

Nonindigenous Species of the Pacific Northwest: An Overlooked Risk to Endangered Salmon?

BETH L. SANDERSON, KATIE A. BARNAS, AND A. MICHELLE WARGO RUB

Nonindigenous species, which are associated with the decline of many threatened and endangered species, are a major threat to global diversity. This risk extends to salmonids, the most widespread threatened and endangered species in the Pacific Northwest. Pacific salmonids traverse large geographic areas that include freshwater, estuarine, and ocean habitats in which they encounter numerous nonnative species. For this article, we examined the extent to which introduced species are a risk to threatened and endangered salmon. We identified all documented nonindigenous species in the Pacific Northwest, including fish, invertebrates, birds, plants, and amphibians. Where data exist, we quantified the impact of nonindigenous species on threatened and endangered salmonids. The results indicate that the effect of nonindigenous species on salmon could equal or exceed that of four commonly addressed causes of adverse impacts—habitat alteration, harvest, hatcheries, and the hydrosystem; we suggest that managing nonindigenous species may be imperative for salmon recovery.

Keywords: nonindigenous species, predation impacts, Pacific Northwest salmonids, Columbia River, Endangered Species Act

Nonindigenous species (NIS) pose one of the dominant environmental threats to biological diversity (Vitousek et al. 1996, Simberloff et al. 2005) and are cited as a cause of endangerment for 48% of the species listed under the US Endangered Species Act (ESA) (Czech and Krausman 1997, Wilcove et al. 1998). In 2005, NIS cost the US economy in excess of \$120 billion (Pimentel et al. 2005), and the occurrence and ranges of NIS are steadily increasing. Despite these high environmental and economic costs, little funding is devoted to tracking the distribution and spread of NIS (Crall et al. 2006, Lodge et al. 2006). Consequently, we do not know enough about NIS impacts on native species to make educated prevention and management decisions (Parker et al. 1999). This lack of information is especially of concern with regard to threatened or endangered species.

The introduction and establishment of nonindigenous fishes has contributed to the decline of native species worldwide (Lever 1996, Helfman 2007). The US Pacific Northwest (Washington, Oregon, and Idaho) is home to 119 plant and animal species that are federally listed as threatened or

endangered, including Pacific salmon (NMFS 1998). Introduced species have been identified as a factor in the decline of many of these listings. During their life cycle, salmonids traverse large geographic areas spanning freshwater, estuarine, and ocean habitats where they encounter numerous nonnative species. These include a number of warmwater fish species that were introduced from eastern North America to provide recreational fishing opportunities. In the Columbia River system alone, juvenile Pacific salmon will encounter no fewer than eight documented nonindigenous predator and competitor fish species en route to the estuary. Many invertebrate and plant species that were also introduced into this system have documented impacts on native communities (Boersma et al. 2006). Despite the collective threat to native ecosystems, no study to date has examined the broad distributional patterns of NIS. Specifically, large-scale efforts to summarize the status of Pacific salmon have generally overlooked the distribution and impact of NIS in freshwater habitats (NRC 1996, Augerot 2005). When they have occurred, discussions of NIS have been specific to individual

fish species (e.g., Beamesderfer and Ward 1994, Fritts and Pearsons 2004). Because efforts to quantify the site-specific impacts of nonnative species have focused on single species interactions, no attempt has been made to understand the cumulative impact of these species on threatened or endangered salmonids or on their habitat.

To complicate matters, spatially explicit data describing the occurrence and distribution of terrestrial, aquatic, and marine NIS throughout the Northwest are not readily accessible to scientists, managers, or the general public (Crall et al. 2006). The US Geological Survey (USGS) maintains a national database of aquatic NIS, the University of Montana maintains a database of exotic plant species in the Northwest, and local reports document many incidental sightings of NIS. However, no comprehensive, spatially explicit database of terrestrial, aquatic, and marine NIS currently exists.

We have attempted to rectify this situation by assembling all known occurrence and distribution records for terrestrial and aquatic NIS into a comprehensive and spatially explicit database. We summarize these occurrences to describe the distributional pattern of NIS in this region. In a given watershed, we quantify the proportion of native and nonnative fish species and ask whether regions with higher numbers of NIS also have higher numbers of threatened and endangered species. The results of this simple correlation point to the need for mechanistic studies evaluating NIS impacts. We identify the potential mechanisms of impact, highlighting predation on salmonids as one example of the many consequences of species introductions. By synthesizing the results from individual site-specific predator studies, we demonstrate that notable predation impacts have been recorded. We emphasize the need to move beyond site-specific research and develop assessments of cumulative NIS impacts on salmon that can be compared with the commonly studied impacts of harvest, hatcheries, the hydrosystem, and habitat alteration—

often referred to as the all-H's. Finally, we quantify the amount of funding allocated for NIS studies compared with funds apportioned to the all-H's. Collectively, our efforts draw attention to the widespread distribution of NIS and their potential role in hastening the decline and impeding the future recovery of threatened and endangered salmon in the Pacific Northwest.

Nonindigenous species in the Pacific Northwest

Knowledge about the numbers and distribution of NIS in the Pacific Northwest is needed to assess the magnitude of their ecological impact across the region. As part of this analysis, it is necessary to document new introductions and delineate the spread of established nonnative species. To this end, we have created a spatially explicit database documenting the presence or absence of NIS to define the geographic locations of NIS within the states of Washington, Oregon, and Idaho (figure 1). We have incorporated data from local, regional, and national databases, as well as from published reports (table 1). We would have liked to have included estimates of abundance or biomass of nonnative taxa to associate with NIS presence or absence; however, these population demographic data are very scarce. This information will be required if we are to quantify the cumulative impacts of NIS. Our compilation effort identified numerous terms used to describe NIS, including “exotic,” “invasive,” “nonnative,” and “alien.” In this article we use the two most common—“nonindigenous” and “nonnative”—and employ them interchangeably.

This spatially explicit database represents a comprehensive synthesis of the information currently available regarding the distributions of NIS across the Pacific Northwest. Although our database incorporates all readily available information in this region, it is undoubtedly biased by the goals and motivations of the disparate sampling efforts, and thus should be presumed to represent minimum distributions

Table 1. Database sources used to identify the spatial distribution of nonindigenous species in the Pacific Northwest.

Taxonomic group	Data sources
Fishes	Daily K, Shrader T, Temple R, Hooton B. 1999. Introduced Fishes Management Strategies Public Review Draft 4-14-1999. Portland: Oregon Department of Fish and Wildlife. Northwest Power and Conservation Council. 2005. Subbasin Plan Amendments: Findings and Responses to Comments. (8 January 2009; www.subbasin.org/library/2005/2005-13.pdf) Temple R, Daily K, Shrader T, Hooton B. 1998. Predation issues: Introduced Fishes Draft Review Version. Portland: Oregon Department of Fish and Wildlife. US Forest Service, Boise National Forest Fish Species. (8 January 2009; www.fs.fed.us/r4/boise/recreation/fishing/fishing-old/documents/fish_species.shtml) Washington Department of Fish and Wildlife. 2005. Warmwater Fishes of Washington. Olympia: Washington Department of Fish and Wildlife. Report #FM93-9. (8 January 2009; http://wdfw.wa.gov/fish/warmwater/warmwater_2005.pdf) Wydoski RS, Whitney RR. 2003. Inland Fishes of Washington. Seattle: University of Washington Press.
Mudsnails	Montana State University. 2007. New Zealand Mudsnails in the Western USA. (8 January 2009; www.esg.montana.edu/aim/mollusca/nzms/)
Aquatic invertebrates, birds, mammals, reptiles, amphibians, fishes, and plants	US Geologic Survey. Nonindigenous Aquatic Species Database. (8 January 2009; http://nas.er.usgs.gov/) Northwest Habitat Institute. Corvallis, Oregon. (8 January 2009; www.nwhi.org)
Plants	Rice PM. INVADERS Database System Division of Biological Sciences. Missoula: University of Montana. (8 January 2009; http://invader.dbs.umt.edu) Washington State Aquatic Plant Survey, Washington Department of Ecology. (8 January 2009; www.ecy.wa.gov/programs/eap/lakes/aquaticplants/index.html#annualsurvey)

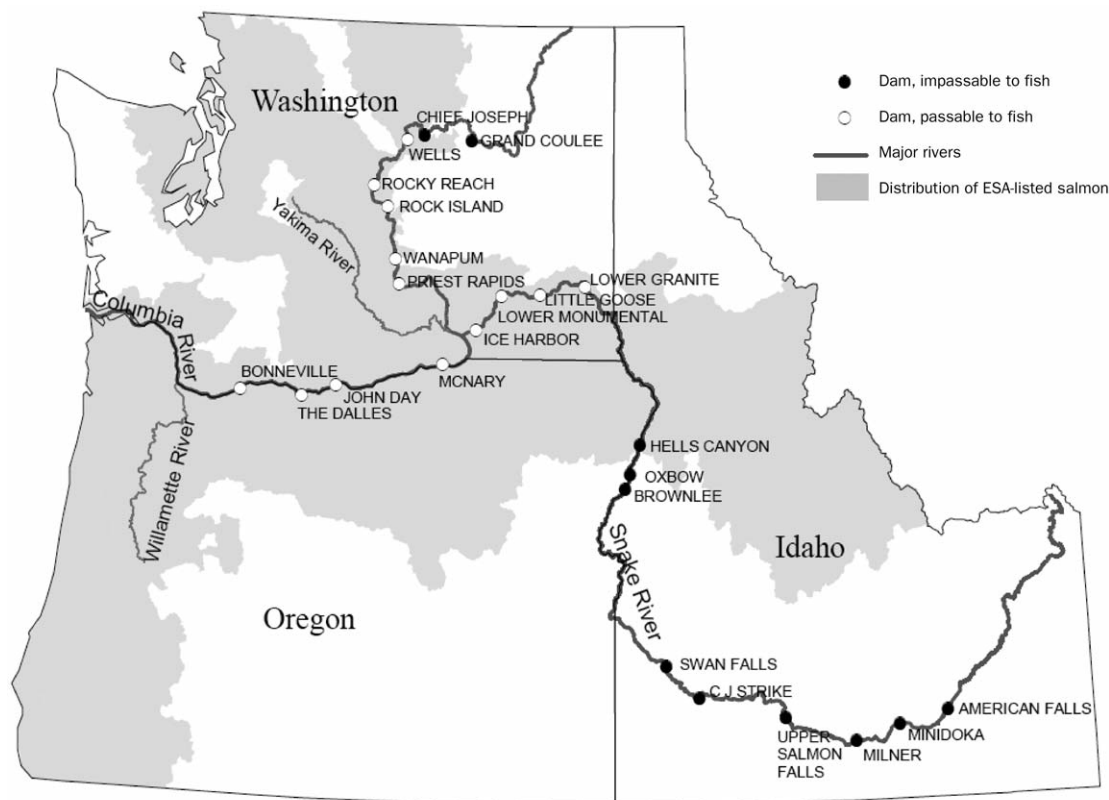


Figure 1. Major rivers, dams, and current distribution of threatened and endangered salmonids in the Pacific Northwest (gray shaded region). Historical distributions and distributions of salmonids not listed under the Endangered Species Act are not depicted.

in the region. Furthermore, the data we have compiled from other sources most likely represent a combination of established NIS as well as reported sightings for which establishment may be in question. Because we were most interested in organisms introduced from outside the Pacific Northwest, we defined NIS as species that were not natively found in Washington, Oregon, or Idaho. Thus, species native to one or more of these states were considered native. Furthermore, as species dispersal occurs over ecological rather than political units, our database was structured using watersheds defined by the USGS fourth field HUC (hydrologic unit code). These watersheds are roughly 1800-square-kilometer areas that represent hydrologically connected areas. Because our primary focus is on the interactions of NIS and salmon, we emphasize aquatic species, although the occurrences of species from other taxonomic groups—such as amphibians, birds, crustaceans, mammals, mollusks, plants, and reptiles—were systematically collected and included in the analysis. Surprisingly, data on the distribution of other major taxonomic groups in this region, such as insects and disease organisms, were unavailable.

Nonindigenous species are present in all regions of Washington, Oregon, and Idaho, with more than 400 NIS found in some watersheds (figure 2). Even those watersheds with the fewest NIS harbor nearly 100 species that were not present only

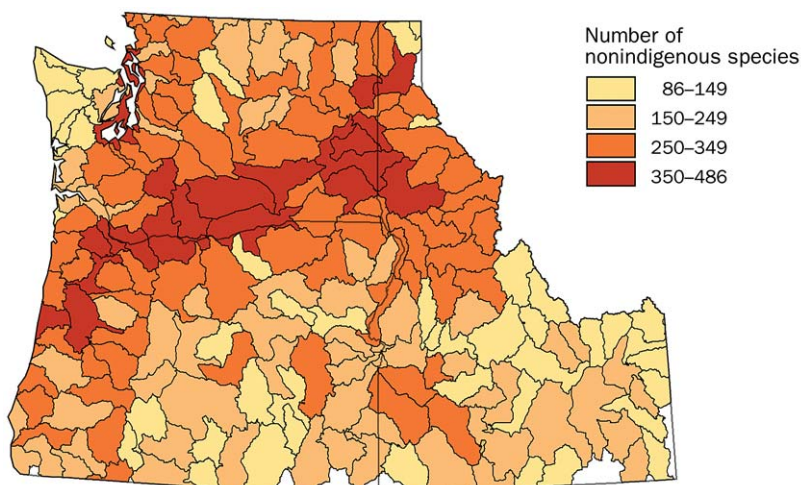


Figure 2. Number of nonindigenous species per fourth field HUC (hydrologic unit code) in Washington, Oregon, and Idaho. Taxonomic groups represented include plants, birds, fishes, amphibians, reptiles, mollusks, crustaceans, mammals, and other groups presented in figure 3.

two centuries ago. In total, more than 900 NIS have been documented within our study region, with the highest concentrations occurring along the Columbia River corridor and in areas with high human population density or intense agricultural activity, such as the Willamette River basin. The majority of NIS in the Pacific Northwest today are plants and fishes (figure 3). Common means of introduction include stocking for recreation (e.g., fish and birds); commerce (e.g., agricultural and landscaping plants, fish and bivalves used in aquaculture); biocontrol of nuisance species; escapes or releases, often of pets (e.g., fish, amphibians, reptiles); human transport through ballast water, biofouling, and fishing boats; and hitchhikers (e.g., fish, plants, crustaceans, mollusks, diseases) (Pimentel et al. 2005, Simberloff et al. 2005).

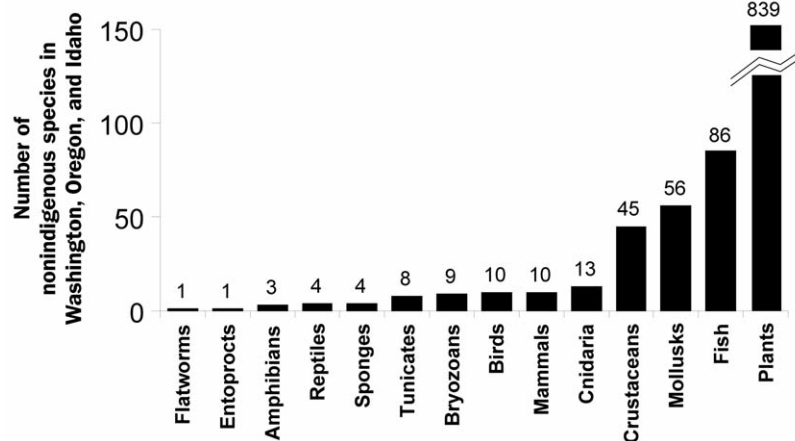


Figure 3. Number of nonindigenous species, by major taxonomic groups, in the Pacific Northwest states (Washington, Oregon, and Idaho).

Nonindigenous fishes and the decline of native fish species

The status of freshwater aquatic fauna is generally more dire than that of their terrestrial counterparts (Richter et al. 1997, Ricciardi and Rasmussen 1999, Rahel 2007). The presence of nonindigenous fishes poses one of the greatest threats to the persistence of healthy native fish populations (Lassuy 1995, Richter et al. 1997, Rahel 2002). Nationwide, introduced fish species have been cited as a factor leading to placement on federal threatened or endangered species lists in 70% of the fish listings (Lassuy 1995) and as a causal factor in 68% of the 40 North American fish extinctions in the last 100 years (Miller et al. 1989). In the western United States, one of every four stream fishes is nonnative, and the impact of nonnatives rivals that of habitat destruction (Schade and Bonar 2005). Using current data, the estimate of future extinction rates of freshwater fauna is approximately 4% per decade, a rate similar to that of tropical rainforest eco-

systems renowned for high rates of species losses (Ricciardi and Rasmussen 1999).

Nonindigenous fish species are ubiquitous throughout Washington, Oregon, and Idaho. The most heavily invaded watersheds have upward of 30 nonindigenous fishes. Similar observations have been made during recent stream surveys conducted in the western United States (Schade and Bonar 2005, Lomnický et al. 2007). Nonnative aquatic vertebrates were present in more than 50% of surveyed stream reaches (Lomnický et al. 2007), with even higher percentages in larger rivers, suggesting that a large portion of habitat occupied by native salmonids is shared with NIS. We observed the highest densities of nonnative fishes in southeastern Oregon and southern Idaho (figure 4). These high-density watersheds are located above Hells Canyon Dam and two other dams, which are impassable barriers to upstream migration of anadromous fish. Interestingly, recovery plans for threatened and endangered salmonids may require that salmonids be provided access to these currently blocked habitats where there are well-established populations of nonindigenous fishes such as channel catfish (*Ictalurus punctatus*), smallmouth bass (*Micropterus dolomieu*), yellow perch (*Perca flavescens*), and walleye (*Sander vitreus*).

Numbering around 60, nonindigenous fish species equal or outnumber native fishes (figure 5a), comprising 54%, 50%, and 60% of the fish species found in Washington, Oregon, and Idaho, respectively. Our estimates for the number of introduced species in these states are similar to or slightly higher than other published numbers, most likely because our database compilation effort is more comprehensive (Nico and Fuller

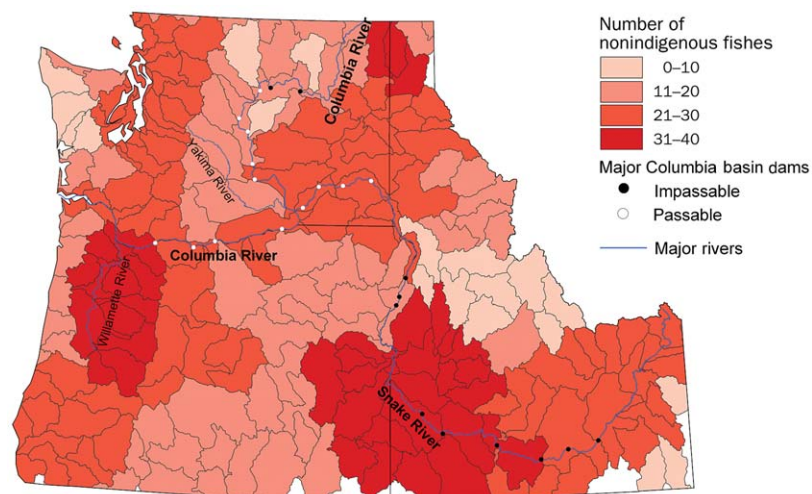


Figure 4. Number of nonindigenous fish species per fourth field HUC (hydrologic unit code) in Washington, Oregon, and Idaho. Dots represent major dams along the Columbia and Snake rivers. HUCs with less than 50% of their area in one or more of the three states were excluded from the spatial analyses and are not shaded (white).

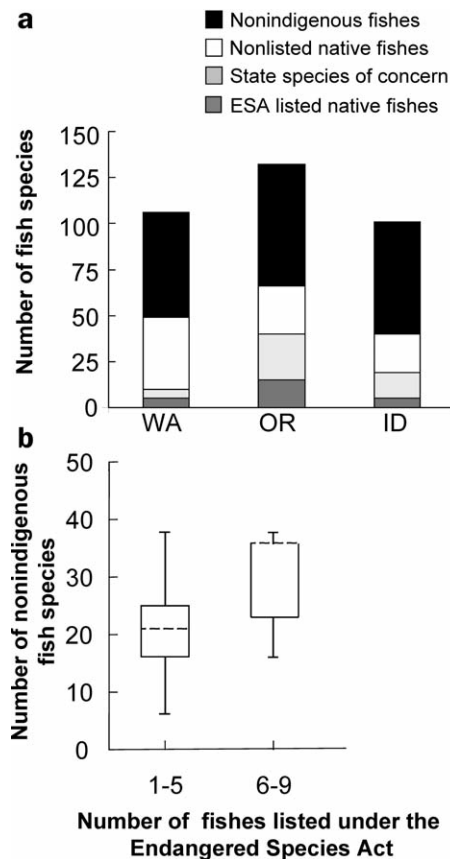


Figure 5. (a) Number of fish species in Washington, Oregon, and Idaho grouped by native or nonindigenous. Native fish species are categorized by status, including state species of concern (includes state endangered, threatened, and species of special concern that are not on the federal list), species listed under the Endangered Species Act (ESA), and species whose current status is satisfactory. (b) Number of nonindigenous fish species in watersheds (fourth field HUC [hydrologic unit code]) with few (1–5) and many (6–9) fishes listed under the ESA in the same HUC. Areas with greater numbers of threatened and endangered fishes have significantly more nonindigenous fish species (two-sample t -test, $p = 0.001$).

1999, Zaroban et al. 1999). Also, the data sources we have incorporated include records of established species as well as recorded observations of NIS that may or may not be established. Some of our data sources did not make this distinction, but among those that did, approximately 85% of the species listed were designated as “established.” The abundance of nonindigenous fishes also reflects the homogenization of freshwater fauna reported across the country (Gido and Brown 1999, Rahel 2002). Of additional concern, 30% to 55% of the 40 to 60 native fishes found in each of the three states are federally listed as threatened or endangered, or are state species of special concern. Twenty-six fish species are federally listed as threatened or endangered in the three states: 17 Pacific salmon evolutionary significant units (*Oncorhynchus* spp.) (USFWS 2005), 3 species of chub (*Cyprinidae*), 3 species

of sucker (*Catostomidae*), the Foskett speckled dace (*Rhinichthys osculus*), the bull trout (*Salvelinus confluentus*), and the Lahontan cutthroat trout (*Oncorhynchus clarki henshawi*). Of these 26 species listings, 71% cite NIS as a cause of endangerment in *Federal Register* notices. Furthermore, our data indicate higher numbers of threatened and endangered fishes in areas with greater diversity of nonindigenous fishes (figure 5b; two-sample t -test, $p < 0.001$). Although the co-occurrence of NIS fishes with threatened and endangered species cannot distinguish cause and effect from preference for similar habitats, the suggestion that nonnative fishes may play a role in the declining status of native fish species merits further evaluation (ISAB 2008).

Mechanisms of introduction and impact

Once they have been introduced and become established, NIS affect individual populations, communities, and ecosystem processes (Rosenzweig 2001, Simon and Townsend 2003). Across these scales, there are multiple mechanisms of impact, including predation, competition, hybridization, infection (disease and parasites), and habitat alteration (Mack et al. 2000, Simberloff et al. 2005). We researched the histories of several of the best known and most widely distributed nonindigenous fish, plant, and invertebrate taxa, many of which have documented or presumed negative impacts on Pacific salmon or on their habitats. The effects of NIS on salmon are not unique to the Pacific Northwest; throughout the world, NIS are a concern to the health of salmon populations, including salmon of eastern North America and Japan (NRC 2004, Helfman 2007, Han et al. 2008). Our case histories include examples of species that affect Pacific salmon ecosystems through three common mechanisms: predation, interactions with other species, and ecosystem modification. The histories identify when and how each species was introduced, synthesize knowledge of their impacts on Pacific salmonids and their habitats, and provide some insights into the rate at which spread has occurred.

American shad (*Alosa sapidissima*) colonized the Columbia River within years of being introduced in 1871 into the Sacramento River, California (Petersen et al. 2003). The spawning adult shad population in the Columbia River now numbers more than 5,000,000, the largest population of American shad in the world (Petersen et al. 2003). Although five times more shad than native salmon return yearly to the Columbia River, no studies have quantified the impacts of shad on salmon ecosystems. Only recently have scientists begun to examine the potential impacts of shad on Columbia River ecosystems, hypothesizing that planktivory by adult and juvenile shad reduces the availability of prey for juvenile salmonids, and further suggesting that the millions of juvenile shad migrating through the Columbia may fuel the growth and survival of other native and nonnative predators in the river that consume salmon (Petersen et al. 2003, Harvey and Karieva 2005, Haskell et al. 2006a). Results from studies to date indicate that juvenile shad prey heavily on zooplankton taxa, which are also a primary prey resource for

juvenile Chinook in the same habitats (Haskell et al. 2006a). Also, food-web models have been developed (Harvey and Karieva 2005) that indicate that juvenile shad may act as a prey subsidy to larger predators of salmonids.

As a result of extensive stocking efforts, brook trout (*Salvelinus fontinalis*) are now well established in streams throughout the Pacific Northwest. In 1913, the first operational brook trout hatchery opened in Washington. The ease of culturing brook trout, coupled with their high fecundity, hastened their spread, and by 1915 the hatchery had released more than one million fish (Karas 1997). The proliferation of brook trout has led to the decline of native bull trout and cutthroat trout through hybridization, displacement, competition, and predation (Gunckel et al. 2002, Dunham et al. 2004, Peterson et al. 2004). Although the potential impacts of brook trout on salmonids remain virtually unexplored, Levin and colleagues (2002) found that the presence of brook trout was associated with a 12% reduction in the survival of juvenile salmon in Snake River basin streams. The mechanism driving this difference in survival is unknown.

Predation is the most quantifiable impact of nonindigenous fishes on native species. Channel catfish, large and smallmouth bass, and walleye are four noteworthy predators in the Pacific Northwest (figure 6). Channel catfish require spawning water temperatures of 21 to 27 degrees Celsius. Consequently, only the Snake (Idaho), Yakima (Washington), Walla Walla (Washington), Tucannon (Washington), and Columbia rivers currently have naturally reproducing populations. In Columbia River reservoirs, large channel catfish (> 67 centimeters) consume thousands of juvenile salmon, which comprise 50% to 100% of their diets (Vigg et al. 1991). A single catfish eats an average of one juvenile salmon every three

days in summer months (Vigg et al. 1991). To date, no studies have combined channel catfish population estimates with diet data to quantify the predatory impact of channel catfish on juvenile salmonids and other native species.

The construction of reservoirs associated with hydrosystem projects has facilitated the spread and establishment of many aquatic nonnative species, as well as the expansion of native species suited to these lotic environments (Harvey and Karieva 2005, Havel et al. 2005). This is certainly the case with smallmouth and largemouth bass (*M. dolomieu* and *Micropterus salmoides*), which are aggressive predators consuming virtually any prey smaller than the size of their gape, including fish, rats, mice, ducklings, frogs, snakes, and salamanders. The introduction of bass by private citizens began in the late 1800s, and since then bass have become well established throughout the region. In areas where freshwater bass have been introduced, predation by bass has contributed to the decline of some native fishes, frogs, and salamanders (Fuller et al. 1999). Although both smallmouth and largemouth bass prey on juvenile salmon, the impact is better documented for smallmouth bass, which consume 35% or more of juvenile salmon outmigrants in some regions (Fritts and Pearsons 2004). In addition, smallmouth bass have changed the size-based predation dynamics in some areas where they have largely displaced the native predator, northern pikeminnow (*Ptychocheilus oregonensis*; Fritts and Pearsons 2006). Unlike the case with pikeminnow, in which larger individuals have higher predation rates, smallmouth bass become piscivorous by two years of age, and their consumption of salmonids is highest for the smaller size classes (Fritts and Pearsons 2006).

Walleye were introduced much more recently than were most other nonnative species, but their means of introduction and spread are less documented. Since their introduction in the mid-1900s, walleye have colonized all reservoirs of the Columbia Basin Irrigation Project, most likely by migrating between reservoirs through irrigation pipes and canals (Lower Columbia Fish Recovery Board 2004). Walleye need warm water temperatures to spawn, and they have successfully established naturally reproducing populations, thus diminishing the incentive for continued stocking. Walleye are known to prey on juvenile Pacific salmon, consuming an estimated 250,000 to 2,000,000 smolts annually in the Columbia River (Rieman et al. 1991, Tinus and Beamesderfer 1994). The Columbia River basin is renowned for its walleye fishing, producing some of the largest individual fish on record.

In addition to NIS that compete with or prey on native taxa, our case histories include nonnative aquatic plant and invertebrate species that alter habitat and ecosystem functions. Nonindigenous aquatic invertebrates have been

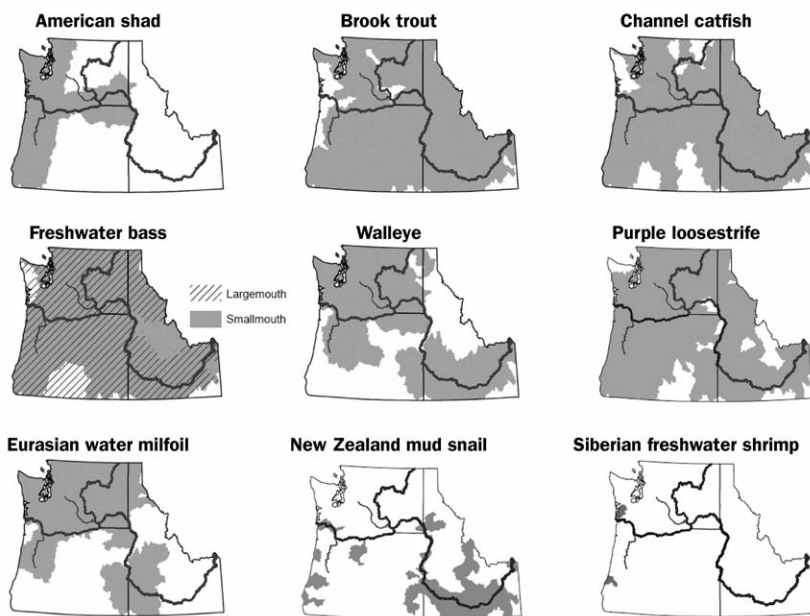


Figure 6. Distribution by fourth field HUC (hydrologic unit code) of non-indigenous fish with documented impacts on salmon, and aquatic plants and invertebrates with the potential to affect salmon streams.

implicated in the collapse of salmon populations elsewhere in the Pacific Northwest (Spencer et al. 1991). Despite the numerical abundance of nonnative plant and invertebrate taxa, the information needed to assess their impacts on aquatic and terrestrial ecosystems is rarely available, and thus the associated implications for habitats occupied by threatened and endangered salmonids are difficult to discern. Accordingly, these case histories are included here. Purple loosestrife (*Lythrum salicaria*) is a stereotypical invasive aquatic plant that was first found in the Pacific Northwest in 1929 (www.ecy.wa.gov/ecyhome.html). It grows rapidly, displacing native sedges and cattails (Blossey et al. 2001). Furthermore, this rapidly decomposing plant has the potential to produce a significant seasonal shift in local nutrient availability from a winter/spring flux to a fall flux. This shift may be detrimental to native fish species dependent on detrital food webs that peak in winter/spring (Blossey et al. 2001). Like purple loosestrife, Eurasian water milfoil (*Myriophyllum spicatum*) may also have been introduced by ballast soils from Europe in the 1800s (Aiken et al. 1979). This aquatic plant forms dense mats of vegetation that can depress dissolved oxygen concentrations at the sediment-water interface as they decompose, having significant effects on various aspects of aquatic ecosystem structure and function (Cronin et al. 2006, Unmuth et al. 2000).

Although their impacts have yet to be assessed, recent invertebrate introductions with the potential to influence salmon populations include the New Zealand mud snail (*Potamopyrgus antipodarum*) and Siberian freshwater shrimp (*Exopalaemon modestus*). The mechanism of the New Zealand mud snail's arrival in the mid-1980s is not known. Although small enough to fit on the tip of a match, these snails form dense colonies that can blanket streambeds. The mud snail can represent more than 95% of the invertebrate biomass in some areas, reaching densities of up to 500,000 individuals per square meter and exhibiting some of the highest reproduction rates observed for stream benthic invertebrates (Hall et al. 2003, 2006). Mud snail colonies have been reported to consume 75% of autochthonous gross primary production (Hall et al. 2003). They feed primarily on bottom-dwelling algae and detritus and can potentially outcompete other macroinvertebrates such as larval mayflies, stoneflies, and caddisflies (potential salmon prey) for food (Kerans et al. 2005). Mud snails have been identified in the stomachs of juvenile Chinook salmon sampled from the Columbia River estuary (Bersine et al. 2008). Whether these snails were intentionally ingested is not clear, but because of its thick shell and operculum, the snail is thought to be a poor nutritional source for salmon and other fish species, compared with insect larvae, fish, or other mollusks (Vinson and Baker 2008).

Unlike the mud snail, which clearly has the potential to affect native species, the potential impacts of the newly identified Siberian freshwater shrimp have not been studied. First detected in the lower Columbia River in 1995, the shrimp was very likely introduced by ship ballast water (Emmett et al.

2002). The prawn has rapidly extended its range and is already found in reservoirs in the lower Snake River (Haskell et al. 2006b). Although there have been no documented impacts to date, this nonnative shrimp may prey on native amphipods, such as *Corophium salmonis*, and directly compete with juvenile endangered salmon for important food resources (Emmett et al. 2002). Alternatively, it may provide a food source for native and nonnative resident fishes that also consume salmon (Haskell et al. 2006b).

We present only a few species histories here; however, each of the more than 700 NIS in the Pacific Northwest has its own unique story of introduction, establishment, and spread. Collectively, these stories demonstrate both how much and how little we know about NIS and their effects on native species and their ecosystems.

Predatory impacts of NIS: A literature review

Predation is the best-documented impact of NIS on Pacific Northwest salmon. Most of the information for the Columbia River basin has been obtained from small-scale studies performed on individual stream reaches or reservoirs, and restricted to an analysis of the impacts of encounters or interactions with a single NIS. Still, the limited numbers of empirical predation studies from the Columbia River basin outnumber those from other large river basins with Pacific salmon (Klamath River, California and Oregon; Sacramento River, California; Fraser River, British Columbia). Although focal studies indicate an enormous potential for NIS to affect salmon production and survival (Poe et al. 1991, Rieman et al. 1991, Vigg et al. 1991, Beamesderfer and Ward 1994, Baldwin et al. 2003), the necessary regional-scale, multi-species studies have not been undertaken.

By assembling all individual reports of predation on salmonids throughout the Columbia River basin, we can begin to ascertain the extent to which predation affects these threatened and endangered fishes. Accordingly, we reviewed all existing peer-reviewed and gray literature reporting the consumption of salmon by NIS for Pacific Northwest waters. Our extensive literature search spanning published results and regional studies identified 27 studies documenting six nonindigenous fish species. Among these studies, diverse metrics were used to quantify consumption of juvenile salmon. Typical measures of predation reported were the percentage of a predator's diet that is composed of salmon and the total number of juvenile salmonids consumed by a predator population. Quantifying the impact of nonnatives requires an examination of both the density and biomass of nonnative taxa relative to native taxa. Only a few studies have attempted to examine predation in this way, reporting results as the percentage of an individual run of juvenile salmon devoured by a predator population. Studies have also reported differing levels of detail about the salmonids consumed. Some have reported prey consumed simply as "salmonids," whereas others specified species and, in some cases, whether the fishes were wild or hatchery produced. (Hatchery fishes are generally tagged or fin clipped before release.) Although

most of the studies that discriminated between hatchery and wild fishes found that predominantly hatchery fishes were consumed, predator populations built on high hatchery outputs may prey more heavily on wild salmon as a result of complex compensatory dynamics in these modified food webs (Lichatowich 1999, Fritts and Pearsons 2004). The circumstances surrounding each of these individual predation studies were seemingly as unique as the diversity of their reporting styles. All told, this diversity of approaches warrants a cautious use of the data. Our goal in assembling these records was to call attention to the cumulative impacts of NIS on salmonids.

Collectively, the data culled from our literature review indicate that the cumulative impact of NIS on salmonids is potentially substantial. Figure 7 summarizes results from the 27 studies that quantified predation by nonindigenous fishes on salmonids. In cases where ranges of values were presented (e.g., 200,000 to 400,000 salmon consumed per year), we plotted the median value for the range given (in this example, 300,000 salmon consumed per year). Of those studies reporting the number of juvenile salmon eaten by individual NIS predators, we found values that ranged from zero to 10.4 million (median value = 5.2 million), with many studies reporting hundreds of thousands of juveniles consumed by a single NIS predator species at a specific study site in the Columbia River basin. At locations in the Columbia River, smallmouth bass and walleye consumed between 18,000 to 2,000,000 and 170,000 to 300,000 juvenile salmonids per year, respectively. Similar predation rates were noted in all geographic areas (Columbia, Snake, and Yakima rivers, and Washington lakes and coast). Results from studies measuring the percentage of an outmigrating juvenile salmon run consumed by one predator species ranged between zero and 40% (figure 7). Studies of individual predator diets also yielded valuable information on the extent to which juvenile salmon were found in predator stomachs. For example, salmonids composed up to 100% of channel catfish diets in the Columbia and Yakima rivers,

and similar percentages were reported for smallmouth bass and walleye diets. Many of these studies quantified diets but did not subsequently determine the predator and prey population sizes needed to estimate an overall predation impact.

Considered in isolation, each of these studies provides minimal insight into cumulative predator impacts, and the divergent methods used by individual studies to record predation by NIS on salmonids make quantifying cumulative impacts virtually impossible. Yet, as salmon migrate up and down the Snake and Columbia rivers, they encounter 20 to 40 NIS, providing the opportunity for multiple direct effects (e.g., predation and competition) and indirect effects (e.g., food-web changes and habitat changes; figure 8). We recognize that co-occurrence of nonnative species does not necessarily correlate with higher impacts. Nonnative fishes may thrive in the Columbia for a number of reasons, including the creation of favorable reservoir habitat, the seasonal influx of juvenile salmon prey, or perhaps the declining numbers of salmon has provided new opportunities for colonization. Discerning cause and effect is difficult because basic information about the abundance, distribution, and ecological effects of most of these nonnatives is lacking. Studies examining predation impacts on salmonids have focused largely on native predators, namely, northern pikeminnow and avian predators such as Caspian terns and cormorants. We found 28 peer-reviewed papers, written since salmon were listed under the ESA in 1992, investigating six native predator species at 19 locations along the Snake and Columbia rivers. By comparison, we found only 22 peer-reviewed studies encompassing six NIS species from 17 sites in the Columbia River basin (figure 8a, 8b, lower panels). Furthermore, research efforts have focused mainly on reservoirs upstream of dams on the Columbia and Snake rivers. By synthesizing data on the spatial distribution and known impacts of NIS on salmonids throughout the Columbia River basin (figures 7, 8), we can begin a discussion of the overall effects of these NIS.

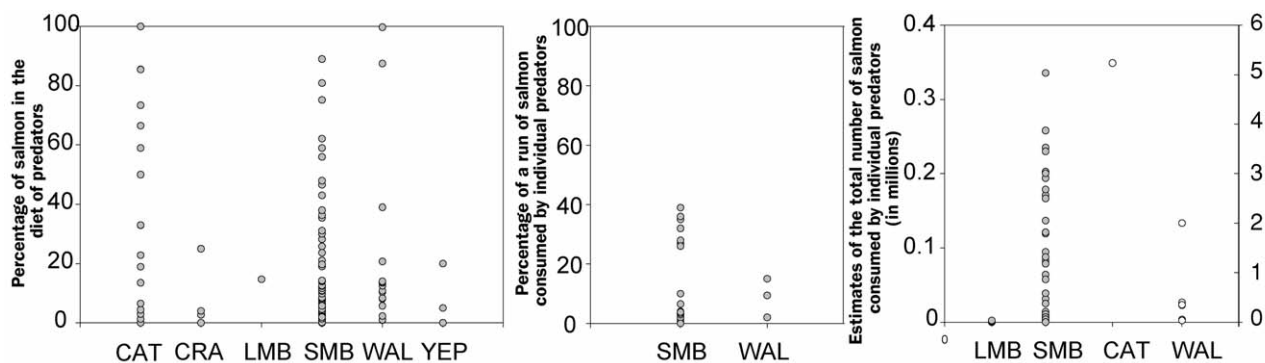


Figure 7. Results from literature review of 27 studies that document the percentage of salmon in the diet of predators (left panel), the percentage of a run of salmon consumed by individual predators (middle panel), and estimates of the total number of salmon consumed by individual predators in a given year (right panel). Species included are channel catfish (CAT), black and white crappie (CRA), large and smallmouth bass (LMB and SMB), walleye (WAL) and yellow perch (YEP). For the right panel, data for LMB and SMB (gray filled symbols) correspond to the left axis, and data for CAT and WAL (open symbols) correspond to the right axis.

Aliens in our midst: Are NIS ignored?

Throughout the Pacific Northwest, the causes of salmon population declines have been dominated by a discussion of the impact of the all-H's—hydrosystem, hatchery, harvest, and habitat. This all-H-centric view has largely ignored the impacts of key NIS in Pacific Northwest watersheds, which may rival the detrimental effects of the all-H's (Ruckelshaus et al. 2002). For example, on a per-run basis, the mortality attributed to NIS predation may be similar to that associated with juvenile passage through each of the eight dams on the Columbia and Snake rivers, estimated at approximately 5% to 15% per dam (Muir et al. 2001).

Similarly, predation by nonnative fishes on outmigrating smolts is roughly equivalent to the productivity declines attributed to habitat loss and degradation (Beechie et al. 1994). Furthermore, although it is difficult to make direct comparisons between adult and juvenile mortality with respect to population impacts, predation rates on juvenile outmigrants are also similar in magnitude to harvest-related mortality rates on adults (3% to 84%; McClure et al. 2003).

Despite clear evidence of the impact of NIS, a consideration of their role still falls outside all-H thinking. To illustrate this point and to quantify the level of funding directed to studies of nonnative species, we analyzed the \$385 million that the Bonneville Power Administration (BPA) Fish and Wildlife program has allocated to research, restoration and enhancement projects from 2007 to 2009 (Eric Schrepel, Northwest Power and Conservation Council [NWPCC], Portland, Oregon, personal communication, March 2008). BPA is required by the Northwest Power Act of 1980 to mitigate the adverse environmental effects imposed by its 31 federal hydropower dams in the Columbia River basin. To do so, BPA awards competitive funding to third-party agencies (e.g., universities, tribal groups, and state agencies) that conduct research and manage natural resources associated with the Columbia River basin. Given their broad geographic and ecological scope, and the relative amount of funding in dollar terms, the projects funded by BPA can logically be presumed to reflect the priorities of scientific inquiry among other funding agencies in this region.

Assisted by the agencies' staff, we scrutinized the NWPCC database of funded projects for the years 2007–2009. First, we identified funded projects with a nonnative species component using key words such as pikeminnow, squawfish, noxious, warm water, nonindigenous, nonnative, exotic, bass, eradication, weed, and control. Next, through careful examination of flagged projects, we classified project funding in accordance with the purpose of the project: research, control, or enhancement of NIS. We evaluated only projects with descriptions available online at the Columbia Basin Fish and Wildlife Authority Web site (www.cbfwa.org/funding_main.cfm). Funding for mixed com-

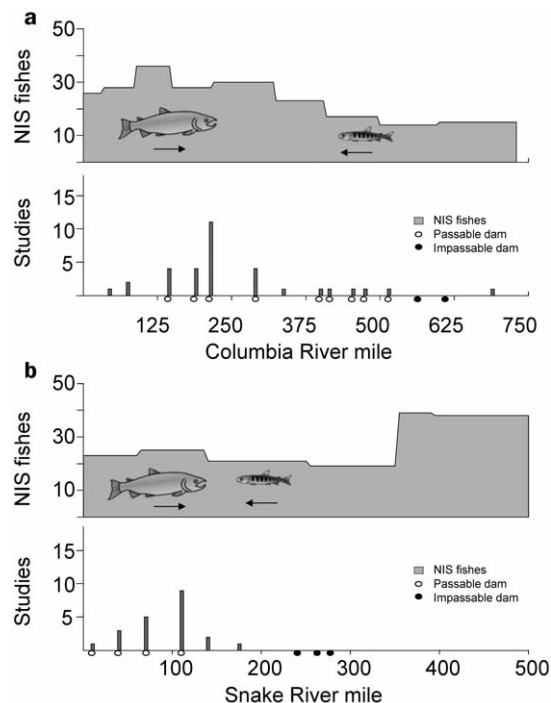


Figure 8. Number of nonindigenous fishes encountered by juvenile and adult salmonids as they migrate down and up the Columbia (a) and Snake (b) rivers. The Columbia River mile zero is located at the Columbia estuary, and the Snake River mile zero is located where the Snake merges with the Columbia River (river mile 325). The lower panel of each graph documents the number of published studies on nonindigenous species and the locations where these studies were conducted. Note that many of these studies were conducted near hydroelectric dams, which are identified by open (passable for salmonids) and closed (impassable for salmonids) circles.

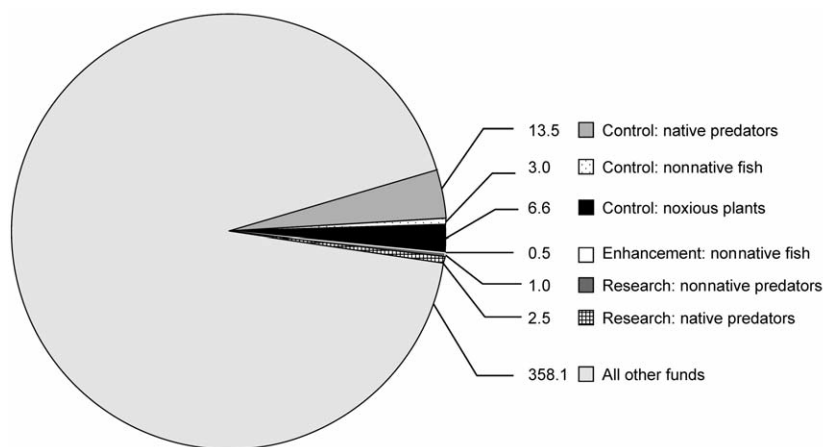


Figure 9. Funding (in millions of dollars) allocated to research and control of nonindigenous species in the Columbia River basin (2007–2009) by Bonneville Power Administration. Projects are categorized in accordance with their purpose: research on native or nonnative species, control (of noxious plants, nonnative fish, and native predators), enhancement of nonnative fish, and all other projects.

ponent projects was classified in an all-or-nothing manner such that funding for projects containing any research component was defined as research, whereas all other funding was allocated in accordance with the predominant project goal. Thus, the results reported here are biased toward funds allocated to nonnative research. Results of our survey indicate that of the \$385 million distributed by BPA over the three-year study period, only approximately 0.3% was directed in whole or in part toward research on the impacts of NIS (figure 9), and slightly less than 1% of funds were allocated to efforts to control nonindigenous fish species. A greater proportion of funding (approximately \$20 million, 5.2%) was spent on projects dedicated to the control and removal of noxious weeds and important native predators (e.g., pikeminnow and avian predators such as terns and cormorants). Although native to the region, these predator species have expanded their distribution and increased in abundance as a result of habitat modifications along the Columbia and Snake rivers. During this same period, \$560,000 was spent on enhancement projects designed to introduce or maintain populations of selected nonnative species. Specific information about the continued stocking of nonnative fishes in the Pacific Northwest is available on state management Web sites. Management agencies are becoming more cautious about introducing and stocking nonindigenous fishes, yet the continued stocking of some nonindigenous fish species reflects the high value attached to sport fisheries in this region.

Considering the percentage of funds allocated to NIS research and the results of our review of impacts, the level of attention given to NIS seems disproportionately small, given the magnitude of the potential threat that NIS pose to native communities. For wide-ranging migratory species, quantifying the impacts of countless NIS that occur over hundreds of miles is a daunting challenge. Thus, the scale of the NIS problem far exceeds the scale of most management and research efforts (ISAB 2008). To date, efforts to examine the role of NIS have been largely limited to site-specific studies of individual species.

Future opportunities for understanding and managing NIS already exist within ongoing research and management programs. The value of site-specific studies grows as results of individual studies are integrated across spatial and temporal scales relevant to the salmon life cycle. For example, as a cohort of juvenile salmon travel from their natal habitats to the ocean, what proportion of those individuals is lost to predation by nonnative species? Because many of the major NIS predators are popular game fishes managed by state agencies, the predator biomass data needed to quantify predation rates on salmonids are quite likely available. Additionally, native predator programs exemplify how the region might develop similar programs to mitigate the damage imposed by NIS and improve the chances of recovery for native species at risk. Only with a broad examination of NIS ecology and impacts by both existing and new research programs can we begin to answer questions that are key to evaluating the cumulative impact of NIS on salmonids.

Acknowledgments

We thank Chris Harvey, Blake Feist, Phil Roni, Ashley Steel, and three anonymous reviewers for insightful comments on drafts of this manuscript; Eric Schrepel at Bonneville Power Administration for assistance with the funding database; Danelle Heatwole for involvement in the early stages of database development; and Su Kim for involvement with graphic design. We are especially grateful to Pam Fuller, nonindigenous aquatic species program coordinator with the US Geological Survey, for helpful discussions and assistance with the data.

References cited

- Aiken SG, Newroth PR, Wile I. 1979. The biology of Canadian weeds, 34: *Myriophyllum spicatum* L. Canadian Journal of Plant Science 59: 201–215.
- Augerot X. 2005. Atlas of Pacific Salmon: The First Map-based Status Assessment of Salmon in the North Pacific. Berkeley: University of California Press.
- Baldwin CM, McLellan JG, Polacek MC, Underwood K. 2003. Walleye predation on hatchery releases of kokanee and rainbow trout in Lake Roosevelt, Washington. North American Journal of Fisheries Management 23: 660–676.
- Beamesderfer RC, Ward DL. 1994. Review of the Status, Biology, and Alternatives for Management of Smallmouth Bass in John Day Reservoir. Clackamas (OR): Oregon Department of Fish and Wildlife Fish Division. Information Reports no. 94-4. (8 January 2009; nrimp.dfw.state.or.us/crl/Reports/Info/94-4.pdf)
- Beechie T, Beamer E, Wasserman L. 1994. Estimating coho salmon rearing habitat and smolt production losses in a large river basin, and implications for habitat restoration. North American Journal of Fisheries Management 14: 797–811.
- Bersine K, Brenneis V, Draheim R, Wargo Rub A, Zamon J, Litton R, Hinton S, Sytsma M, Cordell J, Chapman J. 2008. Distribution of the invasive New Zealand mudsnail (*Potamopyrgus antipodarum*) in the Columbia River estuary and its first recorded occurrence in the diet of juvenile Chinook salmon (*Oncorhynchus tshawytscha*). Biological Invasions 10: 1381–1388.
- Blossey B, Skinner L, Taylor J. 2001. Impact and management of purple loosestrife (*Lythrum salicaria*) in North America. Biodiversity and Conservation 10: 1787–1807.
- Boersma PD, Reichard SH, Van Buren AN. 2006. Invasive Species in the Pacific Northwest. Seattle: University of Washington Press.
- Crall AW, Meyerson LA, Stohlgren TJ, Jarnevich CS, Newman GJ, Graham J. 2006. Show me the numbers: What data currently exist for non-native species in the USA? Frontiers in Ecology and the Environment 4: 414–418.
- Cronin G, Lewis WM, Schiehsler MA. 2006. Influence of freshwater macrophytes on the littoral ecosystem structure and function of a young Colorado reservoir. Aquatic Botany 85: 37–43.
- Czech B, Krausman PR. 1997. Distribution and causation of species endangerment in the United States. Science 277: 1116–1117.
- Dunham JB, Pilliod DS, Young MK. 2004. Assessing the consequences of nonnative trout in headwater ecosystems in western North America. Fisheries 29: 18–26.
- Emmett R, Hinton S, Logan D, McCabe GJ. 2002. Introduction of a Siberian freshwater shrimp to western North America. Biological Invasions 4: 447–450.
- Fritts AL, Pearsons TN. 2004. Smallmouth bass predation on hatchery and wild salmonids in the Yakima River, Washington. Transactions of the American Fisheries Society 133: 880–895.
- . 2006. Effects of predation by nonnative smallmouth bass on native salmonid prey: The role of predator and prey size. Transactions of the American Fisheries Society 135: 853–860.

- Fuller PL, Nico LG, Williams JD. 1999. Nonindigenous Fishes Introduced into Inland Waters of the United States. Bethesda (MD): American Fisheries Society. AFS Special Publication 27.
- Gido KB, Brown JH. 1999. Invasion of North American drainages by alien fish species. *Freshwater Biology* 42: 387–399.
- Gunckel SL, Hemmingsen AR, Li JL. 2002. Effect of bull trout and brook trout interactions on foraging habitat, feeding behavior, and growth. *Transactions of the American Fisheries Society* 131: 1119–1130.
- Hall R, Tank J, Dybdahl M. 2003. Exotic snails dominate nitrogen and carbon cycling in a highly productive stream. *Frontiers in Ecology and the Environment* 1: 407–411.
- Hall R, Dybdahl ME, VanderLoop MC. 2006. Extremely high secondary production of introduced snails in rivers. *Ecological Applications* 16: 1121–1131.
- Han M, Fukushima M, Kameyama S, Fukushima T, Matsushita B. 2008. How do dams affect freshwater fish distributions in Japan? Statistical analysis of native and nonnative species with various life histories. *Ecological Research* 23: 735–743.
- Harvey C, Karieva P. 2005. Community context and the influence of non-indigenous species on juvenile salmon survival in a Columbia River reservoir. *Biological Invasions* 7: 651–663.
- Haskell CA, Tiffan KF, Rondorf DW. 2006a. Food habits of juvenile American shad and dynamics of zooplankton in the lower Columbia River. *Northwest Science* 80: 47–64.
- Haskell CA, Baxter RD, Tiffan KF. 2006b. Range expansion of an exotic Siberian prawn to the lower Snake River. *Northwest Science* 80: 311–316.
- Havel JE, Lee CE, Vander Zanden MJ. 2005. Do reservoirs facilitate invasions into landscapes? *BioScience* 55: 518–525.
- Helfman GS. 2007. *Fish Conservation: A Guide to Understanding and Restoring Global Aquatic Biodiversity and Fishery Resources*. Washington (DC): Island Press.
- [ISAB] Independent Scientific Advisory Board. 2008. Non-native Species Impacts on Native Salmonids in the Columbia River Basin. Portland (OR): ISAB. Report no. 2008-4. (8 January 2009; www.nwcouncil.org/news/2008/08/4.pdf)
- Karas N. 1997. *Brook Trout: A Thorough Look at North America's Great Native Trout—Its History, Biology and Angling Possibilities*. New York: Lyons and Burford.
- Kerans BL, Dybdahl ME, Gangloff MM, Jannot JE. 2005. *Potamopyrgus antipodarum*: Distribution, density, and effects on native macroinvertebrate assemblages in the Greater Yellowstone ecosystem. *Journal of the North American Benthological Society* 24: 123–138.
- Lassuy D. 1995. Introduced species as a factor in extinction and endangerment of native fish species. *American Fisheries Society Symposium* 15: 391–396.
- Lever C. 1996. *Naturalized Fishes of the World*. San Diego: Academic Press.
- Levin PS, Achord S, Feist BE, Zabel RW. 2002. Non-indigenous brook trout and the demise of Snake River salmon: A forgotten threat? *Proceedings of the Royal Society of London B* 269: 1663–1670.
- Lichatowich J. 1999. *Salmon without Rivers: A History of the Pacific Salmon Crisis*. Washington (DC): Island Press.
- Lodge DM, et al. 2006. Biological invasions: Recommendations for US policy and management. *Ecological Applications* 16: 2035–2054.
- Lomnický GA, Whittier TR, Hughes RM, Peck DV. 2007. Distribution of non-native aquatic vertebrates in western U.S. streams and rivers. *North American Journal of Fisheries Management* 27: 1082–1093.
- Lower Columbia Fish Recovery Board. 2004. Lower Columbia Salmon Recovery and Fish and Wildlife Subbasin Plan. (7 January 2009; www.lcfrb.gen.wa.us)
- Mack RN, Simberloff D, Lonsdale WM, Evans H, Clout M, Bazzaz FA. 2000. Biotic invasions: Causes, epidemiology, global consequences, and control. *Ecological Applications* 10: 689–710.
- McClure MM, Holmes EE, Sanderson BL, Jordan CE. 2003. A large-scale, multispecies status assessment: Anadromous salmonids in the Columbia River basin. *Ecological Applications* 13: 964–989.
- Miller RR, Williams JD, Williams JE. 1989. Extinctions of North American fishes during the past century. *Fisheries* 14: 22–38.
- Muir WD, Smith SG, Williams JG, Sandford BP. 2001. Survival of juvenile salmonids passing through bypass systems, turbines, and spillways with and without flow deflectors at Snake River dams. *North American Journal of Fisheries Management* 21: 135–146.
- Nico LG, Fuller. 1999. Spatial and temporal patterns of nonindigenous fish introductions in the United States. *Fisheries* 24: 16–26.
- [NMFS] National Marine Fisheries Service. 1998. Factors Contributing to the Decline of Chinook Salmon: An Addendum to the 1996 West Coast Steelhead Factors for Decline Report. (7 January 2009; www.mwr.noaa.gov/ESA-Salmon-Listings/Salmon-Populations/Reports-and-Publications/upload/chnk-ffd.pdf)
- [NRC] National Resource Council. 1996. *Upstream: Salmon and Society in the Pacific Northwest*. Washington (DC): National Academy Press.
- . 2004. *Atlantic Salmon in Maine*. Washington (DC): National Academies Press.
- Parker IM, et al. 1999. Impact: Toward a framework for understanding the ecological effects on invaders. *Biological Invasions* 1: 3–19.
- Petersen JH, Hinrichsen RA, Gadomski DM, Feil DH, Rondorf DW. 2003. American shad in the Columbia River. Pages 141–155 in Linburg KE, Waldman JR, eds. *Biodiversity, Status, and Conservation of the World's Shads*, vol. 35. Bethesda (MD): American Fisheries Society.
- Peterson DP, Fausch KD, White GC. 2004. Population ecology of an invasion: Effects of brook trout on native cutthroat trout. *Ecological Applications* 14: 754–772.
- Pimentel D, Zuniga R, Morrison D. 2005. Update on the environmental and economic costs associated with alien-invasive species in the United States. *Ecological Economics* 52: 273–288.
- Poe TP, Hansel HC, Vigg S, Palmer DE, Prendergast LA. 1991. Feeding of predaceous fishes on out-migrating juvenile salmonids in the John Day Reservoir, Columbia River. *Transactions of the American Fisheries Society* 120: 405–420.
- Rahel FJ. 2002. Homogenization of freshwater faunas. *Annual Review of Ecology and Systematics* 33: 291–315.
- . 2007. Biogeographic barriers, connectivity and homogenization of freshwater faunas: It's a small world after all. *Freshwater Biology* 52: 696–710.
- Ricciardi A, Rasmussen JB. 1999. Extinction rates of North American freshwater fauna. *Conservation Biology* 13: 1220–1222.
- Richter B, Braun D, Mendelson M, Master L. 1997. Threats to imperiled freshwater fauna. *Conservation Biology* 11: 1081–1093.
- Rieman BE, Beamesderfer RC, Vigg S, Poe TP. 1991. Estimated loss of juvenile salmonids to predation by northern squawfish, walleyes, and smallmouth bass in John Day Reservoir, Columbia River. *Transactions of the American Fisheries Society* 120: 448–458.
- Rosenzweig ML. 2001. The four questions: What does the introduction of exotic species do to diversity? *Evolutionary Ecology Research* 3: 361–367.
- Ruckelshaus MH, Levin P, Johnson JB, Kareiva PM. 2002. The Pacific salmon wars: What science brings to the challenge of recovering species. *Annual Review of Ecology and Systematics* 33: 665–706.
- Schade CB, Bonar SA. 2005. Distribution and abundance of nonnative fishes in streams of the western United States. *North American Journal of Fisheries Management* 25: 1386–1394.
- Simberloff D, Parker I, Windle P. 2005. Introduced species policy, management, and future research needs. *Frontiers in Ecology and the Environment* 3: 12–20.
- Simon KS, Townsend CR. 2003. Impacts of freshwater invaders at different levels of ecological organization, with emphasis on salmonids and ecosystem consequences. *Freshwater Biology* 48: 982–994.
- Spencer CN, McClelland BR, Stanford JA. 1991. Shrimp stocking, salmon collapse, and eagle displacement. *BioScience* 41: 14–21.
- Tinus ES, Beamesderfer RC. 1994. *An Update on the Distribution, Fisheries, and Biology of Walleye in the Lower Columbia River*. Portland (OR): Oregon Department of Fish and Wildlife. Information Report 94-3.
- Unmuth JML, Lillie RA, Dreikosen DS, Marshall DW. 2000. Influence of dense growth of Eurasian watermilfoil on lake water temperature and dissolved oxygen. *Journal of Freshwater Ecology* 15: 497–503.

- [USFWS] US Fish and Wildlife Service. 2005. Threatened and Endangered Species System. (7 January 2009; www.fws.gov/Endangered/wildlife.html)
- Vigg S, Poe TP, Prendergast LA, Hansel HC. 1991. Rates of consumption of juvenile salmonids and alternative prey fish by northern squawfish, walleyes, smallmouth bass, and channel catfish in the John Day Reservoir, Columbia River. *Transactions of the American Fisheries Society* 120: 421–438.
- Vinson MR, Baker MA. 2008. Poor growth of rainbow trout fed New Zealand mud snails *Potamopyrgus antipodarum*. *North American Journal of Fisheries Management* 28: 701–709.
- Vitousek PM, D'Antonio CM, Loope LL, Westbrooks R. 1996. Biological invasions as global environmental change. *American Scientist* 84: 468–478.
- Wilcove DS, Rothstein D, Dubow J, Phillips A, Losos E. 1998. Quantifying the threats to imperiled species in the United States. *BioScience* 48: 607–615.
- Zaroban DW, Mulvey MP, Maret TR, Hughes RM. 1999. Classification of species attributes for Pacific Northwest freshwater fishes. *Northwest Science* 73: 81–93.

Beth L. Sanderson (e-mail: Beth.Sanderson@noaa.gov), Katie A. Barnas, and A. Michelle Wargo Rub are with the Northwest Fisheries Science Center of NOAA Fisheries Service in Seattle, Washington.

ΦΣ

Phi Sigma

ΦΣ

The Academic Honor Society for the Biological Sciences

- established in 1915 for the recognition of academic excellence and research in the biological sciences
- member of the American Institute of Biological Sciences (AIBS)
- member of the Association of College Honor Societies (ACHS)
- affiliate of the American Association for the Advancement of Science (AAAS)

For more information, contact: Henry R. Owen, Ph.D.
President of Phi Sigma Honor Society
Department of Biological Sciences
Eastern Illinois University
Charleston, IL 61920 USA

or visit our web site at: www.phisigasociety.org