None reported
1994	2,095,769	None reported	369	9	None reported
1995	1,897,874	None reported	200	7	None reported
1996	2,001,282	107,000	120	16	2
1997	2,133,791	369,000	2,204	99	53
1998	946,616	22,639	31	17	None reported
1999	1,211,997	115,000	14	3	25
2000	1,296,025	None reported	15	1	None reported
2001	1,497,695	None reported	6	14	None reported
2002	1,138,026	None reported	2	0	None reported

Source: Washington Department of Fish and Wildlife 2001 (data updated 2003).

in southern Chile lost several million fish during heavy storms in 1994–95, and escapes of hundreds of thousands of fish have occasionally occurred in European salmon farms. Since that time, the industry claims to have increased the security of pens by improving their design, but a World Wildlife Fund Report (WWF 2005), based on recent Norwegian government data, states that salmon escape rates from Norway's farms (the world's largest farmed Atlantic salmon producers) in 2001–2004 still ranged from about 350,000 to 750,000 fish annually. The presence of large numbers of farmed salmon in rivers near the pens and in nearby capture fisheries supports the hypothesis that escaped fish may be more common than industry-supplied escape statistics suggest.

In addition to mass escapes during storms, some fish are stocked in net pens but never harvested in normal operations. These fish are termed "leakage" because it is assumed they jump out of the pens or swim through the mesh openings in the nets or cages. Volpe (2001) estimated that leakage accounted for 0.5 to 1.0 percent of the total annual production of Pacific Northwest salmon-rearing operations. For Atlantic salmon farms in Washington and British Columbia, such an escape rate would amount to tens of thousands of fish per year.

Although escape statistics are almost nonexistent for freshwater hatcheries where young Atlantic salmon are reared until transferred to marine pens, there is some evidence that young salmon have entered streams into which hatchery waters are discharged. In July 2003, approximately 250 juvenile Atlantic salmon, "some up to a foot long," were observed in Scatter Creek, a Chehalis River tributary in western Washington that receives discharge water from a commercial Atlantic salmon hatchery (Washington Department of Fish and Wildlife 2003). At present, it is not known whether any of these fish survived to return to the Chehalis River as spawning adults.

Many Atlantic salmon that escape from pens are never seen again (Alverson and Ruggerone 1997), but some are caught by sport or commercial fishers in both marine and freshwater environments, or adult salmon are observed in rivers during spawning surveys (Atlantic salmon, like semelparous Pacific salmon, are autumn spawners). Few are reported relative to the large numbers that escape, but reported captures are likely underestimates of fish actually caught. Captures may not be reported to state agencies, or the fish may be confused with native salmonids.

Although the majority of escaped Atlantic salmon that are captured are taken close to where they originated, some fish are captured at relatively great distances. Soto et al. (2001) found that most escapees stayed near the net pens and continued to feed on food pellets that fell through the netting. However, Brodeur and Busby (1998) captured an immature Atlantic salmon near the Pribilof Islands in the Bering Sea, hundreds of kilometers from where it was presumably reared in British Columbia. Every year Atlantic salmon are taken incidentally in commercial fisheries in the Gulf of Alaska, an area that lacks salmon farms. Adult Atlantic salmon have also been caught or observed in many streams on Vancouver Island (Canada Department of Fisheries and Oceans 2003), as well as in Puget Sound and the Strait of Juan de Fuca. To date, there appear to be no published records of any adult Atlantic salmon originating from salmon farms having been captured in Washington or Oregon coastal streams, or in Columbia River tributaries.

Evidence for Established Atlantic Salmon Populations on the Pacific Coast

Evidence that escaped Atlantic salmon have established populations on the Pacific coast of North America is mixed. Atlantic salmon have been deliberately stocked in streams throughout the world for a century (MacCrimmon and Gots 1979, Waknitz et al. 2002), but successful establishment of anadromous (sea-run) Atlantic salmon populations outside their native range–northwestern Europe, Iceland, and northeastern North America–has been very rare. Table 2 gives examples of attempts to establish Atlantic salmon populations through deliberate introductions.

In North America, Waknitz et al. (2002) reviewed the success rate of deliberate introductions of Atlantic salmon in the United States. They reported that there

Table 2—Examples of attempts to introduce Atlantic salmon outside their native range

Source and year	Destination	Reason	Status
Holland 1929	Indonesia	Fill a “vacant niche”	Failed
United States of America 1971	Cyprus	Aquaculture	Failed, but efforts are continuing
United States of America 1963–64, 1964–67	Australia	Angling	Hatchery maintained
Multiple sources 1864–1995	New Zealand	Angling	Established in one lake and river in South Island
Canada 1904, 1970	Argentina	Aquaculture, angling	Successfully introduced into L. Fagnano, Traful, Carrhue Grande, and some southern rivers
United States of America 1957	Brazil	Angling	Failed
Germany 1935; more recently from Norway	Chile	Angling, aquaculture	Uncertain, but a number of established populations exist in lakes and rivers of southern Chile and the Patagonian region
United Kingdom 1960	Falkland Islands	Angling	Failed
United Kingdom 1960	Kerguelen Islands	Unknown	Failed

Source: Welcomme 1988.

have been at least 170 attempts to establish self-reproducing populations in 34 states, none of which succeeded. Atlantic salmon were first brought to the Pacific Northwest in 1904 (MacCrimmon and Gots 1979) for recreational angling, including some fish stocked in mountain lakes. According to Waknitz et al. (2002), these attempts produced no naturally spawning populations, and Atlantic salmon stocking in Washington State was discontinued in the early 1990s. In Oregon, the best known location of a successful Atlantic salmon fishery is at Hosmer Lake (formerly Mud Lake), a high mountain lake in the Deschutes River subbasin of the Columbia River. Hosmer Lake was barren of fish until brook trout (*Salvelinus fontinalis*) were stocked in 1929, followed by Atlantic salmon in 1958. A successful Atlantic salmon fishery has resulted, but the population is maintained by hatchery spawning.

In British Columbia, approximately 7.5 million juvenile Atlantic salmon were released to establish self-reproducing populations between 1905 and 1934 (MacCrimmon and Gots 1979). With the possible exception of the Cowichan River on lower Vancouver Island (where nonnative brown trout *Salmo trutta* have also become established), there has been no evidence that viable populations resulted from these early attempts. Until the late 1990s, therefore, Atlantic salmon had not become established in the Pacific Northwest, except for very few populations in mountain lakes that were maintained by artificial propagation.

The proliferation of Atlantic salmon farms in Puget Sound and British Columbia in the 1990s, coupled with repeated escapes of large numbers of farmed fish, initiated concerns that unintended populations of this species could invade watersheds where native salmon and steelhead were sharply declining.

The proliferation of Atlantic salmon farms in Puget Sound and British Columbia in the 1990s, coupled with repeated escapes of large numbers of farmed fish, initiated concerns that unintended populations of this species could invade watersheds where native salmon and steelhead were sharply declining (Alverson and Ruggerone 1997). The possibility that Atlantic salmon could become an invasive species harmful to native fauna led to targeted investigations of coastal streams in areas near where escaped fish had been caught or reportedly observed. Volpe et al. (2000) surveyed the Tsitika River in northeastern Vancouver Island, specifically looking for juvenile Atlantic salmon that had been produced by successful spawning of escaped farmed fish. In late summer 1998, 12 unidentified juveniles of the genus *Salmo* were captured, and another 28 were observed but not captured by snorkelers. All were seen in proximity to juvenile steelhead *O. mykiss.* Mitochondrial DNA analysis subsequently confirmed the identity of the specimens as juvenile Atlantic salmon. Fish of two distinct size classes were represented in the sample, and seasonal variation in the growth rings on scale samples indicated stream rearing (including a winter growth check in older, larger specimens) rather than farm rearing. Thus, both age 0+ and age 1+ individuals appeared to be present in the river. Volpe et al. (2000) concluded that the most likely explanation for the presence of juvenile Atlantic salmon in the Tsitika River was natural reproduction of feral adults. The nearest Atlantic salmon farm was approximately 26 km from the river mouth, although it was impossible to determine the exact origin of the parents of juvenile Atlantic salmon found in the study. The authors stated: “Based on our observations, we suggest that Atlantic salmon may constitute an invading species” (Volpe et al. 2000: 902).

Evidence suggesting that Atlantic salmon had become established in a coastal stream was greeted with much concern within the conservation community and denials from the local aquaculture industry. The Canadian Department of Fisheries and Oceans set up an Atlantic Salmon Watch Program (http://www.pac.dfo-mpo.gc.ca/sci/aqua/ASWP_e.htm) as a clearinghouse for information on Atlantic salmon sightings. The Web site includes information about sightings or captures of juvenile and adult Atlantic salmon from British Columbia, Alaska, and Washington from the early 1990s to 2002 (none of the tables contain more recent information). Alaska catches are reported by marine area. Washington catches are reported by marine catch area or by river. British Columbia data include marine captures, adults in fresh water, and juveniles in fresh water. At present there are no records of juvenile

Atlantic salmon caught or observed in streams in Alaska or Washington, except for the fish observed near an Atlantic salmon hatchery in the Chehalis River basin of coastal Washington (see above). In an Internet fact sheet dated August 2001, the Washington Department of Fish and Wildlife states “To date, no naturally-produced juvenile or adult Atlantic salmon have been found in Washington, in spite of extensive monitoring of outmigrating Pacific salmon smolts in the streams and rivers of the state” (Washington Department of Fish and Wildlife 2001). Since 2000, Alaska Department of Fish and Game biologists have snorkeled select streams where adult Atlantic salmon have been sighted, including the Situk River (near Yakutat), Ford Arm (near Sitka), and Ward Creek (near Ketchikan). So far, no juvenile Atlantic salmon produced by spawning feral adults have been detected (Alaska Department of Fish and Game 2005).

Whether escaped Atlantic salmon have actually established breeding populations in British Columbia streams still remains uncertain. According to the Atlantic Salmon Watch Program database, juveniles were observed or captured in 12 streams on Vancouver Island, but 9 of these streams likely held juveniles that escaped from net pens shortly after being transferred from hatcheries and subsequently moved back into fresh water. Only three streams (Adam and Eve River, Amor de Cosmos Creek, and Tsitika River) contained fish that showed characteristics of being the progeny of feral Atlantic salmon spawning (table 3). It is noteworthy that no Atlantic salmon juveniles were collected or observed in the three streams in

Table 3—Freshwater observations of juvenile Atlantic salmon in British Columbia from 1996 to 2002

River/Lake	1996	1997	1998	1999	2000	2001	2002	Total
Adam River					3			3
Amor de Cosmos Creek				113	8			121
Cameleon Harbour Creek [a]							1	1
Carnation Creek [a]		1	3		1		2	7
Georgie Lake [a]	41	21	86	30				178
Keogh River [a]			1	2				3
Lake of the Mountains Creek [a]		3					4	7
Lois Lake [a]	13							13
Pye Creek [a]		1						1
Ritterdon Creek [a]							1	1
Stamp River [a]						3		3
Tsitika River			24	2	3			29
Total	54	26	114	147	15	3	8	367

[a] Atlantic salmon from these sites were believed to be escapees from hatcheries.
Source: Canada Department of Fisheries and Oceans 2003.

2001 and 2002. Most of the juveniles were observed from 1996 to 2000, an interval that included a major El Niňo event accompanied by large storms that resulted in mass escapes from some farms. Volpe (2001) pointed out that less than 1 percent of British Columbia's streams possessing potential Atlantic salmon habitat have been surveyed for this species, and the same is surely true for Alaska and Washington. Therefore, the current status of fully established populations of Atlantic salmon in the Pacific Northwest (if any exist) is unknown.

Based on the existing location of Atlantic salmon farms and records of escaped Atlantic salmon sightings, streams on four national forests may be at risk for this potentially invasive species: the Tongass and Chugach National Forests in Alaska, and the Olympic and Mount Baker-Snoqualmie National Forests in Washington.

National Forest Streams Potentially at Risk of Atlantic Salmon Invasion

Based on the existing location of Atlantic salmon farms and records of escaped Atlantic salmon sightings, streams on four national forests may be at risk for this potentially invasive species: the Tongass and Chugach National Forests in Alaska, and the Olympic and Mount Baker-Snoqualmie National Forests in Washington. Given the large number of coastal streams in the Tongass National Forest, almost any stream to which anadromous salmonids have access can be considered vulnerable. Sightings of Atlantic salmon near the Chugach National Forest have been quite rare and limited to streams in the southern part of the forest. The most recent freshwater sighting was an adult Atlantic salmon captured in the southern Copper River delta in 2003,[1] and it seems likely that the area of vulnerability to invasion is limited to Prince William Sound. In Washington, Mount Baker-Snoqualmie National Forest streams draining into Puget Sound may be at risk, and eastern and northern Olympic National Forest streams draining into Hood Canal and the Strait of Juan de Fuca are also at risk of invasion.

Atlantic Salmon Life History, Habitat Preferences, and Potential Interactions With Pacific Salmon

Migration and Spawning

Within their native range of the North Atlantic Ocean, Atlantic salmon travel over large marine areas. Unlike some species of Pacific salmon, which remain close to their natal river system after entering saltwater, Atlantic salmon move quickly to oceanic foraging grounds in late spring and summer (Hansen and Quinn 1998). Once at sea, Atlantic salmon exhibit considerable variation in the amount of time they remain before returning to spawn. In general, the longer they remain at sea,

[1] Reeves, G. 2003. Personal communication. Research fish biologist, Forestry Sciences Laboratory, 3200 SW Jefferson Way, Corvallis, OR 97331.

the larger they become as spawning adults; large adult males can reach 1.5 m long and weigh up to about 35 kg, whereas the maximum size of females tends to be somewhat smaller (Hendry and Cragg-Hine 2003). Oceanic homing migration begins after 1 to 4 years, with older individuals tending to return earlier than younger ones. Timing of freshwater entry depends on the location of natal rivers. Hansen and Quinn (1998) reported that salmon can enter rivers in Scotland during any month of the year, similar to steelhead in the Pacific Northwest, but salmon from Norway enter rivers only from May to October. Like other anadromous salmonids, olfactory cues acquired as juveniles govern their migratory routes once in fresh water. For naturally spawned fish, most return to their home river or stream. Within a river basin there may be distinct runs of Atlantic salmon that return to different tributaries at different times, similar to some species of Pacific salmon. Stewart et al. (2002) found that timing and location of Atlantic salmon migration was partly under genetic control, suggesting that different breeding populations within a river system can adapt to local conditions.

Atlantic salmon are iteroparous, that is, they are capable of multiple spawning attempts; however, the incidence of repeat spawning is about 10 percent or less in most populations (Mills 1989). Adult Atlantic salmon are strong swimmers and excellent jumpers (the species name derives from the Latin *salio,* to leap). Vertical jumping distances have been reported up to 3.7 m, with horizontal jumping distances measured up to 5 m (Nova Scotia Department of Fisheries and Aquaculture 2005). Migration distances are highly variable, ranging from a few kilometers to more than 500 km. Atlantic salmon may spawn in streams and rivers of almost any size, but there are relatively few records of lake spawning within anadromous populations. Maturing Atlantic salmon generally stop feeding during spawning migrations and instead draw on fat reserves built up prior to entering fresh water.

In both anadromous (sea-going) and adfluvial (lake-going) populations, spawning usually takes place in autumn, although in some rivers spawning may extend into early winter (Atlantic Salmon Trust 2006). Like virtually all salmonids, Atlantic salmon prefer to spawn in clean, well-aerated gravel. Hendry and Cragg-Hine (2003) stated that egg and alevin (sac fry) survival is compromised when the level of sediment less than 2 mm diameter exceeds 20 percent of the spawning substrate by weight. The spawning requirements of Atlantic salmon are therefore quite similar to those of Pacific salmon.

Although females choose the locations of spawning sites, adult males will remain in suitable spawning areas and defend females and their redds against the advances of other males. Dominance hierarchies are normally size-based, and multiple spawning events can occur for both males and females (Mills 1989).

Aggressive behavior, including displaying, chasing, and biting, can also occur in both sexes, with the advantage usually going to the larger individual–size matters more to males than females–or to the individual that has already established a territory (Fleming 1998). Larger individuals are less likely to spawn again than smaller individuals, and females are more likely to exhibit repeat spawning than males. Hendry and Beall (2004) observed that adult salmon with greater fat reserves tended to exhibit more violent and protracted aggressive behavior than those whose fat reserves had been depleted, and they suggested that the condition of fish arriving at the spawning grounds influences reproductive success.

Because both Atlantic salmon and semelparous (1-time spawning) Pacific salmon breed during the same season and in similar locations, there is a possibility that they might interact. Evidence for aggressive encounters between spawning adult Atlantic and Pacific salmon is rare because their native distributions are not sympatric. However, in the Great Lakes region of the St. Lawrence River, Pacific salmon have been successfully introduced and may co-occur with native Atlantic salmon. Tributaries to Lake Ontario are used by naturally reproducing Atlantic salmon and several introduced Pacific salmon species, and the Ontario Ministry of Natural Resources states "There are some studies and anecdotal observations which suggest negative interactions between Chinook salmon and Atlantic salmon spawners" (Ontario Ministry of Natural Resources 2005). The extent to which these interactions reduce the fitness of one or both species has not been reported.

Juvenile Atlantic salmon usually prefer relatively swift streams and rivers for rearing.

Juvenile Morphology and Rearing Habitat

Juvenile Atlantic salmon usually prefer relatively swift streams and rivers for rearing. Young salmon usually emerge from spawning areas in the spring, and newly emergent fry tend to remain near the bottom where they are sheltered from turbulent currents in overlying water (fig. 1).

Although Atlantic salmon juveniles tend to prefer fast water habitats, their body morphology and microhabitat preferences differ somewhat from those of juvenile steelhead, a species that also inhabits swiftly flowing streams, and learning to distinguish them in the field is essential for fish population monitoring. Atlantic salmon have relatively large pectoral fins, which they can angle downward to aid in holding against the bottom (fig. 1). Steelhead, on the other hand, usually occur higher in the water column and do not possess such large pectoral fins. Additionally, the two species can be distinguished in the field by comparing the number and shape of parr marks; the height, shape, and coloration of the dorsal fin; and head coloration. Paired photos of juvenile Atlantic salmon and steelhead fry (age 0+) and parr (age 1+) are shown in figure 2. Many juvenile Atlantic salmon also possess

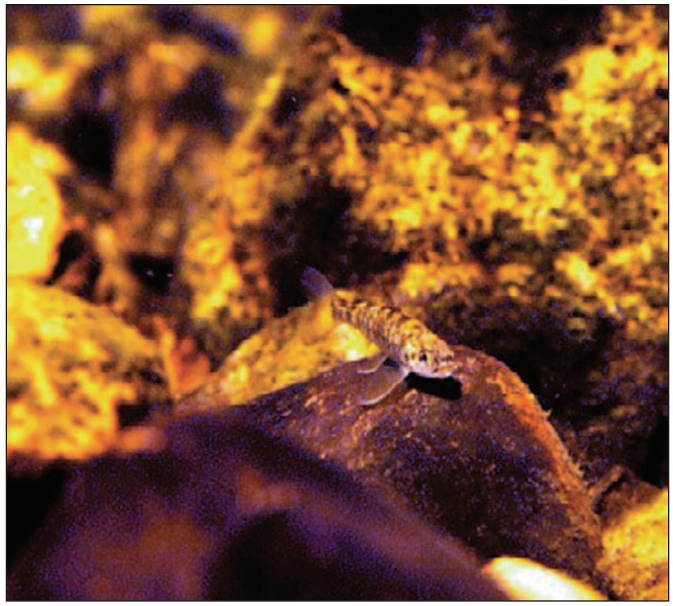
John Volpe

Figure 1—Atlantic salmon fry in a Vancouver Island stream. This fish was believed to be the offspring of feral Atlantic salmon spawning.

small red spots near the lateral line—a trait never seen in steelhead or other Pacific salmon.

Distinguishing juvenile Atlantic salmon from young Chinook and coho salmon is somewhat easier. Juvenile Chinook and coho salmon tend to have deeper bodies, longer and more compressed parr marks, a narrower caudal peduncle, and more deeply forked tails (fig. 3) than juvenile Atlantic salmon. Additionally, juvenile coho salmon usually have a pronounced white band along the leading edge of the dorsal and anal fins. Like steelhead, young of both species tend to occur higher in the water column than Atlantic salmon.

Juvenile Migrations

During the freshwater phase of their life cycle, young Atlantic salmon are usually thought to be highly territorial, to exhibit strong site fidelity, and to rarely move around in streams in response to seasonal changes (Gerking 1959). Immediately after emergence, fry generally move to the edge of the stream where current velocities are more favorable for their small size. As they grow, juvenile Atlantic salmon tend to occupy deeper waters, although they continue to reside in or near swiftly flowing habitats (Gibson 1993, McCormick et al. 1998). Parr (age 1+) appear somewhat less prone to seasonal movements such as can be observed in the migration of juvenile coho salmon to riverine ponds in winter (Peterson 1982), but in severely fluctuating environments Mäki-Petäys et al. (2004) showed that size-mediated

Figure 2—Upper left: Atlantic salmon fry. Upper right: steelhead fry. Lower left: Atlantic salmon parr. Lower right: steelhead parr. Photos: John Volpe (upper and lower left), David Blevens (upper right), and Russ Thurow (lower right).

Figure 3—Left: juvenile Chinook salmon. Right: juvenile coho salmon. Photos: Peter Bisson (left) and Canada Department of Fisheries and Oceans (right).

shifts in preferred depth, velocity, and substrate composition of Atlantic salmon parr can occur throughout the year. Some Atlantic salmon can rear in lakes rather than streams, and this ability has been used to explain the origin of nonanadromous populations (Berg 1985). Additionally, male Atlantic salmon parr can mature in streams and forego anadromy (Fleming 1996). In this respect, they differ from most Pacific salmon species in which freshwater maturation is quite rare (except for landlocked forms such as kokanee [*O. nerka*]).

Smolting takes place when the fish have reached approximately 10 to 20 cm long and often occurs between 2 and 4 years depending on the productivity of the stream. In the Northeastern United States, Baum (1997) reported that about four of five juveniles smolt after 2 years, with the balance smolting after 3 years. Marschall et al. (1998) summarized the evidence that rapidly growing parr often smolt at a relatively young age (2 year), or forego anadromy entirely and mature in streams. There is a positive association between growth rate, smolting and parr maturation, but faster growing, younger smolts are frequently smaller (because they are young) than slow-growing, older smolts. Large, older smolts typically enjoy higher marine survival rates than smaller smolts, as do some species of Pacific salmon. The age structure of Atlantic salmon populations is therefore complex and can be influenced by a variety of environmental and genetic factors related to tradeoffs between age, growth, and survival.

Density Dependence and Interspecific Interactions

Consistent with their territorial behavior as juveniles, there is often a negative relationship between population density, growth, and survival of young Atlantic salmon in lotic environments where rearing space is limited (Elliott and Hurley 1997, Grant et al. 1998). Nislow et al. (2004) found that age 0 salmon in a Connecticut River, New Hampshire, tributary grew more slowly in two low-flow years than in a high-flow year where rearing space included expanded foraging locations. Growth rates were also negatively correlated with population density. Like most stream-dwelling salmonids, juvenile Atlantic salmon exhibit density dependence in response to food and habitat availability.

Within their native range of western Europe and eastern North America, farmed Atlantic salmon regularly escape and enter rivers where they encounter native salmon populations. Jonsson (1997) summarized the potential intraspecific impacts of farmed salmon on their native counterparts in fresh water. Major effects included competition for food, rearing habitat, and mates; altered predation regimes; and increased risks of diseases and parasites. Fleming et al. (2000) studied the population effects of farmed salmon in a Norwegian river and found that farmed fish were competitively and reproductively inferior to wild fish. Farmed salmon achieved less than one-third the reproductive success of native salmon, and the productivity of the native population was reduced by about 30 percent as a result of resource competition and competitive displacement. Fleming and Petersson (2001) reviewed the evidence of hybridization occurs between wild and hatchery-origin Atlantic salmon and found that the fitness of naturally spawning populations was nearly always reduced through interbreeding between wild and hatchery adults. They concluded that Atlantic salmon from hatcheries posed significant ecological and genetic risks to wild populations.

The extent to which juvenile Atlantic salmon influence, or are influenced by, juveniles of other salmonid species is less well known. Atlantic salmon fry and parr can display aggression toward other fishes (Keeley and Grant 1998, also see Fausch 1998), but I was unable to find any evidence that high densities of Atlantic salmon juveniles resulted in reduced populations of other fishes. For example, Raffenberg and Parrish (2003) sampled two streams in Vermont where Atlantic salmon fry had been stocked to accelerate the recovery of naturally spawning populations. The streams contained native brook trout and introduced rainbow trout. No inverse relationships between Atlantic salmon abundance and trout populations were detected; in fact, the more productive sites, that is, those with increased benthic invertebrates, contained higher densities of both salmon and brook trout. The authors concluded that habitat partitioning permitted native species (Atlantic salmon and brook trout) to coexist without negative population consequences.

Because the habitat preferences of juvenile Atlantic salmon and juvenile steelhead overlap considerably (Hearn and Kynard 1986), a major concern about farmed salmon invading Pacific Northwest watersheds is that they would negatively affect already depressed steelhead populations. To test the effect of Atlantic salmon on steelhead in streams, Volpe et al. (2001) stocked experimental stream channels on Vancouver Island with low, medium, and high densities of both species and monitored agonistic behavior and growth. They found that juvenile steelhead displayed more aggressive behavior than juveniles from an Atlantic salmon farm, but steelhead were more than two times more likely to direct aggression at conspecifics than toward members of the other species. Atlantic salmon, although less aggressive overall, were more than two times more likely to attack juvenile steelhead than other Atlantic salmon. Young Atlantic salmon fared poorly when released into habitats already populated by steelhead, but when Atlantic salmon were released into the experimental channels first and had an opportunity to establish foraging territories prior to the introduction of steelhead, the salmon generally outcompeted steelhead. Prior residence, therefore, was an important factor in determining competitive outcomes between the two species (also see O'Connor et al. 2000). Volpe et al. (2001) argued that because Atlantic salmon spawn in late fall or early winter, two or more months prior to most steelhead, their progeny would be likely to have established feeding territories in streams before steelhead fry emerge from spawning gravels. They concluded that "a 2-month head start on the competition would prove to be a significant factor" in affecting the ability of Atlantic salmon to become established in streams where steelhead are present (Volpe et al. 2001: 205).

Food Habits

Juvenile Atlantic salmon are generalized invertevores, feeding mainly on aquatic insect larvae acquired from the benthos or drifting in the stream (Gibson 1993, Mills 1989). The majority of life history studies report that both fry and parr feed on seasonally available aquatic and terrestrial invertebrates (Cunjak 1992, Thonney and Gibson 1989) and I found few scientifically documented cases of juvenile Atlantic salmon in streams feeding on other fishes or on fish eggs, although it would seem reasonable to expect them to consume small fishes or eggs if presented with the opportunity. In Patagonia, adfluvial Atlantic salmon feed on aquatic invertebrates as young and switch to a diet of crustaceans and other fishes as they mature in lakes (Expediciones Chile 2005). Keeley and Grant (1998) found that Atlantic salmon fry initially fed on small chironomid larvae, but as they grew older and larger began taking proportionately larger food items from the drift. They suggested that diet preferences demonstrated that age 1+ and older fish were size selective in their foraging behavior, but they also found that young Atlantic salmon fed on smaller prey items than other salmonids of similar size.

The ecological threat is that established populations of Atlantic salmon could act as competitors but probably not predators on salmon and trout.

Based on the majority of evidence, the likelihood seems low that juvenile Atlantic salmon would prey upon native fishes in Pacific Northwest streams. However, a diet of seasonally available aquatic and terrerstrial invertebrates would place them in direct competition for the food resources of native salmonids. The ecological threat, therefore, is that established populations of Atlantic salmon could act as competitors but probably not predators on salmon and trout.

Diseases and Parasites

Atlantic salmon are known to be vulnerable to a variety of diseases and parasites, particularly those in hatcheries or aquaculture facilities. Parasites from farmed salmon can spread to wild fish when escaped salmon enter rivers to spawn. One of the most serious problems for wild salmon in Norway has been a small monogenetic trematode *Gyrodactylus salaris* that has become established in many river systems and has significantly reduced, and sometimes extirpated, native salmon populations (Håstein and Linstad 1991).

Although *Gyrodactylus* infestations can cause high mortality rates in wild salmon that have been newly exposed to the parasite via escaped farmed salmon, some salmon stocks (as well as populations of other native European salmonids) appear to be resistant to heavy infestations. However, the widespread damage caused by *Gyrodactylus* has been so severe that most countries in western Europe require elaborate quarantine and disinfection procedures for all fish transfers that could spread the parasite. Additionally, a variety of internal parasites have been associated with Atlantic salmon of hatchery origin, but to date, none have been as serious as *Gyrodactylus.*

Atlantic salmon are also vulnerable to many viral, bacterial, and fungal diseases. Outbreaks of these diseases are apparently rare in naturally spawning salmon populations, but can be common in fish raised in a high-density aquaculture environment (U.S. Fish and Wildlife Service 1999). Many of the diseases can be treated in the hatchery by antibiotics and antiviral vaccinations, or by bathing fish in a disinfecting solution. Transfer of viral, bacterial, or fungal diseases from farmed to wild salmon undoubtedly occurs, but epizootics in wild populations directly traceable to farmed salmon are less common than parasite outbreaks. Nevertheless, the virus causing infectious salmon anemia has spread from Norwegian aquaculture facilities to a number of rivers in Europe, and more alarmingly, has also spread to several locations in eastern North America (Cipriano 2002). In addition to causing millions of dollars of lost salmon production in western Europe, the virus is known to infect Chinook salmon, coho salmon, rainbow trout, and several char species.

Parasites and diseases affecting Atlantic salmon in fresh water, and the potential transfers of pathogens from farmed salmon to native species, have not received much research attention in the Pacific Northwest. On the other hand, heavy infestations of both hatchery and wild fish by a marine copepod parasite, the sea louse *Lepeophtheirus salmonis*, has been well documented in British Columbia (Morton et al. 2004). Sea lice are ectoparasites whose early life history stages thrive near marine salmon farms where uneaten food and fish waste can accumulate. Free-swimming life history stages of sea lice (copepodids) can attach themselves to wild fish swimming in the vicinity of net pens and at high infestation rates can be debilitating or lethal.

Morton et al. (2004) found that 90 percent of the juvenile pink salmon and chum salmon (*O. keta*) sampled in the Broughton Archipelago of coastal British Columbia, the site of many of the province's salmon farms, possessed sea lice at a density of greater than 1.6 g lice/g host mass—the purported lethal level for sea lice infestation—and declines of these species have been directly associated with the proliferation of nearby farming operations. In contrast, Morton et al. (2004) found that juvenile salmon sampled from areas without salmon farms possessed almost no sea lice. So serious has the sea lice problem in British Columbia become that a public forum on salmon farming (Leggatt Inquiry) recommended that all net cage salmon farms be removed from coastal British Columbia waters (David Suzuki Foundation 2001).

A question that has received little scientific investigation is the extent to which parasites and diseases endemic to the Pacific Northwest might act as natural barriers to invasions of nonnative salmonids such as Atlantic salmon.

Native Diseases and Parasites as Potential Barriers to Atlantic Salmon Invasion

A question that has received little scientific investigation is the extent to which parasites and diseases endemic to the Pacific Northwest might act as natural barriers to invasions of nonnative salmonids such as Atlantic salmon. Because Atlantic salmon are vulnerable to a wide variety of pathogens, and because their populations may be strongly affected by exposure to a new pathogen (see the discussion of *Gyrodactylus* above), it is possible that parasites and diseases to which Pacific salmon have adapted over time my be highly deleterious to Atlantic salmon and may prevent or hinder their colonization of Pacific Northwest streams.

There is at least one instance in Washington and Oregon where a nonnative species has failed to become established because of an endemic parasite. Brook trout, a species from eastern North America, have been widely stocked in both streams and lakes in the Pacific Northwest but have established breeding populations primarily in montane lakes. They are conspicuously absent from low-elevation coastal streams despite a century of sanctioned and clandestine releases. At present, only two breeding populations of brook trout are known from coastal streams in Washington and Oregon: a small tributary of the Willapa River in Washington, and a tributary of the upper Millicoma River in Oregon. Both streams possess high waterfalls and the brook trout are found only above these falls. Coincidentally, both streams contain the snail *Juga plicifera* below the falls but not above.[2] This snail species hosts an intermediate stage (redia) of a digenetic trematode *Nanophyetus salmincola* (a flatworm parasite) that itself harbors a rickettsia-type pathogen that causes "salmon-poisoning" disease in dogs. The rickettsia are not toxic to fish, but another life history stage (cercaria) of the flatworm carrier leaves its snail host and encysts in the skin and other tissues of salmon. Infested snails can spread the parasites to salmon (Baldwin et al. 1967), and high infestations of the encysted *Nanopyetus* in young salmon can lead to poor swimming performance and kidney damage (Foott et al. 1996). The absence of brook trout where *Nanophyetus*-hosting snails occur and the presence of brook trout where snails are absent suggests that this nonnative salmonid does not tolerate the endemic parasite and has been prevented from becoming established in coastal streams where the snail host is present.

[2] The occurrence of *Juga* below Millicoma Falls was noted by P. Reimers, personal communication, formerly of Oregon Department of Fish and Wildlife, P.O. Box 5430, Charleston, OR 97420. *Juga* was found below the falls on Fall Creek, a tributary to the Willapa River, by P. Bisson (author) and B. Fransen, Weyerhaeuser Company, P.O. Box 9777, Federal Way, WA 98063.

Can their vulnerability to native parasites and diseases be one of the reasons why Atlantic salmon have not established more breeding populations in Pacific Northwest watersheds? This topic deserves additional investigation. Additionally, selection for native disease or parasite tolerance in Atlantic salmon from farming operations, if it occurs, may lead to greater invasive potential over time. Further research should shed light on the ability of endemic pathogens to limit the invasive capability of this species.

Atlantic salmon have established in only a few streams on Vancouver Island; however, the potential for additional invasion exists with continued escapes from holding facilities.

Conclusion

This paper has examined the evidence for escaped Atlantic salmon from marine farming operations or freshwater hatcheries becoming established in Pacific Northwest streams. Evidence suggests that Atlantic salmon have established in only a few streams on Vancouver Island; however, the potential for additional invasion exists with continued escapes from holding facilities. The ecological consequences of feral Atlantic salmon populations have not been thoroughly explored in this region, in part because established populations are rare and limited to a small area. Atlantic salmon spawn at approximately the same time as several species of Pacific salmon, and their substrate preferences are similar to those of native salmon and steelhead. Breeding adult Atlantic salmon may therefore compete with fall-spawning Pacific salmon for spawning sites. Likewise, juvenile Atlantic salmon share rearing habitat affinities with species that occur in swiftly flowing streams, particularly steelhead, resident rainbow and cutthroat trout, and char. Their tendency to be closely associated with the stream bottom may allow a certain amount of microhabitat partitioning with resident and anadromous salmonids, but their food habitats broadly overlap, suggesting that abundant Atlantic salmon fry and parr may compete with native fishes for scarce food and habitat resources. Because Atlantic salmon spawn in late fall or early winter, young will emerge from spawning gravel prior to spring-spawning species. One laboratory study indicates that early fry emergence may give Atlantic salmon an opportunity to establish foraging territories before steelhead and resident trout fry emerge.

Atlantic salmon share rearing habitat affinities with species that occur in swiftly flowing streams, particularly steelhead, resident rainbow and cutthroat trout, and char.

Farmed Atlantic salmon can be vectors of exotic diseases and parasites that, at least in Europe, have had devastating impacts on naturally spawning fish populations. Although freshwater parasite and disease introductions have not been associated with Atlantic salmon farms in the Pacific Northwest, heavy infestations of sea lice near farming sites have been associated with declines in early sea-going Pacific salmon juveniles, particularly pink and chum salmon. It is also possibe that the failure of Atlantic salmon to establish breeding populations in streams where escaped farm salmon are known to have entered may be related to their susceptibility to native parasites and diseases—a situation that could change over time as natural selection favors more disease or parasite-resistant individuals.

The relative risk of Atlantic salmon becoming an invasive species of concern can therefore be partitioned into short (<5 years) and long-term (>5 years) time horizons. The current risk to national forest streams from Atlantic salmon invasions is low and limited to a few forests in northwest Washington and southeast Alaska. However, the long-term risks may be substantial if fish continue to escape from marine rearing pens or freshwater hatcheries. The two greatest risks appear to be that (1) Atlantic salmon may introduce a serious pathogen to native populations, and (2) escaped salmon will eventually adapt to local conditions as selection favors the survival and reproduction of a few individuals. Salmonids in general are capable of rapid evolution because their gamete production is relatively large, they have ample opportunity to hybridize, they are occasionally capable of polyploidy, and they have somewhat flexible life histories. Despite a long history of failure to establish Atlantic salmon from single or a few deliberate introductions, it seems possible that continuous recruitment of fish escaping from farming operations may eventually lead to locally adapted stocks. At that point, the species may rapidly become a dangerous invasive—a pattern that is often seen in other aquatic plants and animals where a prolonged early colonization period is followed by a rapid phase of exponential growth.

Current programs to monitor the establishment of Atlantic salmon in the Pacific Northwest are inadequate.

Table 4 presents potential short- and long-term risks of Atlantic salmon invasion, based on the evidence gathered from peer-reviewed scientific literature, agency reports, environmental and aquaculture industry publications, and the Internet.

Early Detection

Current programs to monitor the establishment of Atlantic salmon in the Pacific Northwest are inadequate. The province of British Columbia remains engaged in surveying streams for this species, but the total number of streams being sampled is still only a fraction of those where Atlantic salmon could invade. The states of Alaska and Washington also have invested minimal effort in surveying for this species, and it appears that the majority of the annual records consist of sport catches, which are not very reliable. Records of juvenile Atlantic salmon often consist of snorkel observations, although it is quite difficult to be certain of a species identification, especially when fish are small and water clarity is poor. Actual captures remain the best method of detecting Atlantic salmon, and confirmation is best carried out by meristic and morphometric analysis supplemented with genetic identification.

Table 4—Summary of major short-term (<5 years) and long-term (>5 years) risks of escaped Atlantic Salmon from salmon farms becoming an invasive species in freshwater ecosystems in the Pacific Northwest

Ecological risk category	Short term	Long term	Strength of empirical evidence
Competition for spawning sites between adult Atlantic and Pacific salmon	Low	Low to moderate. Spawning sites would have to overlap spatially and temporally. Not considered a significant problem in eastern North America where Pacific salmon have been introduced.	Only mentioned in one Canadian study; however, there are relatively few locations where Atlantic salmon and Pacific salmon spawn together.
Competition for rearing space in fresh water	Low	Moderate to high for species that inhabit swiftly flowing streams or possibly lakes, if Atlantic salmon become established.	Documented in at least one controlled laboratory study.
Competition for food resources in fresh water	Low	Moderate. The degree of competition depends on food availability and forage site selection. Atlantic salmon may be less aggressive than native salmonids, but their larger size in spring may give them an advantage in defending the best feeding sites.	Primary evidence comes from studies of sympatric farmed and native Atlantic salmon in Europe, but to date there is no empirical evidence for interspecific competition between Atlantic salmon and Pacific salmon.
Predation on native fishes	Low	Low. Juvenile Atlantic salmon rarely eat other fishes in streams. Landlocked populations in lakes may be piscivorous.	Food habitats of Atlantic salmon juveniles have been well studied in their native range.
Disease/parasite introductions	Low	Moderate to high. Pathogens in farms and hatcheries may become resistant to current treatments and spread more easily to native species.	Widespread documentation of disease and parasite outbreaks caused by escaped farm salmon.

Improvements in monitoring programs could occur by implementing a statistically valid sampling design in streams where Atlantic salmon could potentially be present. A rotating panel sampling regime such as the Enviroinmental Protection Agency's Environmental Monitoring and Assessment Program is an example of a statistically sound protocol for selecting monitoring sites. Additionally, many agencies, tribes, and environmental organizations operate smolt traps to monitor salmon production in Pacific Northwest river basins. Training field technicians to identify Atlantic salmon and collect any that turn up in the traps would take advantage of existing (and continuously funded) sampling programs.

Experience with other nonnative salmonids in this area (e.g., brook trout) suggests that early detection and removal is far easier than having to combat a widespread invasion after the fact.

Should juvenile Atlantic salmon be found in a stream, the watershed can immediately be targeted for intensive surveys to determine the distribution of juveniles within the system and their potential impact on resident and native anadromous species. Depending on the results of these studies, the stream may become a candidate for an Atlantic salmon eradication program. Although this action may seem extreme, experience with other nonnative salmonids in this area (e.g., brook trout) suggests that early detection and removal is far easier than having to combat a widespread invasion after the fact.

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English Equivalents

When you know:	Multiply by:	To find:
Millimeters (mm)	0.039	Inches
Centimeters (cm)	.394	Inches
Meters (m)	3.281	Feet
Kilometers (km)	.622	Miles
Grams (g)	.0352	Ounces
Kilograms (kg)	2.205	Pounds
Metric tons (mT)	1.102	Short tons

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